# Lab 4

# Cratering and the Martian Surface

## 4.1 Overview

Exercise four continues our study of terrestrial surface evolution, shifting from the Moon to Mars and exploiting an extensive reservoir of recent high-resolution Martian surface imaging. While exercise three centers on a hands-on cratering experiment, exercise four presents another side of scientific experimentation by having students analyze the terrain within ten surface images drawn from NASA spacecraft archives. These images cover regions dominated by volcanic activity, water-carved features, and water floods caused by volcanic activity studied by the Thermal Emission Imaging System (THEMIS) and the Mars Orbiter Laser Altimeter (MOLA). The cratering record (the surface density of craters of various sizes) is used as a proxy for surface age.

Surface images are presented through a dedicated web-application with pre-loaded images. As shown in Figure 4.1, the tool contains a large-scale view of the surrounding region and a detailed close-up image of a central region extending over a width of three to seventeen kilometers. Students identify and count craters of 250 to 500 meters in size on the larger regions, and focus on smaller craters (down to radii of 16 meters on images with scales of three meters per pixel) on the smallest, highest-resolution, images.

There are several lessons to be learned from the cratering counts data analysis, in addition to the specific topics related to surface evolution. The first is to acquire the skill of reading logarithmic axes, and to understand how logarithms allow us to study behavior over many orders of magnitude. We devote a stand-alone guide to this topic and also focus on it during the associated video tutorial, to help students to understand how to perform the task. The second lesson relates to measuring the number of craters on a given surface down to more than one size limit in order to make multiple estimates of the same surface age. The third lesson relates to the natural distribution of craters across a surface, and the idea that by

