Look But Don't Touch

Exploration with Remote Sensing

Lesson Overview

Lesson Summary

Students learn about one of the most valuable methods of investigating other worlds in the Solar System: remote sensing. In Activity 1, students study aerial photographs to identify geologic features, determine how they differ from one another, and examine the processes involved in their formation. In Activity 2, students investigate how remote observations of a planetary surface can be used to create geologic maps. By the end of the lesson, students will understand how data gathered by spacecraft can not only be used to investigate the properties of an object, but also how it was formed, how it has evolved over time, and how it is connected to other objects nearby.

Grade Level
5–8

Duration
Three 45-minute class periods

Essential Question

What kind of tools can we use to explore unknown environments?

Lesson 3 of the Grades 5-8 Component of the *Mission Design* Education Module

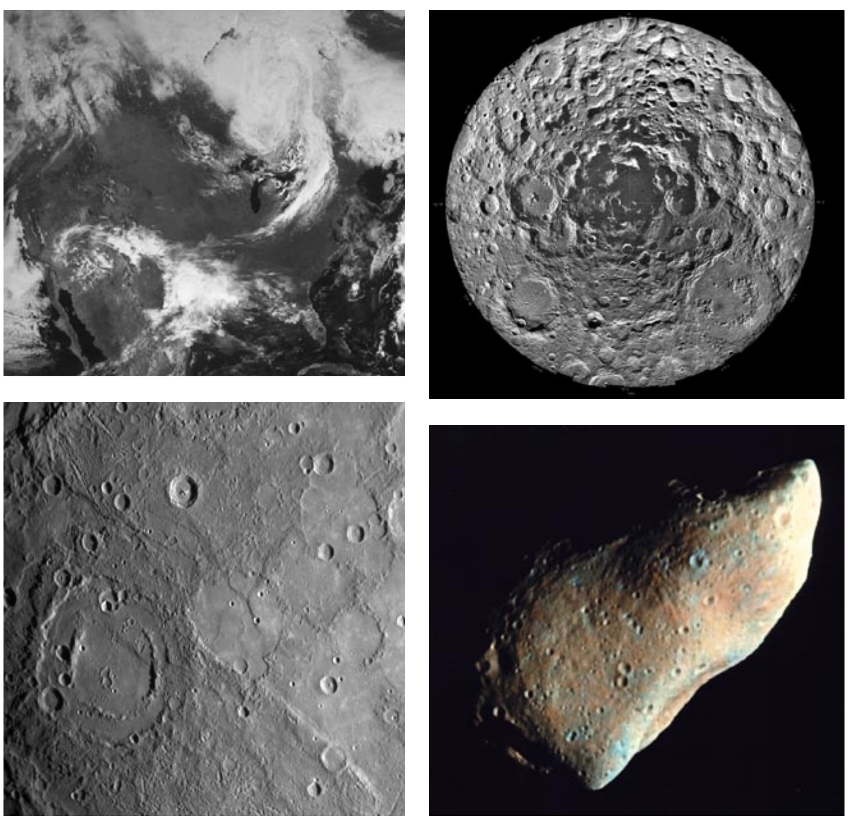


Figure 1. Remote sensing is an important tool for not only understanding the behavior of the Earth (top left: picture of North America taken by the GOES-8 satellite), but also for exploring other worlds in the Solar System such as the Moon (top right: picture of the lunar south pole area taken by the Clementine spacecraft), other planets (bottom left: an image of the surface of Mercury taken by the MESSENGER spacecraft) and small Solar System objects (bottom right: picture of the asteroid Gaspra taken by the Galileo spacecraft.)

(Picture credits: NOAA; http://www.colorado.edu/geography/gcraft/notes/remote/remote_f.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JHUAPL/CIW: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/gal_p40450c.html)

This lesson was developed by the National Center for Earth and Space Science Education (http://ncesse.org).

Objectives

Students will be able to do the following:

- Describe different ways to explore objects remotely.
- Identify four major geologic processes operating on the Earth as shown in aerial photographs.
- Explain how data gathered remotely can be used to identify landforms on planetary surfaces, in this manner helping determine the geologic history of the explored area.

Concepts

- The large variety of geologic landforms on the Earth are formed by four basic geologic processes: volcanism, tectonism, erosion, and impact cratering.
- The same geologic processes can be found operating on other worlds in the Solar System, though not every world features all processes.

MESSENGER Mission Connection

The MESSENGER spacecraft is not going to land on the surface of Mercury, but will go into orbit around the planet, instead. Like many other probes exploring other worlds in the Solar System, MESSENGER will conduct its observations of its target plant via remote sensing, using the methods discussed in this lesson. The scientists will examine the data gathered by the spacecraft to form a better understanding of Mercury's properties, and how the planet has changed over time.

Standards & Benchmarks

National Science Education Standards

Standard D1: Structure of the earth system

- Land forms are the result of a combination of constructive and destructive forces. Constructive forces include crustal deformation, volcanic eruption, and deposition of sediment, while destructive forces include weathering and erosion.

Standard A2: Understandings about scientific inquiry

- Science and technology are reciprocal. Science helps drive technology, as it addresses questions that demand more sophisticated instruments and provides principles for better instrumentation and technique. Technology is essential to science, because it provides instruments and techniques that enable observations of objects and phenomena that are otherwise unobservable due to factors such as quantity, distance, location, size, and speed. Technology also provides tools for investigations, inquiry, and analysis.

AAAS Benchmarks for Science Literacy

Benchmark 4C/M2:

- Some changes in the earth's surface are abrupt (such as earthquakes and volcanic eruptions) while other changes happen very slowly (such as uplift and wearing down of mountains). The earth's surface is shaped in part by the motion of water (including ice) and wind over very long times, which acts to level mountain ranges. Rivers and glacial ice carry off soil and break down rock, eventually depositing the material as sediments or carrying it in solution to the sea.

Benchmark 4C/M8:

- There are a variety of different land forms on the earth's surface (such as coastlines, rivers, mountains, deltas, and canyons.)

Benchmark 3A/M2:

- Technology is essential to science for such purposes as access to outer space and other remote locations, sample collection and treatment, measurement, data collection and storage, computation, and communication of information.

Science Overview

During most of human history, exploration has consisted of people traveling to unknown environments and returning with tales, records, and samples of the explored area. With advancements in technology, new ways to explore have become available. New methods are especially important for space exploration, because human space travel is dangerous and expensive at present time. If our understanding of the Universe were limited to where human beings have traveled, we wouldn't know of anything beyond the Moon. But with telescopes peering into the farthest reaches of space, and with robotic spacecraft traveling to the many worlds of the Solar System, we have been able to form a good understanding of the Universe around us.

Remote Sensing

Of special importance in modern space exploration is the method of remote sensing: exploring an environment from a distance, without the need of humans or even robotic spacecraft actually going to the area that is explored. Remote sensing is the process of gathering information about an object or a phenomenon without direct physical contact by the instruments used in the investigation. Instead, devices such as cameras and telescopes are used to make observations remotely, even from space. By carefully studying the gathered data, scientists can form an understanding of the properties of the area, and even how it may have come to be the way that it is. Technically, all telescope observations of even the farthest reaches of the Universe are examples of remote sensing, but the term is most often used in the context of the exploration of the Earth as a planet and of other worlds in the Solar System, and the rest of the discussion here will concentrate on this aspect.

While remote sensing means that the investigators cannot touch or sample the explored environment directly, using this method allows them to see a larger area at one time. This makes it possible to make connections between the explored area and other nearby features, and so we can gain a better understanding of the "big picture" aspect of the environment. It is this property that makes remote sensing useful for studying the Earth as a planet. By studying aerial photographs—pictures taken from airplanes and balloons—and satellite images, it is possible to recognize surface features that might be difficult to see otherwise. By making observations of other nearby features, scientists can even form a narrative of how the different geologic features may have formed, and how their relationship may have changed over time.

Recognizing Geologic Processes Remotely

Geologic processes often result in distinctive surface features. For example, landforms such as steep, conical hills with a small summit crater indicate that they are volcanic in origin. Deep canyons, like the Grand Canyon, are the result of a river carving through rock over millions of years.

The challenge of remote sensing is recognizing the processes that created the observed features purely on the basis of the gathered data, without any actual sampling of the objects. The geologic processes shaping the surface of the Earth can be divided into four categories: volcanism, tectonism, erosion, and impact cratering. Many of them operate also on other worlds in the Solar System, though not all of them operate on every world. Please note that the discussion that follows is not intended to be a comprehensive description of each geologic process; rather, it is a brief listing of the various processes deemed important for the present purposes.

Volcanism

Volcanism is a process where a rupture on the planet's surface allows molten rock (lava), ash, and gases to escape from below the surface. The landform most commonly associated with volcanism is a conical hill or a mountain (called a volcanic cone or a volcano), which was built by accumulations of lava flows and which spews lava, ash, and gases from a crater at its summit. However, volcanism can be associated with many different kinds of surface features, such as lava domes, where viscous lava has accumulated, or lava plains, where lava has spread over a large area and formed a plateau. See Figure 2 for examples on volcanism in the Solar System.

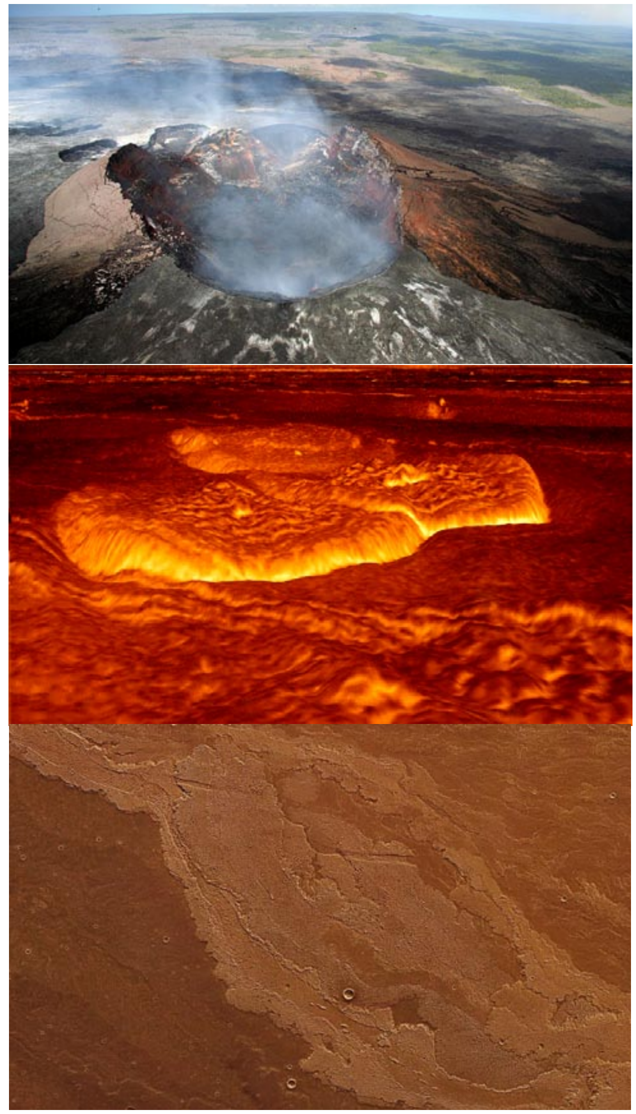


Figure 2. Examples of volcanism in the Solar System: the Pu'u 'Ō'ō crater in the Kilauea volcano in Hawaii (top); computer-generated image based on radar data of volcanic pancake domes in Alpha Regio, Venus (middle; the features in the image have been exaggerated in the vertical direction by 23x); lava flows have that have formed smooth plains in the Daedalia Planum region on Mars (bottom). (Picture credits: USGS/ Hawaiian Volcano Observatory: http://hvo.wr.usgs.gov/kilauea/update/archive/2007/Jul/IMG_5625c-CCH_L.jpg; NASA/JPL: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_p38870.html; ESA/DLR/FU Berlin, G. Neukum: http://esamultimedia.esa.int/images/marsexpress/444-20090909-6396-6-co-01-DaedaliaPlanum_H1.jpg)

There are other features called volcanoes that do not involve hot lava. For example, cryovolcanoes (ice volcanoes) involve the eruption of volatile materials such as water, ammonia, and methane from beneath the icy surfaces of the worlds in which they are located. They have been observed on Neptune's moon Triton and on Saturn's moon Enceladus. Indirect evidence of cryovolcanoes has been seen on other icy moons (such as Europa, Titan, Ganymede, and Miranda), and it is possible that they could operate on many different icy worlds in the Solar System.

Surface features associated with some kind of volcanism are common on solid Solar System bodies. While most worlds do not have signs of active volcanism at present, they have been volcanic at least at some point in their past. For example, the tallest known volcano in the Solar System is the 27-km (17-mile) high Olympus Mons on Mars, and Io, a moon of Jupiter, is currently the most volcanically active body in the Solar System.

