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Evidence for very recent melt-water and debris flow activity in gullies in a young mid-latitude crater on Mars

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ABSTRACT

Terrestrial debris flows and their deposits are mainly studied and monitored because of their hazardous nature. On Mars they may serve as geomorphologic indicators of transient liquid water. We compared the morphology of debris flow-like deposits within a young (~0.2 Ma) mid-latitude crater on Mars with debris flow fans on Svalbard as possible terrestrial analogues. It was our objective to constrain whether dry granular flow or processes related to water-saturation at or close to the surface were responsible for the formation of the deposits within the crater. We found that the morphological attributes of the deposits on Mars are very similar to debris flows in Svalbard and include overlapping terminal lobes, debris tongues and snouts, debris-flow fans, scoured channels with medial deposits (debris plugs), and clearly defined lateral deposits (levées). Furthermore, the interior crater walls display a range of landforms indicating aspect-dependent degradation, ranging from debris flow-dominated pole-facing slopes, to east-and-west-facing single channel gullies and north-facing talus cones (granular flow). Our findings suggest that the debris flows are not related to impact-induced heating and release of meltwater. We further suggest that degradation of a latitude dependent dust–ice mantling unit may only have played a minor role in this youthful terrain. Instead, we propose that the debris flows are mainly formed by melting of very recent snow deposits after the termination of the last martian ice-age. As such they may represent some of the most recent geomorphological indicators of transient liquid water in the martian mid-latitudes. The distinct north–south asymmetry in degradation further demonstrates that insolation-controlled slope processes are surprisingly efficient on Mars during the last <1 Myr.

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1. Introduction

On Earth, debris flows are mainly studied and monitored because of their hazardous nature (e.g., Coussot and Meunier, 1996; Jakob and Hungr, 2005). On Mars debris flows have been linked to the formation of gullies (Costard et al., 2002; Hartmann et al., 2003), whose mode of formation has been puzzling for the science community since their discovery by Malin and Edgett (2001). Gullies on Mars are known to display a range of different morphologies, but typically include a source alcove, a chute or channel and a depositional fan (Malin and Edgett, 2001). Numerous models have been proposed to explain the origin of the gully landforms such as release of water from aquifers (e.g., Malin and Edgett, 2000; Gaidos, 2001), melting of ground ice (e.g., Costard et al., 2002), and melting of snow (e.g., Christensen, 2003). In addition, a number of "dry" processes have been proposed, such as dry mass movements (Treiman, 2003) and CO_2 driven processes (Musselwhite et al., 2001). However, none of these dry processes are able to form all of the observed morphologic attributes of martian gullies, and the latter is unlikely due to stability relations of CO_2 on Mars (Stewart and Nimmo, 2002). A dry mass-wasting mechanism that may account for some debris-flow-like morphology of recent and contemporary bright gully deposits is frosted granular flow (Hugenholtz, 2008). However, the latitudinal distribution (e.g., Milliken et al., 2003; Dickson et al., 2007; Kneissl et al., 2010), Earth-analogue studies (e.g., Head et al., 2007; Reiss et al., 2011), detailed geologic studies (e.g., Schon et al., 2009; Reiss et al., 2010), and modeling (e.g., Williams et al., 2009) suggest that scenarios of top-down of melting of ice and snow packs are more likely to form gullies. Several authors have studied the morphology of gully channels (e.g., Mangold et al., 2010) and gully fans (e.g.,

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Levy et al., 2010; Lanza et al., 2010; Reiss et al., 2011), and they support this notion. Hence, for the majority of gullies, there is a consensus that the most likely medium involved in their formation was water (e.g., Dickson and Head, 2009). Attention is now drawn towards the source of water and the dominant transport/deposition mechanism of sediments for gully-fan formation (e.g., Conway et al., 2011; Reiss et al., 2011). The observed range of gully-fan morphologies suggests a couple of depositional mechanisms. These will likely vary at spatial and temporal scales due to regional and local differences in climate (e.g., Dickson and Head, 2009; Morgan et al., 2011; Aston et al., 2011), water source and water availability (e.g., Malin and Edgett, 2001; Márquez et al., 2005; Levy et al., 2009; Raack et al., 2012), lithology (e.g., Reiss et al., 2009) and topography (Dickson et al., 2007). Recent studies on gully morphology suggests that the dominating mechanism is fluvial deposition (e.g., Reiss et al., 2011), in contrast to debris-flow dominated fans which have only been documented at a few sites on Mars (Levy et al., 2010; Lanza et al., 2010; Reiss et al., 2011). In this respect, debris flows seem to play only a minor role in sediment transport on Mars. Previous reports show that the debris-flow-like deposits within Hale crater (Reiss et al., 2011) and on the Protonilus Mensae mesa (Levy et al., 2010) formed smooth-textured debris lobes and levées of particles not resolvable in HiRISE resolution (~25 cm/pxl). The likely source of the water in these two cases was melting of ice within the atmospherically derived dust–ice mantle (Levy et al., 2010; Reiss et al., 2011). Modeling and morphology (Mangold et al., 2010), and results from slope–area analyses on Mars and known gully systems on Earth (Lanza et al., 2010; Conway et al., 2011) suggest a general dominance of debris flow processes on Mars, although the plan-view morphological evidence is not consistently present. Hence, the relative role of debris flows in gully formation is under debate.

