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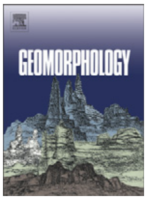

Polygon pattern geomorphometry on Svalbard (Norway) and western Utopia Planitia (Mars) using high-resolution stereo remote-sensing data

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ABSTRACT

Polygonal systems formed by thermal contraction cracking are complex landscape features widespread in terrestrial periglacial regions. The manner in which cracking occurs is controlled by various environmental factors and determines dimension, shape, and orientation of polygons. Analogous small-scale features are ubiquitous in Martian mid- and high-latitudes, and they are also inferred to originate from thermal contraction cracking. We studied the geomorphometry of polygonally-patterned ground on Svalbard to draw a terrestrial analogy to small-scale polygonal structures in scalloped terrain in Martian mid-latitudes. We performed a comparative quantitative terrain analysis based on high-resolution stereo remote-sensing data (HRSC-AX and HiRISE) in combination with terrestrial field data and multivariate statistics to determine the relationship of polygon geomorphometry to local environmental conditions. Results show that polygonal structures on Svalbard and in Utopia Planitia on Mars are similar with respect to their size and shape. A comparable thermal contraction cracking genesis is likely. Polygon evolution, however, is strongly related to regional and local landscape dynamics. Individual polygon dimensions and orthogonality vary according to age, thermal contraction cracking activity, and local subsurface conditions. Based on these findings, the effects of specific past and current environmental conditions on polygon formation on Mars must be considered. On both Earth and Mars, the smallest polygons represent young, recently-active low-centered polygons that formed in fine-grained ice-rich material. Small, low-centered Martian polygons show the closest analogy to terrestrial low-centered ice-wedge polygons. The formation of composite wedges could have occurred as a result of local geomorphological conditions during past Martian orbital configurations. Larger polygons reflect past climate conditions on both Earth and Mars. The present degradation of these polygons depends on relief and topographical situation. On Svalbard the thawing of ice wedges degrades high-centered polygons; in contrast, the present appearance of polygons in Utopia Planitia is primarily the result of contemporary dry degradation processes.

1. Introduction and background

Many landforms on Mars show similarities with periglacial features on Earth. On Earth these landforms reflect the effects of cold-climate conditions often in connection with permafrost dynamics. However, some of the periglacial features on Mars seem inconsistent with the prevailing Martian hydrological and climatic conditions because, like on Earth, water must have played an important role during their formation. The study of their characteristics, distribution, and spatial associations would therefore allow conclusions to be drawn about the climate history of Mars; thus, such a study can be used to indicate past and present environmental conditions. For instance, polygonal surface structures are a widespread phenomenon in periglacial landscapes on both Earth and Mars. This allows several conclusions to be drawn by analogy, but leaves open an important question: are these structures morphological analogs only, or is there a genetic relationship between them?

Patterned ground with polygon diameters ranging from meters to tens of kilometers has been described for many years on Mars (e.g., Lucchitta, 1981; Mellon, 1997; Seibert and Kargel, 2001; Mangold, 2005; van Gasselt et al., 2005; Levy et al., 2009a, 2010). While medium-sized (>100 m in diameter) and giant polygons (several kilometers) are suggested to originate by tectonic processes (e.g., Hiesinger and Head, 2000; Yoshikawa, 2003) or by desiccation in the case of medium-sized polygons (El Maarry et al., 2010), many authors have inferred that small-scale patterns (<100 m in diameter) are formed as thermal contraction polygons, analogous to terrestrial ice- and sand-wedge polygons (e.g., Seibert and Kargel, 2001; Mangold, 2005; Mellon et al., 2008; Levy et al., 2009a, 2010). Recently, it could be shown by mechanical modeling that the maximum size of polygons

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formed by thermal contraction is limited to a few decameters (El Maarry et al., 2010).

Generally, the average diameters of thermal contraction polygons on Earth range between a few meters and a few decameters. Low-centered polygons can be distinguished from high-centered polygons. Low-centered polygons are commonly characterized by outlining furrows, which are delineated by raised rims. Upturning rims form as a result of thermal expansion and lateral displacement of the active-layer (i.e., the upper soil layer which thaws seasonally) material above a growing ice or sand wedge (Mackay, 1980). High-centered polygons are the result of ice-wedge degradation followed by the enlargement and deepening of the polygon-outlining troughs (e.g., Washburn, 1979). Ice-wedge polygons are the most common type of thermal contraction polygons in more humid arctic regions. In hyper-arid polar deserts (e.g., the Antarctic ice-free areas, Canadian high Arctic), liquid water is lacking and cracks are commonly filled by eolian material or sand, building sand-wedge polygons (e.g., Péwé, 1959; Sletten et al., 2003; Bockheim et al., 2009) (Table 1). If local conditions favor the occasional support of moisture, composite wedges can develop (Murton, 1996). Special types of sand-wedge polygons described from the Antarctic Dry Valleys are high-centered sublimation polygons (Marchant et al., 2002; Marchant and Head, 2007). However, sand-wedge polygons can hardly be distinguished from ice-wedge polygons in the plan view (Black, 1976).

