**MARTIAN GULLIES: VARIETY OF SETTINGS AND IMPLICATIONS FOR FORMATION PROCESSES.** J.L. Heldmann[1] , K.S. Edgett[2], O.B. Toon[3], and M.T. Mellon[4], [1]NASA Ames Research Center, MS 245-3 Moffett Field, CA 94035, Jennifer.Heldmann@nasa.gov, [2]Malin Space Science Systems, San Diego, CA [3]University of Colorado, Program in Atmospheric and Oceanic Sciences & Laboratory for Atmospheric and Space Physics, Boulder, CO [4]University of Colorado, Laboratory for Atmospheric and Space Physics, Boulder, CO

**Introduction:** Middle- and high-latitude, kilometer-scale, geologically young gullies were first recognized on Mars in images from Mars Global Surveyor [1]. One of the models for their formation is seepage and surface runoff of liquid water escaping from a shallow, subsurface aquifer (often, it is forgotten that the model is more complex than this—undermining and collapse contribute to alcove formation, and mass movement and eolian processes continue to modify the landforms to this day). However, some middle- and high-latitude gullies occur on slopes that do not seem to have characteristics that fit the groundwater model; these have been noted by some researchers as features that falsify the groundwater model and instead favor other models, including melting of snowpacks and mass movement involving no contribution from a liquid or gas lubricant. These other gully forms occur on eolian dune slip faces, crater central peaks, and isolated mountains and massifs. However, these gullies and gully-like features are geomorphically distinct from the more common, typical gullies that occur on the walls of craters, valleys, troughs, and pits. Hence, here we describe and classify the range of gully features according to differences in morphology, geographic distribution, and geologic setting. Each class of features might have formed by different processes.

**Gully Classes and Settings:** All four gully classes described here (CL, SD, CP, IP) occur at middle to high latitudes in both Martian hemispheres [1, 2, 3].

*Classic Features (Type CL).* Classic, or type CL gullies form on the walls and slopes of craters, troughs, channels, pits, and other depressions which have an overlying, relatively flat plateau upslope from the gully alcove [2, 4]. Generally, Type CL gully morphology can be divided into three parts: alcove, channel, and apron. The central, identifying attribute of any Martian gully is its channel, but in many cases it is the mutiple lobed nature of the apron deposits that suggests debris flows rather than dry mass movements contributed to their genesis. Some gullies have an alcove that formed on the slope above the channel and the majority of gullies have an apron of debris located where the channel reached the bottom of the slope. However, not all gullies have all three geomorphic segments, especially alcoves [1].

A quantitative study of gully characteristics based on MOC, MOLA and TES data suggests that the gullies were formed by the release of liquid water from a shallow (several 100 m deep) subsurface aquifer [2]. A shallow aquifer can occur where competent rock layers trap water below ground while maintaining an overlying dry and thermally insulating soil layer. The dry, insulating overburden allows geothermal heat to maintain liquid water at only a few hundred meters depth. Indeed, the depth to the typical channel head is positively correlated with the depth of the 273 K isotherm when using an overburden thermal conductivity value measured by the MGS TES [2].

*Sand Dune Features (Type SD).* Gully-like forms were also found on sand dune slip faces [5, 6, 7]. Dune gullies are extremely rare and most commonly found on dunes in just a few of the mid-latitude dune fields in craters of Noachis Terra. All dune gullies occur on slopes that face generally poleward; equatorward-facing slip faces on the same dune as a gully will exhibit slip face avalanches, suggesting that the dune gullies, too, result from slip face avalanching, but with some added attribute that forms a channel in the avalanche deposit. Two distinct types of gully-like dune features exist on Mars. These two classes are distinguished by their unique morphologic qualities.

The uppermost portion of the first, type SD1, is characterized by a lack of well-developed alcoves. Instead of channels emanating from an eroded, theater-shaped depression, channels commence from the top or near the top of a slip face. In a few cases there is an extremely small (less than 10 m long) eroded depression at the top of the channel. The Type SD1 channels typically begin at the top of the sand dune and run essentially parallel down the length of the slope. Type SD1 channels are commonly leveed and there is almost always a lack of an apron at the base of the slope.

The second, type SD2 features, are also found on sand dunes and are also rare and most commonly found in Noachis Terra. The type SD2 features are complex with varying alcove morphologies in adjacent structures. One feature has a small alcove (< 7 m in length) which is located at the top of the sand dune. The adjacent Type SD2 feature lacks such a well-developed alcove. Instead, the channel-like structure seems to emanate from the dune crest, although the channel does appear slightly widened at the uppermost reaches near the dune crest, reaching a maximum width of nearly 3 m at its widest point.