Here we report on unusually well-preserved debris-flow-like deposits in an unnamed 4.7-km diameter crater in the southern hemisphere of Mars. The range of observed details corresponds very well to typical morphologic attributes of terrestrial debris flows (e.g., Coussot and Meunier, 1996; Johnson and Rodine, 1984). Contrary to previously identified debris-flow-like landforms on Mars, these deposits contain a significant amount of large-particle material (i.e. individual clasts are resolved in HiRISE imagery), which has been incorporated in the deposits. Furthermore, the interior crater walls display a range of aspect-dependent degradation, ranging from debris-flow-like deposits on pole-facing slopes, to east-and-west-facing single channel gullies and north-facing talus cones (granular flow). This raises the following questions: Why do so clearly-defined debris-flow-like deposits occur here and not in other previously documented young craters in similar settings? What is the timing of these morphological events? What is the most likely source of water? Here we characterize the morphology of the martian debris-flow-like deposits and their relationship to the other mass-wasting landforms within the crater. Furthermore, we compare their morphology to debris-flow deposits in Svalbard to be able to constrain the depositional mechanisms of the martian landforms. We use crater size–frequency distribution to constrain the age of the crater.

2. Data used

In order to compare observations on Mars to Earth, martian and terrestrial data sets with similar characteristics were used. Data sets from Mars include those obtained from the Mars Reconnaissance Orbiter (MRO) Context Imager (CTX) with an image resolution of ~6 m/pxl (Malin et al., 2007), High Resolution Imaging Science Experiment (HiRISE) with an image resolution of ~25 cm/pxl (McEwen et al., 2007), Thermal Emission Imaging System (THEMIS) (Christensen et al., 2004) with an image resolution ~100 m/pxl and Mars Express Orbiter (MEX) High Resolution Stereo Camera (HRSC) with an image resolution between ~10 and ~30 m/pxl (Neukum et al., 2004; Jaumann et al., 2007). Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter topographic point data (MOLA) (Smith et al., 2001) were also included in the analyses. MOLA point data has a vertical resolution of less than a meter on a smooth surface but may increase to ~10 m on ~30° slopes (Smith et al., 2001). HiRISE and CTX images have been processed using ISIS3 software and analyses have been done in ArcGIS 10.2. HiRISE images were projected to 25 cm/pxl and elevation data was derived from MOLA points. THEMIS night-time IR images show the surface temperature at 100 m/pxl resolution and make it possible to differentiate thermo-physical properties of surface materials (i.e. composition, structural integrity and grain sizes). For the terrestrial part of this study, we used images obtained with an airborne version of the Mars Express High Resolution Stereo Camera (HRSC) called HRSC-AX (Neukum et al., 2001). Like HRSC, HRSC-AX is a multi-sensor push-broom instrument with 9 CCD line sensors mounted in parallel with channels for nadir panchromatic, stereo panchromatic and color imaging (Jaumann et al., 2007). The processed panchromatic nadir orthoimages have a spatial resolution of ~20 cm/pxl. Data were acquired during a flight campaign in July/August 2008 (Hauber et al., 2011a). Image analysis has been complemented by four field expeditions in 2008, 2009, 2011 and 2012, respectively, for ground truth. For comparison we used satellite imagery of Mars obtained by HiRISE which has a comparable spatial resolution of 25 cm/pxl. By doing so, we avoid the problem of scaling between the two data sets. Morphometric measurements of the Svalbard debris flows were done using a digital elevation model derived from the HRSC-AX data with draped imagery. The DEM has a horizontal grid size of 50 cm.

3. Background

3.1. Ice-rich latitude dependent mantle terrain and its relationship to gullies on Mars

The mid-to-high latitudes on both hemispheres at Mars are dominated by a surficial, meters thick draping smooth deposit, which is suggested to be an air-fall deposit of fine-grained particles, cemented by atmospherically deposited ice (Kreslavsky and Head, 2000). This deposit is found equatorward of 30° in both hemispheres (Kreslavsky and Head, 2000; Mustard et al., 2001). This mantle, named the latitude-dependent mantle (hereafter named LDM) has been recognized to be geologically recent (e.g., Mustard et al., 2001; Milliken et al., 2003) and its formation is suggested to be driven primarily by Mars obliquity excursions and orbital variations (Laskar et al., 2004), as follows. Mean polar insolation is predicted to increase at high obliquity and volatiles located at the poles will sublimate and redistribute to lower latitudes (Head et al., 2003; Levrard et al., 2004; Morgenstern et al., 2007; Madeleine et al., 2009). At latitudes between ~30° and ~60° on both hemispheres the mantle appears dissected, which has been interpreted as current loss of ground-ice by sublimation and deflation of sediment (Mustard et al., 2001). The relationship between obliquity variations and climate led Head et al. (2003) to the interpretation of a recent ice age during a period of enhanced mean obliquity from approximately 2.1 to 0.4 Ma. The strong spatial correlation between gullies and the dissected LDM led some authors to suggest a linkage between gully formation and degradation of the LDM (e.g., Dickson and Head, 2009; Schon and Head, 2011, 2012; Dickson et al., 2013). In most cases gullies incise the LDM and fans display a smooth surface texture where individual clasts are not resolvable in HIRISE images, suggesting

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