Tectonism

Tectonism involves motions in the rocks under the surface of a planet, causing faulting, folding, or other deformation of the planet's crust. Many kinds of surface features can be created as a result of these motions. For example, mountains and valleys can be created on different sides of a fault, when one side of the fracture moves in the opposite direction (up in this example) from the other (down.) On the Earth, tectonic features are

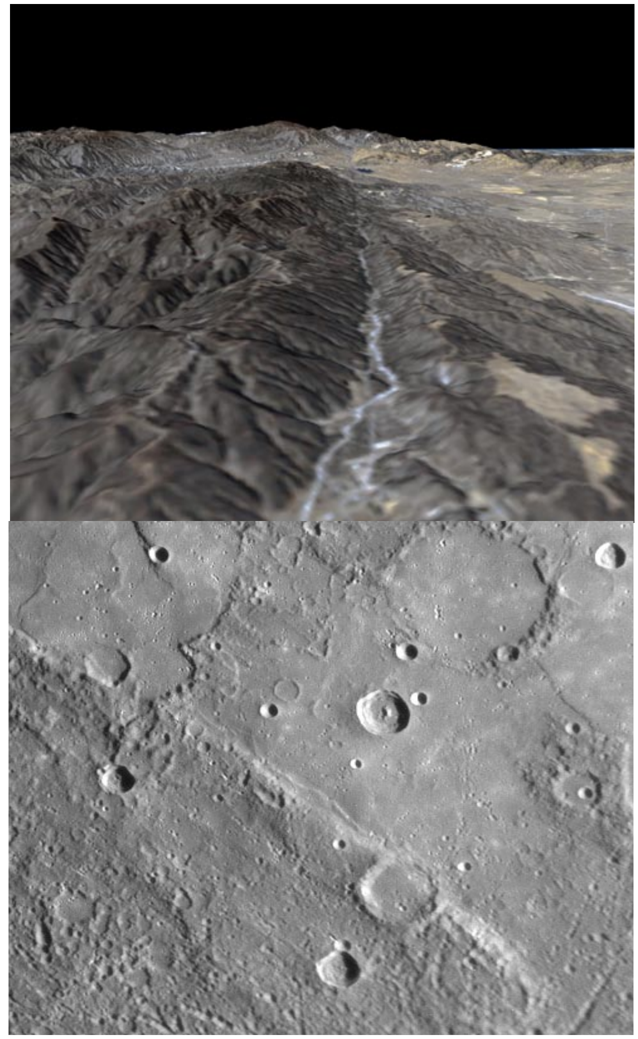


Figure 3. Examples of tectonism in the Solar System: the San Andreas Fault in California (top), depicted in a computer-generated perspective view based on spacecraft data, is the tectonic boundary between the North American plate on the right, and the Pacific plate on the left; a prominent scarp (cliff) that cuts through the side of an impact crater on Mercury is the surface expression of a major crustal fault system on the planet (bottom). (Picture credits: NASA/JPL/NIMA: http://photojournal.jpl.nasa.gov/catalog/PIA02745; NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png)

caused mainly by the motion of tectonic plates. Our planet's lithosphere (the crust and the rigid, uppermost part of the mantle), is broken into eight major and several minor plates. When these plates move on the surface of the Earth (at a typical speed of 5-10 cm, or 2-4 inches, per year), tectonic features are created especially at the plate boundaries. As a result, the plate boundaries are the places on our planet where features such as tall mountain ranges or deep ocean trenches are located, or frequent earthquakes occur. Tectonic features also appear on other worlds in the Solar System, but there is no clear evidence for plate tectonics having occurred at any time on any other planet besides the Earth. Instead, the tectonic features on the other Earth-like worlds in the Solar System were probably created by other motions in the rocks under the surface, such as deformation associated with large impact craters or the shrinking of the world. See Figure 3 for examples of tectonism in the Solar System.

Erosion

Erosion is the degradation of a planet's surface caused by the action of water, ice, wind, gravity (or a combination of these agents.) The eroded materials are often transported to another location where they are then deposited. These processes can erode existing landforms (e.g., a cliff crumbling down due the action of wind, rain and gravity) or create new ones (e.g., a river carving a channel through rock.) The amount of erosion suffered by a surface feature can give information about its age. While not all agents of erosion exist on

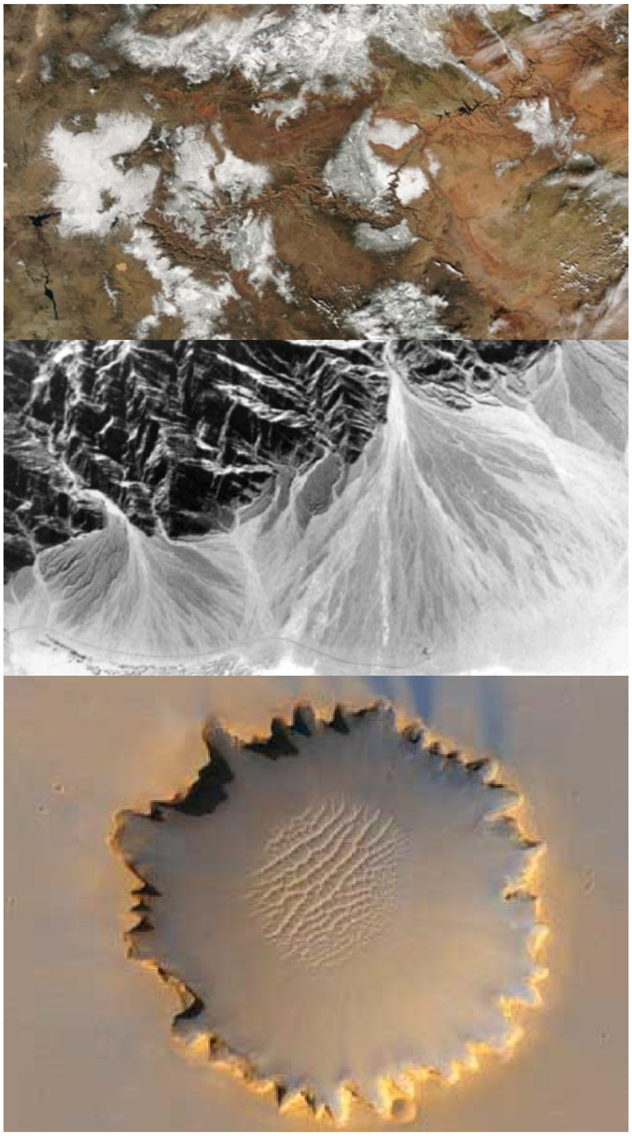


Figure 4. Examples of erosion in the Solar System: snow highlights the Grand Canyon, which has been carved onto the Colorado Plateau by the Colorado River over millennia (top); alluvial fans coming down from the Panamint mountains near Stovepipe Wells, California (center); the rims of the Victoria crater on Mars have been eroded by wind and gravity, and the crater has been partially filled by sand. (Picture credits: NASA Earth Observatory: http://earthobservatory.nasa.gov/IOTD/view.php?id=5033; UIllinois Catalog of Stereogram Aerial Photographs, #125; http://media.nasaexplores.com/lessons/01-056/images/fig25.gif; NASA/JPL/UA: http://photojournal.jpl.nasa.gov/catalog/PIA08813).

all worlds in the Solar System, all solid surfaces appear to have experienced at least some kind of erosion. For example, a world that does not have water flowing on its surface, such as the Moon, will experience different kind (and amount) of erosion than a planet with a complex water cycle such as the Earth. See Figure 4 for examples of erosion in the Solar System.

Impact Cratering

Impact craters (see Fig. 5) are geologic structures formed when a meteoroid, an asteroid, or a comet smashes into a world with a solid surface. Asteroids are large chunks of rock and metal, ranging in size from a few hundreds of meters to a few hundred kilometers. Comets are mixtures of ices (water ice, as well as carbon dioxide and ammonia ices), rock, and dust. A meteoroid is a piece of stone, metal, or ice debris from a comet or an asteroid that travels in space; they come in all sizes, even down to micrometeoroids. If one of these objects crosses the Earth's orbit, it may fall onto our planet. When the object flies through the atmosphere, it can be seen as a meteor in the sky as it burns up because of the heating by the atmosphere. If the falling object is sufficiently large, part of it may survive the flight through the atmosphere and strike the ground.

The impact causes surface material (rocks, dust, ice, and whatever else is located nearby) to be thrown away from the impact site. As a result, a (usually) circular depression on the ground—a crater—is

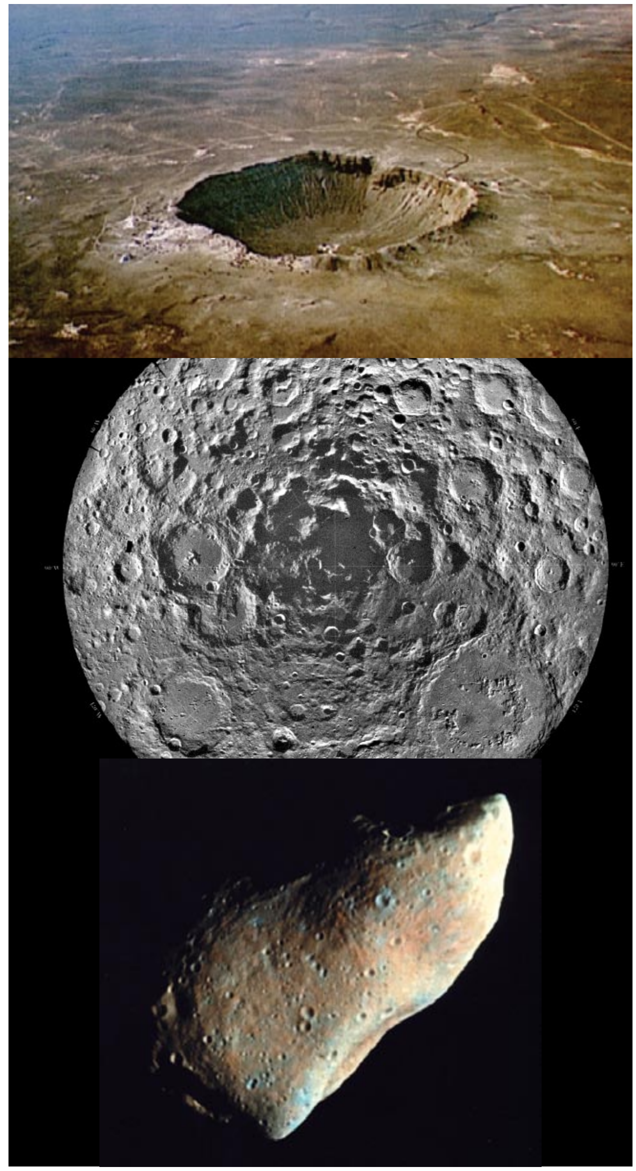


Figure 5. Examples of impact craters in the Solar System: The 1.2-km (0.7-mile) wide Meteor Crater (also called the Barringer Crater) in Arizona was created by the impact of a large meteor about 50,000 years ago (top); the lunar south pole area has numerous impact craters of all sizes (middle); even small Solar System objects such as the asteroid Gaspra have many impact craters (bottom.) (Picture credits: D.Roddy. LPI/USRA: http://www.lpi.usra.edu/publications/slidesets/craters/slide_10.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JPL/Brown University: http://photojournal.jpl.nasa.gov/catalog/PIA01609)

formed. Small impactors excavate a crater only slightly larger than the impactor, while a large impactor can create much more havoc on the surface. The material thrown out of the crater is called collectively the ejecta, and it can often be seen as a distinct feature around the crater.

All planets in the Solar System have been bombarded by meteoroids, asteroids, and comets during their history. The large atmospheres of the giant planets (Jupiter, Saturn, Uranus, Neptune) hide the evidence of impacts these massive worlds have experienced in the past, but there is plenty of evidence of impacts on the surfaces of the inner planets (Mercury, Venus, Earth, and Mars.) Craters can also be found on the surfaces of moons, dwarf planets, and even on asteroids and comets themselves. Large impacts were common during the early history of the Solar System, and most solid surfaces show evidence for a heavy bombardment period early in their history. On the Earth, evidence of this bombardment has been erased by the activity of the other geologic processes, but on other objects lower levels of geologic activity has left the evidence more visible. Another difference in the properties of impact craters on different worlds in the Solar System is that if a world has a substantial atmosphere, many small impactors burn up when they fly through the atmosphere, and no small craters are visible on the surface, while on objects that do not have this protective blanket, even micrometeoroids can impact the ground and create tiny craters.

Photogeologic Mapping

Recognizing the geologic processes which formed the surface features visible in aerial or satellite photographs is the first step in preparing geologic maps. A geologic map is similar to a regular map in that it shows what the features on the surface look like, but it includes additional information by portraying graphically the different types of rocks and structural features (such as folds and faults.) The map also features an interpretation of the basic geologic data, such as information on the processes thought to have created the features, and how the landforms are related to each other,. In this manner, a geologic map allows scientists to record their interpretations of the observations in a form that can be easily understood by others. This also makes it possible to compare observations from different locations to help us better understand the geologic history of the world.

The basic component of a geologic map is the rock unit, which is defined as a three-dimensional body of rock that has uniform composition and was formed during some specific interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain. The map also identifies structural features, such as faults or riverbeds visible on the surface. In essence, photogeologic mapping starts with examining a surface depicted in a photograph, and dividing the surface features into different units and structural features according to their type, composition, origin, and estimated age. Different units can be identified based on their:

- ***morphology***: the size, shape, texture, and other distinctive properties of the landforms;
- ***albedo characteristics***: the range of brightness from light (high albedo) to dark (low albedo);
- ***color***: not only visible color differences, but also different types of light not visible to the human eye, such as infrared, ultraviolet, etc.;
- ***the degree of erosion:*** how much the surface has eroded or how well it has been preserved;

and other properties visible in the photograph. Once the rock units and the structural features have been identified, it must be determined how they were formed; that is, which geologic processes were responsible for creating them.

The next step is to determine how the units and structural features are related; most importantly, determine the order in which the units and features were formed. This process is called determining the stratigraphic relation of the features, since it is an example of stratigraphy, the branch of geology that studies the origin, composition, and distribution of rock layers. The principles used for this purpose include:

- ***the principle of superposition***: for units and structural features that are laid (even partially) on top of each other, the oldest (the one that formed first) is on the bottom, and the youngest (the one that formed most recently) on top.
- ***the law of cross-cutting relations***: for a unit or a structural feature to be modified (via volcanism, impacts, tectonic faulting, erosion, etc.) it must first exist. For example, if there is a fault going through a rock unit, the underlying unit is older than the tectonic event that created the fault.
- ***embayment***: if a bay-like feature is formed when one unit "floods into" (embays) another, the flooding unit must be younger than the one being flooded.
- ***impact crater distribution***: in general, older units have more craters, more large craters, and more degraded (eroded) craters than younger units.

Once the stratigraphic relation has been determined, the units are listed on the side of the map in order from the oldest (at the bottom of the list) to the youngest (at the top) as the stratigraphic column. Finally, using the information gathered during the previous steps, it is possible to write a geologic history of the area. The geologic history describes the events that created the observed surface in a chronological order from the oldest to the youngest. The history includes an interpretation of the observed units: the geologic processes that formed them and events that have modified them after their formation.

