PLANETARY SCIENCE RESEARCH
PSRD Discoveries

Headline Article
May 27, 2011

Timeline of Martian Volcanism

--- High-resolution images allow a larger range of crater sizes to date calderas and the last major periods of volcanic activity on Mars.

***Written by* Linda M. V. Martel**
Hawai'i Institute of Geophysics and Planetology

Click for full image data.

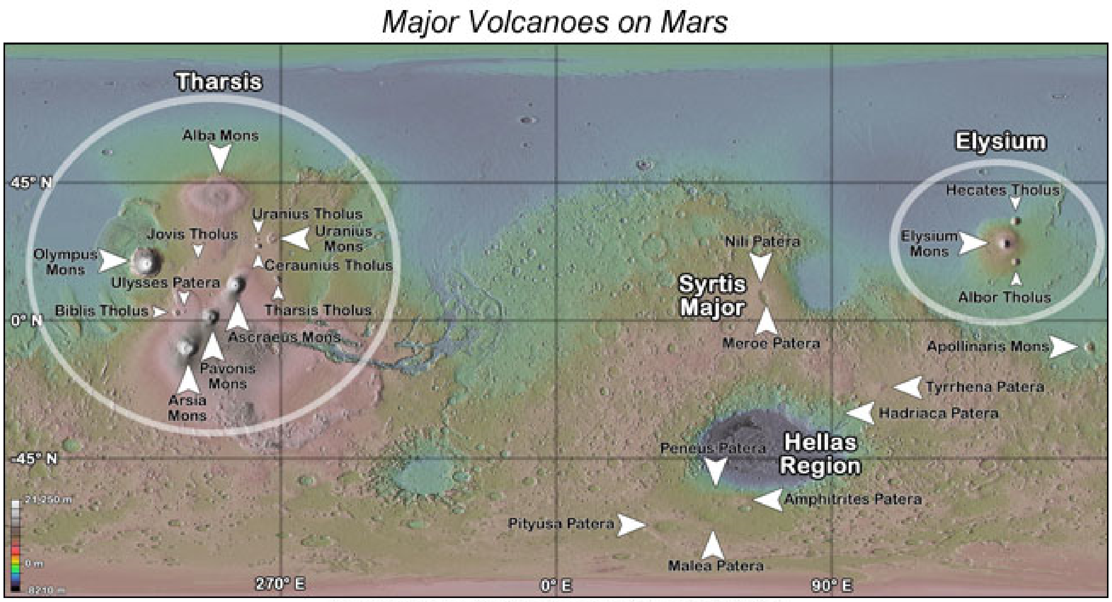
A recent study of Martian volcanism presents a timeline of the last major eruptions from 20 large volcanoes, based on the relative ages of caldera surfaces determined by crater counting. Stuart Robbins, Gaetano Di Achille, and Brian Hynek (University of Colorado) counted craters on high-resolution images from the the Context Camera (CTX) on Mars Reconnaissance Orbiter to date individual calderas, or terraces within calderas, on the 20 major Martian volcanoes. Based on their timeline and mapping, rates and durations of eruptions and transitions from explosive to effusive activity varied from volcano to volcano. The work confirms previous findings by others that volcanism was continuous throughout Martian geologic history until about one to two hundred million years ago, the final volcanic events were not synchronous across the planet, and the latest large-scale caldera activity ended about 150 million years ago in the Tharsis province. This timing correlates well with the crystallization ages (~165-170 million years) determined for the youngest basaltic Martian meteorites.

Reference:

- Robbins, S. J., Di Achille, G., and Hynek, B. M. (2011) The Volcanic History of Mars: High-Resolution Crater-Based Studies of the Calderas of 20 Volcanoes, *Icarus,* v. 211, p. 1179-1203, doi: 10.1016/j.icarus.2010.11.012.
- **PSRDpresents:** Timeline of Martian Volcanism --**Short Slide Summary** (with accompanying notes).