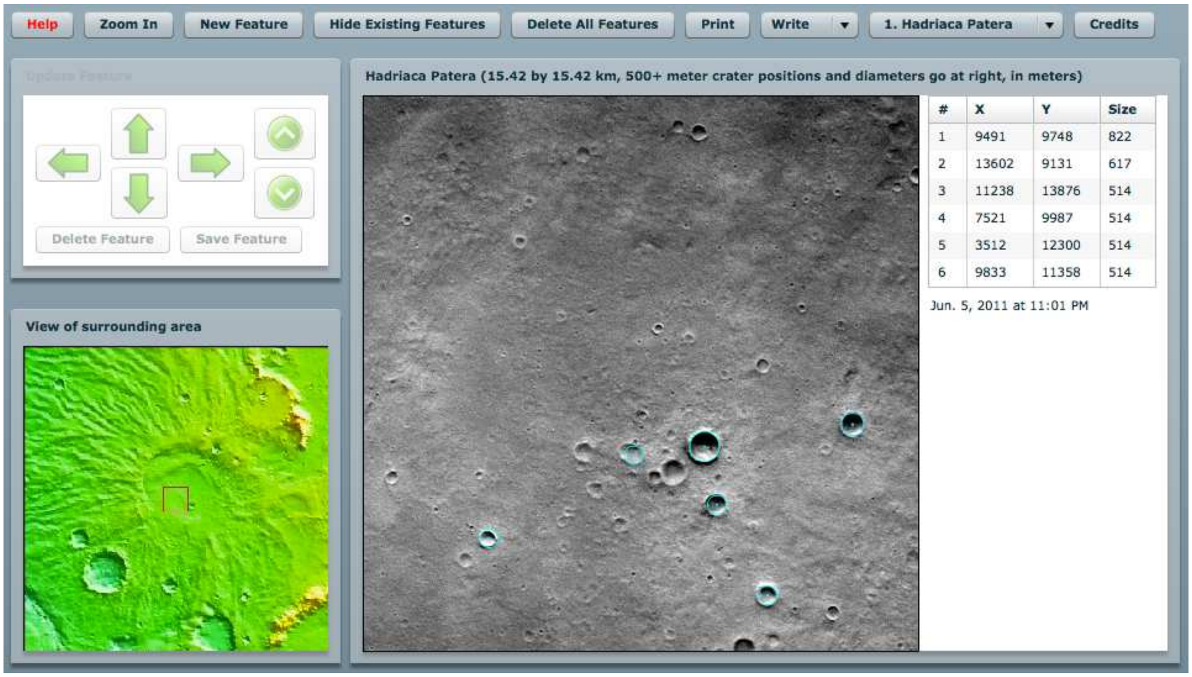


Figure 4.1: A screen capture of our Martian cratering web-application, presenting large-scale color images of regions characterized by various types of surface evolution and close-up, higher-resolution black and white images of central regions for analysis. Students identify all craters that are larger than a certain size within each close-up image. The crater counts are then used to determine an age for the region. Circles are overlaid on top of each crater and adjusted in position and size to match each feature, and a zoom option allows students to focus on individual features.

increasing the size of the sampled region we reduce the relative size of the associated errors on the crater counts, due to Poisson statistics.

## 4.2 Learning Objectives

After completing this laboratory exercise, the student should be able to do the following:

- Appreciate the breadth of Martian geological and climate history.
- Describe the appearance of the Martian surface, understand why certain features occur in certain regions, and discuss the available physical evidence regarding probable evolutionary histories.
- Estimate local surface densities of craters, given detailed images and physical scale measurements, in order to determine the ages of varied surfaces.
- Compare and contrast Martian and terrestrial volcanoes, understand the history of

volcanism on Mars, and discuss whether Martian volcanoes are still active, given the available evidence for recent eruptions.

- Compare and contrast Martian and terrestrial water histories, evaluate the history of surface water flow volcanism on Mars, and discuss evidence for recent surface water flows on Mars.

- Distinguish between network valleys and outflow channels, by morphology.

- Read values from a logarithmic plot, and understand how it differs from a linear plot.

- Create histograms of several samples of data, and decide whether or not differences between the samples are statistically significant.

## 4.3 Teaching Toffees

Teaching toffees are practical tips based on the hard-won experience of fellow instructors.

For all GEAS lab exercises:

Please have students access the list of components for the lab exercise (lab chapter, video tutorial, web applications, report template) directly from the GEAS website so that they use the current version of all tools.

By having them save and share the lab report template, they will have their work backed up automatically and instructors will be able to observe their progress 24/7. This allows instructors to check for appropriate progress towards intermediate goals over a two-week period, and for students and instructors to interact asynchronously through threaded comments placed in the report margins at exactly the point where a question occurs. Note that the Lab #1 video tutorial describes how to work with Google resources, and there is a two-page handout on the lab website as well.

Students sometimes try to complete the lab exercise by skipping over the lab chapter entirely and working from just the report template. This is not an effective learning strategy, nor does it save time. The report template contains only abbreviated forms of the questions with spaces for answers, but none of the context or framework for the questions.

We strongly encourage you to strongly encourage all of your students to watch the video tutorial before beginning to work on the exercise. If a picture is worth a thousand words then a video might be worth a million words. Each tutorial is designed to introduce the scientific concepts that motivate the companion exercise. Because students may be working remotely on their own, it also focuses on the most potentially challenging aspects of each project and walks them through key steps by showing them what they look like in practice.

For Lab #4 in particular:

The three labs #1 (Fundamentals of Measurement and Error Analysis), #3 (Cratering and the Lunar Surface), and #4 (Cratering and the Martian Surface) can form a cohesive six-week sequence, particularly for classes which emphasize the solar system or geology.

The video for this exercise includes a detailed introduction to our crater-fitting web application, highlighting each of the controls used when fitting a circular aperture to a crater to illustrate their usage. It shows how to derive a crater surface density from the number of craters above a given size found within a field, and then how to determine a corresponding surface age from Figure 4.5. This includes an explicit description of how to read values along the logarithmic axes. This is followed by a filmed meeting between a teaching assistant and a student, in which the student models common concerns about how to work with logarithms and goes through the process of reading values along an axis.

