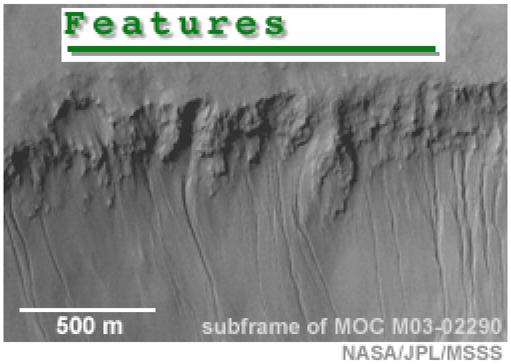

posted August 29, 2003

Gullied Slopes on Mars

--- Do the Martian gullies tell us something about the stability and distribution of near-surface water?

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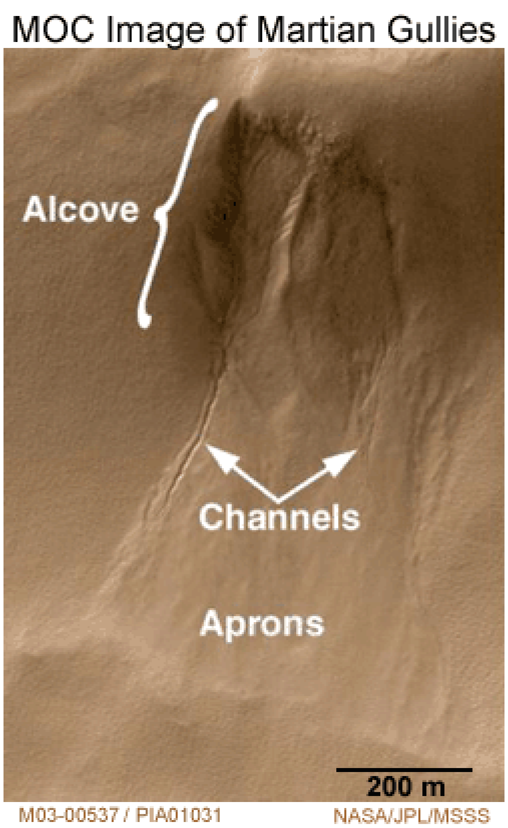
There are a lot of gullies on certain Martian slopes and just about as many ideas of how they formed. The proposed origins of gullies include seepage of groundwater or brines, outbursts of CO_2, snowmelt, geothermal activity, or dry flows of windblown dust and silt. Research teams have been publishing their hypotheses since the gullies were first announced in 2000, and the discussions are still lively. For example, a quick search of the terms "Martian or Mars or gullies or seepage" on the NASA Astrophysics Data System (link opens in a new window) delivered nearly 20 references to papers or abstracts published just in the past eight months. Gullies are such a hot topic, some researchers would argue, because they could indicate sources of liquid water at shallow depths. PSRD provides a rundown of the leading hypotheses to explain how Martian gullies form and how researchers use chemical data from Martian meteorites and knowledge of the Earth to support their points of view.

The reference that started it all:
(See more references at the end of the article.)

Malin, M. C. and Edgett, K. S. (2000) Evidence for Recent Groundwater Seepage and Surface Runoff on Mars. *Science,* v. 288, p. 2330-2335.

Discovery of Gullies



Michael Malin and Kenneth Edgett (Malin Space Science Systems) made the initial announcement in 2000 of the discovery of Martian gullies in Mars Global Surveyor MOC images (2 to 8 meter/pixel resolution). They found gullies located at middle and high latitudes, particularly on interior walls and central peaks of craters, on pit walls in the south polar region, and on walls in two large valleys (Nirgal Vallis and Dao Vallis). Typical middle-latitude gullies occur within a few hundred to five hundred meters of the local surface. In early 2003, Edgett and Malin updated their account after looking at an additional two-years' worth of images and studying 10,000 gullies. We begin our coverage by summarizing their observations and interpretations.

LEFT: Three main elements of Martian gullies, the alcove, channel, and apron are shown on this subframe of MOC image M03-00537/PIA01031, located near 54.8^{o}S, 342.5^{o}W.