Figure 6 shows an example geologic map. The relative ages of the units marked on the map were determined in the following manner: The

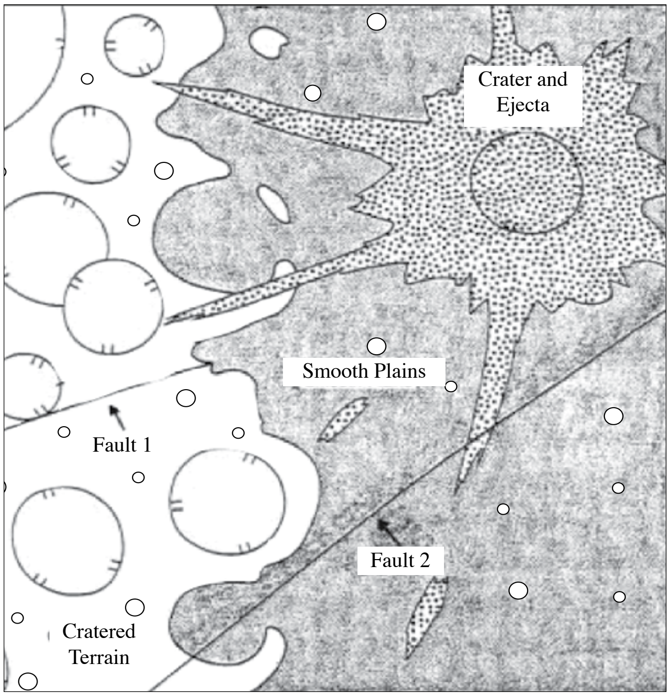


Figure 6. An example of a geologic map of a planetary surface. In addition to the graphical portrayal of the different rock units and structural features (top left), the complete map includes a description of the units, including observations of their characteristics and interpretation of their origin (top right), and a stratigraphic column describing the age relations between the units and structural events identified in the map (right.) (Picture credit: NASA: http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf)

Unit Descriptions

Unit Name	Observation	Interpretation
Crater and Ejecta	Rough, blocky surface, high albedo, crater in the middle	Crater and ejecta formed by impact
Smooth Plains	Smooth plains, few craters, low albedo, rounded edges	Volcanic flow
Cratered Terrain	Rugged, heavily cratered plains, high albedo	Old unit, possibly of volcanic origin, has had extensive cratering

Stratigraphic Column

	Geologic Unit	Structural Event
Youngest ↑		Fault 2
	Crater and Ejecta	
	Smooth Plains	
		Fault 1
Oldest	Cratered Terrain	

cratered terrain has more (and larger) craters than the smooth plains unit, indicating that the cratered terrain unit is older. Fault 1 cuts across the cratered terrain, but does not continue across the smooth plains. This suggests that the faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains; the smooth plains unit is younger than the cratered terrain and fault 1. The large impact crater mapped as its own unit, as well as the crater's ejecta unit (material ejected from the crater into the surrounding area), occurs on top of the smooth plains unit, and thus is younger. Finally, fault 2 cuts across all the units, including the crater's ejecta; it is therefore the youngest feature in the region. The geologic history that could be derived from this map would be the following:

The cratered terrain is the oldest surface in the picture. It was cratered by impact activity over time, and then faulted by tectonic activity. After the tectonic activity, a smooth plains unit was created by volcanic activity. Cratering continued after the formation of the smooth plains, as seen by the craters visible on top of the smooth plains and the large, young crater (and its ejecta), which is mapped as its own unit. Finally, there has been additional tectonic activity after the impact that created the young crater, as indicated by the fault which goes through the crater's ejecta.

Anyone who reviews the map show in Figure 6 can now construct the same geologic history of the region without having to go through all the steps of constructing the map themselves.

Remote Sensing as One Tool in a Planetary Explorer's Toolbox

There are many other methods to explore worlds in the Solar System besides remote sensing that are important, from robotic spacecraft landing on planets and performing chemical analyses of soil samples to humans traveling to explore other worlds (such as the Moon) themselves. These other methods are used to answer questions that remote sensing cannot answer conclusively, for example to determine the absolute ages of lunar rocks or to look for water ice under the surface of Mars. However, because remote sensing can be done from a spacecraft flying by or orbiting a world, without the need to actually land on the explored world, it can be used in many different missions, and so it is the most commonly used tool in a planetary explorer's toolbox today.

Lesson Plan

Warm-Up & Pre-Assessment

1. Lead a discussion of what maps are and how they are useful. You can begin by asking, "If you wanted to explore a region of the country with which you are unfamiliar, what would you need?" As the students begin to offer suggestions, lead them to the concept of a map. Show the students a map of your home state and ask them to define what a map is and why it is useful. Use leading questions and statements: "What kinds of information are contained in a map?" and "How does the size of the map compare to the real size of the state?" Ask the students if a six-story-high map would be useful. Discuss how most maps are a size that makes it comfortable for the user to hold them. With the help of a map, we can explore things that may be much larger, further away, or more treacherous than we would normally be able to explore. A map can be a powerful tool of exploration.

2. Lead a discussion about the different kinds of information that can be shown on a map. Show the students the state map again and ask what types of information it tells them (examples include roads, city names, etc.) Ask the students what types of things this map does *not* tell them (examples include elevation, many natural features, climate, etc). Show the students other types of maps such as a topographic map and ask the same questions.

3. Discuss how the different types of maps are made. How was the information in the maps gathered? How difficult would it be for each of the different types of maps to be made? How did people make maps in ancient times? When was the first map of the whole Earth made? Explain that we had a good understanding of the layout of the continents on the surface of the Earth even before the space age, just by people exploring the surface of our planet by foot, land vehicles and airplanes. Point out that satellite technology has helped us make different kinds of maps of the Earth very accurately. If you have access to old maps, you can show the students how our understanding of the surface of the Earth changed from ancient times to medieval times to the present day. How do the students think we could make maps of other planets?

Materials

Per Class:

- ▼ Map of your home state
- ▼ A variety of other types of maps: topographic, weather, etc.

Activity 1: Geologic Landforms Seen in Aerial Photographs

Students study a series of aerial photographs of different terrains on Earth. In answering questions about the areas depicted in the pictures, the students become acquainted with landforms created by four major geologic processes: erosion, impact cratering, tectonism, and volcanism.

Materials

Per Class:

- Overhead projector
- *Geologic Landforms on Other Worlds Transparency*

Per Group of 2 or 3:

- Metric ruler
- Student Worksheet 1

Preparation

1. Make an overhead transparency of the *Geologic Landforms on Other Worlds Transparency* located in the back of the lesson, and make copies of Student Worksheet 1 for the class.
2. You may want to review the four major geologic processes featured in this activity with the students before starting the activity. While there is a brief description of these processes in Student Worksheet 1, the activity assumes that the students are somewhat familiar with these concepts. Additional information can be found on the Web sites listed in the *Internet Resources & References* section.
3. Divide students into groups of two or three.

Procedures

1. Lead a brief discussion about how geologic processes often result in distinctive landforms or surface features. For example, steep, conic hills with small summit craters are distinctive as volcanic in origin. Ask the students how they think these features are studied best: from the ground or from the air? *(Desired answer: Both. Observations from the ground provide information on small-scale details, while observations from the air provide a large-scale overview that may be difficult to develop from the ground.)*
2. Ask the students to explain the following terms: erosion, impact cratering, tectonism, and volcanism. Ask what kind of landforms each of these processes would create and whether the features would look the same from the ground and from the air. If the students were flying in an airplane and saw one of these landforms, how could they tell what process created it? *(Desired answer: Each process creates landforms with distinctive features. By*

comparing the features of the observed landform with what is known from other sources, one can deduce the probable origin of the landform.)

3. Hand out copies of Student Worksheet 1, and make sure the students understand the vocabulary used in the activity. Have the students work in their groups and follow the procedures in Student Worksheet 1. The Worksheet is not intended to test the students' understanding of the different geologic processes, but to promote thinking about what the different landforms look like from the air, and how the processes responsible for creating the surface features can be identified from aerial or satellite photographs. The section "Synthesis" of Student Worksheet 1 brings the students' knowledge together to help them understand how scientists can identify surface features seen from the air or from space, as well as determine the order in which surface features located near each other were formed.

Teaching Tips

- ▼ Student Worksheet 1 can be given as a homework assignment if you do not have enough class time. However, it is important to have the *Discussion & Reflection* as a class because the conversation will lead into Activity 2.
- ▼ Remind the students that they will be graded on their ability to use evidence to support their answers in all cases.

Discussion & Reflection

1. Go through the photographs shown in Student Worksheet 1 with the class and ask each group what they learned from the pictures. What is the advantage of studying a photograph taken from the air rather than studying it from the ground at the actual location of the feature? *(Desired answer: you can see a larger area from the air, and so you can get the "big picture" of the feature. This can make it easier to determine how the features were formed and how they relate to other features nearby.)* Can the students think of any disadvantages from studying the landforms just from the air? *(Desired answer: you are limited by the resolution of the photograph and are not able to see small details, which may be important for deciphering the whole story of the landform.)* Which method do the students think is more useful in determining how a particular landform was formed? *(Desired answer: it depends on the situation, but an aerial photograph is a great starting point, since it allows us to understand the "big picture" of the area in*

general, including determining the probable origin of the feature. Additional studies on the ground concentrating on the small-scale features can be performed later to refine our understanding.)

2. Ask the students what they learned about the features other than just how to identify them (*Desired answers include: how landforms often relate to other features nearby; how similar features can look slightly different depending on their age or interaction with other nearby features.*)

3. Place the *Geologic Landforms on Other Worlds Transparency* on the overhead projector so the entire class can see it. Have the students identify the same four geologic processes that they were investigating on the Earth operating on other worlds in the Solar System. Would the students be able to determine what created these features based on what they have learned of landforms on the Earth? Explain to the students that this is how scientists studying other planets can determine what they see in similar pictures: they use the information that generations of explorers have gathered about the many planet-shaping processes on the Earth to understand the same processes occurring on other worlds in the Solar System. The students will do the same in Activity 2.

Activity 2: Photogeologic Mapping

The students will explore photographs of another world in the Solar System to see how they can recognize the same geologic processes that operate on the Earth. They create a geologic map of a planetary surface by identifying mapping units and structural features in a photograph and placing the units in a time sequence.

Materials

Per Class:

- Overhead projector

Per Group of 2 or 3:

- Blank overhead transparency
- Set of transparency markers
- Roll of tape
- Student Worksheet 2

Preparation

1. Gather together the materials needed for this activity.
2. Divide students into groups of two or three.

Procedures

1. Ask the students how they might identify surface features on other planets just by looking at them from above, as they did in Activity 1 for features on the Earth. (*Desired answers include: the size, shape and texture of the feature (morphology), the color, the brightness of the feature and how it changes from light to dark (albedo characteristics), and the amount of erosion the surface has suffered.*) This is a good time to introduce the vocabulary which is used in the activity but with which the students might not be familiar.
2. Lead a discussion about geologic mapping of other worlds in the Solar System. For example, remind the students of the maps discussed during the Warm-Up, and ask students why making a map of another planet might be useful. (*Desired answers may include: if we ever wanted to send spacecraft to land on these worlds, having a map would be a good idea so that we know where the spacecraft should land; mapping another world could help us learn more about its structure and history; comparing maps of different planets could help us understand how the planets are similar and how they are different.*)
3. Ask the students what might be a good first step in making a map. (*Desired answer: identify features that can be seen in a photograph of the area to be mapped.*) Discuss how identifying the basic features (rock units and structural features) in a photograph is the first step in making a geologic map. Explain that a

unit is a surface feature (three-dimensional body of rock) that has a uniform composition and was formed during some specified interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain, while structural features could include faults or riverbeds.

4. Ask the students: after identifying the mapping units, what would a scientist want to know about them (based on what the students learned in activity 1)? (*Desired answer: which geologic process formed them.*)

5. Ask the students what might be the next task in preparing a geologic map? Take a few suggestions before discussing that scientists want to understand how the mapping units relate to each other. Explain that the relationships between the ages of the units and the structural features in a geologic map is called the *stratigraphic relation*. Ask the students what kind of information could be used to determine how the ages of the different units correspond with each other. Take a few suggestions before introducing the four stratigraphic relationships discussed in the activity: a) the principle of superposition, b) the law of cross-cutting relations, c) embayment, and d) impact craters. You can use the following examples to illustrate the four different principles:

   a) Ask the students to imagine their bedroom with dirty clothes on the floor. Imagine that every day, the students pile their dirty clothes on top of the ones from the day before. If their parents came in to do the laundry, how would they know which clothes have been in the pile the longest? (*Desired answer: the clothes at the bottom of the pile would have been there the longest.*) Similarly, the principle of superposition states that when mapping units are placed on top of each other, the oldest (those that were formed first) are at the bottom and the youngest (those that were formed most recently) on the top.

   b) Ask the students to imagine a crack in the sidewalk. Ask students: which happened first, the construction of the sidewalk, or the creation of the crack? (*Desired answer: the sidewalk had to exist before it got cracked.*) Similarly, the law of cross-cutting relations states that for a mapping unit to be modified (by impacts, tectonic faults, erosion, etc.), it must first exist as a unit. That is, if there is a fault going through a unit, the underlying unit is older than the tectonic event that created the fault.

   c) Ask the students if they have ever looked at downspouts after a spring rain when tree pollen, seeds and other debris have washed down from the roof. Does the water and the debris carried with it coming out of the spout tend to form a specific shape? (*Desired answer: it usually forms a fan-like shape.*) What would happen if the water and the debris flowed into a layer of sand on the ground? (*Desired answer: the water and debris would push sand away, creating the fan-shaped feature in the sand layer.*) This is an example of embayment. In a bay-like feature, the unit "flooding into" (embaying) must be younger than the unit being flooded; in our example, this means that the event of water and debris flowing onto the sand is younger (more recent) than whatever event caused the sand to be in front of the waterspout.

d) Ask the students to imagine two sidewalks: one that is old and another that has just been paved. How could they tell the difference? (*Desired answer: the older sidewalk would be more weathered than the newer one.*) Ask the students to imagine that the sidewalks are near a mining site, and, as rocks are hauled away for processing, a lot of them fall down on the sidewalks and create holes on the surface. How could the holes help tell which sidewalk is older? (*Desired answer: the older sidewalk would have more holes; maybe there could be holes on top of each other; maybe some of the older holes would have been smoothed out over the years from the rain, people walking on them, etc.*) Similarly, on planetary surfaces, impact crater frequency can be used to determine the relative ages of different surfaces. In general, older units show more craters, larger craters, and more eroded (degraded) craters than younger units.

