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Potential desiccation cracks on Mars: A synthesis from modeling, analogue-field studies, and global observations

M.R. El-Maarry [a,*], W. Watters [b], N.K. McKeown [c], J. Carter [d], E. Noe Dobrea [e,f], J.L. Bishop [g], A. Pommerol [a], N. Thomas [a]

[a] Physikalisches Institut, Bern Univeristät, Sidlerstrasse, 5, 3012 Berne, Switzerland
[b] Whitin Observatory, Department of Astronomy, Wellesley College, Wellesley, MA, 02481, USA
[c] Department of Physical Sciences, MacEwan University, Edmonton, Alberta, Canada
[d] Institut d'Astrophysique Spatiale, Paris-Sud University, Orsay, France
[e] Planetary Science Institute, Tucson, AZ, 85719, USA
[f] NASA Ames Research Center, Mountain View, CA, 94035, USA
[g] SETI Institute, Mountain View, CA 94043, USA

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ABSTRACT

Potential desiccation polygons (PDPs) are polygonal surface patterns that are a common feature in Noachian-to-Hesperian-aged phyllosilicate- and chloride-bearing terrains and have been observed with size scales that range from cm-wide (by current rovers) to 10s of meters-wide. The global distribution of PDPs shows that they share certain traits in terms of morphology and geologic setting that can aid identification and distinction from fracturing patterns caused by other processes. They are mostly associated with sedimentary deposits that display spectral evidence for the presence of Fe/Mg smectites, Al-rich smectites or less commonly kaolinites, carbonates, and sulfates. In addition, PDPs may indicate paleolacustrine environments, which are of high interest for planetary exploration, and their presence implies that the fractured units are rich in smectite minerals that may have been deposited in a standing body of water. A collective synthesis with new data, particularly from the HiRISE camera suggests that desiccation cracks may be more common on the surface of Mars than previously thought. A review of terrestrial research on desiccation processes with emphasis on the theoretical background, field studies, and modeling constraints is presented here as well and shown to be consistent with and relevant to certain polygonal patterns on Mars.

1. Introduction

1.1. Polygonal patterns on Mars

Surface polygonal patterns are common on Mars. These patterns attain a range of shapes and variable sizes, which can vary from cm- to km-sized patterns. Historically, most of the surface patterns, in particular those observed at high latitudes (>45°), were classified as periglacial features that evolve through thermal contraction (e.g., Mutch et al., 1976; Lucchitta, 1981; Mellon, 1997; Seibert and Kargel, 2001; Mangold, 2005; Levy et al., 2009; Lefort et al., 2010). Nevertheless, the desiccation mechanism was consistently proposed as an alternative mechanism since the Viking era of exploration (e.g., Mutch et al., 1976). The reason for the frequent suggestion of these two hypotheses is the morphological similarity between polygonal features created by desiccation and thermal contraction at the size-scales that were initially observed (5–20 m-range) making it difficult to differentiate between them on the basis of remote sensing alone.

With the introduction of orbiting high resolution cameras that had tens of meters-scale of spatial resolution and enough spatial coverage and mission longevity to map the entire surface of Mars, researchers observed a latitudinal dependence in the distribution of patterned ground with a clear preference for high latitudes, which indicated that most of the surface patterns, except for perhaps the tectonically-controlled km-sized polygons in Utopia (e.g., Pechmann, 1980; McGill and Hills, 1992; Moscardelli et al., 2012), form by thermal contraction in a periglacial-like climatic setting. Indeed, the current climate on Mars and a multitude of data that indicate that Mars has been cold for the past ~3 byr support these conclusions (Fairén, 2010 and references therein).

* Corresponding author.
E-mail address: mohamed.elmaarry@space.unibe.ch (M.R. El-Maarry).

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Furthermore, numerical models that take into account the daily and seasonal temperature variations, the presence of near-surface ice, and surface albedo and thermal inertia of frozen soils (e.g., Mellon, 1997; Fisher, 2005; Mellon et al., 2008) have yielded accurate predictions of the expected size-scales of thermal-contraction polygons (TCPs) on Mars (5–20 m in size). These estimates have since been validated by other measurements such as the detection of near-surface ice (within the first meter of the surface) at high latitudes by the Gamma Ray Spectrometer (Boynton et al., 2007) and in-situ analyses made by the Phoenix lander (Smith et al., 2009; Mellon et al., 2009) in addition to extensive mapping work (e.g., Mangold, 2005; Levy et al., 2009), which has recognized the important role of ice-rich soils in shaping the high latitudes of Mars.

A significant leap in our understanding of surface morphology and active processes on Mars was achieved with the insertion of the Mars Reconnaissance Orbiter (MRO) into orbit in 2007. In particular, the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) onboard MRO allowed observation of the surface of Mars at unprecedented sub-meter (0.25–0.5 m/pixel) scales. Taking advantage of such spatial resolutions, more surface fracture patterns were observed, particularly in the southern highlands, which differ from the conventional morphology and size-scale of TCPs on Mars. In addition, these features do not show a significant latitudinal dependence but instead a regional preference for sedimentary environments that could have harbored liquid water more than 3 byr ago.