Largest Volcanoes on Mars

The volcanoes on Mars, though inactive, stand as proof of past volcanic activity whose timing, duration, and cessation are hot topics in planetary science. In fact, the planet's geologic history owes much of its action to volcanism (as well as tectonics, wind, water, and impact cratering). We'll get back to impact cratering, but for now the map, below, shows the locations of 24 major volcanoes on Mars. Twelve of these are in the region, covering about 25% of the planet's surface, known as Tharsis. Here the spectacular shield volcano, **Olympus Mons**, looms 18 kilometers over the surrounding landscape. Another six volcanoes are near the Hellas basin, two form the Syrtis Major complex, three form the Elysium complex, and one more major volcano lies just to the southeast of Elysium. Each is marked on the map by a white arrow. Robbins, Di Achille, and Hynek included all in their study except four volcanoes, southwest of the Hellas basin, because of insufficient data coverage. Their dataset came from the Context (CTX) Camera, onboard NASA's **Mars Reconnaissance Orbiter**, which as of February 2010 had completed mapping 50% of the planet's surface. Though eruptions or outbreaks from the volcanoes have not been captured in any images of Mars acquired since NASA and the European Space Agency began orbiting and imaging the planet, some say you can't entirely rule out current volcanism. Perhaps small volcanic activity is simply unnoticed because our sensors and cameras are not in the right place at the right time to see it. Nevertheless, large-scale major volcanic activity on Mars has finished. Stuart Robbins and coauthors set out, as others have done before them using other datasets, to constrain the length of time over which the major volcanoes were last active, and by extension, determine a timeline of the last episodes of volcanic activity on Mars.



(From Robbins *et al.*, 2011, *Icarus*, v. 211, p. 1179-1203.)

This MOLA (Mars Orbiter Laser Altimeter) shaded relief map shows the locations of the 24 major volcanoes on Mars. They are not distributed equally, but in regions indicated by the white circles around Tharsis and Elysium. Two more volcanoes form the Syrtis Major complex, six are near the Hellas impact basin, and one, Apollinaris Mons, lies southeast of Elysium. White arrows point to the volcanoes in question. Robbins and coauthors analyzed all of them with the CTX dataset except the four volcanoes southwest of Hellas Basin.

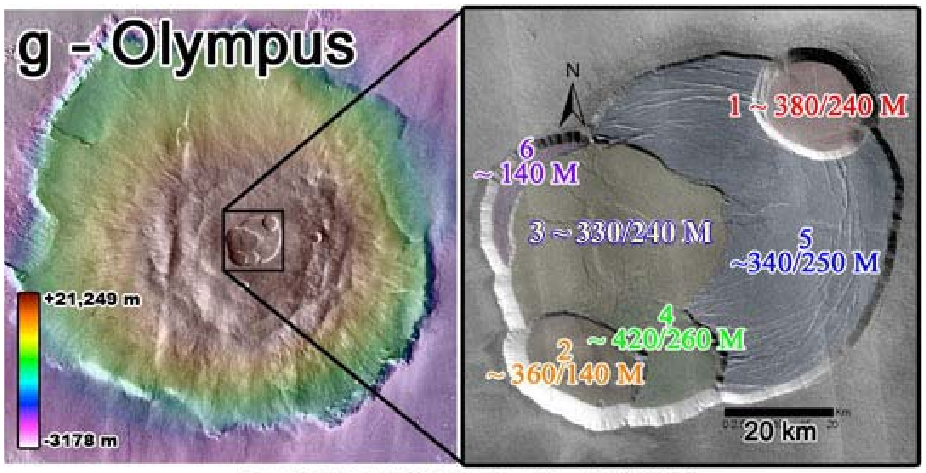
Generations of Calderas Dated by Crater Counting Method