6. Discuss different ways that one could graphically represent situations where one item is older than another. What if there is more than one item involved? For example: if there are five children in a family, how could you graphically portray the order of the children from the oldest to the youngest? Discuss how, in a geologic map, once the age relations of the surface features have been determined, the units and structural features are listed in order from the oldest (at the bottom) to the youngest (at the top) in what is called the stratigraphic column.

7. Hand out Student Worksheet 2. Make sure the students read the introduction before starting to work on the rest of the Worksheet to reinforce the basic concepts discussed as a class.

Teaching Tip

▼ Remind the students that they will be graded on the ability to use evidence to support their answers in all cases.

Teaching Tip

- After the teams have completed Student Worksheet 2, their maps can be overlaid for comparison with one another. There will be some variation in the maps based on the characteristics different teams chose to delineate each unit. Have the students discuss the reasoning behind their unit selections.

Discussion & Reflection

1. Discuss with the students how the basic process they went through in the activity is how much of science is done: exploring unknown environments such as planetary surfaces with the help of what is known from previous explorations in other contexts, such as exploring geologic processes operating on the Earth.

2. Ask the students why it is important to figure out what happened first, second, or third in the explored area. Discuss how the primary objective in preparing a photogeologic map is to derive a geologic history of the region. The geologic history synthesizes the events that formed the surface seen in the photograph—including interpretation of the processes in the formation of rock units and events that have modified the units—and is presented in chronological order from the oldest to the youngest. Combining maps and geologic histories from different regions helps us form an understanding of the global geologic history of the world, which in turn may help reveal the history of the part of the Solar System where the world is located.

Extension

- Have the students investigate the process of cratering and the way crater comparison can be used to establish relative ages of surfaces on different planetary bodies by completing the lesson *Impact Craters: A Look at the Past* (http://journeythroughtheuniverse.org/downloads/Content/Voyage_G58_L10.pdf) from the *Voyage: A Journey through Our Solar System* Education Module.

Curriculum Connections

- *Geography*: In this lesson, the students identify features on other worlds by recognizing what we know about the Earth. Have the students investigate how geographers use the techniques discussed in this lesson to prepare different kinds of maps.
- *Math*: In this lesson, the students use trigonometry to calculate the slopes of volcanoes, although it is done without going into details. If you want the students to have more practice connecting math and science, you can give them elevations of various mountains and have them calculate their slopes. You can then discuss what scientists can learn by looking at the slopes of volcanoes and mountains; for example, they can characterize different types of volcanoes.

Closing Discussion

1. Ask the students to identify other ways in which a spacecraft can study a planet, and what the benefits are for each of those ways. For example, a spacecraft could land on a planet and sample the soil, it could measure the magnetic field around the planet, etc. Discuss the benefits and drawbacks of remote sensing techniques versus more direct exploration methods. You can point put, for example, that by taking aerial photographs, scientists can get a big picture of an entire area, but they cannot sample the soil and determine its composition in detail, while exploring other worlds in the Solar System by landing on them and exploring just the areas around the landing site would not give us a global view of the world. By combining the different approaches one gains a deeper understanding than by exploring via one method alone.
2. Discuss with the students how the same geologic processes have created many of the features on Earth-like worlds. By examining similar features on different worlds, we can understand their relative ages, compositions, amount of activity at present time, etc. Having several different worlds with which to compare data gives us a better understanding of how the different processes act under slightly different circumstances.
3. Discuss with the students how all current explorations of unknown worlds build on the body of knowledge of not only the world being explored, but also of other similar worlds. For example, knowing what geologic processes are likely to operate on a given world

makes it easier to recognize and classify other features (e.g., one does not expect to find features created by rivers on worlds that do not have flowing liquids on their surface.) No investigation is made in isolation, and it is necessary to understand the previous work on similar topics to draw solid conclusions of the properties of the world under study.

4. Discuss with the students the limits that the current technology places on our desire to explore other worlds in the Solar System. For example, while we might want to send hundreds of human explorers to roam the surface of Mars to create a detailed map of the planet, it is not possible at present time. Instead, we can develop technological tools and methods to learn as much as we can from whatever vantage point is available. Remote sensing is a great solution to this problem, since it allows for a global view of other worlds without any human being having to physically travel to each explored location.

Assessment

4 points

- Student used evidence to support his or her answers in the "Synthesis" section of Student Worksheet 1.
- Student used evidence to support all other answers in Student Worksheet 1.
- Student used evidence to support his or her answers in the "Geologic of Planet Mercury" section in Student Worksheet 2.
- Student used evidence to support all other answers in Student Worksheet 2.

3 points

- Student met three of the four above criteria.

2 points

- Student met two of the four above criteria.

1 point

- Student met one of the four above criteria.

0 points

- No work completed.

Internet Resources & References

MESSENGER Web Site

http://messenger.jhuapl.edu

American Association for the Advancement of Science, Project 2061, Benchmarks for Science Literacy

http://www.project2061.org/publications/bsl/online/bolintro.htm

National Science Education Standards

http://www.nap.edu/html/nses/

Google Earth

http://earth.google.com/

Lunar and Planetary Institute's "About Shaping the Planets" Web site (more information on volcanism, tectonism, erosion, and impact cratering)

http://www.lpi.usra.edu/education/explore/shaping_the_planets/background

NASA's Planetary Photojournal

http://photojournal.jpl.nasa.gov/

USDA's Aerial Photography Field Office

http://www.apfo.usda.gov/

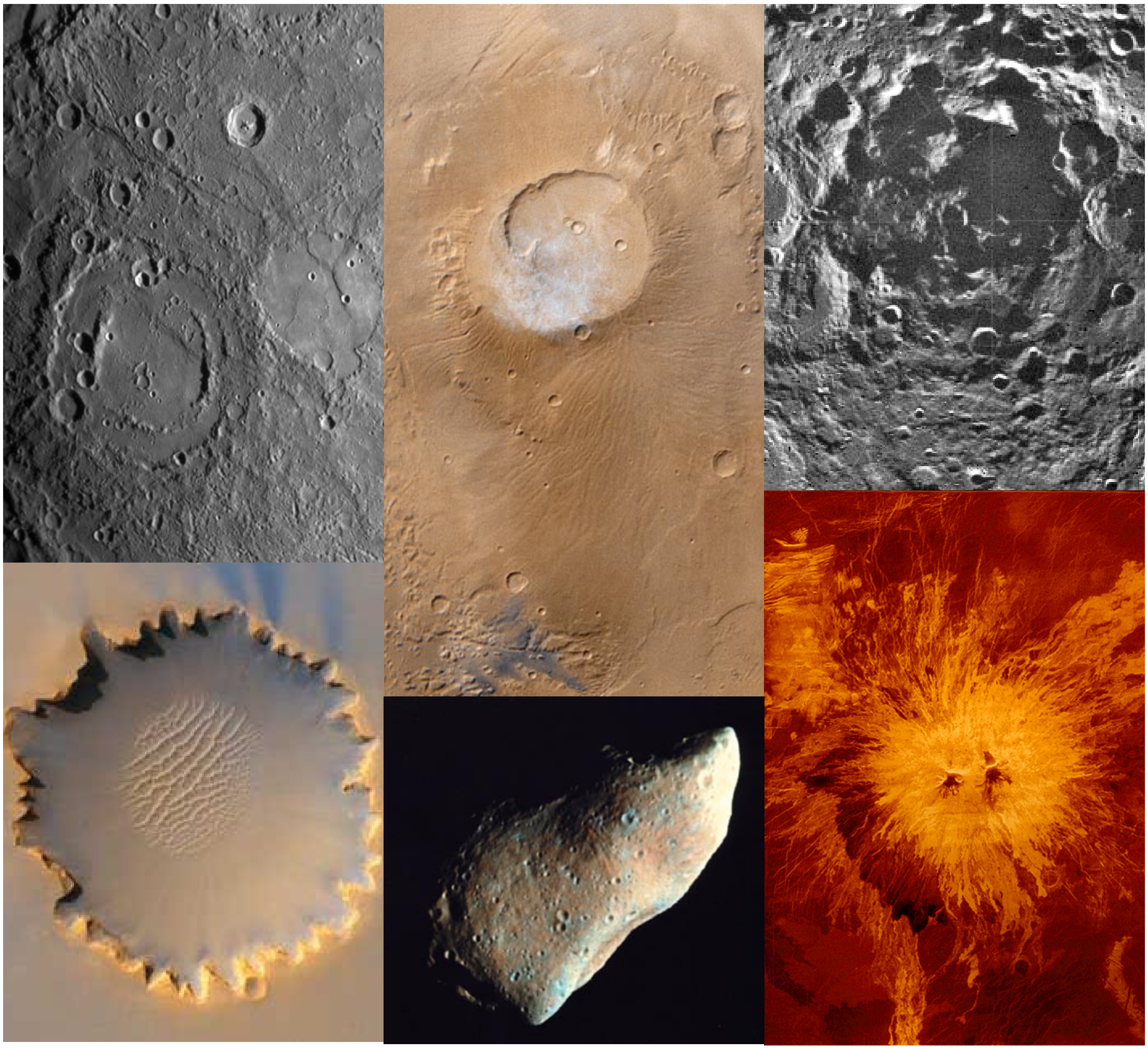
U.S. Geological Survey Aerial Photographs and Satellite Images

http://erg.usgs.gov/isb/pubs/booklets/aerial/aerial.html

Acknowledgements

Activity 1 has been adapted from "Geologic Landforms Seen on Aerial Photos" (http://solarsystem.nasa.gov/educ/docs/Geologic_Landforms_Aerial.pdf), and Activity 2 from "Introduction to Photogeologic Mapping (http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf) from *NASA's Activities in Planetary Geology for the Physical and Earth Sciences*.

Geologic Landforms on Other Worlds Transparency



Shown above: top left: the surface of Mercury with impact craters and tectonic features; top middle: Apollinaris Patera volcano on Mars; top right: heavily cratered south polar region of the Moon; bottom left: eroded Victoria impact crater on Mars; bottom middle: the cratered surface of the asteroid Gaspra; bottom right: the Sapas Mons volcano on Venus.

(Picture credits: NASA/JHUAPL/CIW: http://messenger.jhuapl.edu/gallery/sciencePhotos/pics/EN0108828359M.png; NASA: http://antwrp.gsfc.nasa.gov/apod/ap990513.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/clm_usgs_17.html; NASA/JPL/UA: http://photojournal.jpl.nasa.gov/catalog/PIA08813; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/gal_p40450c.html; NASA: http://nssdc.gsfc.nasa.gov/imgcat/html/object_page/mgn_p38360.html)

Geologic Landforms in Aerial Photographs

Materials

- Metric ruler
- Piece of paper (letter-size or smaller)

Your team: ______________________________

____

____

Date: ______________________________

Introduction

The geologic processes shaping the surface of the Earth can be divided into four categories:

- ***Volcanism*** is a process where a rupture on the Earth's surface allows molten rock (lava), ash, and gases to escape from the hot interior. The landform most commonly associated with volcanism is a conical hill or a mountain (called a volcanic cone or volcano), which is built by the accumulation of lava flows and which spews lava, ash, and gases from a circular crater at its summit. Old lava flows hardened to solid rock can often be seen coming down the sides of a volcano.

- ***Tectonism*** involves motions in the rocks under the Earth's surface, causing fractures, faulting, folding, or other deformation of the crust. Many kinds of surface features can be created as a result of these motions, for example mountains and valleys can form on the different sides of a fault, when one side of the fracture moves in the opposite direction from the other. On the Earth, tectonic features are caused mainly by the motion of the tectonic plates.

- ***Erosion*** is the degradation of the Earth's surface caused by the action of water, ice, wind, and gravity, with the eroded materials often transported to another location where they are deposited. These processes can either erode existing landforms (e.g., a cliff crumbling down due the action of wind, rain and gravity) or create new ones (e.g., a river carving a channel through rock.) The amount of erosion suffered by a surface feature can give information about its age.

- ***Impact craters*** are formed when pieces of rock and/or ice arriving from space (in the form of a meteoroid, an asteroid, or a comet) strike the Earth. The impact causes surface material (rocks, dust, ice, and whatever else is located nearby) to be thrown away from the impact site. As a result, a (usually) circular depression on the ground—a crater—is formed. Material thrown away from the impact site is sometimes visible around the crater and is called the crater's ejecta.

The geologic processes result in distinctive landforms, which can be recognized by their size, shape, texture, and other distinctive features. By studying aerial photographs you will learn to identify different geologic landforms and the processes involved in their formation.

Volcanism

1. Examine the aerial photograph of the Mount Capulin volcano in New Mexico (Figure S1.) The volcano is the dark area in the upper left of the picture. The small circular feature at its center is the volcanic crater, a depression in the ground from which molten rock (lava), ash, and gases escaped from under the surface. A white spiraling line leads from the crater to the base of the volcano. A lava flow (labeled A) is visible in the lower part of the picture.