Gullies have three characteristic parts: head alcoves, channels that extend downslope from the bottoms of alcoves, and triangular aprons of debris that broaden downslope. The head alcove is a depression that tapers downslope. It may be small or absent if it occurs at an overhanging rock layer. Channels, of course, are the most striking features of the gully systems; they generally begin deep and broad at a specific exposed rock layer, then taper downslope. They are banked, sinuous, and sometimes braided. Gully channels are free of debris, suggesting to Malin and Edgett that there was enough energy during their creation to flush down materials. Depositional aprons occur below the head alcove, down the slope, and sometimes continue out past the base of the slope. Channels appear to cut down into the aprons.

Malin and Edgett's mapping shows that there are more gullies in the south than in the north but that they occur, with few exceptions, poleward of 30^{o} latitude in both hemispheres. Gullies also occur in regional clusters. Gullies in a cluster tend to begin at the same rock layer exposed in the walls of different craters and troughs in the region.

A lack of impact craters on the channels and aprons suggests that the gullies are geologically young--the youngest features on the slopes where they form. Malin and Edgett observed gully aprons that partly cover windblown dunes or polygonally patterned ground (a periglacial or freeze/thaw feature). In other cases, the aprons and channels are partially mantled by dune sand. On Earth, dunes and patterned ground are known to change easily with environmental conditions or are generally short-lived on geological timescales, that is, less than hundreds of thousands of years. This would lend support to the hypothesis that the Martian gullies are relatively young. But, in fact, we don't know their ages. Malin and Edgett compared MOC images to twenty-year-old Viking images and could not see any evidence of new gully formation or gully movement at the scale of tens of meters. They estimate, based on the relationships of the gullies to underlying ground and to the lack of craters, that the gullies are probably older than 20 years but younger than a million years.

Groundwater seepage

Malin and Edgett favor gully formation by liquid water, specifically by groundwater seepage from shallow aquifers (underground layers of porous rock that yield water) and subsequent surface runoff. In their analysis, groundwater flows through and along bedrock layers a few hundred meters or less below the surface, perhaps backing up behind ice barriers, until it breaks through to the surface where the rock layers are exposed (for example in the walls of craters or troughs). Then the water flows downslope, perhaps in plunging outbursts, carving gully channels and depositing debris aprons. The clustering of gullies could be explained if the rock layers and aquifers are limited in size and lateral extent.

Gullies in the northern wall of a crater at 39.1°S, 166.1°W
Subframe of MOC image E11-04033