The numbers of impact craters on planetary surfaces increase with time. Ancient surfaces can become saturated with craters, with each new crater effectively wiping out an older one so that the number of craters no longer increases. The fact that an older surface has more craters on it than a younger surface is the basis of a planetary chronology based on counting craters. While this method of counting craters to determine relative ages of surfaces has been around since the 1970s, the advent of new imaging systems onboard Mars orbiting spacecraft has allowed researchers to identify and count ever-smaller craters, increasing the range of diameters they can measure and improving the counting statistics. This is especially beneficial for studies of the **calderas** of Martian volcanoes. Robbins and coauthors mapped the summit regions of their 20 volcanoes on Mars covered by the CTX dataset at **resolutions** of 5.5-7.5 meters per pixel. Individual images were ultimately mosaicked to a standard map projection at 10 meters per pixel before the impact craters were measured and counted. Previous mapping of volcanic calderas used images with 10-30 meters per pixel resolution from the High Resolution Stereo Camera (HRSC) on the ESA **Mars Express** orbiter, sometimes combined with Mars Orbiter Camera (MOC) narrow-angle images obtained from NASA **Mars Global Surveyor** (see, for example, the **PSRD** article: **Recent Activity on Mars: Fire and Ice**.) Prior to these studies, the **Viking** orbiter cameras provided resolutions of 150-300 meters per pixel (though limited areas were imaged at 8 meters per pixel).

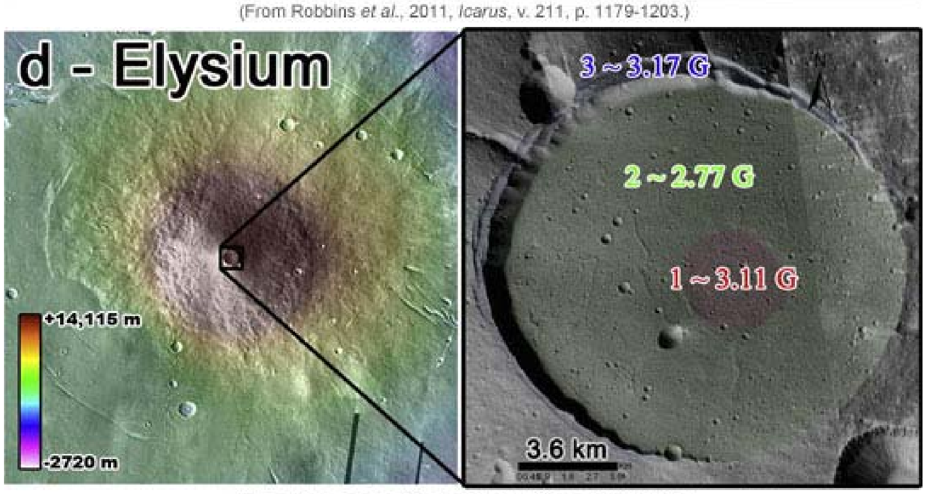
Robbins and collaborators mapped the Martian calderas based on **stratigraphic** relationships, taking into account topographic and erosional features that suggested modification or mantling. Places where a surface was covered by young, nonvolcanic debris were not included in the crater counting. These materials included any inferred glacial deposits and rock glaciers, alluvial materials, aeolian features, landslides, and significant crater ejecta blankets on the caldera units. They used texture, shape, topography, and thermophysical properties to discriminate different calderas or possible nested calderas on a volcano, and generally used a simple numbering scheme based on elevation with number 1 given to the caldera at lowest elevation, and so on.

Next they counted the crater population on each caldera surface, measured crater diameters, and grouped the craters into size bins. The resulting crater size-frequency distributions show cumulative number of craters per km^2 versus diameter of crater in kilometers. The CTX data allowed Robbins and colleagues to use diameters ranging from 10 meters up to >100 kilometers; their work is statistically complete to crater sizes down to 60 meters.

To convert relative timing to absolute ages, Robbins and colleagues fit their size-frequency distributions to **isochrons**, which are defined as the size distribution of craters found on a surface of a specified age, if no other processes have obliterated or altered the surface. They fit their data to isochrons based on the methods established in 2001 by William K. Hartmann (Planetary Science Institute, Tucson, AZ) and Gerhard Neukum (Freie Universität, Berlin, Germany). Examples of the results reported by Robbins, Di Achille, and Hynek for two volcanoes, Olympus Mons and Elysium Mons, are shown below. They used a range of diameters (rather than only one) that paralleled the established isochron function. Other diameter ranges that did not parallel the isochrons were assumed to be altered by weathering (erosion, infilling, etc.) or contamination by secondary craters, or affected by incomplete counts (for diameters less than 50-70 meters) or other non-age-related issues. The bulk of these massive volcanoes built up over a long time, but these results give a good idea of the timing of their last major, summit eruptions.