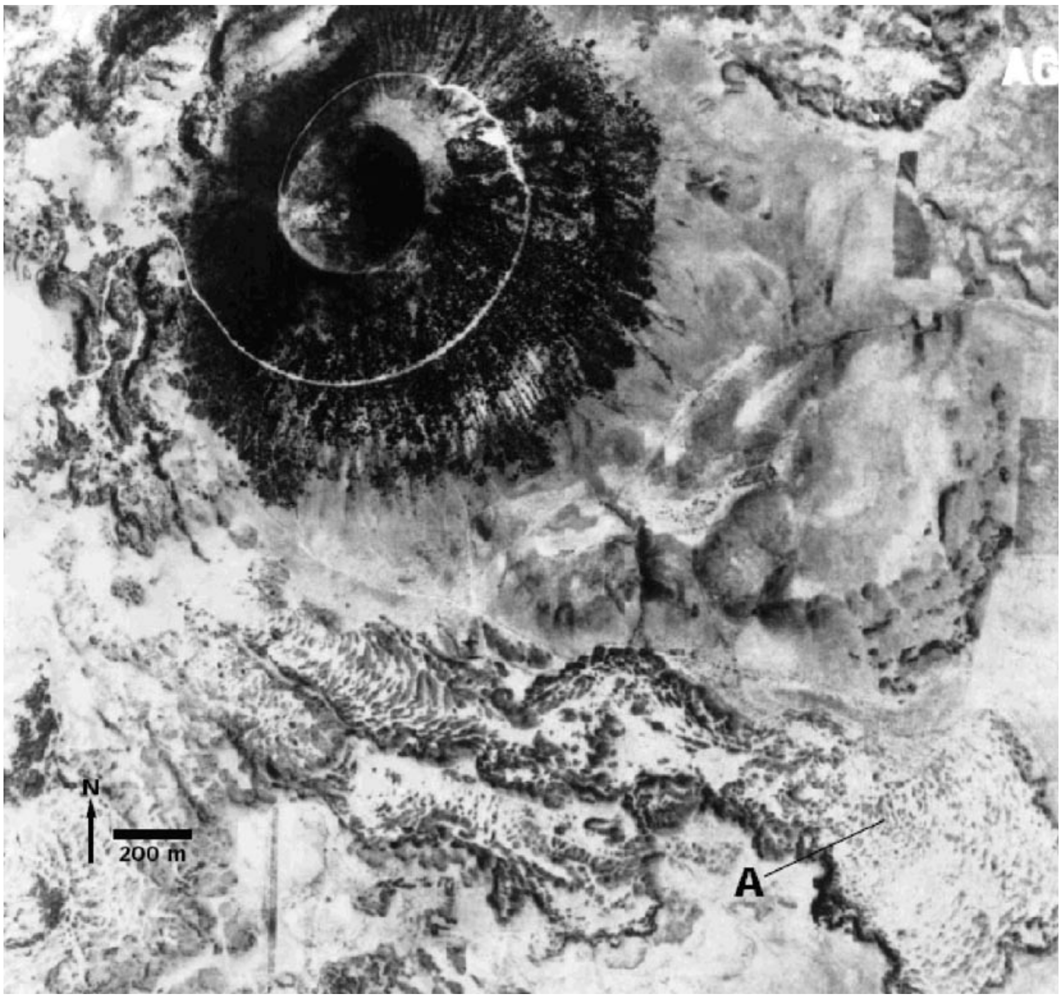


Figure S1. Aerial photograph of the Mount Capulin volcano in New Mexico. North is to the top of the picture. The small figure to the left shows a view of the volcano seen closer to the ground. (Picture credits: University of Illinois Catalog of Stereogram Aerial Photographs #105; U.S. Geological Survey: http://libraryphoto.cr.usgs.gov/htmllib/btch126/btch126j/btch126z/btch126/tde00005.jpg.)

a. Describe the general shape of the volcano and the crater at the top.

____

____

____

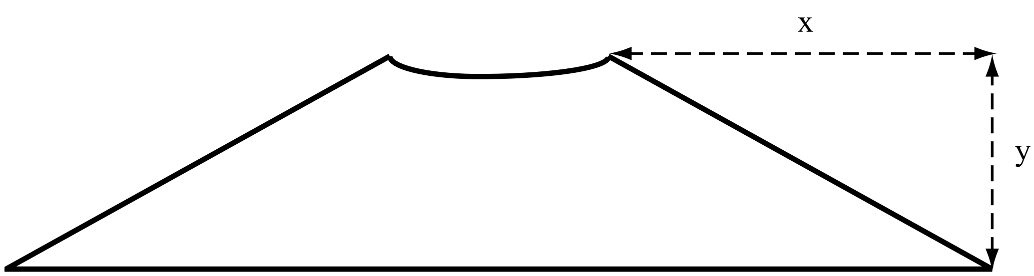
b. What is the winding, spiraling white line that goes from the base of the volcano to the crater rim?

____

____

____

2. Based on the known elevation of Mt. Capulin (334 m) and the information provided by the aerial photograph, it is possible to calculate the slope of the volcano's sides. This simple sketch of Mt. Capulin will help:



a. Using your ruler and the scale bar in Figure S1, determine the distance x, measured from the base of the volcano (which is at the edge of the dark area, the bottom of the hill) to the edge of the crater at the top. Place your ruler so that the "0" mark is at the easternmost edge of the crater and the ruler points due east, and then measure the distance to the base of the volcano.

Scale: 200 m in reality = ______________ cm in the photograph

x = ______________ cm in the photograph

= ______________ m in reality

b. The height of the volcano, y, is 334 m. If the slope of a line is determined by dividing the height, y, by the distance, x, calculate the slope of the volcano's sides:

Slope $= \frac{y}{x} =$ ______________

3. Examine the lava flow labeled A in Figure S1.

a. Describe the surface of the lava flow. (For example, does it appear rugged or smooth?)

b. Trace the flow back to its point of origin. Where is the probable source of the flow?

4. Study the aerial photograph of the Mt. Tavurvur volcano in Papua New Guinea (Figure S2.)

a. How is the volcano similar to Mt. Capulin?

Figure S2. Aerial photograph of the Mt. Tavurvur volcano on the eastern Pacific island of New Britain, Papua New Guinea. North is to the upper left corner. The small picture to the left shows a view of the volcano as seen from the ground. (Picture credits: Univ. Of Illinois Catalog of Stereogram Aerial Photographs, #102; U.S. Geological Survey: http://volcanoes.usgs.gov/Imgs/Jpg/Rabaul/30410142-032_large.jpg)

b. How is it different (for example, are there any differences in their shapes or sizes)?

____

____

5. Mt. Tavurvur has erupted many times during its existence. How does the shape of the crater at its summit support this statement?

____

____

____

6. Estimate the slope of Mt. Tavurvur's sides the same way as you did for Mt. Capulin.

a. First, draw and label a sketch similar to the one in Step 2:

b. The height of Mt. Tavurvur is 225 m. Measure the distance x from the edge of the volcano at the ocean to the rim of the summit crater and calculate the slope of the volcano.

Scale: 200 m in reality = ____________________ cm in the photograph

x = ____________________ cm in the photograph

= ____________________ m in reality

Slope = $\frac{y}{x}$ = ____________________

c. Compare the two slopes. Which slope is higher; that is, which mountain is steeper? What does this mean? For example, which would be harder to climb and why?

7. List at least three factors that might affect the slope of a volcano.

Tectonism

Tectonic faults can be identified on aerial photographs as straight or gently curving features, often creating clear divisions between different landforms. Examine Figure S3 (next page), which shows in image of the San Andreas fault in California. A fairly straight valley extends from the bottom toward the top of the photograph. Over time, the ground on the left side of the fault is moving away from the viewer (toward the top of the picture), with respect to the ground on the right.

8. In what way has the fault affected the mountains visible in the photograph?

9. Tear a piece of paper in half. Place the two halves on a desk side by side. Draw a line from one piece across the tear to the other side. Making sure that the edges of the pieces remain in contact, slide the paper on the left away from you and the paper on the right toward you. This motion illustrates what

occurs along the San Andreas fault and how it affects the features along it. This type of fault is called a *strike-slip fault*.

a. What would have happened if the line on the paper was actually a road crossing the fault?

____

____

____

b. Are there any features like this visible in Figure S3?

____

____

____

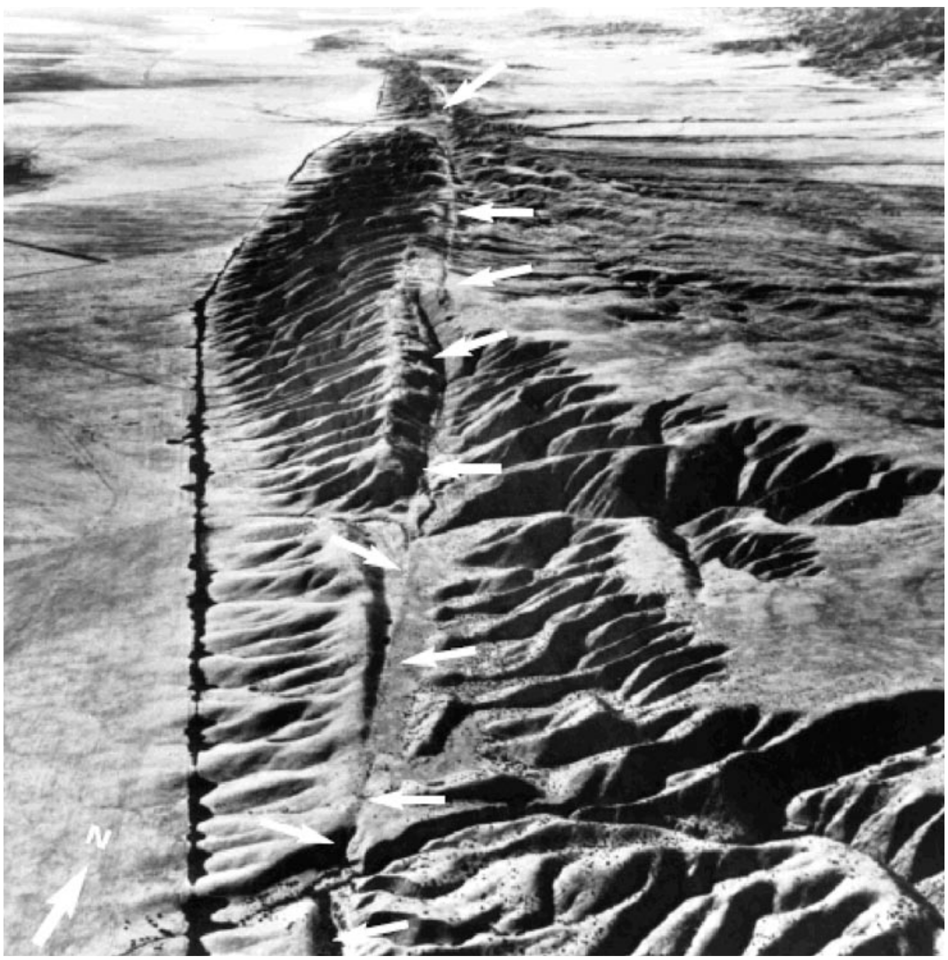


Figure S3. Aerial photograph of a part of the San Andreas fault north of Los Angeles. The white arrows in the picture point to the fault; the straight dark line to the left of the fault is vegetation. The foreground area is about 3.5 km (2.2 miles) across. (Picture credit: photograph by Robert E. Wallace, U.S. Geological Survey).

10. One landform distinctive to tectonism is called a *graben* (for an example, see Figure S4). A graben is a valley bounded on both sides by *normal faults*, which occur in a region that is being stretched. In this case, the central block is moving downward with respect to the sides. Note the difference with the strike-slip fault, where the movement took place horizontally along the fault. Investigate the diagram of a graben below Figure S4. Blocks A, B, and C are separated by normal faults. The direction in which the blocks want to move along the faults are marked by the arrows. For block B to have enough space to move down, what has to occur to blocks A and C?

____

____

____

Figure S4. Aerial photograph of "The Grabens," Canyonlands National Park, Utah. These graben fault blocks are caused by the movement of underlying salt layers. (Picture credit: National Park Service, Canyonlands National Park)

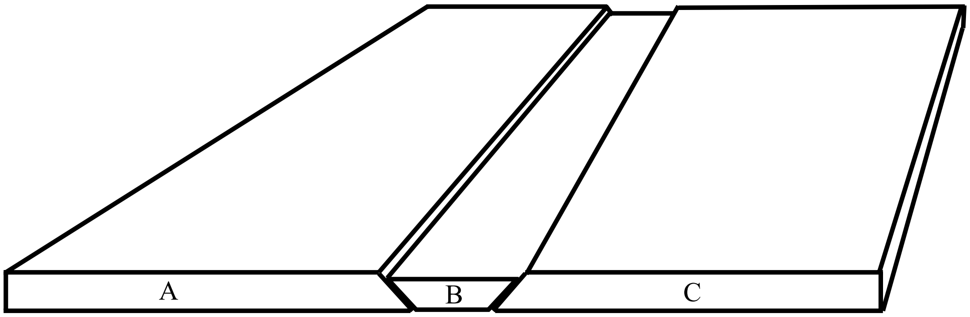


Diagram of a graben

Erosion

11. Figure S5 is an aerial photograph of alluvial fans at Stovepipe Wells, Death Valley, California. These features result from the build-up of alluvium (gravel, sand, and clay) that accumulates at the base of mountains. The term "fan" is used to describe the general shape of the feature.

a. By looking at the picture, what is the source of the alluvium that makes up the fans?

____

____

b. Which agents of erosion (wind, water, gravity) might have generated the alluvium? Support your answer with evidence from the picture.

____

____

Figure S5. Aerial photograph of alluvial fans near Stovepipe Wells, Death Valley, California. Panamint mountains lie to the top of the picture. North is to the bottom left. The small picture on the left shows a view of the mountains from the ground. (Picture credits: University Of Illinois Catalog of Stereogram Aerial Photographs, #125; U.S. Geological Survey: http://mojave.usgs.gov/rvde/images/DantesView-1328Small.jpg)

c. Which agents might have deposited it? Support your answer with evidence from the picture.

____

____

d. Once deposited, how might the alluvium be further eroded?

____

____

12. Figure S6 is an aerial photograph of the Delta River in central Alaska. The river carries melt water and silt from glaciers to the Pacific Ocean. Because rivers of this type are usually shallow and carry lots of sediments, they often deposit the sediments along the stream to form sandbars. The sandbars can redirect the river flow, giving the river the branching, braided appearance visible in Figure S6.

a. How is the Delta River an agent of erosion that works to change the surface?

____

____

Figure S6. The Delta River, a braided stream in central Alaska. North is to the top. The small picture below shows a view of the river from the ground. (Picture credits: U.S. Navy photograph courtesy of T. L. Péwé, Arizona State University; Bureau of Land Management: http://www.blm.gov/pgdata/etc/medialib/blm/ak/gdo/delta_river_plan.Par.73704.Image.360.480.1.gif)

b. Do the individual river channels appear to be permanent, or do they change position with time? Explain your answer.

Impact Craters

13. Examine the photographs of the Meteor Crater in Arizona (Figure S7.)

a. Describe the crater's general shape.