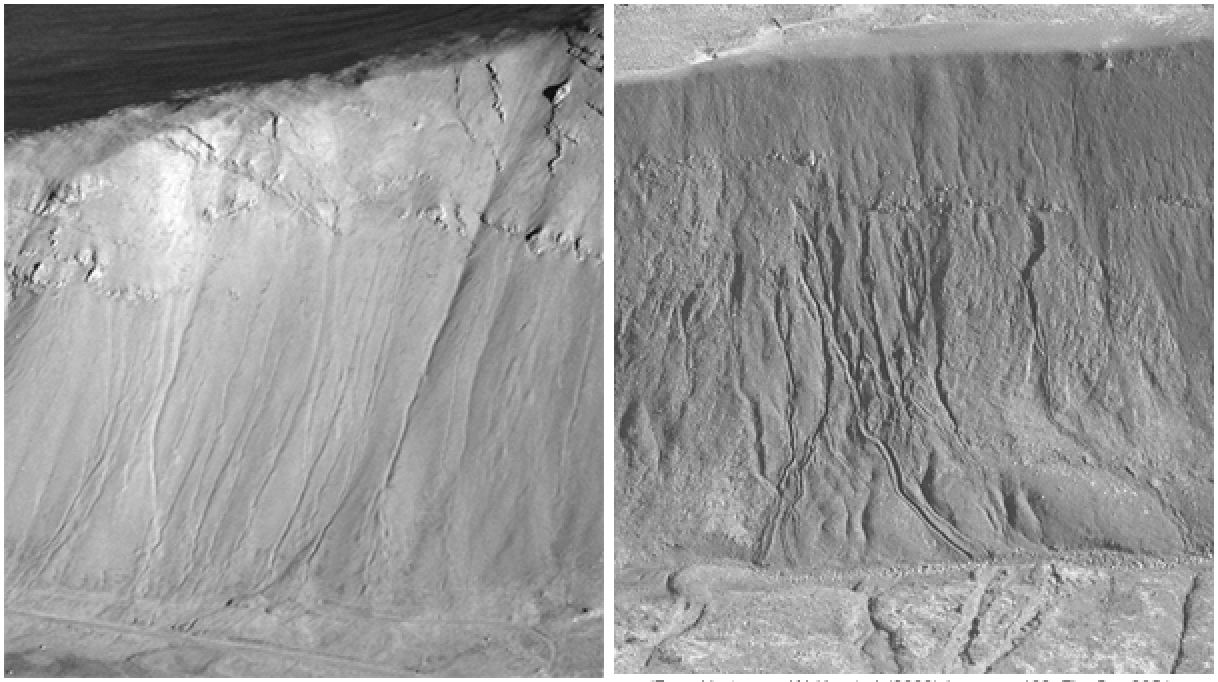
NASA/JPL/Malin Space Science Systems

Gullies on a north wall of a crater captured by the Mars Orbiter Camera.

An origin requiring liquid water must resolve the issue of how to stabilize it on the surface at the mid-latitudes where the gullies are found. The answer, according to planetologists, lies in the changes in Martian climate caused by changes in the planet's obliquity--the magnitude of the tilt of its spin axis. Calculations show that the obliquity of Mars slowly increases and decreases between 15° (axis is almost straight up) and 35° over a hundred-thousand-year cycle, but may occasionally reach 60° over million-year cycles. (Now Mars' obliquity is 25.2°, very similar to Earth's obliquity which is 23.5° and only varies by 4°.) Researchers say that the obliquity cycles produce climate changes on Mars that cause melting of ground ice and ongoing redistribution of water between the poles and mid-latitudes. For example, at high obliquity the icy Martian poles warm up in the summer because of the increased sunlight. Perhaps the gullies formed during one of these periods when the obliquity was higher than it is today.

Gullies in Iceland

Hillside gullies in Iceland have identical scales and surface expressions to gullies discovered on Mars--similarities that strengthen the case for a water origin. William Hartmann (Planetary Science Institute, Tucson, AZ) and colleages Thorsteinn Thorsteinsson and Freysteinn Sigurdsson (both Icelandic researchers) report that the best Icelandic analogs are on basaltic talus slopes where gullies formed by debris flows initiated by ground water saturation and/or by drainage of water from cliffs higher on the slopes. They argue that if there was uniform water saturation of the talus slopes, then gullies would begin wherever the material broke loose on the cliff face. However, Martian gullies and many of the Icelandic examples appear to originate from specific rock layers--observations that support the idea that the water exited the cliff from an aquifer.



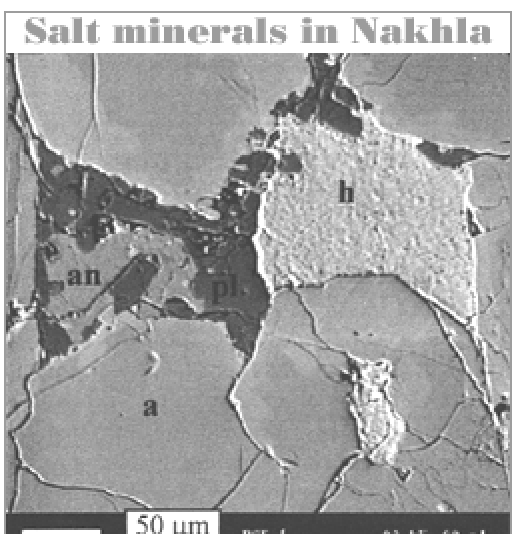
(From Hartmann, W. K., *et al.* (2003) *Icarus*, V. 162, Fig.8b, p. 268.)
Icelandic gullies analogous to Martian gullies

(From Hartmann, W. K., *et al.* (2003) *Icarus*, v. 162, Fig. 5, p.265.)
Icelandic gullies analogous to Martian gullies

These photographs from the work by Hartmann, Thorsteinsson, and Sigurdsson show hillside gullies in Iceland with similar characteristics and dimensions to Martian gullies noted by Malin and Edgett. **LEFT:** Tall cliff about 500 meters high, located 15 kilometers northeast of Reykjavik, Iceland is full of gullies similar to Martian gullies. Hartmann and colleagues observe that gullies begin near the base of blocky ourcrops seen in the upper part of the cliff. **RIGHT:** Icelandic slope composed of hyaloclastic debris (basaltic fragments formed by the flowing or intrusion of lava or magma into water, ice, or water-saturated sediment) showing gully formation from a specific layer. Levees on these Icelandic gullies are more visible than in most of the Martian examples.