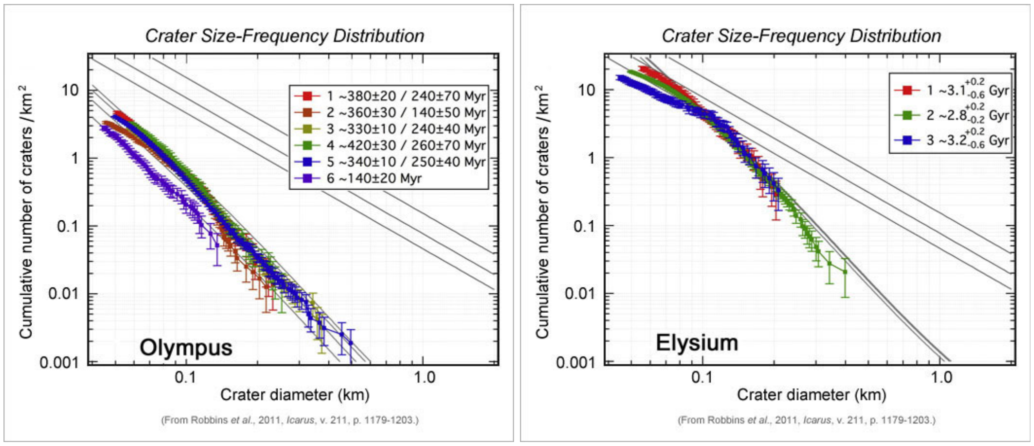


(From Robbins *et al.*, 2011, *Icarus*, v. 211, p. 1179-1203.)



(From Robbins *et al.*, 2011, *Icarus*, v. 211, p. 1179-1203.)

Volcanoes are shown on basemaps created with THEMIS Daytime IR images combined with MOLA altimetry-color-coded maps. Top: Olympus Mons (18.5°N, 133.2°W) is mapped with six calderas numbered according to elevation, lowest elevation is 1, next higher is 2, etc. The estimated age of each surface, determined by the crater size-frequency data, is shown by the caldera number. (M is millions of years.) Five of the calderas have split ages where the younger age is at larger crater diameters and the older age is at smaller diameters. Bottom: Elysium Mons (25°N, 147°E) has a large, main caldera partly surrounded by a second caldera, and a third smaller caldera in the center. Ages are statistically identical. (G is billions of years.)