The most challenging mathematical aspect of this exercise is the idea of logarithms, and their utility in illustrating behavior over many orders of magnitude. Students who are unfamiliar with logarithmic plots should benefit from the video tutorial, particularly if they first read through the two-page handout on Linear and Logarithmic Plots and then review it while following along with the tutoring session in the video.

A common mistake is to treat the space between successive small tick marks on an axis linearly rather than logarithmically, when placing an intermediate value on the axis between two tick marks. However, because these spaces represent at most a factor of two change in value, the resulting error in determining a surface age will not invalidate the result. It is definitely helpful to explicitly tell students to not simply default to the closest tick mark to their value, but to make a point of interpolating between tick marks.

A student can in fact complete the exercise with an incomplete comprehension of logarithms and still understand how ages are being derived from crater counts and determine usable age estimates for each field.

The most common computational error made by students is to divide by the wrong surface area (typically reusing a surface area found for a previous field) when computing a surface density of craters, or to forget to divide by any surface area at all.

Occasionally a student will miss the fact that for the Hadriaca Patera field the number of craters larger than 250 meters is given to them in the exercise text – they do not need to count additional craters on the image down to the lower size limit.

## 4.4 Keywords

Amazonian Period – The last of three major periods in Martian history, lasting from 1.8 billion years to the present. This era is named for Amazonis Planitia, a low plain in the northern hemisphere. Amazonian surfaces exhibit a varied morphology, but contain relatively few impact craters. The bulk of the historical record of cratering on these surfaces has been erased by lava flows, glacial activity, and even occasional liquid water flows. Much of the northern hemisphere is thought to have been resurfaced during the Amazonian Period.

Billion – Ten raised to the ninth power, or $1,000,000,000$.

Caldera – A caldera is a circular crater, the relic of a volcanic explosion or the collapse of a volcanic cone. Caldera is also the Spanish word for cauldron, in reference to the basin-shape of the depression.

Central vent volcano – A volcano with a central vent is constructed as debris and lava are ejected from an upthrust, cylindrical vent, forming a symmetrical structure around it.

Crater – A crater is a generally circular surface depression, caused by an impact or an explosion, a volcano, or a geyser.

Density – The density of a three-dimensional object is equal to its mass divided by its volume (or the mass per unit volume), and is typically measured in units of grams per cubic centimeter, or kilograms per cubic meter. The density of water is one g $cm^{-3}$, while rock is roughly three times more dense, and steel has a density of eight g $cm^{-3}$. One could also refer to the surface density of features found on a planetary surface, for example, with units of counts (the number of features) per unit area.

Hesperian Period – The second of three major periods in Martian history, lasting from 3.5 till 1.8 billion years ago. This era is named for Hesperia Planum, an elevated plain in the southern hemisphere. The largest volcano on Mars, Olympus Mons, was active during this time. Surfaces dating back to the Hesperian lack the pattern of large, densely packed craters characteristic of the older Noachian era, as many were erased by intense volcanic activity. Large bodies of water, and catastrophic releases of water, were also believed to be common, and carved channels in regions like the Chryse Palitia basin. The southern hemisphere contains many regions thought to date back to the Hesperian Period.

Impact crater – An impact crater is one produced by the collision of an object with a planetary body's surface.

Lava – Lava flows are streams of liquid rock, or magma, which reach the surface of a terrestrial body through volcanic eruption.

Logarithm – The word logarithm comes from the Greek words for *proportion* and *number*, and means "a number that indicates a ratio." In the expression $x = 10^e$, the exponent $e$ is the base 10 logarithm of the number $x$. When we plot numbers on a logarithmic scale, we can compare data over wide ranges on a single plot. As ones moves along a logarithmic axis by set amounts, one multiplies by a certain factor (rather than adding a certain amount, as is done along a linear axis).

Mercator projection – A Mercator projection is a cylindrical map of a spherical surface, such as the surface of a planet. By convention, west and east run from left to right, with north at the top and south at the bottom. Because lines of constant latitude are spread out across the entire plot, the regions near to the poles are greatly extended in width relative to those at the equator. (This is why Greenland, Iceland, and Antarctica, for example, appear so huge on Mercator projections of the Earth's surface.)