Brines Rather Than Water

Donald Burt and Paul Knauth (Arizona State University) offer an alternative to fresh water to produce Martian gullies. They raise the possibility that eutectic brines (by definition liquids containing dissolved salts that are the last to freeze and the first to melt) in near-surface aquifers have oozed out of valley walls to form the gullies. They further argue that calcium chloride brines would have the low freezing points and low vapor pressures to be stable at the middle latitudes where gullies have been observed. Brines in the Martian subsurface could be sandwiched between a top layer of ice and bottom layer of salts.



From Bridges, J.C. and Grady, M.M. (1999) *Meteoritics & Planetary Science*, v. 34(3), p. 407-415.

The brines hypothesis is strengthened by studies of Martian meteorites that show the rocks were exposed to brines on Mars.

LEFT: Back-scattered electron image of salt minerals in Martian meteorite Nakhla. Mineral symbols: h=halite, a=augite, an=anhydrite, pl=plagioclase.

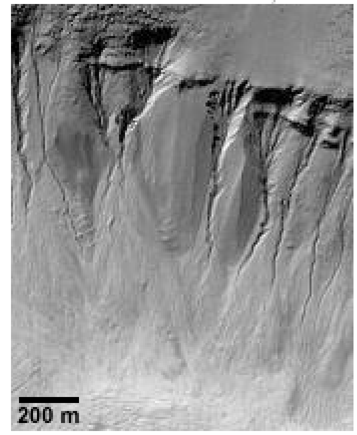
Secondary mineral assemblages in Martian meteorites provide information about the interaction between fluids in the Martian crust and the parent igneous rock. Meteorite experts, such as John Bridges and Monica Grady (Natural History Museum, London), say that the salt minerals in Nakhla formed through brine evaporation on Mars. This is direct evidence that there are brines on Mars at least some of the time.

The likelihood of brines on Mars has lead some researchers, for example Eric Gaidos (University of Hawaii) to suggest that brines originate from deep aquifers that are pressurized by freezing. They've termed this cold-climate process "water volcanism." Gaidos thinks that the gullies are simply an expected consequence of freezing of aquifers.

Brines on Mars should be highly electrically conducting, and their presence may someday be confirmed by geophysical detection. THEMIS data from the Mars Odyssey spacecraft may be able to provide chemical evidence in support of the brine origin by detecting surface residues of salt minerals at the gullies.

Carbon dioxide

Gullies in crater near 39°S, 200°W

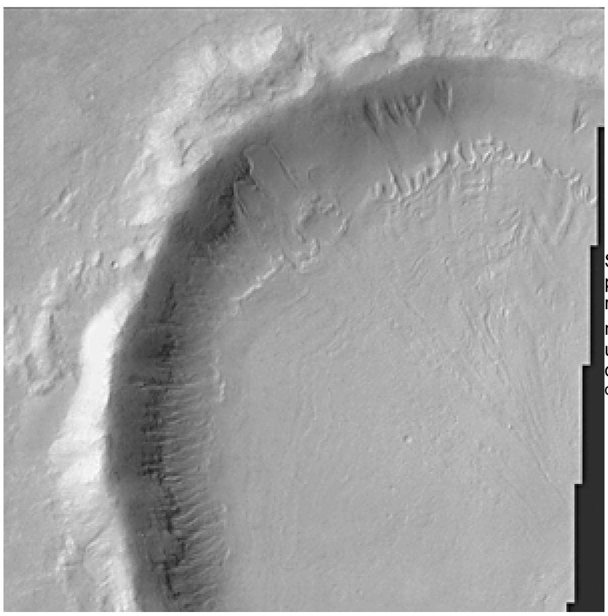


MOC2-388/PIA04570 NASA/JPL/MSSS

Carbon dioxide (CO_2) seasonal outbursts, perhaps due to Mars' obliquity cycles, have been evoked to explain the Martian hillside gullies. According to some researchers (for example, Donald Musslewhite, Timothy Swindle, and Jonathan Lunine of University of Arizona) liquid CO_2 aquifers build up behind plugs of dry-ice and eventually break out and vaporize at the surface during periods of seasonal heating. The gullies would form because of the fluidized flow of gas and suspended rock debris. On Earth similar landforms are produced by suspended flows of volcanic ash and gas from erupting volcanoes but without the head alcoves. Still, it's a matter of debate whether or not gas-supported flows on Mars could produce the banked and sinuous gully channels observed in the orbital images.