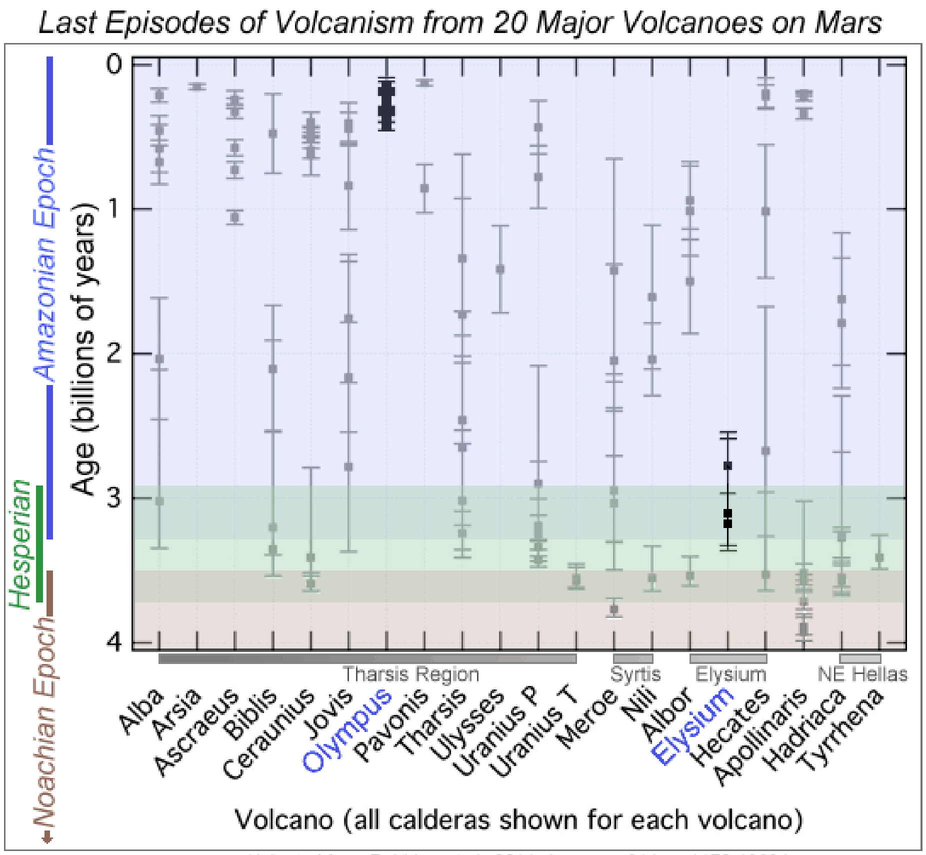
A crater size-frequency distribution shows the cumulative number of craters per squared kilometer area plotted against crater diameter to derive the ages of the surfaces. The age is determined by the slope of the isochron line. (Myr is millions of years. Gyr is billions of years.) Each estimated age is shown with plus/minus uncertainties determined by Robbins and coauthors. Log-log plots were constructed for each volcano in the study. Olympus Mons data is on the left, Elysium Mons data is on the right.

In these cumulative size-frequency plots with log-log axes, isochron lines have a characteristic negative slope due to the greater abundance of smaller craters than larger craters. Over time the line shifts to the right. In addition to isochrons, three straight, parallel lines show the 10%, 5%, and 3% lies of geometric saturation, which means a surface has enough craters on it that a new one will obliterate an equivalent existing one. The calderas on Elysium show an example of a surface reaching the 3% saturation level.

There are a few issues inherent in the crater counting project. First, the ages of the calderas are open to some interpretation due to the crater size-frequency distributions failing to parallel isochrons over a large diameter range. For example, a caldera may parallel the 3.0 billion-year isochron between crater diameters of 0.6 to 1.0 kilometer, but then trail to lower ages at smaller diameters. The team assumed this to be evidence of resurfacing in the caldera. Secondly, there is a factor of two uncertainty in isochrons themselves. The third issue is secondary craters--the relatively small craters formed when ejecta of a primary crater hits the surface. Secondary craters may confuse the results by increasing the number of smaller craters. Robbins and coauthors carefully mapped the secondary craters they identified in the calderas (using standard techniques of elongated shapes, clustering, lines of craters) and suggest that they may not be statistically important in the isolated, caldera regions they examined. Finally, it is important to remember that we do not have rocks from known locations on Mars to use for radiometric dating to establish absolute ages of the Martian surfaces. Until we do, these ages will be approximate.

Volcanic Activity on Mars Through Time

Based on their dated calderas, Robbins and colleagues created a timeline of the last volcanic activity from the summit of 20 large volcanoes, shown below. We added color bars to represent the three Martian geologic epochs. You'll notice that the colors overlap because the timing of the epochs is not known precisely due to different models of the rates of impact crater formation on Mars. The timeline appears on the next page.



(Adapted from Robbins *et al.*, 2011, *Icarus*, v. 211, p. 1179-1203.)

Timeline produced by Robbins, Di Achille, and Hynek to illustrate caldera ages and last episodes of major volcanism from 20 large volcanoes on Mars. Olympus Mons and Elysium Mons, the two volcanoes highlighted in this article, are darkened. Geologic settings of the volcanoes are also noted along the x-axis. In addition to time given in billions of years on the y-axis, we also show color-coded stripes for the Martian epochs from youngest to oldest: Amazonian (blue), Hesperian (green), and Noachian (brown). The epochs are based on the times given by Hartmann and Neukum (2001); overlapping boundaries are due to different models of the rates of impact crater formation on Mars.

