5. Alcove-less gullies suggest a candidate source of meltwater

Could the ice-rich latitude-dependent mantle be a source of water for formation of these gullies? Examination of HiRISE data helps to address this question. The most prominent gully system occurs in the central part of the crater wall (Fig. 2A and C). Smaller surficial gullies also occur, however, in the degraded mantle on the crater wall (Fig. 2B and D). These features lack alcoves, have shallowly incised channels, and have depositional fans that extend onto the cratered floor surface (Fig. 2A). Furthermore, shallow channels emanating from the mantle feed into the larger gully system (Fig. 2C, arrows 1–3) and occur independently nearby the larger gully (Fig. 2C, arrow 4). In Fig. 2B, the uppermost narrow channels (arrows 1 and 2) are choked with sediment (arrow 3) above a more deeply incised portion of the channel that is also choked with sediment (arrow 4); below this, a channel segment (arrow 5) and subsequent deposition (arrow 6) suggest multiple sediment transport episodes in the development of this gully. In Fig. 2D, the upper reaches (arrows 1 and 2) of the channel are shallower and appear restricted by the boundary of a mantle layer (Fig. 2A). The occurrence of these small-scale surficial gullies and channels in the degraded mantle, without alcoves that could serve as accumulation zones for snow, provides independent evidence that gullies can form through degradation and melting of the ice-rich mantling deposits. This is consistent with interpretations (e.g., Head et al., 2003) of the correlation between gully activity and obliquity-driven climate cycles (Fig. 1).

In summary, the intimate association of the degrading portions of the ice-rich latitude-dependent mantle with the sources of gullies on the crater wall, and the similarities of gully channels and fans to features formed by liquid water-related fluvial activity (e.g., Head et al., 2007, 2008; McEwen et al., 2007), strongly favor a fluvial origin for many of the major gully features sourced from melting ice-rich mantle material. Modeling the stability of snow and buried snow and ice, Williams et al. (2009) showed that melting in these latitude bands could take place during peak insolation geometries for a part of the year. Furthermore, the chronostratigraphic marker links the earliest time of this gully activity to the latter part of the recent glacial period (Fig. 1). On the basis of these analyses, we hypothesize that the steep slopes of the crater wall preferentially orient the ice-rich mantle deposits so that peak insolation trends during obliquity excursions (Fig. 1) (similar to the peak insolation geometries described by Costard et al. (2002)) cause melting of ice (e.g., in a manner similar to that envisioned by Williams et al. (2009)). The liquid water liberated by melting of ice during periods of peak insolation resulted in multiple phases of fluvial activity that formed the gullies. Continued ablation (melting and sublimation) resulted in the degradation and removal of much of the ice-rich mantle deposit.

6. Activity during the current "interglacial" period

Gasa crater, source of the pervasive secondaries, also hosts multiple gullies, which must post-date the impact event. On the basis of the chronostratigraphy, these gullies can provide insight into the nature of gully activity in the waning stages of the "glacial" period and into the current "interglacial." Kolb et al. (2010b) described the Gasa crater gullies as the best preserved (freshest morphological appearance), relative to gullies of their other study areas; they investigated gully development by analyzing the gradient where deposition begins (apex slope of the fan) using digital elevation models derived from HiRISE stereo pairs. Analysis of Gasa crater gullies by Kolb et al. (2010b) shows that ten gullies have apex slopes characteristic of "wet or fluidized emplacement" (16.3–20.4°) and eleven gullies have apex slopes consistent with dry granular flows (20.7–26.4°). These data are consistent with the Gasa impact occurring prior to the likely waning of meltwater generation for gully formation, which we suggest is contemporaneous with the damping of obliquity-climate cycles, ~400 ka (Fig. 1). Kolb et al. (2010b) also found that the morphologically freshest appearing gullies were more likely to have apex slopes consistent with the movement of dry material, while more degraded gullies were more likely to have slopes consistent with wet flows. "Our results suggest that gully formation required a time-limited fluidization mechanism, possibly liquid water, that major gully formation is not occurring today, and that activity in gullies today is likely dry mass wasting perhaps aided by CO_2 frost," concluded Kolb et al. (2010b). Dundas et al. (2010) detected recent rockfalls and other minor geomorphic changes in two Gasa gullies and suggested a link between the annual CO_2 frost cycle and these events, but concluded, "None of these observations contradict the hypothesis that gullies are initiated by H_2O snowmelt or that this process drives a significant fraction of gully erosion." In summary, these observations suggest that the role of liquid water in gully activity may have become less important in the transition to the current interglacial period, as environmental conditions became less extreme and ice-rich mantling deposits became depleted.

