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Laboratory simulations of Martian gullies on sand dunes

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[1] Small gullies, observed on Mars, could be formed by groundwater seepage from an underground aquifer or may result from the melting of near-surface ground ice at high obliquity. To test these different hypotheses, a cold room-based laboratory simulation has been performed. The experimental slope was designed to simulate debris flows on sand dune slopes at a range of angles, different granulometry and permafrost characteristics. Preliminary results suggest that the typical morphology of gullies observed on Mars can best be reproduced by the formation of linear debris flows related to the melting of a near-surface ground ice with silty materials. This physical modelling highlights the role of the periglacial conditions, especially the active-layer thickness during debris-flow formation. **Citation:** Védie, E., F. Costard, M. Font, and J. L. Lagarde (2008), Laboratory simulations of Martian gullies on sand dunes, *Geophys. Res. Lett.*, *35*, L21501, doi:10.1029/2008GL035638.

1. Introduction

[2] The recent discovery of groundwater seepage and surface runoff on Mars suggests the local occurrence of subsurface liquid water at mid- and high latitudes during recent periods. It has been proposed that surface runoff features result from subsurface seepage of water [*Malin and Edgett*, 2000; *Márquez et al.*, 2005], deep aquifers [*Gaidos*, 2001], brines [*Andersen et al.*, 2002], near-surface ice melting during recent periods (10^5 to 10^6 years) of high obliquity [*Costard et al.*, 2002; *Gilmore and Phillips*, 2002; *Hartmann*, 2003; *Mangold et al.*, 2003] or during seasonal melting [*Reiss and Jaumann*, 2002; *Kossacki and Markiewicz*, 2004], recent period snowmelt (within the past 10^5 to 10^6 years) [*Christensen*, 2003; *Lee et al.*, 2001], geothermal heating [*Mellon and Phillips*, 2001], liquid CO_2 breakout [*Hoffman*, 2000; *Musselwhite et al.*, 2001] or dry landslides [*Treiman*, 2003; *Shinbrot et al.*, 2004; *Bart*, 2007]. Among this wide variety of surface runoff features, an unusual example of debris flow on sand dunes exhibit very specific morphology. They are characterised by (i) being limited to sand-dune slopes, (ii) a typical morphology with long regular and narrow channels, (iii) the development of networks comprising long, parallel down-dip flows (Figure 1). The precise processes of these gullies' formation remain speculative and terrestrial analogues have not been yet described. For this reason our study focuses on the formation of the characteristic morphology by means of various laboratory simulations performed within a cold room. Here, the objective was to simulate linear gullies, like those observed on Mars, and to evaluate the respective influence of different parameters in terms of their efficiency for the formation of these gullies. Based on these laboratory simulations, we report the possibility of explaining these gully features on sand dunes to result from surface to near-surface melt of volatile-rich material. In this study, we describe how the depth of the active layer significantly controls the formation of Martian linear gullies observed in the Russell crater. Such an interpretation has important consequences in term of recent climatic change on Mars.

2. Gullies on Dunes

[3] The SW flank of the megadune in Russell crater (55°S and 347°W) exhibits over 300 long, narrow linear gullies, that were first discovered by *Mangold et al.* [2003] and subsequently described by *Reiss and Jaumann* [2003] and *Miyamoto et al.* [2004]. These gullies are *c.* 2.5 km in length, less than 10 m in width and their mean slope is 10°. They begin from regularly spaced small alcoves just under the crest of the dune (Figure 1). Individual gullies exhibit linear, narrow channels with levées. In the MOC and THEMIS images, relatively small distal-lobes are found at the downslope end of the channels. From high resolution HIRISE images, most of the terminal deposits do not show terminal lobes, but rather a concentration of small pits of unknown origin (possibly thermokarst processes). The composition of these debris flows over the sand dunes implies that these structures are composed of finer particles than normal terrestrial debris flows [*Mangold et al.*, 2003].

[4] These dune gullies show levées and sinuosity with connections. Current seasonal melting has been proposed to explain gullies that occur on hillslopes [*Bridges et al.*, 2001] or on dunes [*Reiss and Jaumann*, 2002, 2003]. Recent HIRISE images clearly show a blanketing of CO_2 frost covering the southern flank of dunes. Dark spots observed on the tops of the dunes are attributed to the sublimation of CO_2 [*Mangold et al.*, 2003]. The possibility of snowmelt has not been excluded [*Lee et al.*, 2001; *Christensen*, 2003].