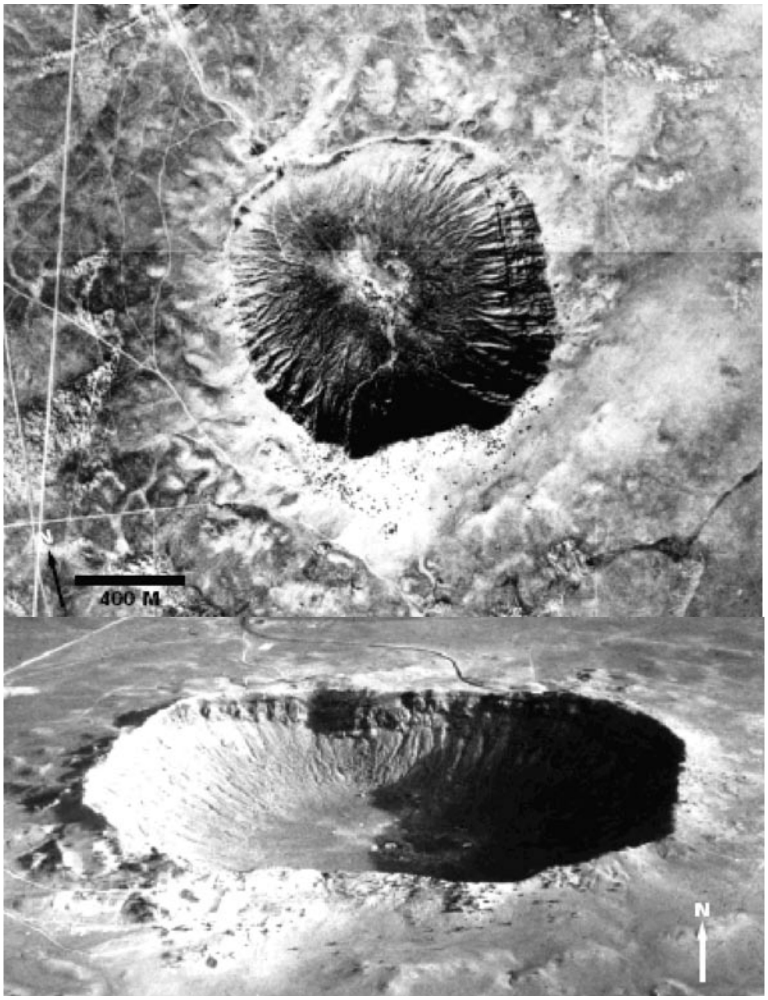


Figure S7. Aerial photographs of the Meteor Crater in Arizona taken from straight up (top left) and from an angle (bottom left.) One of the best preserved impact craters in the world, the Meteor Crater was formed about 50,000 years ago. The small figure below shows a view of the crater from the surface. (Picture credits: University of Illinois Catalog of Stereogram Aerial Photographs, #5; b, Photograph courtesy U.S. Geological Survey; Photograph courtesy of Tony Rowell via NASA Astronomy Picture of the Day: http://apod.nasa.gov/apod/ap090811.html)

b. Even though the Meteor Crater is one of the best preserved craters in the world, it has suffered some erosion. List some evidence for erosion visible in the photographs.

____

____

____

14. The asteroid that created the crater is estimated to have been about 50 m across. Measure the diameter of the Meteor Crater using your ruler and the scale marked in the picture. How do the sizes of the crater and the asteroid compare?

Scale: 400 m in reality = ______________________ cm in the photograph

Diameter of the Meteor Crater = ______________________ cm in the photograph

= ______________________ m in reality

Crater size versus meteor size: = $\frac{\text{crater size}}{\text{asteroid size}}$ = ______________________

15a. How is the shape of the Meteor Crater different from the volcanic landforms in Figures S1 and S2?

____

____

____

____

b. How is it similar to the volcanic landforms?

____

____

____

____

16. Examine the aerial photograph of the Roter Kamm impact crater in Namibia (Figure S8.)

a. Describe the shape of the crater.

b. Does the Roter Kamm crater look fresh or eroded compared to the Meteor Crater? Explain.

17a. How is the Roter Kamm crater different from the volcanic landforms in Figures S1 and S2?

b. How is it similar to the volcanic landforms?

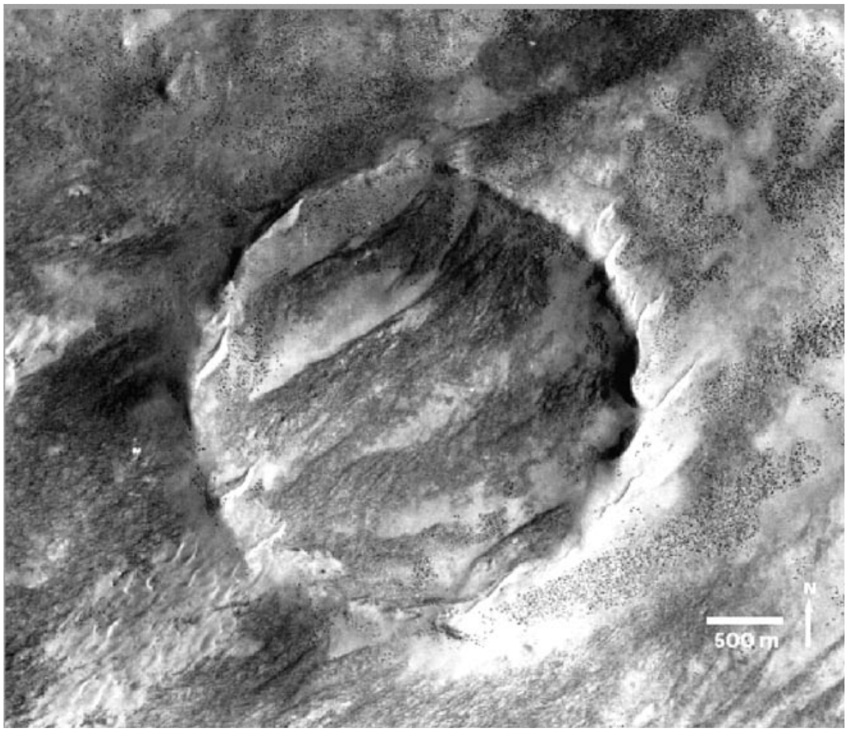


Figure S8. The Roter Kamm crater in Namibia. This impact crater is 2.5 km (1.6 miles) across and formed about 3.7 million years ago. (Picture credit: photograph courtesy Robert Deitz; from Meteoritics, vol. 2, pp. 311-314, 1965.)

Synthesis

18. Geologic processes produce landforms that have different morphology. Straight-line (or slightly curving) features tend to be formed by tectonics. More curving features (such as river valleys) are typically formed by erosion. Volcanism forms lava flows in irregular shapes and patches and often builds cone-shaped volcanoes with a small crater at the summit. Impact craters are roughly circular depressions in the ground caused by meteoroid, asteroid, and comet impacts.

Figure S9 shows a view of northern Arizona. There are landforms in the picture that were shaped by three of the four principal geologic processes discussed in this lesson. For each labeled landform (A-G), identify its type and the process that formed it. Write down evidence to support your claims.

A: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

B: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

C: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

D: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

E: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

F: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

G: Type: ______________________________

Process: ______________________________

Evidence: ______________________________

____

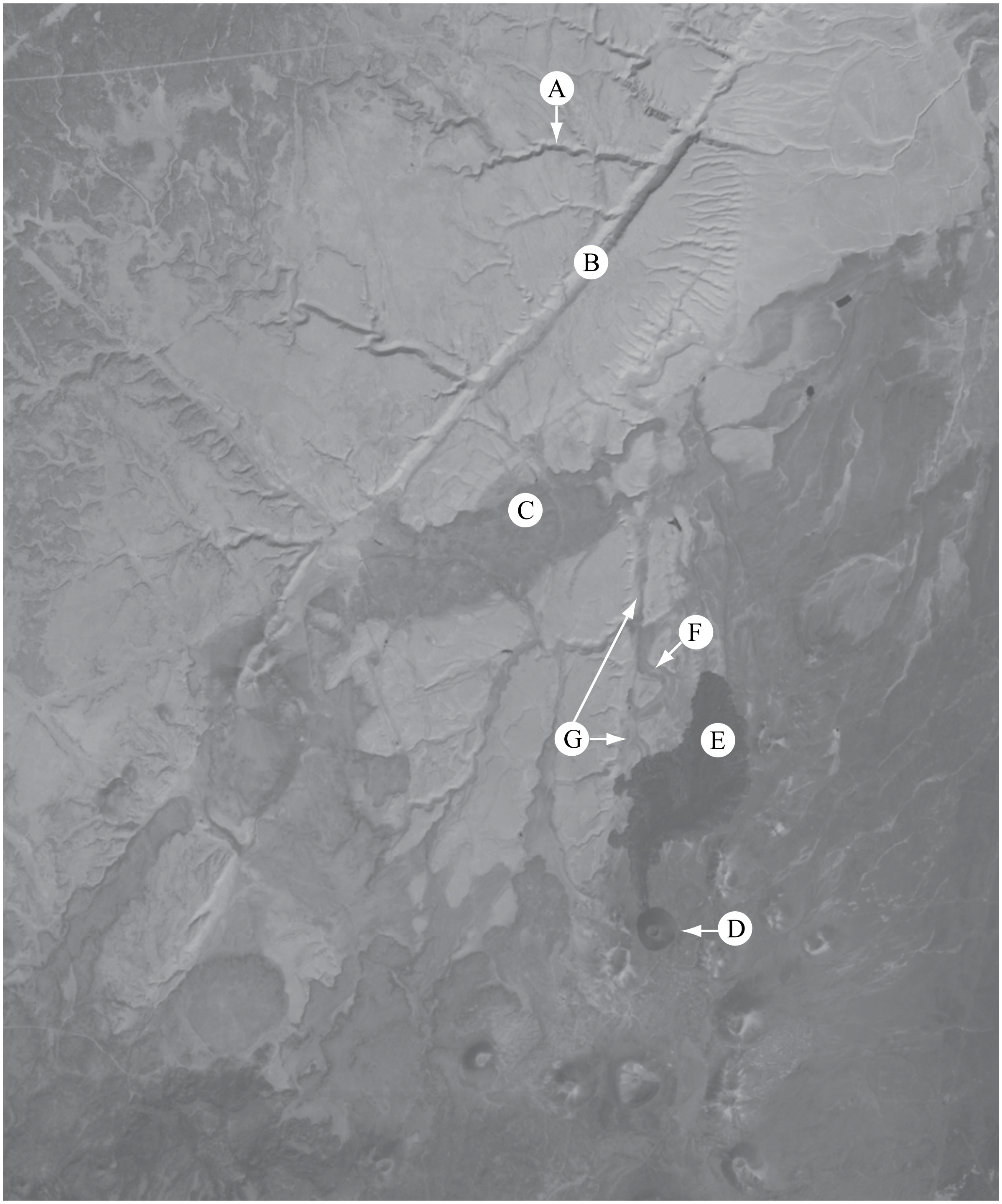


Figure S9. Image of northern Arizona taken by Landsat satellites. Geologically interesting features are marked with the letters A-G. North is to the top of the picture. (Picture credit: NASA/Landsat/U.S. Geological Survey: http://edcsns17.cr.usgs.gov/EarthExplorer)

19. Identify a place in the photograph where a pre-existing graben has affected the behavior of a volcanic flow that took place later. [Hint: look at the behavior of the dark grey feature.]

a. Sketch in the box below what you see in this area:

b. Describe in words what you think happened at this location.

20. Determine the sequence of events that affected the region shown in Figure S9. Mark in the list below the order in which the events occurred, from the first (1) to the most recent (5):

______ river and stream valleys formed

______ dark (black) volcanic materials were deposited

______ medium gray volcanic flows were deposited

______ light gray plains were formed

______ tectonism produced grabens

Explain why you chose this order:

21. Large impacting objects such as asteroids have fallen rarely to the Earth in the last few million years, but billions of years ago large impacts were common. It is reasonable to assume that throughout the geologic history of the Earth, as many impacts have occurred on our planet as on the Moon. Why, then, do we see so few craters on the Earth today, while so many remain visible on the Moon?

Photogeologic Mapping

Materials
- ▼ Blank overhead transparency
- ▼ Set of transparency markers
- ▼ Roll of tape

Your team: ______________________________
____
____
____

Date: ______________________________

Introduction

Recognizing geologic processes that formed landforms visible in photographs taken of the surface of another world in the Solar System is the first step in preparing a geologic map of the world. A geologic map is similar to a regular map in the sense that it shows what the features on the surface look like, but it also includes additional information by portraying graphically the different types of rocks and structural features found on the surface. The map also includes interpretation of the basic data, such as information on the processes that created the features, and how the landforms are related to each other. In this manner, a geologic map makes it possible for scientists to record their interpretations of the observations in a form that can be easily understood by other scientists. This makes it possible to compare observations made at different locations to help us understand the geologic history of the world.

The basic component of a geologic map is the *rock unit*, which is defined as a three-dimensional body of rock that has uniform composition and was formed during some specific interval of time. For example, a unit could be a lava plain or an impact crater on top of the lava plain. The map also identifies structural features, such as faults or riverbeds visible on the surface. In essence, photogeologic mapping starts with examining a surface depicted in a photograph, and dividing the surface features into different units and structural features according to their type, composition, origin, and estimated age. Different units can be identified based on their:

- ▼ ***morphology***: the size, shape, texture and other distinctive properties of the landforms;
- ▼ ***albedo characteristics***: the range of brightness from light (high albedo) to dark (low albedo);
- ▼ ***color***: not only visible color differences, but also different types of light not visible to the human eye, such as infrared, ultraviolet, etc.;
- ▼ ***the degree of erosion***: how much the feature has eroded or how well it has been preserved;

and other properties visible in the photograph.

Once the rock units and the structural features have been identified, it must be determined how they were formed; that is, what geologic processes were responsible for creating them (volcanism, tectonism, erosion, impacts.) The next step is to determine how the units and structural features are related to each other; most importantly, determine the order in which the units and features were formed. This is also called determining the stratigraphic relation of the features, since it is an example of stratigraphy, a branch of geology that studies the origin, composition, and distribution of rock layers. The methods used for this step include:

- ***the principle of superposition***: for units and structural features that are (even partially) on top of each other, the oldest (the one that formed first) is on the bottom, and the youngest (the one that formed most recently) on top.
- ***the law of cross-cutting relations***: for a unit or a structural feature to be modified (via volcanism, impacts, tectonic faulting, erosion, etc.) it must first exist. For example, if there is a fault going through a rock unit, the underlying unit is older than the tectonic event that created the fault.
- ***embayment***: if a bay-like feature is formed when one unit "floods into" (embays) another, the flooding unit must be younger than the one being flooded.
- ***impact crater distribution***: in general, older units have more craters on them, and the craters are larger and more degraded (eroded) than younger units.