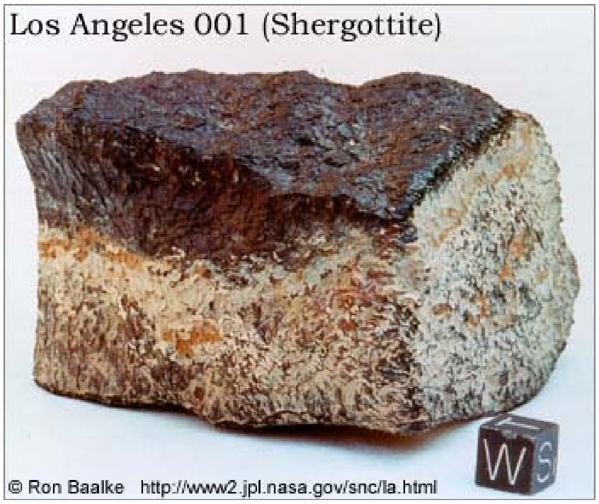
The team published specifics for each volcano in their study, but in general terms, the timeline says:

- Generally the smallest volcanoes in their study show the oldest caldera ages, while the largest volcanoes show the youngest caldera ages.
- Apollinaris Mons has the oldest calderas, dating back to 3.9 billion years ago. It was also the first volcano to die out.
- The final major volcanic events did not occur at the same time across the planet.
- After activity at Apollinaris Mons shut off, major volcanism ended throughout the rest of the highlands and Syrtis Major, then in the smaller Elysium volcanoes and finally in the largest of the Tharsis volcanoes.
- Every volcano they studied was active through the Hesperian epoch, while all volcanoes except for Tyrrhena Patera and Apollinaris Mons were active through at least the Early Amazonian.
- The major summit volcanism on Mars ceased about 100-150 million years ago, but more recent, scattered minor events cannot be ruled out.

In addition to the timing of volcanic activity on Mars, the team also considered the style of eruptions from the calderas in their study. They noted two surface features in the summit calderas that they attributed to an effusive style of volcanism: (1) recognizable flow-lines in lava flows emanating from the source, and (2) better-defined caldera rims. Effusive volcanic eruptions refer to the outpouring of (volatile-poor or volatile-free) lava onto the ground in contrast to the more violent, explosive style of eruption caused by rapid escape of volatiles from the parent magma. Robbins and coauthors suggest a transition from explosive to effusive activity occurred at different times for the Martian volcanoes, but say that generally the transition was made around the Hesperian-Amazonian boundary. This change in eruptive style is generally correlated to a decrease in near-surface water, but more detailed studies of each volcano and its related deposits are required to better understand trends in eruptive styles.

The Timeline and Martian Meteorites

The timeline of volcanic activity presented by Robbins and colleagues is interesting from a cosmochemical point of view, as researchers determine the crystallization ages of Martian meteorites, and consider the most likely source areas of these rocks. The Martian meteorites are grouped into four main types with crystallization ages ranging from 4.1 billion years (for ALH 84001) to about 165 million years (for Shergotty), based on **radiometric dating**. The **shergottites** are the most abundant type and the youngest of the Martian meteorites. They are basalts and basaltic cumulates with crystallization ages typically in the range of 165 to 170 million years. While shock heating has been known to disturb isotopic systems, and recent analyses helped to recalculate the crystallization age for ALH 84001 (see for example the **PSRD** article: **A Younger Age for the Oldest Martian Meteorite**), a wide body of isotopic work supports the young crystallization ages for the shergottites. Crater counting tells us that young volcanic landscapes are widespread in the Tharsis region, leading Robbins and coauthors to agree with previous assessments that Martian meteorites a few 100 million years old likely came from the younger flows of the Tharsis Montes. Other types of studies, in addition to crater counting, are also useful in assessing potential source regions of Martian meteorites, for example, global searches of infrared data by Vicky Hamilton (Southwest Research Institute, Boulder, CO) and colleagues using the Thermal Emission Spectrometer (TES on Mars Global Surveyor) to map areas with spectral similarities to Martian meteorites. To be sure, researchers in the laboratories are learning all they can about the Martian meteorites while others continue to search remote sensing data for large, young impact craters in young Martian volcanic areas where rocks escaped and landed on Earth.