[5] Typical gullies, originating from the top of isolated peaks and from dune crests, were first reported by *Baker* [2001] and *Mangold et al.* [2003]. In these examples, the involvement of a subsurface aquifer seems unlikely. The morphometric characteristics of Martian gullies, especially the existence of levées, sinuosity and connections, strictly limits the formation of gullies by rapid flows of rock-water mixture containing a high proportion of sediment.

[6] Field studies in Greenland [*Costard et al.*, 2002] have shown that debris flows are not systematically formed by groundwater seepage, but that they can simply result from the thawing of near-surface ice (melting of the active layer). This occurs when the latter becomes impregnated by liquid

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Figure 1. Linear gullies on the surface of a sand dune in the Russell crater on Mars. HIRISE image PSP_002904_1255 (25 cm/pixel). The image is 2 km wide. Credit NASA/JPL/University of Arizona.

water during the melting of snow and the interstitial ice [*Larsson*, 1982; *Harris and Gustafson*, 1993]. The melting of the active layer then represents the main source of liquid water. Debris flows are usually initiated when the critical shear stress is reached following the increase of fluid pressure within the weathered debris layer [*Johnson and Rodine*, 1984; *Iverson*, 1997]. Terrestrial studies also show that permafrost thaw can decrease the stability of hillslopes [*Huscroft et al.*, 2003; *Davies et al.*, 2001; *Harris et al.*, 2001; *Nelson et al.*, 2002; *Pissart*, 2005], particularly in the context of global warming. These climatic conditions could be reached on Mars during high-obliquity periods [*Costard et al.*, 2002].

3. Laboratory Simulations

[7] The relative importance of the main parameters affecting the debris-flow dynamics is, however, hard to assess from high resolution images. Too many factors work simultaneously and their interdependence makes their analysis very difficult. Laboratory simulation studies provide the opportunity for more detailed monitoring than Mars imagery. For this purpose, the experimental slope was designed to simulate debris flows on sand dunes with various slope angles, different granulometry and permafrost characteristics (active-layer depth, ice content). In this experiment, we did not take into account the influence of the lower atmospheric pressure and we assume liquid water to be stable during the debris-flow formation. To simulate a periglacial environment these experiments require a cold room, large enough to accommodate an experimental slope (Figure 2). We used the facility at the University of Caen/CNRS in France, in a laboratory dedicated to physical geomorphological modelling [*Calmels and Coutard*, 2000; *Font et al.*, 2006; *Védie*, 2008].

[8] In this experiment, we assumed that the scale effect was not a limited factor. Here, we restricted our approach to the relative importance of the parameters studied and their consequential influence on the morphology. Our small-scale experiment used a rectangular box of 2.5 m, 0.55 m wide and 0.50 m deep in which a ground surface of fine sand (D_{50} = 200 μm; $Wp_{(max)}$ = 19 %) or silt (D_{50} = 20 μm; $Wp_{(max)}$ = 31%) materials was saturated with water (Figure 2). Two morphologies were tested, with a median slope gradient of 15° in one case and 25° in the second. The upper and lower slope-gradients were kept constant (50° and 8° respectively). Two types of water supply were tested (Figure 2):

[9] 1. To simulate a perched aquifer, a solid and porous synthetic foam was placed on the top of the rim crest. Then

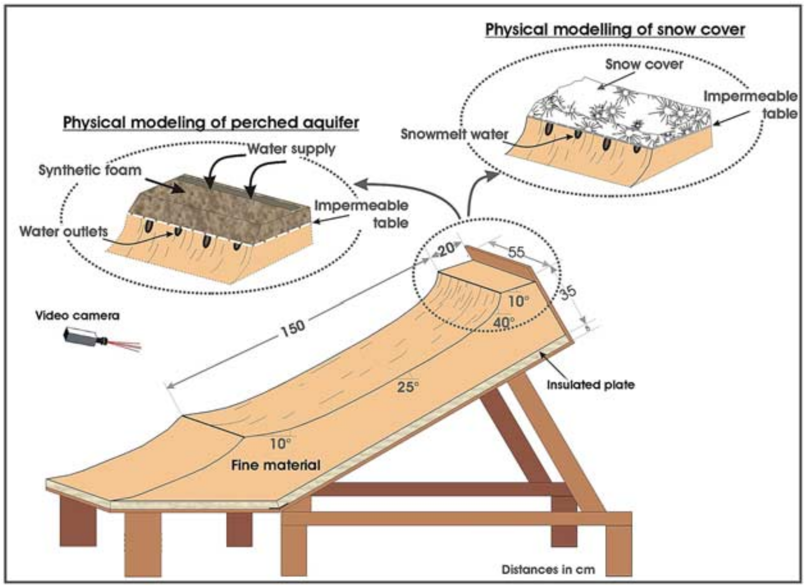

Figure 2. Close-up of the apparatus used for the physical modelling of the debris flows.