Once the stratigraphic relation has been determined, the units are listed on the side of the map in order from the oldest (at the bottom of the list) to the youngest (at the top) as the stratigraphic column. Finally, using the information gathered during the previous steps, you can write a geologic history of the region. The geologic history describes the events that formed the surface seen in the photograph in a chronological order from the oldest to the youngest.

Figure S10 (on the next page) shows an example of a geologic map. The relative ages of the units marked on the map were determined in the following manner: The cratered terrain has more (and larger) craters than the smooth plains unit, indicating that the cratered terrain unit is older. In addition, fault 1 cuts across the cratered terrain, but does not continue to the smooth plains. This suggests that the faulting occurred after the formation of the cratered terrain and prior to the formation of the smooth plains, indicating that the smooth plains unit is younger than the cratered terrain and fault 1. The large impact crater and its ejecta unit (material ejected from the crater into the surrounding area) are mapped as a separate unit, and since it is on top of the smooth plains unit, the crater and ejecta unit is younger. Finally, fault 2 cuts across all the units, including the crater's ejecta, and is therefore the youngest event

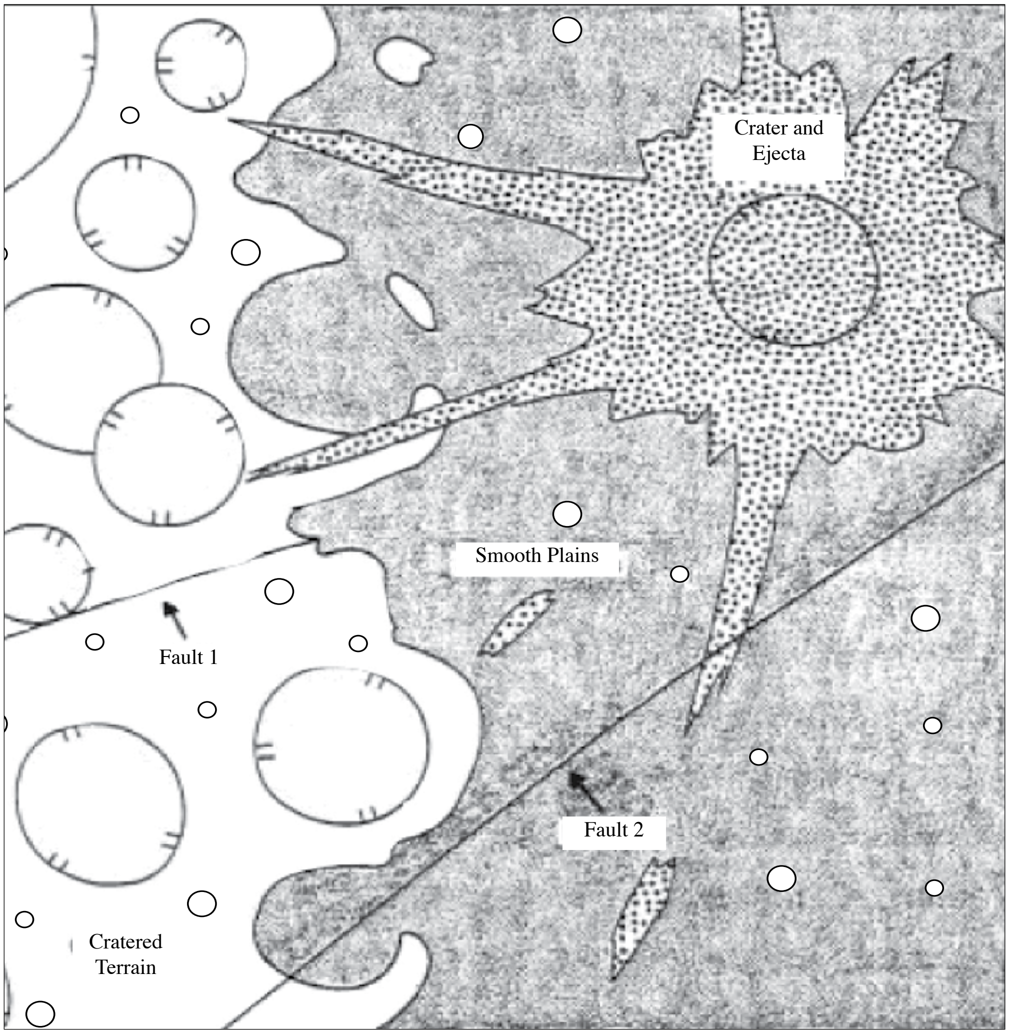


Figure S10. An example of a geologic map of a planetary surface. In addition to the graphical portrayal of the different rock units and structural features (left), the complete map includes a description of the rock units, including observations of their characteristics and an interpretation of their origin (bottom left), and a stratigraphic column describing the age relations between the rock units and structural events identified in the map (bottom right.) (Picture credit: NASA: http://solarsystem.nasa.gov/educ/docs/Intro_Photogeologic_Map.pdf)

Unit Descriptions

Unit Name	Observation	Interpretation
Crater and Ejecta	Rough, blocky surface, high albedo, crater in the middle	Crater and ejecta formed by impact
Smooth Plains	Smooth plains, few craters, low albedo, rounded edges	Volcanic flow
Cratered Terrain	Rugged, heavily cratered plains, high albedo	Old unit, possibly of volcanic origin, has had extensive cratering

Stratigraphic Column

Youngest ↑ Oldest

Geologic Unit	Structural Event
	Fault 2
Crater and Ejecta	
Smooth Plains	
	Fault 1
Cratered Terrain	

in the region. The geologic history that could be derived from this map is the following:

The cratered terrain is the oldest surface in the area. It was cratered by impact activity over time, and then faulted by tectonic activity. After the tectonic activity, a plains unit was created, probably by volcanic activity. Cratering continued after the formation of the smooth plains, as shown by the small craters on top of the smooth plains and the large, young crater (and its ejecta), which is mapped as its own unit. There has been additional tectonic activity after the impact which created the young crater, as indicated by the fault which goes through the crater's ejecta.

Anyone who reviews the map shown in Figure S10 can construct the same geologic history of the region without having to go through all the steps of constructing the map themselves.

Geology of the Planet Mercury

1. Examine Figure S11, a photograph of the surface of Mercury taken by a spacecraft. The area shown in the picture is a great illustration of the complex geologic history of the planet. Let's examine the features visible in the image in greater detail.

a. What types of main terrain can you detect? [Hint: think about the main types of terrain in the sample geologic map, S10] .

b. Which terrain do you think is the oldest? Which is the youngest? Explain your answer.

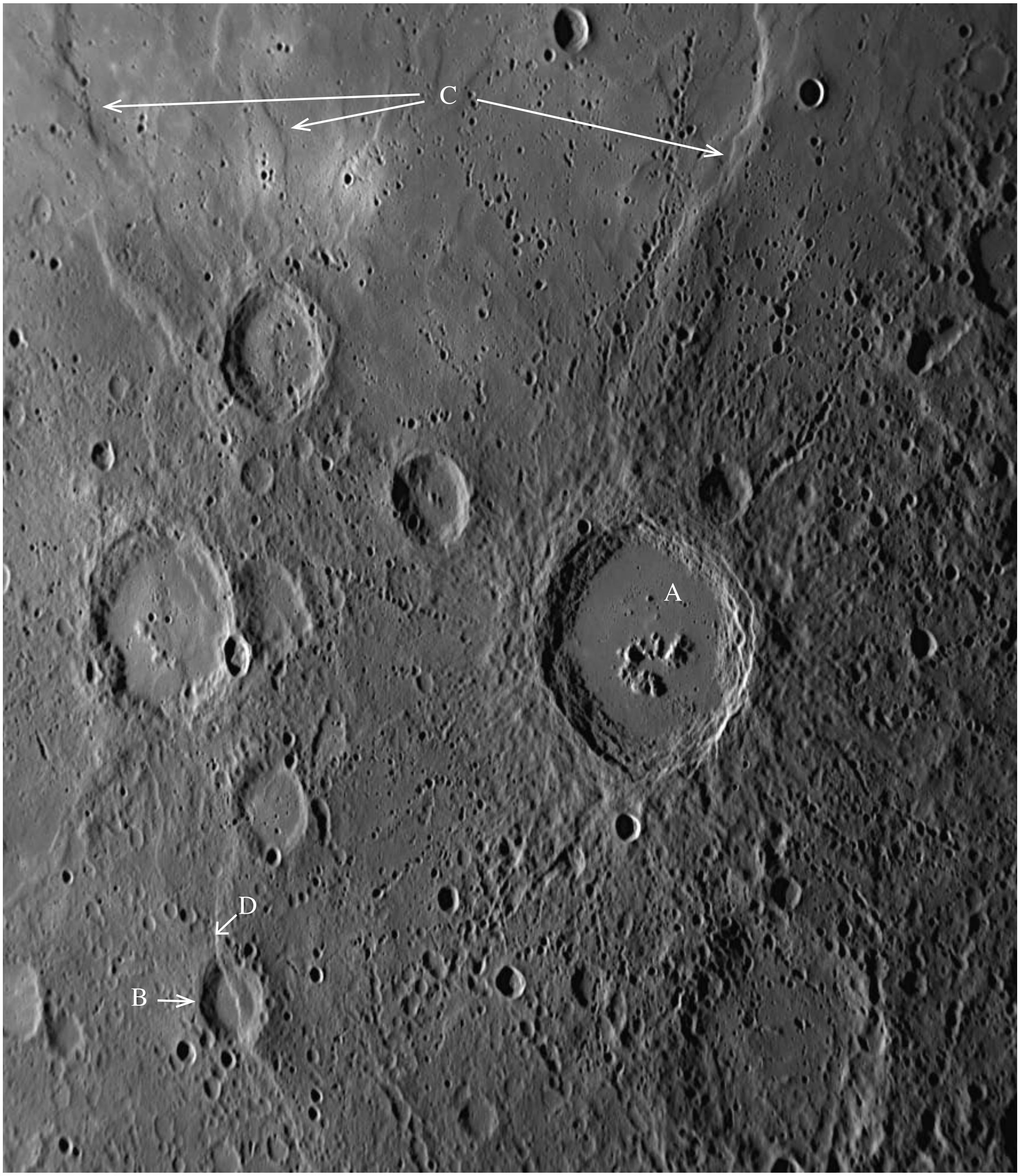


Figure S11. A photograph of the surface of Mercury taken by the MESSENGER spacecraft in 2009. Letters A-D mark geologically interesting features. (Picture credit: NASA/Johns Hopkins University Applied Physics Laboratory/ Carnegie Institution of Washington: http://messenger.jhuapl.edu/gallery/sciencePhotos/image.php?page=1&gallery_id=2&image_id=352)

2. What geologic features and landforms can you see in the picture?

a. Signs of volcanic activity? (Examples: volcanoes, smooth lava plains)

b. Signs of tectonic activity? (Examples: faults, grabens) [Hint: remember that tectonic faults are not always in straight lines but may sometimes have gently curving appearance.]

c. Signs of erosion? (Examples: riverbeds, sand moved by wind, crater walls degraded by the action of rain, wind, ice, or gravity) [Hint: remember which planet the photograph depicts and which agents of erosion are likely to act there.]

d. Signs of impact cratering? (Examples: impact craters, ejecta around craters)

3. Tape a blank overhead transparency over Figure S11. Mark on the transparency the four corners of the photograph as reference points in case the sheet shifts while you are working on it. The transparency will be the basis for your photogeologic map.

4. Draw the boundaries between the main types of terrain you identified in Step 1.

5. Write the mapping unit descriptions of the terrains in the table below. Label the units on your map.

Unit Name	Observation	Interpretation

6. Let's investigate the relationship between the terrains, the craters and a few of the tectonic features visible in the photograph. Trace a few of the largest craters on your map (be sure to include craters marked A and B), and some of the tectonic features (be sure to include at least a couple of the so-called wrinkle ridges marked C and the cliff marked D.)

a. What is the age relation between the terrains you identified? What observations did you use to decide?

b. Note the large crater (A) in the image. A crater this large can have central mountain peaks at the center of the crater, large ejecta blankets around it, and even secondary craters, where material blasted away from the impact site strikes the ground some distance away from the crater. Secondary craters can be recognized as a string or a group of small craters around the main crater. What is the age relation between the large crater (A) and the terrains you identified in Step 5? (That is, is the crater older or younger than the terrains?) Explain your answer.

c. What is the age relation between the wrinkle ridges (C) and the surrounding terrain? (That is, are the ridges older or younger than the terrain?) Explain your answer.

d. What is the age relation between the cliff (D) and the surrounding terrain? Explain.

e. What is the age relation between the cliff (D) and the mid-size crater (B) on it? Explain.

7. Place the geologic units (terrains) and the structural features marked A-D in the correct sequence in the stratigraphic column below. List the oldest at the bottom and the youngest at the top.

	Geologic Unit	Structural Feature
Youngest		
Oldest		

8. Using your unit descriptions and stratigraphic column, write a geologic history for the area you have mapped. Use evidence from the photograph and your map to support your answer.

ANSWER KEY

Please note that in the following, it is assumed that the photographs in the worksheets are not reduced or enlarged during printing/copying.

STUDENT WORKSHEET 1

1. a. The volcano has a circular base and a circular crater. The sides of the volcano have been affected by erosion. There is a lava flow down the side (marked with A in the photograph.)

   b. A road.

2. a. Scale: 200 m in reality = 1.0 cm in the photograph.

   x = 3.0 cm in the photograph; therefore x = 600 m in reality.

   b. Slope = 334 m / 600 m = 0.56

3. a. The surface is somewhat rugged.