Meteor – The term meteor is used to refer to a particle of debris (space dust) which has entered the atmosphere of a planet or satellite. It also refers to the visible path left by such an object.

Meteoroid – A meteoroid is a particle of rocky or metallic debris found in space. If a meteoroid enters the Earth's atmosphere it becomes a meteor, and upon landing any surviving remnant is called a meteorite.

Million – Ten raised to the sixth power, or $1,000,000$.

Network valley – A network valley is one of a set of branching valleys found on Mars, with a resemblance to terrestrial river drainage basins. They are usually less than five kilometers wide, though they may extend for thousands of kilometers in length.

Noachian Period – The first of three major periods in Martian history, dating from formation epoch 4.5 billion years ago to 3.5 billion years ago. This era is named for Noachis Terra, a large southern hemisphere highland. Surfaces dating back to the Noachian are covered with many craters, and exhibit the largest impact craters, but widespread evidence for water erosion suggests that the planetary surface was warm and wet during this time. They are found predominantly in the southern hemisphere.

Outflow channel – An outflow channel is a particular type of surface feature found on Mars. Outflow channels are wide and long, and contain streamlined remnants of ancient features which have been sculpted by the passage of fluids (such as lava or water flows). They can extend over hundreds of kilometers in length, and can be up to a few hundred kilometers wide as well. Kasei Vallis is a prominent example of such.

Plate tectonics – Plate tectonics defines a theory of planetary surface dynamics in which a planet's outer skin (the lithosphere) is broken into plates. These plates are driven by internal heat, and shift and interact in various ways (including collisions).

Proto-planetoid – This word is a combination of "proto", meaning first or earliest, and "planetoid," meaning minor planet. The proto-planetoids in the early solar system were the largest of the building blocks which combined (through collisions) to form the major planets which we know, and love, today.

Rille – The word rille (also rill) is used to denote long trenches, or brooks or streams, and was often used in describing lunar features seen through the first telescopes.

River delta – A river delta is land formed from sediment (silt) that builds up at the mouth of a river, where it flows into an ocean or other large body of water.

Scablands – Scablands are erosive features, composed of flat, elevated land characterized by poor soil and little or no vegetation, marked by dry channels which formed through the action of glaciers. The Channeled Scablands of the state of Washington were created by the Missoula Floods during the Pleistocene era, and are the most well-known of such features.

Shield volcano – A shield volcano is one that has built up from fluid lava flows. The name comes from the distinctive large, extended size and low height (low profile), giving rise to a shape that resembles the shield of a warrior.

Terrestrial – The term "terrestrial" means Earth-like or pertaining to the Earth's surface. Planets with rocky surfaces are sometimes called Terrestrial planets, in contrast to the Jovian gas giants.

Topography – A topographical representation of a region involves a detailed physical description, including the relative positions and elevations of features.

Trench – A trench is a long ditch, or a long steep-sided valley.

Tributary – A tributary is a stream that flows into a larger body of water.

Watershed – A watershed is an elevated ridge of land which divides two regions which drain into separate rivers, or a single region which drains into a river or other body of water.

## 4.5 Relevant Lecture Chapters

This laboratory exercises draws upon the material in Chapter 12: The Terrestrial Planets and Chapter 11: The Formation of the Planets.

## 4.6 References and Notes

1. The images used in the Martian craters web-application are images from NASA spacecraft. All Thermal Emission Imaging System (THEMIS) images are used courtesy of NASA, JPL, and Arizona State University.

(a) A detailed image (a subset of V01433003) of Hadriaca Patera was taken by THEMIS, and an overview image of the surroundings was taken by the Mars Orbiter Laser Altimeter (MOLA). An appropriate journal reference for MOLA is "The Global Topography of Mars and Implications for Surface Evolution," by Smith et al. in *Science*, vol. 284, pp. 1495-1503 (1999).

