**Formation of Gullies on Mars: Link to Recent Climate History Implicates Surface Water Flow Origin.** James W. Head and David R. Marchant.

### Summary:

The geological record of an impact crater interior microenvironment typical of the mid-latitudes of Mars shows that formation of gullies immediately followed a recent period of mid-latitude glaciation. Geological evidence indicates that in the recent past, sufficient snow and ice accumulated on the crater wall to cause glacial flow and filling of the crater floor with debris-covered glaciers. As the period of glaciation waned, debris-covered glaciers ceased flowing, accumulation zones lost ice, and newly exposed wall alcoves became the locus of snow/frost deposition, entrapment, and preservation. During the warming trend toward the end of glaciation, melting of residual snow and ice in alcoves formed fluvial channels and sedimentary fans.

### Background:

Because the current temperature-pressure regime is below the triple point, it came as a major surprise when Malin and Edgett [1] reported the discovery of young features apparently carved by running water. Termed gullies, these consist of an alcove, channel and fan (Fig. 1a). These observations generated a host of alternative explanations for the gullies, including (summarized in [2]): 1) bottom up liquid sources, such as the release of subsurface groundwater or subsurface liquid CO₂, perhaps aided by geothermal activity; 2) top-down water sources, such as the accumulation and melting of surface snowpacks, or melting of near-surface ground ice; and 3) dry granular flow. Here we assess the stratigraphic relationships in a crater interior typical of many gully occurrences. These data provide evidence that gully formation is linked to glaciation and to recent climate change that provided conditions for snow/ice accumulation and top-down melting.

### Observations:

The latitudinal dependence of gullies shows a distinct concentration in 30-50° latitude bands [3], and a significant number form on impact crater interior walls [4]. For this reason, we chose to analyze in detail the geology of a crater interior in the ~40° latitude range in order to assess geomorphic features and stratigraphic relationships associated with gullies. A 10.5 km-diameter crater (~155.3E, 40.1° S) displays well developed gullies (Fig. 1a) and a very asymmetric wall and floor topography (Fig. 2). Crater floor morphology shows multiple lobate depressions along the base of the northern wall directly upslope of multiple parallel lobate flow textures on the floor; these in turn merge and converge toward two major southern floor lobes (Fig. 2a-b). The characteristics of the surface morphology and the array of geomorphic features implicate snow and ice in the crater modification. The surface texture of the floor lobes is very similar to that of older mid-latitude lobate debris aprons, lineated valley fill, and concentric crater fill, all interpreted to involve a significant amount of ice in their formation [e.g., 5]. The topography and surface morphology are very similar to deposits at the dichotomy boundary interpreted to be debris-covered glaciers in valley systems [e.g., 6]. Lobe-shaped spatulate depressions along the northern base of the crater wall (Fig. 3a,b) are similar to remnant features interpreted to be due to flow of glacial ice in other craters at this latitude. Furthermore, a change in climate between the time that the broad floor lobes were emplaced and today is indicated by the fact that the multiple lobe-shaped spatulate features are new depressions, interpreted to mean that the previously existing snow and glacial ice have sublimated, and the glaciers beheaded. Further evidence for climate change is seen from superposition relationships at high resolution along the northern crater wall (Fig. 3a,b). Gullies are superposed on, and postdate, the period of active ice lobe formation. The crater interior maps show that gullies (Fig. 1a) occur in the regions that would have been the accumulation zones for ice flowing into the lobate spatulate depressions. Superposition relationships show that the gullies form on the base of the slope and the lobate spatulate depressions indicate a younger age (Fig. 3b-d). Broad alcoves high on the crater wall contain channels in their interiors that exit the alcoves, extend downslope, and terminate in a distal fan along the base of the wall slope in the interiors of the lobate depressions. The very close stratigraphic relationships between the gullies and the lobate depressions (Fig. 3a-b) strongly suggest a genetic relationship related to the waning stages of the glaciation that marks the modification of the crater floor. We interpret the sequence of events on the floor and wall as follows: 1) accumulation of snow and ice on the wall to sufficient thickness to cause flow; 2) formation of debris-covered glaciers to produce the major floor lobes; 3) decrease in snow and ice accumulation on the crater walls to cause recession of ice lobes, ultimately leaving the beheaded lobate spatulate depressions; 4) formation of gullies on the crater walls and distal fans in the empty spatulate depressions (Fig. 4).

There is clear evidence that activity in the gully fans was episodic (Fig. 3b-d). Early distal fans are deformed by a pervasive series of closely-spaced fractures that are generally parallel to the base of the slope. Later fans are clearly superposed on both the earlier fans, and on their deformed bases (Fig. 3c-d). The most recent fans consist of anastomosing distributary channels on the fan surface and distal channel deposits.
What are the sources of the fluid causing the gully erosion? We interpret the trends in the stratigraphic relationships in the crater to mean that climatic conditions changed from those favoring significant glaciation, to those favoring progressively less snow and ice accumulation, ultimately leading to conditions in which there was patchy seasonal snow and ice on the northern crater walls. Such accumulation would concentrate snow and ice specifically in the topographic traps of the alcoves, where shielding would further favor perennial ice retention. For example, a long-term warming trend might cause such an evolution in glaciation and ice retention, with the latter phases conducive to seasonal heating and melting of snow/ice accumulated in the alcoves to cause water flow and formation of gully channels and fans. What are the causes of the observed trends? The latitude dependence of gully occurrences, the similarity of their occurrences with those of viscous flow features here and elsewhere on Mars [3], and their general relationship to a widely distributed latitude-dependent young mantling deposit [e.g., 7], strongly suggest a link to climate change and variations in the astronomical parameters that drive climate change. Specifically, recent astronomical parameter solutions for the last 20 million years [8] show that obliquity has been progressively decreasing in average magnitude and amplitude over that time. Such changes would tend to make the mid-latitudes progressively warmer up to the present time, when water ice is generally not stable in the uppermost part of the regolith at these latitudes. Thus, we interpret gullies to have formed in the waning stages of this glaciation when warming conditions were such that patches of snow and ice in gully alcoves could seasonally melt and form fluvial channels and fans [9; Fig. 16]. Current Mars conditions may be too cold and dry for top-down melting to occur in these microenvironments, but accumulation and melting of wind-blown snow and ice may permit the mechanism to operate on Mars relatively recently.


Fig. 1. Gullies (alcoves, channels and fans). (a) On crater interior wall; (b) Wright Valley, McMurdo Dry Valleys, Antarctica. Wind-blown snow in alcoves and channels melts during austral summer causing fluvial activity [10].

Fig. 2. Impact crater (-155.3E, 40.1S). (a) CTX p02_001842_1397 xi.40S155W. (b) Sketch map showing main geologic features. (c) Asymmetrical crater profile shows that crater has been modified from initial morphology. MOLA profile 15161.

Fig. 3. Detailed relationships of geomorphic features in the crater interior. (a, b) Gullies forming on upper wall emplace fans that are clearly superposed on the central parts of the arcuate spatulate depressions. (c,d) Deformed gully channel and fan deposits form fractures and terraces at base of slope along the crater wall. The most recent channels and fans clearly postdate the fractures. HiRISE PSP-001842_1395.

Fig. 4. Perspective view of wall gullies superposed on spatulate depressions.