Snow melt

Philip Christensen (Arizona State University) proposes a different model in which melting of an overlying snowpack provides the source of water to erode gullies. Gullies form on the snow-covered slopes when melt water flows over or seeps into the slope materials. If the snow layer collapses, then water could erode the underlying ground leaving the gullies as evidence of the process. Christensen says the snow fell when water was transported from the warmer poles to colder mid-latitudes during high obliquity periods. Then melting occurred during low obliquity when mid-latitude temperatures increased and the water was stable beneath an insulating cover of snow. Christensen thinks remnants of snowpacks are still present on mid-latitude, pole-facing slopes and says melting could be happening right now. Snowmelt explains many of the gully characteristics without requiring near-surface aquifers as the source of the water. Little chemical weathering or mineralization of the surface would be expected if the gullies were formed by snowmelt because of the near-freezing temperatures and short duration, thus eliminating the need to look for evaporation deposits as evidence of the process.


2001 Mars Odyssey THEMIS image V01229004

Subscene of THEMIS visible band image of gullies purportedly formed by snowmelt on a crater wall with remnants of snow cover. The crater is in Terra Sirenum near 39°S, 166°W. The scene is illuminated from the upper left, but has been contrast stretched to show more detail. Image width is 3 kilometers. Higher Resolution will open in a new window.

Geothermal Activity

Geothermally heated ground ice has also been invoked as source water forming the gullies. Several researchers, including Hartmann and colleagues citing their work in Iceland, hypothesize that Martian volcanism provided sources of sporadic subsurface heating that could melt ground ice and produce aquifers. Thermal data from Mars Odyssey could help determine the likelihood that geothermal heating is involved in gully formation.

Dry Flows

In a completely different mechanism, Martian gullies are not related to liquids of any sort. Dry flows of windblown dust and silt can display the same features observed in the Martian gullies according to Allan Treiman (Lunar and Planetary Institute, Houston). The locations and distribution of the gullies, he says, are consistent with atmosphere circulation models that show that wind deceleration occurs in the same areas as the gullies. Deceleration would cause suspended sediments to drop out and be deposited on wind-protected slopes. If these slopes are steep, says Treiman, then gullies will form. Treiman's hypothesis evokes massive snow avalanches on Earth, where movement is by dry granular flows.

RIGHT: An avalanche in progress in the Cariboo Mountains, British Columbia, Canada. (Photo by Brad White. www.avalanche.org)

Whether or not the Martian gullies tell us something about the stability and distribution of near-surface water is yet to be answered conclusively. But the quest for the answer is keeping a lot of people busy, planetary geologists curious about the history of water on Mars and astrobiologists, just to name a few. Using multiple data sets, such as MOC images, MOLA altimeter data, and TES thermal data from Mars Global Surveyor, researchers Jennifer Heldmann and Michael Mellon (Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder) reported preliminary findings in February, 2003 at the NASA Astrobiology Institute General Meeting that support the idea that water from shallow aquifers (perhaps 200 to 300 meters beneath surface) formed the gullies. Mars Odyssey neutron spectrometer data confirm that the Martian surface poleward to 60^{o} contains from 35wt% to 100wt% water-ice buried beneath a shallow layer of ice-free material [see PSRD article Dirty Ice on Mars]. As more data are analyzed we will have a clearer understanding of how the gullies formed. And new data should be bountiful from the currently orbiting Mars Global Surveyor and Mars Odyssey spacecrafts and future international missions as well as continuing studies of meteorites and of analogous gullies on Earth.

Additional Resources

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Mars Orbiter Camera Image Gallery at Malin Space Science Systems. Opens in a new window.

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