HOW MUCH WATER IS NEEDED TO MAKE GULLIES ON MARS: A CONCEPTUAL MODEL.

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Conceptual Model for Gully Formation: Examination of gullies on Mars by researchers confirm the basic morphologic elements originally identified by Malin and Edgett [1]: the gully system consists of an alcove (source area) typically in bedrock, a channel (or chute) incised into slope mantling debris, and an apron of sediment discharge from the channel.

Analog studies on Earth by others [2] and our own field investigations (New Zealand, Iceland, Chile, and the American Southwest) suggest a general morphodynamic model for gully and fan systems formed by flowing water that may be applicable to Mars (Figure 1). Portions of this conceptual model have been implied by many studies on Mars. We identify three primary process zones: a water source area (typically in bedrock), a sediment entrainment zone (bedrock slope mantled with impact breccia, colluvium, eolian deposits, and, on Mars, a mixture of fine sediment and ice termed "pasted-on" material), and a depositional zone (that progressively flattens as the mode of transport shifts from mass flow and on Earth to fluvial and lake deposition). Empirical studies on Earth and Mars suggest that each of these zones can be distinguished by characteristic slopes (Fig. 1), in which the water source region tends to be steeper than 50^o, the entrainment zone extends from ~50^o to 20^{o,} and the deposition zone progressively declines from debris flow dominated (down to ~5^o) and, if present, the fluvial and flat lake sediments. These depositional slopes are self-formed and can indicate the dominant process.

When runoff from the water source area crosses the lower sediment mantled zone, entrainment occurs. Typically, field studies report what has been called a "fire hose effect" [e.g., 3-5] in which runoff rapidly entrains into the channel sediments, undermines adjacent banks that collapse onto the flow and transforms it into a surging debris flow, trapping and mixing water and sediment and gaining in size until it reaches lower unconfined slopes where deposition ensues. In flows with poorly sorted sediment, the coarse fraction will migrate to the sides and front of the flow, leading to levee formation where low fluid pressure and high inertial stress prevails, and a snout that may be pushed downslope by the flow [e.g., 6-7].

The key to mobilization and transport to lower (fan) slopes is the entrainment of fine sediment (i.e. silt and clay), which can increase as entrainment continues [8]. Fine sediment makes the fluid more viscous, effectively keeping water from draining from the coarse fraction (which would otherwise cause deposition on steep slopes), it elevates the fluid density and thus the buoyancy force, and reduces grain collision rates, reducing the resistance to flow and enabling transport on gentle slopes [e.g., 6, 9-10]. Hence, the abundance of fines in the debris mantling the slope will strongly influence mass flow behavior.

Low flows into the channel (i.e., chute) that do not cause entrainment to mass flows will transport sediment fluvially. These flows will be confined by gully walls and, on the fans, by the levees left by the debris flows. Flow of sufficient duration may spill past the debris flow deposits and build a lower gradient alluvial fan downslope. Hence, both debris flow and fluvial processes may occur in gullies depending on the magnitude of runoff. Also, gully development may involve a developmental threshold, in that initial incision will focus subsequent runoff and mass failure from the upslope source area. The growing walls driven by incision will lead to increased sediment flux to the channel, enhancing entrainment and incision. This model suggests conventional sediment transport equations do not readily apply to Martian gully systems.

Meteor Crater as a Test Bed: Meteor Crater, Arizona [11,12], shows all the elements of this model and is ideal for developing methods to calculate the frequency and volumes of water required for entrainment, transport, and deposition processes. The slope mantling materials are composed of impact breccia, overlain by colluvium and then subsequent- at lower slopes- deposition of debris flow, fluvial and lake sediments (Fig. 1). Wall fractures locally enhance source area erosion rates. Runoff that has cut the gullies and generated debris flows and fluvial features may be rainfall-induced, snowmelt, or, during the Pleistocene, groundwater seepage. In all three cases the barren upslope bedrock provides a clear runoff source and, thus, introduces water in a manner similar to that proposed for Mars. Based on lack of evidence of rilling or strong sheetwash on the relative smooth talus slopes between the gullies, surface runoff from the sediment-mantled slopes to the gullies is probably small compared to that off the barren headwaters.

