THE FORMATION AND EVOLUTION OF YOUTHFUL GULLIES ON MARS: GULLIES AS A LATE-STAGE PRODUCT OF MARS' MOST RECENT ICE AGE. J. L. Dickson[1] and J. W. Head[1], [1]Brown University, Department of Geological Sciences, Providence, RI, 02912, jdickson@brown.edu.

Introduction: The discovery of youthful gullies on Mars [1] provided strong evidence for short-duration flow of liquid water within the last several million years, an era not generally considered conducive to the stability of liquid water at the surface [2]. Given average conditions below the melting point for all of Mars and the apparent correlation between bedrock layering and gully alcoves, *Malin and Edgett* [1] invoked seepage from a subsurface aquifer to explain the observed morphology and distribution of gullies. The global distribution of gullies (only at mid- and high-latitudes, mostly on pole-facing slopes, etc.) implicates climatic processes in their formation, which *Mellon and Phillips* [3] used to argue that a subsurface liquid aquifer is dammed by a layer of ground ice at gully locations. Obliquity oscillations would yield freezing and expansion of the subsurface aquifer, breaching the ground ice layer along the slope face and carving channels downslope.

Shortly after their discovery, *Baker* [4] documented gullies emanating from the crest of the central peak of Hale Crater in the southern mid-latitudes. The occurrence of gullies on isolated peaks unlikely to host subsurface aquifers spawned a new suite of hypotheses for gully formation that centered around "top-down" melting of surface snowpacks [5-7], frost [8], and ground ice within the top meter [9-10]. These two end-member hypotheses (groundwater and "top-down") have persisted without resolution through the end of the Mars Global Surveyor (MGS) mission and the beginning of the Mars Reconnaissance Orbiter (MRO) mission. Here, we synthesize the global observations made from MGS and use that as a foundation for the high-resolution (HiRISE) and high-spatial-context (CTX) data from MRO in an effort to test these hypotheses.

Global Distribution: The tripartate morphology (head alcove/channel/distributory fan) defined by *Malin and Edgett* [1] has been used to map the global distribution of gullies by several workers [1, 11-16]. Gully distribution is governed by several factors, including latitude [1], orientation [1,11-16], slope of the host surface [12, 15], and elevation [12, 15-16].

Latitude. Gullies do not occur equatorward of 27° [1]. In each hemisphere, gullies occur most frequently between 30°-42° [11], with a strong preference for the southern hemisphere. Some strong regional concentrations include the eastern rim of Hellas, Newton Basin, southern Utopia, and the northern rim of Argyre Basin.

Elevation. The distribution of gullies is generally consistent with the distribution of absolute elevations in each hemisphere as measured by the Mars Orbiter Laser Altimeter (MOLA), with no elevation ranges showing abnormally high concentrations [12,15-16]. Gullies are not, however, observed at extreme elevations [15]. Gullies are not observed on Thaumasia (greater than 3 km above the MOLA datum), or on the floor of Hellas (greater than 5 km below the MOLA datum).

Orientation. In the southern hemisphere, gullies follow reliable orientation trends as a function of latitude. Between 30°-44°S, gullies are almost exclusively poleward facing [9,12,14-15], whereas higher latitudes show a preference for equator-facing gullies [9,12,15]. Northern hemisphere gullies show some orientation trends [13,16], but not as strong as in the southern hemisphere.

Slope. Gullies only form on extremely steep slopes (>20°), with an average alcove slope of ~26.8° based upon calculations from MOLA track data [15]. Preliminary measurements from HiRISE stereo pairs suggest that these values may be underestimates, as alcoves average 30° at HiRISE scale [17]. This dependence on steep slopes is reflected in the global distribution, as gullies generally form equatorward of the "smoothed" terrain that characterizes the high-latitudes of each hemisphere when calculated from MOLA topography at a 0.6 km baseline [18].

Geologic Context: Gullies form on all types of steep slopes on Mars. While gullies are most common on impact crater walls and valley walls, several workers have acknowledged the presence of gullies on the flanks of isolated peaks like mesas, massifs, knobs, central peaks, and dunes [4,6,9,11-12,14-15]. These gullies share the same distribution properties of gullies on crater/valley walls [14-15], and share similar morphology [14], with the exception of gullies on dunes.

Detailed Geology: The HiRISE camera onboard MRO has allowed for unprecedented sub-meter analysis of small-scale geologic features like gullies. Here, we highlight four findings made possible by these new data.

Cold-trapping. The Blue-Green channel that covers the middle 20% of all HiRISE images is well-suited for the detection of seasonal frost. We have used these color data to document multiple examples [e.g. 7, 21] of seasonal frost being preserved in both alcoves and channels after frost had been removed from the surrounding slope face.

Episodic Activity. *Schon et al.* [19] documented a sequence of fan-emplacement events within one gully separated by the emplacement of a field of secondary craters. We have found several similar stratigraphic relationships that confirm what had been suggested from preliminary MOC data [1]: gullies are active episodically, and models for their formation must also explain their evolution over time.

Association with ice-related features. It was observed in MOC data that gullies are spatially consistent over the globe with Viscous Flow Features (VFF) and dissected mantle material [11]. CTX and HiRISE data have allowed for the analysis of detailed stratigraphic relationships among these features, arguing for an evolutionary sequence of ice accumulation, glacial advance and retreat, with melting of retreating ice forming gullies in the final stage of glacial recession [7]. We have documented a series of gullies in the southern hemisphere that are in various stages of this sequence. These data suggest that gullies are not anomalous features, but late-stage products of the most recent ice ages of Mars.