(b) A detailed image (a subset of E1001691) of Pavonis Mons was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by MOLA.

(c) A detailed image (a subset of M1003730) of Arsia Mons was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by MOLA.

(d) A detailed image (from orbit 40364) of channelized flows on the southwestern flank of Olympus Mons was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(e) A detailed image (a subset of V33498005) of Nirgal Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(f) A detailed image (a subset of V12508008) of Tiu Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(g) A detailed image (a subset of V07993006) of Warrego Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(h) A detailed image (a subset of V01786010) of Ares Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(i) A detailed image (a subset of V02544003) of Dao Vallis was taken by THEMIS, and an overview image of the surroundings was taken by MOLA.

(j) A detailed image (a subset of MOC-m0703839) of Cerbeus Fossae was taken by the Mars Orbiter Camera, and an overview image of the surroundings was taken by the Viking craft.

2. Figure 4.1 is a mosaic of four crater images. The 2006 image of Crater Lake, a caldera lake in Oregon, is shown under a GNU Free Documentation License, courtesy of Pakistani photographer Zainub Razvi. The image of Ceraunius Tholus was taken with the Mars Orbiter Camera (a subset of MOC2-305) on the NASA Mars Global Surveyor spacecraft. The image of Hyginus Crater (frame 3073 in the Lunar Orbiter Photo Gallery at the Lunar and Planetary Institute) was taken with the NASA Lunar Orbiter 3. The 2010 image of Mauna Kea, a Hawaiian volcano with an abundance of telescopes, is shown under a GNU Free Documentation License, courtesy of Wikipedia contributor Nula666.

3. Figure 4.2 contains three NASA images of the Martian surface; it is used courtesy of the U.S. Geological Service. It can be found in an online lesson plan on impact craters, at http://arizona.usgs.gov/Flagstaff/Outreach/CenterEPO/craters/2relage/ra_OH2.pdf.

4. Figure 4.3 is a Mercator projection of the entire Martian surface, assembled from albedo images taken with THEMIS on the NASA Mars Global Surveyor spacecraft. The journal reference is “The Mars Global Surveyor Thermal Emission Spectrometer Experiment: Investigation description and surface science results,” by Christensen et al. in *The Journal of Geophysical Research*, vol. 106, 23, pp. 823-871 (2001).

5. Figure 4.4 is a relief map (derived from altimetry) of the Tharsis Montes region on Mars, taken with MOLA on the NASA Mars Global Surveyor spacecraft.

6. Figure 4.5 was created by Nicole Vogt and is based on information provided in the journal article "Martian Cratering VI: Crater Count Isochrons and Evidence for Recent Volcanism from Mars Global Surveyor," by William K. Hartmann in *Meteoritics and Planetary Science*, vol. 34, pp. 167-177 (1999).

7. Figure 4.6 is an image of Martian lava flows taken with the Mars Orbiter Camera (a subset of MOC2-m0701051) on the NASA Mars Global Surveyor spacecraft. It is centered in the northeast Cerberus plain, north of Tartarus Colles.

8. Figure 4.7 is an image of Ares Vallis taken with THEMIS (a subset of V01786010) on the NASA Mars Global Surveyor spacecraft and produced by NASA/JPL/Arizona State University.

9. Figure 4.8 contains four NASA images of the Jovian moons Callisto, Europa, Ganymede, and Io, all taken with the Galileo Orbiter spacecraft. The image of Callisto is a subset of MRPS93539, which was produced by the Jet Propulsion Laboratory; P48507 MRPS79079 of Europa was produced by Arizona State University; P50040 MRPS89768 of Ganymede was produced by Brown University; MRPS96034 of Io was produced by the University of Arizona.

10. Figure 4.9 is of the Ceraunius Caldera floor, in the Ceraunius Tholus region on Mars, taken with the Mars Orbiter Camera (a subset of MOC2-489) on the NASA Mars Global Surveyor spacecraft and produced by Malin Space Science Systems.