EXPERIMENTAL STUDY OF CO_2 SUBLIMATION AS A TRIGGER FOR MASS WASTING.

M. E. Sylvest[1] , J. C. Dixon[1], A. Barnes[2], and G. Ito[1,3], [1]Arkansas Center for Space & Planetary Sciences, University of Arkansas, Fayetteville, AR, [2]Center for Advanced Spatial Technologies, University of Arkansas, Fayetteville, AR, [3]University of Michigan, Ann Arbor, MI.

Introduction: The role of CO_2 frost in the development and modification of Martian gullies has gained increased interest in response to the observation of contemporary changes in gully morphologies [1]. CO_2 vapor-supported density flow was suggested [2] shortly after Malin & Edgett first described gully morphology observed with the Mars Orbiter Camera [3]. Yet, the mechanics and extent of CO_2 frost-related processes on Martian gully evolution remain unclear. Proposed mechanisms have included CO_2 frost avalanches [4,5], frosted granular flow [5], and sediment fluidization [6]. Other studies have focused on CO_2 ice as a trigger for debris avalanches [7].

Our objectives are to experimentally explore the behavior of simulated Martian slopes in response to CO_2 frost sublimation, and to identify and characterize relationships between factors that influence slope morphology. The results of these experiments will serve as benchmarks for a multi-scale, multi-physics numerical model, patterned after Denlinger and Iverson [8].

Methods: Two experimental apparatus configurations have been used.

Experiment 1. A 12 x 18 x 12 cm tall Lexan box (fig. 1a) was filled with ~5 to 10 mm of JSC Mars-1 regolith simulant. Up to 5 mm of granular CO_2 ice (average grain size ~2 mm, maximum < 5 mm) mixed with regolith, was layered over the regolith base.

After sample preparation, the box was placed at an angle (20° to 35°) under a 300 W halogen lamp ~25 cm above the slope surface. The slope surface was recorded with an HD webcam until all apparent sublimation and slope movement ceased, typically around 40 minutes.

Experiment2. A12 x 30 cm Plexiglass box with sloping sides was used (fig.1b). A vertical baffle was used to confine a rectangular column of regolith, ~12 cm high, in the tall end of the box. 1 to 2 cm of granular CO_2 ice was layered on top of the column, and 0.5 – 1 cm of regolith was spread over the ice. The box was then placed under a 150 W halogen lamp. The baffle was removed, allowing the layered ice and regolith column to collapse and settle at the angle of repose. A matched pair of HD cameras, mounted with the lamp ~33 cm above the base of the slope, simultaneously recorded the slope surface until sublimation and slope movement essentially stopped.

Photogrammetry: Prior to experimentation, a fine point marker was used to place 10 black dots – control points – around the box rim, and at each corner of the Plexiglass box base. A calibrated DSLR camera/lens and close-range photogrammetric software were then used to create a 3D model of the box, establish a three-dimensional Cartesian coordinate system relative to the base plane of the box, and export the precise (overall RMS 0.48 mm) XYZ coordinates of each control point.

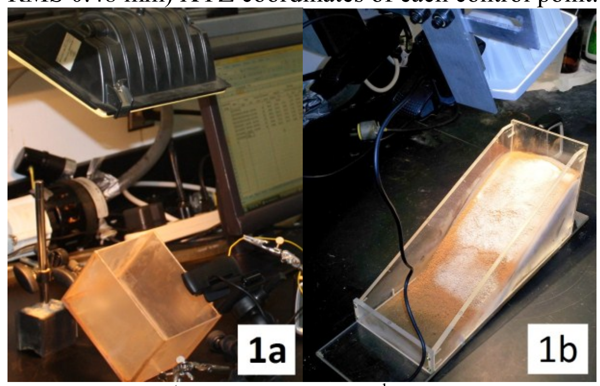

Figure 1. (a) 1st experiment. (b) 2nd experiment.

The matched HD webcams were affixed to a purpose-built mount with a stereo baseline of 9 cm. At the end of each experiment, the webcam mount was manually repositioned and stabilized at several locations above the box. Stereo image pairs were collected from the video at several time intervals throughout the video, and at several locations as the cameras were repositioned. These image pairs, along with the control point coordinates, were used to photogrammetrically derive fully referenced digital elevation models (DEMs) with a horizontal resolution of 0.34 mm.

Results & Discussion: A variety of mass wasting styles were observed, under a range experimental conditions. These were observed to be related to levels of surface activity. For experiments with the least activity, the only mass movements were due to sliding of the entire slope as a single unit along the bottom of the box, for the first experimental configuration; and subsidence, due to the removal of the CO_2 volume, for the second configuration.