Alcove/Channel relationships. HiRISE data show that gully channels frequently emanate from the *crest* of alcoves, not the base (Fig. 1b). Often these channels are located topographically above the surrounding ejecta deposits. It had been proposed that alcoves form from undermining and collapse of material headward of a seepage point [1,12]. We feel that these new data argue that alcoves form at least in part in the same manner as alcoves at equatorial latitudes along steep slopes: by mass-wasting that produces dry talus piles (Fig. 1a). Once formed, alcoves can then serve as cold-traps and localized climates that serve to collect and preserve wind-blown snow, as is observed in the Mars-like Antarctic Dry Valleys [20].

Once these sheltered locations are exposed to the intense sunlight through the thin martian atmosphere, temperatures above the melting point are likely to have been achieved at gully locations at obliquity values that have occurred within the last ~5 myr. [9]. Modeling of the martian climate at 33° [9] and 35° [22] obliquity predicts small amounts of surface melting at locations where gullies are observed. This model of small amounts of melting recurring many times is most consistent with the global distribution and detailed geology of martian gullies and similar to gully activity in the Antarctic Dry Valleys [23].

References: [1] Malin, M. and Edgett K. (2000) *Science, 288,* 2330. [2] Carr M. (1996) *Water on Mars,* Oxford U. Press. [3] Mellon, M. and Phillips, R. (2001) *JGR*, 106, 23,165. [4] Baker, V. (2001) *Nature*, 412, 228. [5] Lee, P. et al. (2001) *LPSC*, 32, 1809. [6] Christensen, P. (2003) *Nature*, 422, 45. [7] Head, J. et al. (2008) *PNAS*, 105, 13,258. [8] Hecht, M. (2002) *Icarus*, 156, 373. [9] Costard, F. et al. (2002) *Science*, 295, 110. [10] Gilmore, M. and Phillips, E. (2002) *Geology*, 30, 1107. [11] Milliken, R. et al. (2003) *JGR*, 108, 5057. [12] Heldmann, J. and Mellon, M. (2004) *Icarus*, 168, 285. [13] Bridges, N. and Lackner, C. (2006) *JGR*, 111, E09014. [14] Balme, M. et al. (2006) *JGR*, 111, E05001. [15] Dickson, J. et al. (2007) *Icarus*, 188, 315. [16] Heldmann, J. et al. (2007) *Icarus*, 188, 324. [17] Parsons, R. et al. (2008) *AGU*, Fall Meeting, P41A-1350. [18] Kreslavsky, M. and Head, J. (2000) *JGR*, 105, 26,695. [19] Schon, S. et al. (2009) *Geology*, in press. [20] Marchant, D. and Head, J. (2007) *Icarus*, 192, 187. [21] Dickson, J. and J. Head (2009), *in prep.* [22] Williams, K. et al. (2009) *Icarus*, in press. [23] Head, J. et al. (2007) *7th Int. Con. Mars*, 3118.

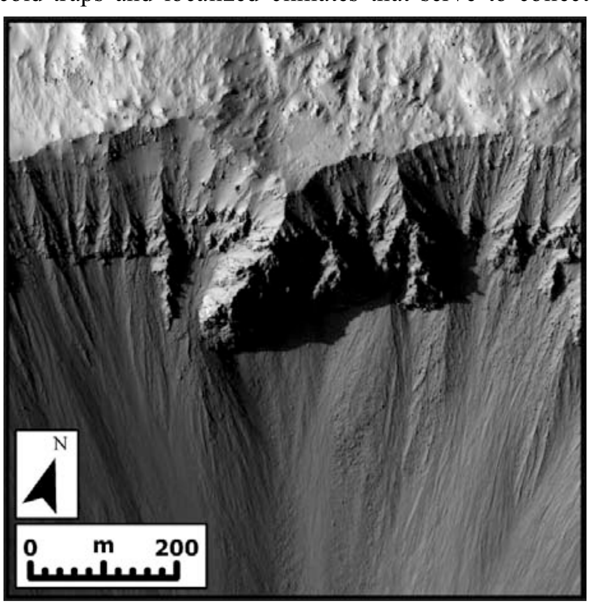

Figure 1a. Alcoves found along the rim of Zunil crater at 7.7°N, yielding dry talus piles along the crater wall. HiRISE PSP_002397_1880.

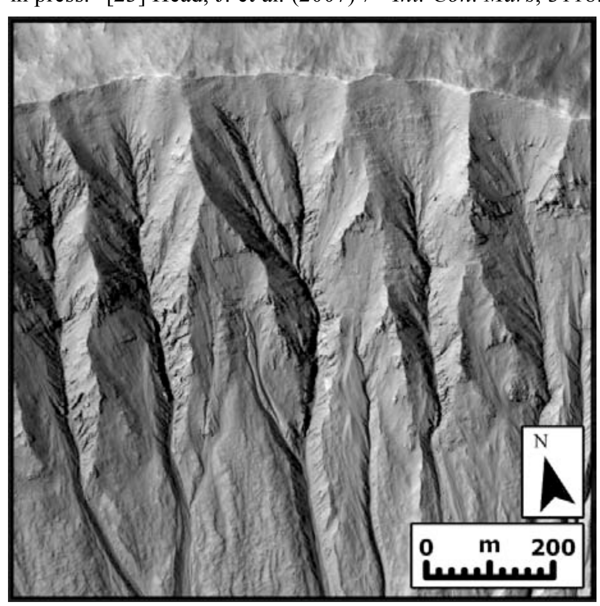

Figure 1b. Alcoves with gully channels found along the rim of an unnamed crater at 34.1°S. HiRISE PSP_005985_1455.