Type SD1 features might form from erosion due to ice which condenses from the atmosphere and forms at the crest of a dune, tumbles downhill, and then eventually sublimates away into the atmosphere. The ice could be knocked loose as it starts to sublimate and/or melt away, causing undercutting and a removal of the support structure for the ice itself. Alternatively, ice-cemented sand from the near-surface of the dune might serve as an erosional agent. Some HiRISE images of gullies on dunes in Russell Crater suggest the presence of subsurface ice. If blocks of ice-cemented sand were destabilized near the dune crest due to small amounts of melt then this material could likewise serve to erode the Type SD1 channel features. By contrast, Type SD2 features most likely formed from dry mass movement down the slip face of an indurated dune [8, 9].

*Central Peak Features (Type CP).* Type CP features form on crater central peaks. The heads of these Type CP features do not begin at a consistent depth beneath the overlying ridge, and are typically not associated with cohesive strata layers. Alcove depressions are generally absent or much less prominent than the alcoves of Type CL. Debris aprons can be found on Type CP features but are sometimes absent. In cases where Type CP features lack aprons, there is no evidence for a change between erosion within the channels to deposition within an apron. The substrate underlying Type CP channels is also distinct from that observed for Type CL gullies. Type CP features on central peaks often have a wide (at least 3 km based on the MOC narrow angle imaging scales) swath of smoother material crosscut by channel-like features.

The formation of Type CP features may thus be connected to the formation of the crater central peaks. Sometimes the central peak is composed of more resistant rock strata located below the surface [10, 11], and such a layer could have served as an aquiclude for a deep reservoir if water was present at depth on Mars. Other potential water sources to feed these gully features includes water within the permafrost and/or adsorbed water within the soil which can be heated and mobilized from the impact event [12, 13]. Perhaps the fracturing of the rock beneath the crater allows for a connection between a pre-existing deep water reservoir and the surface expression of the central peak. Deformed strata below a crater are uplifted towards the crater center [10, 14] and so the central peak would be an obvious outflow site for released subsurface water.

*Isolated Peak Features (Type IP).* Type IP features are found on isolated peaks, mountains, and massifs. The majority of Type IP features are located on the mountains that rim the Argyre Basin.

The morphology of the Type IP features is similar to the morphology of the Type CL features. In general, the Type IP features exhibit an alcove, channel, and depositional apron features. However, Type IP features exhibit a larger range in alcove depths even among features that are adjacent compared to Type CL features. In addition, Type IP features tend to have fewer individual features clustered together compared to Type CL features.

The formation mechanism of the Type IP features is unknown. We offer several scenarios that are consistent with the observations. The responsible fluid, assuming a liquid is involved at all, could emanate from the subsurface and fractures and faults in the rock (remember, the majority of these are on the eroded, mountainous remains of the Argyre impact basin) may provide a natural mechanism for transporting to the surface in these regions. We note, however, that since the alcove depths are not as consistent within a system compared with the Type CL features, the subsurface must be comparatively more complex to control the observed variation in outlet locations. Also, because Type IP features typically have fewer individual gully-like features clustered in one locale compared with the Type CL gullies, less water may be available from the source to feed and carve these features. Therefore if the water feeding the Type IP features is stored underground in and/or around the massifs, the physical size of available space to store the water is less for the Type IP features compared with the Type CL gullies.

**Conclusions:** Type CL gullies on Mars are found on a variety of terrain types (crater walls, valley walls, graben, etc.) and despite this diversity in geologic setting exhibit remarkable similarities in morphology and physical dimensions. These gullies might have been formed by release of water from the subsurface [1, 2, 15]. Gullies on eolian dunes, crater central peaks, and isolated massifs have been used by others to suggest that the groundwater hypothesis is falsified. However, such features are geomorphically distinct from Type CL gullies and cannot with confidence be used to rule out the subsurface aquifer hypothesis.

**References:** [1] Malin, M.C. and K.S. Edgett (2000) *Science, 288*. [2] Heldmann, J.L. and M.T. Mellon (2004) *Icarus*, *168*. [3] MEPAG Special Regions Science Analysis Group (2006) *Astrobiology*, **6**. [4] Heldmann, J.L. et al. (2007) *Icarus 188*. [5] Mangold, N. et al. (2002) *Lunar and Planet. Sci. Conf.*, #1215. [6] Mangold, N. et al. (2003) *J. Geophys. Res*., *108*. [7] Reiss, D. and R. Jaumann (2003) *Geophys. Res. Letters, 30(6)*. [8] Treiman, A.H. (2003) *J. Geophys. Res*. *108*. [9] Shinbrot, T. et al. (2004) *P. Natl. Acad. Sci*., *101*. [10] Hartmann, W.K. (1999), *Moons and Planets*, Wadsworth Publishing Company, Belmont, CA. [11] Pieters, C. (1982) *Science*, *215*. [12] Stewart, S.T and T.J. Ahrens (2003) *J. Geophys. Res, 30*. [13] Stewart, S.T and T.J. Ahrens (2005) *J. Geophys. Res*., *110*. [14] Wilshire, H.G. and K.A. Howard (1968) *Science 162*. [15] Mellon, M.T. and R.J. Phillips (2001) *J. Geophys. Res*., *106*.