At the greatest activity levels, frequent slides of individual particles dominated. Although we expect these small events might singly, or cumulatively, trigger larger-scale movements, no definitive cases have been isolated. In a very limited number of cases, pits and scarps (on the order of 3 to 5 mm) were observed to result from large-scale slides.

In order to assess the influence of controlling factors, motion detection software was used to measure the frequency of trigger events as detected in each video recording as an indicator of activity level. Fig. 2 correlates detected event frequency against initial slope angle, initial ice mass, ambient air temperature and relative humidity. Frequencies and control variables were normalized and scaled to facilitate direct comparisons between dimensionally dissimilar parameters.

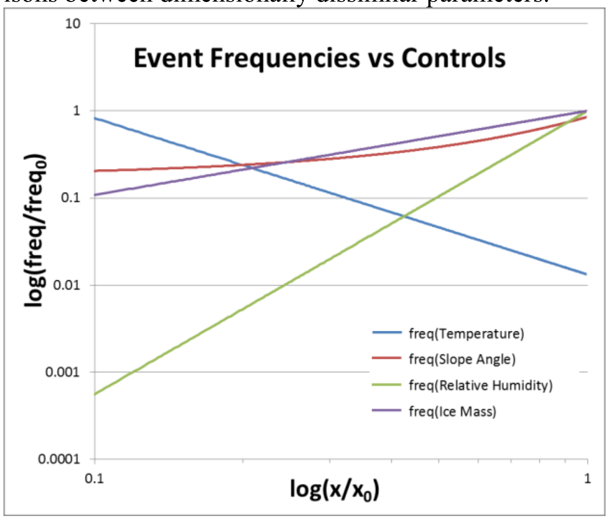

Figure 2. Log-Log comparison of normalized mass wasting event frequency as function of: ambient temperature, mean slope angle, relative humidity and initial CO_2 ice mass. **x/x_0** represents the ratio of the particular control value a reference value.

Larger-scale mass wasting, resulting in gully morphologies similar to those described by Malin [3], are most likely on steep slopes, and slopes with high curvature [9]. Our results demonstrate an exponential growth in trigger event frequency with increasing mean slope angle.

Over the range our experiments, the influence of the initial mass of CO_2 ice on trigger frequency is of similar magnitude to that of slope angle. However, the effect of steepening slope will increase more rapidly than the rate of increasing ice mass, based on the best-fit data curves.

The strongest measured influences on trigger event frequency were relative humidity and air temperature (Fig. 2). Increased humidity provides H_2O for frost formation. Under our experimental conditions, this frost was primarily dendritic, providing little cohesion. The additional mass of the frost may act to destabilize the slope surface, although this was not readily apparent by direct observation.

Although the CO_2 sublimation rate increases with increasing temperature, for a given absolute humidity, as the temperature increases, the relative humidity decreases. The stronger influence of relative humidity on trigger frequency overcomes any increase in sublimation rate. Decreasing air temperature favors frost formation, not only due to increasing relative humidity, but also by reducing the temperature gradient between the slope surface and moisture in the air. Determining the independent effect of temperature will require the ability to control the temperature, pressure and absolute humidity above the slope.

Changes in slope surface morphology can be usefully detected using GIS approaches. Figure 3 is an example of the vertical differencing of DEMs at two time intervals. The vertical displacement of each pixel on the slope surface is color coded from maximum cut, in dark red, to elevation gain, in blue. This representation is then draped over the surface model at the later interval.

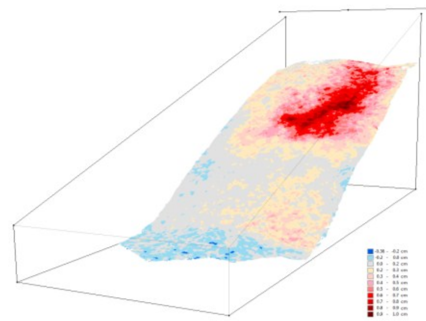

Figure 3. Example DEM of final slope surface with draped color gradient indicating vertical displacement between the first and last DEM surfaces.

Conclusion: Sublimation of CO_2 can trigger small-scale mass wasting. Steeper mean slope angles, and increased initial CO_2 ice mass, both increase the frequency of mass wasting trigger events. Likewise, decreased ambient temperature and increased relative humidity combine to increase trigger frequency, although additional work is required to determine the extent of their individual influences.

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Acknowledgements: This work was funded in part by the Fulbright College of Arts & Science, University of Arkansas, Fayetteville, AR. We thank the Center for Advanced Spatial Technologies for photogrammetric services, and C. Owens, Center of Excellence for Poultry Science, for use of laboratory space.