This photograph shows an example of a Martian shergottite, the 452.6 gram stone named Los Angeles. It has a crystallization age of 170±7 million years. A one-centimeter square cube is shown for scale. Photo by Ron Baalke (Jet Propulsion Lab), click photo for more information. [**Data link** from the Meteoritical Bulletin].

Additional Resources

Links open in a new window.

- **PSRDpresents:** Timeline of Martian Volcanism --**Short Slide Summary** (with accompanying notes).

- Hamilton, V. E., Christensen, P. R., McSween, Jr., H. Y., and Bandfield, J. L. (2003) Searching for the Source Regions of Martian Meteorites using MGS TES: Integrating Martian Meteorites into the Global Distribution of Igneous Materials on Mars. *Meteoritics and Planetary Science,* v. 38(6), p. 871-885. [**Martian Meteorite End Member Maps**].
- Hartmann, W. K. and Neukum, G. (2001) Cratering Chronology and the Evolution of Mars. *Space Science Review,* v. 96, p. 165-194.
- Martel, L. M. V. (January 2005) Recent Activity on Mars: Fire and Ice. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/Jan05/MarsRecently.html**.
- Neukum, G., Jaumann, R., Hoffmann, H., Hauber, E., Head J. W., Basilevsky, A. T., Ivanov, B. A., Werner, S. C., van Gasselt, S., Murray, J. B., McCord, T., and the HRSC Co-investigator team (2004) Recent and Episodic Volcanic and Glacial Activity on Mars Revealed by the High Resolution Stereo Camera. *Nature,* v. 432, p. 971-979.
- Robbins, S. J., Di Achille, G., and Hynek, B. M. (2011) The Volcanic History of Mars: High-Resolution Crater-Based Studies of the Calderas of 20 Volcanoes, *Icarus,* v. 211, p. 1179-1203, doi: 10.1016/j.icarus.2010.11.012.
- Taylor, G. J. (May 2010) A Younger Age for the Oldest Martian Meteorite. *Planetary Science Research Discoveries.* **http://www.psrd.hawaii.edu/May10/YoungerALH84001.html**.
- Website for the Mars Reconnaissance Orbiter **Context Camera**, from Malin Space Science Systems.

More references about crater size-frequency distributions and isochrons for Mars:

- Hartmann, W. K. (2005) Martian Cratering 8: Isochron Refinement and the Chronology of Mars. *Icarus,* v. 174, p. 294-320, doi: 10.1016/j.icarus.2004.11.023.
- Hartmann, W. K. (2007) Martian Cratering 9: Toward Resolution of the Controversy about Small Craters. *Icarus,* v. 189, p. 274-278, doi: 10.1016/j.icarus.2007.02.011.
- Hartmann, W. K. and Werner, S. C. (2010) Martian Cratering 10: Progress in Use of Crater Counts to Interpret Geological Processes: Examples from Two Debris Aprons. *Earth and Planetary Science Letters,* v. 294, p. 230-237, doi: 10.1016/j.epsl.2009.10.001.
- Michael, G. G., and Neukum, G. (2010) Planetary Surface Dating from Crater Size-Frequency Distribution Measurements: Partial Resurfacing Events and Statistical Age Uncertainty. *Earth and Planetary Science Letters,* v. 294, p. 223-229, doi: 10.1016/j.epsl.2009.12.041.
- Neukum, G., Basilevsky, A. T., Kneissl, T., Chapman, M. G., van Gasselt, S., Michael, G., Jaumann, R., Hoffmann, H., and Lanz, J. K. (2010) The Geologic Evolution of Mars: Episodicity of Resurfacing Events and Ages from Cratering Analysis of Image Data and Correlation with Radiometric Ages of Martian Meteorites. *Earth and Planetary Science Letters,* v. 294, p. 204-222, doi: 10.1016/j.epsl.2009.09.006.