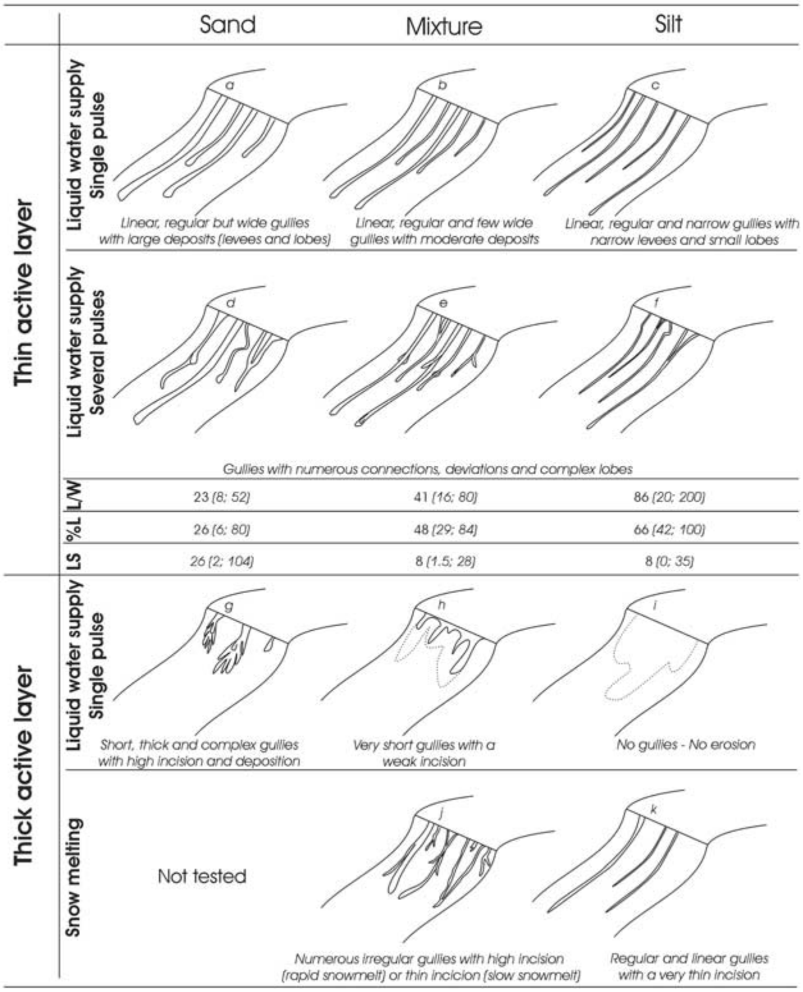

Figure 3. Synthesis of gully morphologies obtained from physical modelling. In the thin active layer cases, some quantification was made: LS = Lobe Superficy; %L = % of gully confined by lateral levées; L/W = Length/Width ratio. The minimum and maximum values are given in brackets. On the Russell crater, L/W ratio of the gullies is close to 120, lobes are insignificant (LS is close to 0) and %L are not clearly defined.

during thawing, a controlled water supply (0.2 L) was injected into the foam.

[10] 2. Inflowing snowmelt water during thawing was simulated (2 L) using fine particles of ice (<1 mm) that covered the complete upper part of the slope.

[11] For each experiment, the material was initially saturated immediately before freezing. Permafrost was created at depth (0.50 m) with a temperature of −10°C. After freezing, the surface of the frozen soil was then progressively warmed from the top to control formation of the active-layer. The model was instrumented using temperature sensors (platinum resistance thermometers Pt100) to survey the freezing front and permafrost thickness. During each simulation and the development of possible associated gullies, a video recording was made using a 3CCD digital video camera (Panasonic NV-GS400). This allowed later analysis and repeated observation to the flow dynamics.

4. Experimental Results

[12] Dry destabilisations [*Treiman*, 2003; *Shinbrot et al.*, 2004] were first simulated close to the crest of the experimental dune. Triggered mass-wasting was large, unchannelised and they became assimilated into landslides. Their morphology was completely different from those of the linear debris flows observed on the Russell crater dune. Secondly, we undertook some experiments using a thin snow cover over the whole slope surface, as suggested by *Lee et al.* [2001]. In the typical situation, no debris flows were observed, probably because the melting of the snow cover was too limited and diffuse. Then we used a perched aquifer and local snow melting, in order to induce a relatively abundant, local water supply (Figure 3). It appears that the best situation to generate experimental gully morphologies similar to those on Mars was by using a preferential pulse of water (melting of local snow cover or superficial aquifer discharge on the upper simulated cornice) over ice-rich permafrost. In this setting, gully morphology was particularly sensitive to four factors: active-layer thickness (periglacial conditions), material cohesion, liquid (water) supply and slope gradient.