Preliminary Findings: Through the National Center for Airborne Laser Mapping we obtained high-resolution LiDAR data, contoured to 0.25-m. A simple slope map (Fig. 2) highlights the domains described in the model above. Slopes steeper than 30 degrees are mainly bedrock dominated or line the channels cutting through talus. Downslope, paired and unpaired levees (indicative of debris flows) crisscross the slopes down to ~5°. Commonly, there are lobate deposits some distance downslope from the mouth of each gully, which indicate the deposition of a debris flow snout. Multiple boulder snout deposits can be found throughout a single leveed channel. Mappable channels exiting the gully often do not extend past the farthest downslope lobate deposit, but the levee tracks can continue all the way to the crater floor, which was once a paleolake. We have mapped (in the field) over 10 individual gully systems around the perimeter of the crater, and sampled boulder levees at one of those sites for cosmogenic nuclide (CN) dating. At each site, we delineated the transition from entrainment to deposition (as indicated by the presence of lateral levees), recorded levee and lobate deposits (to calculate volumes of sediment associated with an event), and for sites that had evidence of recent fluvial activity, we surveyed cross-sections of the fluvial channels and conducted pebble counts on sheet-wash deposited bars to estimate discharges required for sediment motion.

The gully system that we sampled for CN dating has a well-preserved pair of levees leading to a distinct thumb-shaped deposit (defining the most recent debris flow event) that crosses a much older pair of levees created by an older debris flow. Boulders over half a meter in diameter are in the levees in both the younger and older flows; the levees themselves are ~4-6 m apart and ~0.5-0.7 m high. The local slope for both the younger and older flows is ~10%. The estimated volume of sediment at the terminal snout and levee is ~283 m^3, based on field surveys and LiDAR data. If 20% of that volume at the time of transport were water (based on the average water content of debris flows [7]), then a minimum of 56 m^3 of water was needed to cause transport. The source area above the levees is ~1700 m^2; hence a minimum of 3.3 cm of runoff from the source area was needed to generate the flow. As a start for estimating the flow that leads to incision we used cross-sectional surveys and pebble counts to calculate a critical shear stress (and critical discharge) for initial motion of alluvial gravel deposited (median size of ~52 mm) on the bed between the debris flow levees after the debris flow event, using slope-dependent critical shear stress calculations [13]. This yielded an estimate of discharge that is equivalent to ~3 cm/hr runoff from the source area, though the water source is not specified. The exposure ages of the boulders sampled in the levees range from ~10,100-18,700 years, suggesting the debris flow events occurred during the Pleistocene, as opposed to fluvial transport, which is still occurring today.

Implications for Mars: Quantitative assessment of how much water is involved in gully and fan formation is a key goal for understanding Martian climate. Our quantitative observations at Meteor Crater substantiate the conceptual model outlined above and provide the first of several calibration points needed to determine the amount of fluid flow that produced some of the gullies on Mars. Importantly, our approach does not require that debris flows be generated by rainfall runoff, which is unlikely on Mars, rather it is only meant to constrain water volumes.

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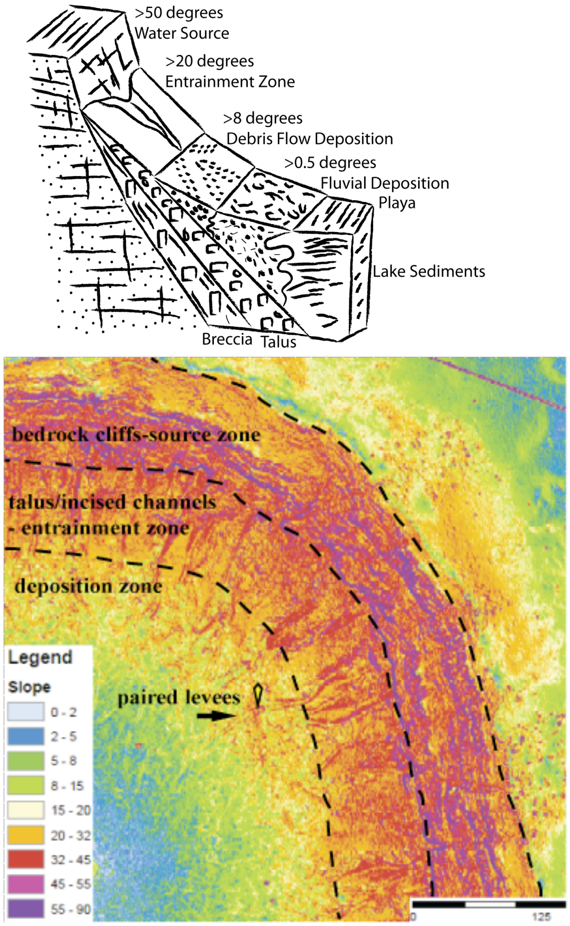
Figures:



(1) Conceptual sketch of primary process zones distinguished by characteristic slopes (2) slope map (on 0.25-m gridded data) of NE corner of Meteor Crater, marker shows location of gully system discussed above

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