7. Conclusions and implications

New chronostratigraphic data and observations have improved our understanding of the processes and climate context for the formation and evolution of martian gullies. While mid-latitude gullies on Mars are geologically young features dating to the latest Amazonian, their principal formation is likely to have preceded the current (0–400 Kyr) epoch of lower and more stable obliquity (Fig. 1). In our interpretation, melting of ice-rich deposits related to degradation of a latitude-dependent mantle was responsible for a major portion of the fluvial activity forming gully channels and depositional fans (Fig. 2). Erosive gully-forming flows are likely to have been dominated by fluvial sediment transport (e.g., McEwen et al., 2007, 2010; Head et al., 2007; Schon et al., 2009a), with a few cases of water-lubricated debris flows (e.g., Levy et al., 2010; Lanza et al., 2010). In contrast, present-day gully activity may favor dry mass movements, which appear to exhibit a seasonal modulation related to the CO_2 frost cycle (Dundas et al., 2010; Diniega et al., 2010). Seasonal monitoring and ongoing change detection campaigns (e.g., McEwen et al., 2010) will be essential to investigate active processes and to characterize geomorphic changes on steep slopes and in gullies.

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References

Arfstrom, J., Hartmann, W.K., 2005. Martian flow features, moraine-like ridges, and gullies: Terrestrial analogs and interrelationships. Icarus 174, 321–335.

Boynton, W.V. et al., 2002. Distribution of hydrogen in the near surface of Mars: Evidence for subsurface ice deposits. Science 297, 81–85.

Byrne, S. et al., 2009. Distribution of mid-latitude ground ice on Mars from new impact craters. Science 325, 1674–1676.

Christensen, P.R., 2003. Formation of recent martian gullies through melting of extensive water-rich snow deposits. Nature 422, 45–48.

Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent martian debris flows by melting of near-surface ground ice at high obliquity. Science 295, 110–113.

Dickson, J.L., Head, J.W., 2009. The formation and evolution of youthful gullies on Mars: Gullies as the late-stage phase of Mars' most recent ice age. Icarus 204, 63–86.

Dickson, J.L., Head, J.W., Kreslavsky, M.A., 2007. Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography. Icarus 188, 315–323.

Diniega, S., Byrne, S., Bridges, N.T., Dundas, C.M., McEwen, A.S., 2010. Seasonality of present-day martian dune-gully activity. Geology 38, 1047–1050.

Dundas, C.M., Byrne, S., 2010. Modeling sublimation of ice exposed by new impacts in the martian mid-latitudes. Icarus 206, 716–728.

Dundas, C.M., McEwen, A.S., Diniega, S., Byrne, S., Martinez-Alonso, S., 2010. New and recent gully activity on Mars as seen by HiRISE. Geophys. Res. Lett. 37. doi:10.1029/2009GL041351.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Nature 426, 797–802.

Head, J.W., Marchant, D.R., Dickson, J., Levy, J., Morgan, G., 2007. Transient streams and gullies in the Antarctic Dry Valleys: Geological setting, processes and analogs to Mars. In: Cooper, A.K., Raymond, C.R., and the 10th ISAES Editorial Team (Eds.), Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES, USGS Open-file Report 2007-1047, Extended Abstract 151, 4pp.

Head, J.W., Marchant, D.R., Kreslavsky, M.A., 2008. Formation of gullies on Mars: Link to recent climate history implicates surface water flow origin. Proc. Natl. Acad. Sci. USA 105, 13258–13263.

Kolb, K.J., Pelletier, J.D., McEwen, A.S., 2010a. Modeling the formation of bright slope deposits associated with gullies in Hale Crater, Mars: Implications for recent liquid water. Icarus 205, 113–137.

Kolb, K.J., McEwen, A.S., Pelletier, J.D., 2010b. Investigating gully flow emplacement mechanisms using apex slopes. Icarus 208, 132–142.

Kreslavsky, M.A., Head, J.W., 2000. Kilometer-scale roughness of Mars: Results from MOLA data analysis. J. Geophys. Res. 105, 26695–26711.

Kreslavsky, M.A., Head, J.W., 2002. Mars: Nature and evolution of young latitude-dependent water-ice-rich mantle. Geophys. Res. Lett. 29. doi:10.1029/2002GL015392.

Lanza, N.L., Meyer, G.A., Okubo, C.H., Newsom, H.E., Wiens, R.C., 2010. Evidence for debris flow gully formation initiated by shallow subsurface water on Mars. Icarus 205, 103–112.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., Robutel, P., 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. Icarus 170, 343–364.

Levrard, B., Forget, F., Montmessin, F., Laskar, J., 2004. Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity. Nature 431, 1072–1075.

Levy, J.S., Head, J.W., Marchant, D.R., Kowalewski, D.E., 2008. Identification of sublimation-type thermal contraction crack polygons at the proposed NASA Phoenix landing site: Implications for substrate properties and climate-driven morphological evolution. Geophys. Res. Lett. 35. doi:10.1029/2007GL032813.

Levy, J.S., Head, J.W., Dickson, J.L., Fassett, C.I., Morgan, G.A., Schon, S.C., 2010. Identification of gully debris flow deposits in Protonilus Mensae, Mars: Characterization of a water-bearing, energetic gully-forming process. Earth Planet. Sci. Lett. 294, 368–377.