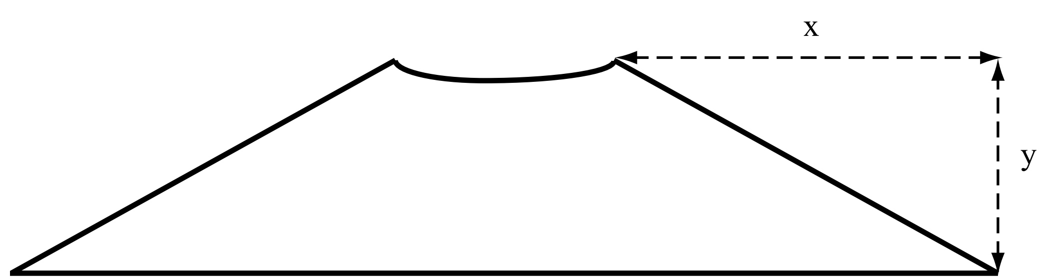
   b. The source of the lava flow is probably at the base of the crater near the road.

4. a. They are similar in shape (conical), with a central depression, the volcanic crater, at the top. They both have old lava flows coming down the sides of the mountain.

   b. The crater of Mt. Tavurvur is more irregular in shape, not quite as circular as the crater on Mt. Capulin.

5. The crater is not perfectly circular but somewhat scalloped, which suggests that it has been reshaped several times by multiple volcanic eruptions.

6. a. The schematic is the same as for Mt. Capulin:



b. Since the edge of the volcano is very irregular, the answers will vary. Here is one example:
Scale: 200 m in reality = 1.5 cm in the photograph.
x = 3.2 cm in the photograph; therefore x = 430 m in reality.
Slope of Mt. Tavurvur = 225 m/430 m = 0.52.
Since the slope of Mt. Capulin (from question 2b) is 0.56, it has a slightly steeper slope than Mt. Tavurvur (but not very different). Mt. Capulin would be harder to climb because it is steeper.

7. Answers may vary but could include the following: Single eruption versus multiple eruptions over time, the type of material (ash versus lava), how viscous the lava was (which depends on its temperature and composition), the amount of time the lava flows from the crater. After the volcano is formed, erosion by wind or rain may affect the slopes.

8. The fault cuts through the mountains and can be seen as a depression. The rocks along the fault were ground together and weakened, so that they were more easily eroded than the rocks away from the fault.

9. a. The road would have been cut and separated.

   b. There are at least two off-set features along the fault: near the middle of the photo, and near the bottom of the photo. (The features in this case are drainage valleys and not roads.)

10. Blocks A and C must move apart and away from block B in the horizontal direction.

11. a. The alluvium is material eroded from the Panamint mountains.

   b. All three agents have acted to produce materials eroded from the mountains, but water probably was the main agent, since there are features that look like drainage valleys on top of the mountains leading to the start of the alluvium fan features. The rivers have brought sediments from the mountain and deposited it on the sides. Material is also brought down the mountain by the action of gravity. One can also see some ripples in the feature probably caused by the wind.

   c. By all three agents but mainly by water carrying sediments from the mountains. Features that look like river beds or drainage valleys come from top of the mountains to the start of the alluvium fans, suggesting that the material was deposited by water.

   d. It would be eroded by the agents of wind, water, and gravity. For example, sand dunes are visible alongside the fans, providing evidence of erosion by the wind.

12. a. The river carries material from one place (glacier) to another (the Pacific Ocean.) Along the way, it deposits material on the river banks to form sandbars. The river also can remove material from its banks.

    b. The river channels change position with time. Dry and semi-dry (ponds present) channels are visible in the foreground of the photo, indicating that they have carried water before but do not do so at the moment.

13. a. It is a roughly circular depression in the ground, with its sides somewhat squared from a perfect circle.

    b. The walls are grooved, indicating erosion by running water. It looks like material from the sides of the crater has falled down to the bottom. The rim of the crater has eroded from a more circular shape it may have had originally.

14. Scale: 400 m in reality = 1.4 cm in the photograph.
    Diameter of the crater = 4.2 cm in the photograph; therefore x = 1,200 m in reality.
    Size of crater / size of asteroid = 48.

15. a. The Meteor Crater is much wider than a volcanic crater compared with the vertical size of the feature. Impact craters excavate (occur at ground level and dig out below ground level), while volcanoes are built up above ground level and have a crater on top of the mountain. A volcano also has material flowing from the crater to the surrounding area; an impact crater may have an ejecta blanket around it, but it is usually not as extensive or complex as lava outflows from a volcano.

    b. They have the same circular shape with a crater in the center.

16. a. It is circular but has a somewhat subdued appearance: the rim looks worn, and not very clearly defined. The center of the crater seems to have been partly filled with sediment, as shown by the presence of sand dunes.

    b. The Roter Kamm crater appears to be more eroded than the Meteor Crater. It appears to have filled with material from the crater sides and the surrounding area, and is therefore probably not quite as deep (compared with the size of the crater), as the Meteor Crater.

17. a. The crater does not appear as high or as steep.

    b. They all are circular and have raised rims.

18. A. Type: River valley; Process: Erosion; Evidence: curving feature carved into rock.

    B. Type: Graben; Process: Tectonism; Evidence: straight-line feature that is lower than the rocks on either side of it.

    C. Type: Lava flow; Process: Volcanism; Evidence: large-scale flow with darker color (medium gray) compared with the surrounding area (light gray.)

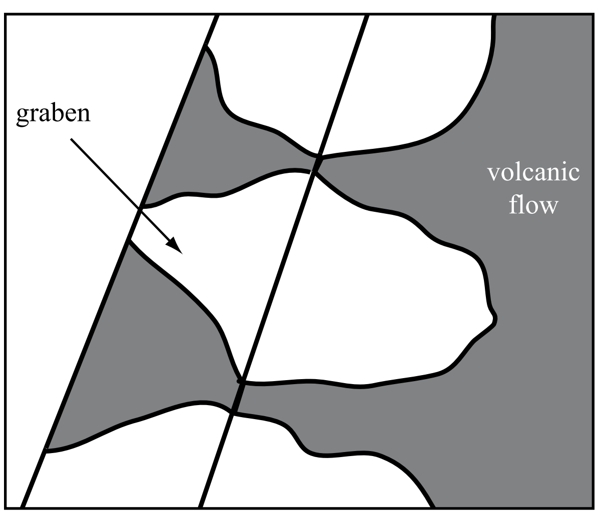
    D. Type: Volcano; Process: Volcanism; Evidence: cone-shaped hill which has a crater on top and which appears to be located in the middle of an area with lava flows.

    E. Type: Lava flow; Process: Volcanism; Evidence: dark material flows in an irregular pattern across the area and seems to have its source on a cone-shaped volcano.

    F. Type: Lava flow in a pre-existing river valley; Process: Erosion followed by volcanism; Evidence: winding feature (similar to A) that seems to be at least partially filled with new medium-gray material from a lava flow.

    G. Type: Graben; Process: Tectonism; Evidence: roughly straight-line feature similar to B.

19. a. Schematic of an area where a volcanic flow interacts with a pre-existing graben (southeast of the location of the letter G):



    b) Volcanic material flowed into the pre-existing graben valley in two separate places. The flows spread out in a fan shape.

20. _3_ river and stream valleys formed

_5_ dark (black) volcanic materials were deposited

_4_ medium gray volcanic flows were deposited

_1_ light gray plains formed

_2_ tectonism produced grabens

Explanation: The light gray plains appear to be the basis on which all other features are formed. The rivers and lava flows flood into the grabens (rather than the grabens cutting across existing rivers and lava flows, for example, as indicated by the fact that the rivers are widest on both sides of the graben just before going into the graben), so the grabens were formed next. At least some of the rivers have been affected by later lava flows, so they were formed after the grabens but before the lava flows. The dark lava flow is on top of the medium gray lava flows (as shown by places where the dark lava appears to flow on top of the medium gray lava), which means that it is younger of the lava flows.

21. On the Earth most craters have been erased by the other active geologic processes: volcanism, plate tectonics, and erosion (especially wind and water.) On the Moon, the effect of these agents has been much less: some of them do not exist at all (plate tectonics, wind and water), while others have not been active for quite some time (volcanism.)

Student Worksheet 2

Answers will vary depending on the students' interpretation of the image. Note that, for this activity, it is not as important for the students to correctly identify all the features in the photograph as it is for them to logically justify their answers.

1. a. Answers will vary. At a minimum students should list the following: Terrain One: smooth plains—smooth, brighter (higher albedo), less cratered areas; Terrain Two: heavily cratered terrain—rough, slightly darker (lower albedo), heavily cratered areas with craters of various sizes. Possible additional terrains include: large young craters with ejecta around them and older, more eroded craters.

   b. Answers will vary depending on the terrains the student identified. For the terrains listed in question 1a, the heavily cratered terrain is older than the smooth plains, because it has more craters, and the smooth plains seem to have formed so that they cover the heavily cratered terrain, rather than the other way around. The young craters are on top of the other terrains.

2. a. Smooth lava plains, but no sign of volcanoes (the craters are impact craters.)

   b. Several faults, especially in the upper part of the image; the faults are gently curving features. Features C and D are examples.

   c. Some of the craters appear to have degraded, probably due to gravity, since wind and water are not candidates for being agents of erosion on Mercury.

   d. Many craters of different sizes in all parts of the image, with craters fewer in the smooth terrain than in the heavily cratered terrain. Features A and B are examples.

5. Unit Descriptions

Unit Name	Observation	Interpretation
Smooth plains (or whatever name the students give to the unit on top)	Smooth plains, fewer (and mostly small) craters, higher albedo	Volcanic flow
Heavily cratered terrain (or whatever name the students give the unit at bottom)	Rougher surface, numerous craters of various sizes, lower albedo	Old, heavily modified surface, possibly of volcanic origin

6a. The smooth plains are younger than the heavily cratered terrain. The latter contains more craters, larger craters (as well as small craters), and more eroded craters. It is overlain by the volcanic smooth plains.

b. The crater is younger than either of the terrains. The main crater is on top of the heavily cratered terrain, and the secondary craters appear to reach all the way to the smooth plains, indicating that the secondary craters were formed after the smooth plains unit.

c. The wrinkle ridges are younger than the smooth plains because they are on top of the unit and are not covered somewhere along their length.

d. The cliff is younger than the heavily cratered terrain because it is completely on top of the terrain and is not covered somewhere along its length.

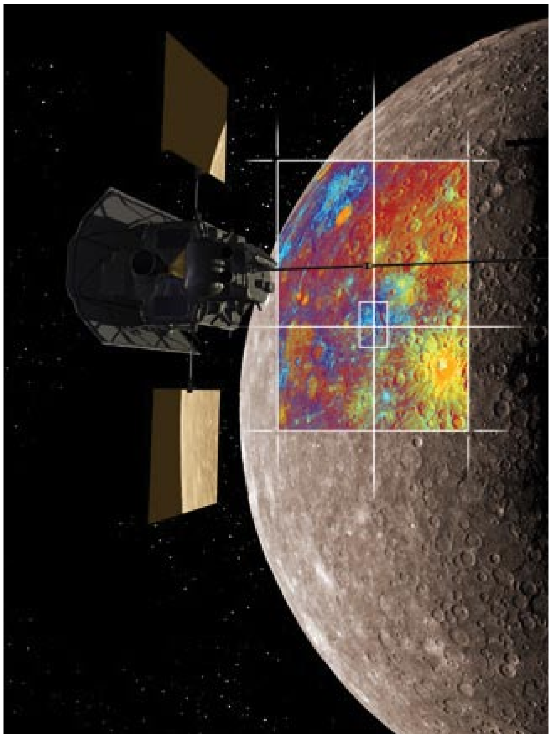
e. The crater is older because the cliff cuts through it.

7. The stratigraphic column:

	Geologic Unit	Structural Features
Youngest		Large young crater (A)
		Wrinkle ridges (C)
	Smooth plains	
		Cliff (D)
		Mid-size crater (B)
Oldest	Heavily cratered terrain	

12. This region was initially covered by the heavily cratered terrain unit, which is possibly of volcanic origin. The unit has been modified by continued cratering and tectonism, as evidenced by the cliff (D) that cuts through the mid-size crater (B). Volcanic flows occurred in the map area, represented by the smooth plains unit. No source area of the flows is identifiable within the mapped area. Cratering continued after the formation of the smooth plains unit. There has been a continuation (or reactivation) of tectonic activity in the area, indicated by the wrinkle ridges (C). Finally, cratering has continued, as shown by the presence of the large young crater on top of the two main geologic units, with secondary craters seemingly on top of the wrinkle ridges.

MESSENGER Mission Information Sheet



MESSENGER is an unmanned NASA spacecraft that was launched in 2004 to study the planet Mercury. After three flybys of its target planet in 2008 and 2009, the spacecraft will go into orbit around Mercury in 2011. It will not land but will make detailed observations from orbit. MESSENGER will never return to the Earth, but will stay in orbit around Mercury to gather data until at least 2012.

MESSENGER is an acronym that stands for "MErcury Surface Space ENvironment, GEochemistry and Ranging," but it is also a reference to the name of the ancient Roman messenger of the gods: Mercury, who, it was said, wore winged sandals and was somewhat of a trickster.

MESSENGER will be the second spacecraft ever to study Mercury; in 1974 and 1975 Mariner 10 flew by the planet three times and took pictures of about half the planet's surface. MESSENGER will stay in orbit around Mercury for about one Earth year, during which time it will make close-up and long-term observations, allowing us to see the whole planet in detail for the first time.

During its mission, MESSENGER will attempt to answer several questions about Mercury. How was the planet formed and how has it changed? Mercury is the only rocky planet besides the Earth to have a global magnetic field; what are its properties and origin? What is the nature and origin of Mercury's very tenuous atmosphere? Does ice really exist in the permanently shadowed craters near the planet's poles? Mercury is an important subject of study because it is the extreme of the terrestrial planets (Mercury, Venus, Earth, Mars): it is the smallest, one of the densest, it has one of the oldest surfaces and the largest daily variations in surface temperature—but is the least explored. Understanding this "end member" of the terrestrial planets holds unique clues to the questions of the formation of the Solar System, evolution of the planets, magnetic field generation, and magnetospheric physics. Exploring Mercury will help us understand how our own Earth was formed, how it has evolved, and how it interacts with the Sun.