The term polygon is here used *in sensu* Washburn (1979), Yershov (2004), and French (2007) as a form of patterned ground indicative of continuous cold climates and the presence of permafrost. These polygonal networks are formed by thermal contraction fissures (Lachenbruch, 1962, 1966) after an initial crack is reactivated recurrently (Mackay, 1974, 1992) and widened through subsequent filling by water, sand, or soil (Péwé, 1959; Black, 1976; Sletten et al., 2003; French, 2007). The frozen ground cracks under volumetric tension due to long cold periods and a severe soil temperature drop in winter (Yershov, 2004; Christiansen, 2005; Fortier and Allard, 2005). This in turn depends on the coefficient of thermal expansion which is larger in ice-rich sediments than in ice-free sediments (Lachenbruch, 1962) (Table 1). The strength and direction of stress vectors during thermal contraction, which determine dimension, shape, and orientation of thermal contraction polygons, are controlled by various factors such as air and ground temperature variations, subsurface conditions (i.e., rheology and water/ice content), topography, and stress-free vertical surface (e.g., breaks, other cracks, terrain edges, and talik rims). Some of these factors are summarized in Table 1; these factors offer the possibility of estimating the subsurface and climate conditions that existed during polygon formation by geomorphometric properties.

Although no clear evidence for the processes responsible for the formation of small-scale polygons on Mars can yet be presented, the distribution of these polygons at middle to high latitudes (Mangold, 2005; Levy et al., 2009a) and their spatial relationship to ground ice on Mars (Mangold et al., 2004) suggest that these landforms are formed by thermal contraction cracking, which is controlled by specific periglacial climatic and subsurface conditions (Levy et al., 2010). Furthermore, the relationship of likely active thermal contraction polygons to periglacial landscape features in a geomorphologic context compared to terrestrial analogs allows conclusions to be drawn about small-scale polygon origin on Mars. However, even if most of the conclusions about Martian polygon evolution are very detailed and plausible, they frequently offer only qualitative explanations. Only a few studies have been done regarding polygon geomorphometry on Mars using quantitative methods (e.g., Rossbacher, 1986; Pina et al., 2008; Dutilleul et al., 2009; Haltigin et al., 2010). Therefore, based on very-high-resolution stereo remote-sensing data, comparative quantitative terrain analysis in combination with geomorphological and sedimentological field data from terrestrial polygons was used to verify the hypothesis that polygonal structures on Earth and Mars, which are similar in appearance, originate from comparable processes. Additionally, a multivariate statistical approach has been applied to validate and compare the relationship of polygon geomorphometry to the topographical conditions of various polygonal sites from a mid-latitude region on the Martian northern hemisphere and an analogous high-arctic region in central Spitsbergen (Svalbard) (Hauber et al., 2011, in press). The main objective of this paper is, first to highlight the relationship between geomorphometric parameters of thermal contraction polygons and site-specific topographical and subsurface conditions on Earth. Second, this understanding will be applied to give insights into formation processes and subsurface conditions of small-scale polygonal patterned ground on Mars by comparison of their associated geomorphometry. Bearing in mind the regional geomorphological context of diverse polygonal fields within periglacial landscapes, this work focuses on Adventdalen (Svalbard) and on the scalloped terrain in Utopia Planitia (Mars).

2. Characterization of study areas

2.1. Svalbard (Adventdalen)

The Svalbard archipelago, and in particular its largest island, Spitsbergen (Fig. 1), exhibits a diverse inventory of periglacial landforms in close spatial proximity. Svalbard is situated in the zone of continuous permafrost (Brown et al., 1998), which is widespread primarily outside the 60%-glacier-covered area (Humlum et al., 2003).

Table 1
Literature-based compilation of climate and subsurface conditions in relation to various thermal contraction polygon properties.

Indicator	Control factors	Effects	Reference
Polygon formation	Air and soil temperature, grain size	In silt, clay, and peat: <−3 °C in sand and gravel: −8 °C to −10 °C	Washburn (1979); Romanovskii (1985); Yershov (2004)
	Insulation	Limiting the continuous frost cracking	Washburn (1979); French (2007)
Polygon diameter	Temperature gradient	Large gradient → harsher climate → smaller polygons	Yershov (2004); French (2007)
	Rheology of frozen ground	Heat conductivity (grain size, ice content) → fine-grained, high ice content → smaller polygons	Lachenbruch (1962, 1966)
Polygon form	Stress free zones	Orthogonal → near the cooling surface hexagonal → in larger distance	Romanovskii (1977)
	Ground homogeneity	Hexagonal patterns – stress balance	Lachenbruch (1962); French (2007)
	Stage of development	Secondary cracking → polygon subdivision → more regular and orthogonal	Lachenbruch (1966); French (2007)
Polygon orientation	Stress relief	Oriented if stress-free vertical surfaces exist (i.e., anisotropy of strength)	Lachenbruch (1962)
Polygon nets	Drainage	Small nets → <27° slope Large nets → to 31° slope	Washburn (1979)
Ice or sand wedge formation	Atmospheric and ground humidity	High aridity → sand wedge polygons	Péwé (1959); Black (1976); French (2007)
Ice-wedge polygon formation	Soil temperature, grain size	In clay → <−2 °C, in gravels → <−6 °C	Romanovskii (1985)