1.2. Early climatic conditions on Mars

The geological record of Mars suggests that it has been cold and dry for most of the last 3 byr, except for regionally localized transient events (see Fairén, 2010 and references therein). However, a significant debate remains regarding the first billion years that followed the planet's formation of a solid crust, which generally corresponds to the Noachian period (Scott and Tanaka, 1986; Hartmann and Neukum, 2001). The Noachian crust records various lines of evidence that suggest that there may have been a more globally active hydrological cycle (Carr, 1996 and references therein), and potentially a warmer climate. This evidence includes the presence of valley networks and associated deltas (e.g., Carr, 1986, 1995; Baker et al., 1991; Gulick, 2001; Fasset and Head, 2008; Di Achille and Hynek, 2010; Hynek et al., 2010), explosive volcanism, which involves the interaction and mixing of magma with near-surface volatiles (e.g., Reimers and Komar, 1979; Blasius and Cutts, 1981; Hynek et al., 2003; Wilson and Head, 2007; Kerber et al., 2012), in addition to the surface mineralogical diversity and wide extent of clay minerals as well as other hydrous phyllosilicates (e.g., Poulet et al., 2005; Bibring et al., 2006; Mustard et al., 2009; Murchie et al., 2009; Ehlmann et al., 2009, 2011; Wray et al., 2009; Carter et al., 2010) and salts such as carbonates (e.g., Ehlmann et al., 2008a, 2008b), sulfates (e.g., Langevin et al., 2005; Mangold et al., 2008; Murchie et al., 2009; Wray et al., 2010, 2011) and chlorides (Osterloo et al., 2008, 2010).

Imaging spectrometers, in particular the "Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité" (OMEGA) imaging spectrometer (Bibring et al., 2004), and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) have identified thousands of sites rich in hydrous minerals, and in particular smectites, which are a special family of phyllosilicate minerals that have a high affinity for water, and generally form in environments that feature liquid water activity. In association with these smectites and other hydrous minerals, many researchers have noted the presence of polygonal crack patterns, which have been more often than not, attributed to desiccation of the once water-saturated smectites (e.g. Ehlmann et al., 2008a, 2008b, 2009; Wray et al., 2010, 2011; Erkeling et al., 2012; Bishop et al., 2013a; McKeown et al., 2013; El-Maarry et al., 2013a). Since the vast majority of phyllosilicate occurrences is confined to Noachian-aged terrains (Bibring et al., 2006; Carter et al., 2013), which formed in a period of debatable climatic conditions, understanding the processes that create polygonally cracked terrains can shed light on the climatic conditions during the time of their formation.

1.3. Structure and organization of the paper

We present here a synthesis of the collective evidence that shows that desiccation cracks are more common on the surface of Mars than previously thought. In Section 2, we initially review the state of terrestrial research that is relevant to our study on desiccation processes, field studies, and modeling constraints. At this point we should point out that throughout this paper, we will be citing many terrestrial studies that describe desiccation in terrestrial "soils" that generally include organic matter and imply some form of biological influence, which is generally different from the description of a "sediment", which is a form of material that is eroded, transported and deposited by physical processes such as wind or water. However, in our description of clay-bearing terrains or deposits on Mars, we may sometimes use the terms "soil" and "sediment" interchangeably since a "soil" is generally regarded in planetary literature as simply any fine-grained material including those sufficiently fine-grained to be mobilized by wind (e.g., Karunatillake et al., 2007, and references therein). In Section 3 we present an inventory of the sites on Mars containing potential desiccation polygons (PDPs) and review their geologic setting. Finally, we discuss possible means of identifying desiccation polygons from other polygonal patterns on Mars, as well as their potential value as lithological and climatic indicators in Section 4.

2. Advances in terrestrial research on desiccation

2.1. The desiccation mechanism

Desiccation is usually achieved through evaporation from the surface, or diffusion processes either through the migration of liquid water due to differences in water potential, or vapor transport due to changes in water vapor pressure. The degree to which a material (soil or sediment) contracts with loss of volatiles (usually liquid water) depends on its capacity for holding these volatiles on a macro scale through having a significant pore or void volume within the solid structure, and on a micro scale through its chemical activity and/or ability to accommodate water molecules within its crystal structure (El-Maarry et al., 2012). Generally, the more clay-rich (grain size <2 μm) the soil or sediment is, the more it will shrink with desiccation. In addition, certain clay minerals, known as smectites, are known for their chemical affinity to swell (sometimes several magnitudes beyond their dry volume) and accommodate considerable amounts of water through formation of water interlayers on a molecular level (Velde, 2010).

If the desiccated materials are not allowed to shrink effectively, stresses (mainly tensile) begin to build-up within the desiccated medium creating a stress zone. The thickness of the stressed zone is affected by many factors such as the desiccation rate, the mineralogy, the soil or sediment's physical properties and the presence/absence of salts, which mainly influences the desiccation rate (e.g., Plummer and Gostin, 1981). The stresses that build-up with desiccation may lead to the formation of tensile cracks in the desiccation medium, which we investigate further in the next section.