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A new dry hypothesis for the formation of martian linear gullies

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ABSTRACT

Long, narrow grooves found on the slopes of martian sand dunes have been cited as evidence of liquid water via the hypothesis that melt-water initiated debris flows eroded channels and deposited lateral levées. However, this theory has several short-comings for explaining the observed morphology and activity of these linear gullies. We present an alternative hypothesis that is consistent with the observed morphology, location, and current activity: that blocks of CO_2 ice break from over-steepened cornices as sublimation processes destabilize the surface in the spring, and these blocks move downslope, carving out levéed grooves of relatively uniform width and forming terminal pits. To test this hypothesis, we describe experiments involving water and CO_2 blocks on terrestrial dunes and then compare results with the martian features. Furthermore, we present a theoretical model of the initiation of block motion due to sublimation and use this to quantitatively compare the expected behavior of blocks on the Earth and Mars. The model demonstrates that CO_2 blocks can be expected to move via our proposed mechanism on the Earth and Mars, and the experiments show that the motion of these blocks will naturally create the main morphological features of linear gullies seen on Mars.

1. Introduction

Observations of long, shallow, and narrow features eroded into the lee-slope of a mega-dune in Russell crater (Fig. 1A) were first reported by Mangold et al. (2002). Further imaging by the Mars Orbiter Camera (MOC) on the Mars Global Surveyor and the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter has demonstrated that these *linear gullies* (terminology adopted within recent literature (Dundas et al., 2012; Védie et al., 2008) to differentiate these features from gullies of alcove–channel–apron [ACA] form) are found within many dune fields and on sandy crater walls within the mid-latitudes on pole-facing slopes (Di Achille et al., 2008; Reiss et al., 2007). These slopes typically range from 7° to 12° (well below the angle at which a dry granular material is expected to flow (Jouannic et al., 2012; Mangold et al., 2003; Reiss et al., 2007)), but the gully alcoves and grooves appear to originate within the steeper upper slope (can be >25°; Jouannic et al., 2012). Over the past three Mars years, HiRISE images show that existing grooves have elongated and new grooves have formed at the start of each spring (Dundas et al., 2012; Reiss et al., 2010; this study), demonstrating that these features are active in the present-day martian climate.

As shown in Fig. 1, a linear gully on Mars consists primarily of a long (few hundred meters up to 2.5 km) groove that has near-uniform width (generally a few to 10 m wide, and sometimes with slight narrowing downslope), is near-linear throughout most of its length (but sometimes contains zones of low-to-high sinuosity), and is commonly surrounded by levées. Groove incision depth is usually from less than 1 m to 2 m and appears shallowest within regions of lowest slope (at the base of the dune), but some portions can exceed 3 m (Jouannic et al., 2012). The groove is generally topped by a small alcove and/or converging small grooves that originate at the dune brink (or, if on a sandy slope, where sand first becomes visually apparent). Downslope, the groove abruptly ends and lacks a debris apron. It sometimes ends with a terminal pit, sometimes in a chain of pits, or sometimes in a series of divergent small grooves, each with a terminal pit. A pit generally has a diameter comparable to, but larger than the groove width. Grooves sometimes converge downslope. Except within the very distal portion, they do not diverge.

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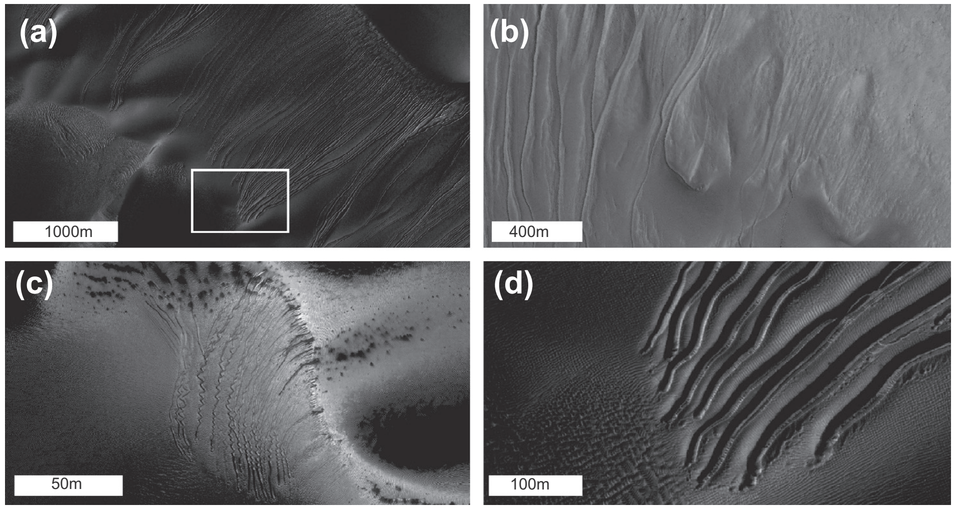

Fig. 1. Examples of martian linear gullies: (a) long linear gullies on a dune in Russell crater (PSP_001440_1255), (b) gullies on a sandy wall of Avire crater (ESP_019709_1390), (c) extremely sinuous linear gullies in Kaiser crater (PSP_010749_1325), (d) terminal pits along dune gullies in Russell crater (PSP_001440_1255, inset in (a)).