4.1. Active Layer

[13] We undertook various experiments using a large range of active-layer depths (from 1 mm to 2 cm). A relatively thin active layer was needed to form long, narrow

Figure 4. Narrow gullies with lateral levées and relatively small terminal lobes. The morphological characteristics of these gullies on silt are similar to those found in the Russell crater on Mars. The analogy with Figure 1 is striking. At the top sinuous channels occur on the rim crest. In the middle slope connections between gullies and the variation of their growth by successive waves of debris occur, resulting from several pulses of water from the rim crest.

linear gullies comparable to those seen on Mars (Figure 3). When active-layer thickness exceeded *c*. 5 mm, incision increases, resulting in a high quantity of transported material which then forms substantial accumulations (levées and terminal lobes). In this case, the large deposits inhibited the following flows which lead to the development of complex and non-linear gullies.

4.2. Material

[14] To test the influence of lithology, we used different frozen materials (three different grain-size distributions from fine sand to silt) but with the same volume of water supply and similar active layer thickness. It appeared that silt material strongly increased the length/width ratio of the debris flows and the percentage of channel length confined by levées (Figure 3). Moreover, the surface area of the deposits, especially those of terminal lobes, were relatively high (on average *c*. 26 cm^2) for sandy gullies in comparison to silty lobes (8 cm^2). It might imply that the Martian dunes in the Russell crater are made of a very fine and cohesive material.

4.3. Water Supply

[15] To obtain such linear gullies, a single pulse of water was required. Each gully resulted from one source of water expressed by a single wave. When several pulses of water from the rim crest flowed downslope, successive waves of debris were observed. Then slope morphology showed various connections between gullies and the variation of their growth (Figures 3d–3f and central gully in Figure 4).

4.4. Slope Gradient

[16] Depending on the rheological properties of terrestrial debris flows [*Johnson and Rodine*, 1984], the variation of debris flows' velocities are related to the small variation of slope angle. The width of both channels and levées follows that law. We did some experiments with a variation of the slope angle in which channels and levées appeared larger on low slopes, as observed by *Mangold et al.* [2003] in the gullies of Russell crater dune. Experiments showed an average increase of channel width from 1.3 to 3 cm (+130%), with slope gradients of respectively 20 and 10°. We also noted a clear difference for levée-width which reached 8 mm on a low slope gradient (10°), for example, and only 3 mm on a slope tilted at 45°.

5. Concluding Remarks

[17] Over 40 laboratory simulations were carried out in the cold room over two years, in order to understand the formation of gullies on Martian sand dunes. Laboratory simulations have allowed us to reproduce gullies that developed a morphology that is extremely close to those of gullies observed on the Russell crater megadune. This work confirms that periglacial debris flow could be an important formative process for the genesis of such typical morphologies, different from that known on the surface of Earth. We then suggest that these morphologies, observed on the Martian dunes, could best be explained by the melting of near-surface ground ice in silty materials [*Védie*, 2008] (Figure 3). Localised, rapid melting of superficial ground ice could destabilise the superficial part of the soil and trigger debris flow which then propagates downwards in a linear direction. This physical modelling highlights the role of the active layer during the debris-flow formation. This work demonstrates that a periglacial environment, with a near surface permafrost table, is required to form the Martian gullies. The implication for Mars is that Martian dunes in the Russell crater should be expected to be constructed of ice-riched silty materials. This interpretation agrees with the low albedo, which should correspond to volcanic sands [*Mangold et al.*, 2003]. Finally, laboratory simulations attest to the efficiency of periglacial processes that control both erosion and gully development. Near-surface ice-rich permafrost leads to a rather low sinuosity, to an homogeneity and to a high length of the channel. The effects of the silty material increase both the length/width ratio of the channel and the percentage of channel length confined by lateral deposits. Our experiments suggest that the morphology of the gullies observed on the Mars surface implies the presence of ice-rich permafrost with a relatively thin active layer. The active layer, together with the permafrost table, control the characteristic morphology of these linear gullies, whatever may be the origin of the water (snow melt, a perched aquifer or the melting of permafrost).

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