Many studies have attempted to explain the mechanism(s) responsible for formation of these features. The most common hypothesis is that linear gullies are formed by water-supported debris flows (e.g., Costard et al., 2002; Gargani et al., 2012; Jouannic et al., 2012; Mangold et al., 2003; Mangold et al., 2010; Miyamoto, 2004; Reiss and Jaumann, 2003; Reiss et al., 2010; Védie et al., 2008) based on proposed morphological resemblance to terrestrial landforms carved by flowing water. Dry hypotheses have also been proposed: based on correlations observed between defrosting markers and gullies in Russell crater, Hansen et al. (2007) proposed that sublimation of CO_2 could play a role in linear gully activity. Di Achille et al. (2008) examined pits found on Noachis and Aonia Terrae dunes and suggested that defrosting processes, glacial-like creep, and rolling sand–ice aggregates may form these features.

In this paper, we present a new and detailed look at a dry hypothesis: that seasonal CO_2 ice forms in the winter and breaks into blocks that fall down the dune slope, carving out a groove and leaving a terminal pit when the block comes to a rest and sublimates. First, we discuss some of the shortcomings of the debris flow theory (Section 2). We then describe, in detail, the dry hypothesis (Section 3). We present analogue and experimental evidence that the main morphological features, placement, and activity of martian linear gullies can form through interactions between solid blocks of CO_2 ice with a granular surface and *without the need for liquid water* (Section 4). We demonstrate consistency between the morphology predicted by the proposed mechanism and both analogue features formed by falling blocks on a range of surfaces and experiments involving dry ice blocks moving down terrestrial dune slopes. We also report on observations of blocks that briefly appear within linear gullies on Mars. We discuss a theoretical model of the mechanism by which CO_2 ice is able to levitate and move down shallow slopes (Section 5) and use this to scale relevant forces between Earth and Mars conditions.

2. Debris flow hypothesis

Debris flows consist of a gravity-driven mass of poorly sorted sediment, dispersed within a fluid slurry (Iverson, 1997; Takahashi, 1981). Both solid and fluid forces strongly influence the motion of the flow as the pore fluid mediates inter-granular friction and collisions but do not completely suspend the sediment, thus distinguishing debris flows from related phenomena such as dry granular flow, rock avalanches, turbidity currents, and sediment-laden water floods. The resultant geomorphological feature is generally composed of a source alcove, a single linear channel with lateral ridges (levées), and a terminal distal cone or fan. These features can also exhibit pervasive, fluid-like deformation such as the movement of even boulder-rich debris through tortuous channels, across gentle slopes, and around obstructions (Iverson et al., 1997).

The debris flow hypothesis was originally applied to martian linear gullies by Costard et al. (2002) based on morphological analogy between these martian landforms and debris flows in Greenland and following a suggestion by Malin and Edgett (2000) that ACA gullies found on crater walls were formed due to groundwater seepage and surface runoff. Costard et al. (2002) suggested the linear gullies (and ACA gullies) formed during a previous period of high obliquity, when water ice may have accumulated in large volumes within the near-subsurface at the top of the dune and then melted. Subsequent studies have since examined this meltwater-based formation mechanism (e.g.,Mangold et al., 2010; Miyamoto, 2004) in efforts to quantitatively connect observed morphology to fluid metrics, and some have even hypothesized that debris flows could occur under the present climate conditions due to episodic or seasonal melting of water ice (Reiss and Jaumann, 2003; Reiss et al., 2010).

Many observations, experiments, and theoretical models, however, do not support the debris flow hypothesis. In particular:

(1) Martian linear gullies have two salient morphological features that are unexplained by the debris flow theory: the absence of depositional aprons at the terminus and presence of meandering patterns (Fig. 1C). Some studies have hypothesized complicated mechanisms to account for these features, such as a progressive increase in water-fraction downslope (Gargani et al., 2012; Jouannic et al., 2012) or pulses of water over ice-rich permafrost (Védie et al., 2008). However, laboratory and numerical models involving simulated debris flows on dune slopes have generally been unable to reproduce these morphologies (e.g., Coleman et al., 2009; Conway et al., 2011; Mangold et al., 2010). Moreover, naturally-occurring terrestrial debris flows on cold-climate aeolian dunes do not yield meandering channels and do form well-defined terminal lobes or aprons (e.g., Bourke, 2005; Hugenholtz et al., 2007; Hooper et al., 2012). Thus, it remains unexplained how debris flows on a