Voyage: A Journey Through Our Solar System

Grades 5-8

Lesson 10: Impact Craters: A Look at the Past

On a visit to the National Mall in Washington, DC, one can see monuments of a nation—Memorials to Lincoln, Jefferson, and WWII, the Vietnam Veterans Memorial Wall, and Washington Monument. Standing among them is *Voyage*—a one to 10-billion scale model of our Solar System—spanning 2,000 feet from the National Air and Space Museum to the Smithsonian Castle. *Voyage* provides visitors a powerful understanding of what we know about Earth's place in space and celebrates our ability to know it. It reveals the true nature of humanity's existence—six billion souls occupying a tiny, fragile, beautiful world in a vast space.

Voyage is an exhibition that speaks to all humanity. Replicas of *Voyage* are therefore available for permanent installation in communities worldwide (http://voyagesolarsystem.org.)

This lesson is one of many grade K-12 lessons developed to bring the *Voyage* experience to classrooms across the nation through the *Journey through the Universe* program. *Journey through the Universe* takes entire communities to the space frontier (http://journeythroughtheuniverse.org.)

Voyage and *Journey through the Universe* are programs of the National Center for Earth and Space Science Education (http://ncesse.org). The exhibition on the National Mall was developed by Challenger Center for Space Science Education, the Smithsonian Institution, and NASA.

Lesson 10: Impact Craters: A Look at the Past

Lesson at a Glance

Lesson Overview

The countless craters, big and small, that are found on the surfaces of planets and moons record a violent history of collisions across the entire Solar System. It is a story that spans billions of years. Studies of craters—their shapes, sizes, number in a given area, and whether they are superimposed upon or beneath other geologic features—provide an understanding of how this story may have unfolded. In the first Activity students simulate how impact craters are formed, and how the appearance of a crater depends on the energy of the impacting object. In the second Activity, photographs of the cratered surfaces of other worlds are examined to reveal information about a world's history, and the history of the entire Solar System.

Lesson Duration

Two 45-minute class periods

Core Education Standards

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 D2: Earth's history

- The earth processes we see today, including erosion, movement of lithospheric plates and changes in atmospheric composition, are similar to those that occurred in the past. Earth history is also influenced by occasional catastrophes, such as the impact of an asteroid or comet.

AAAS Benchmarks for Science Literacy
Benchmark 4C2:

- 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 in sediments or carrying it in solution to the sea.

ESSENTIAL QUESTION

- What can craters tell us about the history of objects in the Solar System?

CONCEPTS

Students will learn the following concepts:

- Impact craters are depressions or pits on the ground formed by impacts by objects falling from space.
- The surface of the Moon has more impact craters than Earth because there are processes on Earth that erase and retard this type of cratering.
- Scientists can tell a lot about a world simply by studying the craters on its surface.

OBJECTIVES

Students will be able to do the following:

- Examine impact craters and determine some properties of the object which created it.
- Decipher the history of objects in the Solar System based on the nature of its craters.

SCIENCE OVERVIEW

WHAT IS AN IMPACT CRATER?

Impact craters are geological structures formed when a meteoroid, an asteroid, or a comet smashes into a planet, a moon, or another Solar System object with a solid surface. Asteroids are large chunks of rock and metal, ranging in size from a few hundreds of meters/yards to a few hundred kilometers/miles. While asteroids can be found in various places in the inner Solar System, most of them orbit the Sun in the main Asteroid Belt between the orbits of Mars and Jupiter. Comets are sometimes called dirty snowballs or "icy mudballs" because of their composition: they are a mixture of ices (water ice, as well as carbon dioxide and ammonia ices), rock, and dust. There are probably a trillion comets orbiting the Sun in the outer reaches of the Solar System. Some comets have orbits that, while keeping them much of the time well beyond the orbit of Neptune, on occasion bring them close to the Sun, at which time we can see them as comets in the sky. Asteroids and comets both are thought to be leftover material from the time the planets (and other large Solar System objects) were formed. A meteoroid is a piece of stone, metal, or ice debris from a comet or an asteroid that travels in space. Most meteoroids are no bigger than a pebble. They can be found throughout the Solar System. If a meteoroid crosses Earth's orbit, it may fall onto our planet. When a meteoroid flies through the Earth's atmosphere, it can be seen as a meteor in the sky as it burns up because of the heating by the atmosphere. If the meteoroid is sufficiently large, part of it may survive the flight through the atmosphere and fall to the ground. These pieces are then called meteorites.

All inner planets in the Solar System (Mercury, Venus, Earth, and Mars) have been bombarded by meteoroids, asteroids, and comets during their history. Craters can also be found on the surfaces of moons, dwarf planets, and even on asteroids and comets themselves. While most asteroids and comets today are on orbits that rarely bring them close to a planet, the case was different when the our planetary system was young and there was a lot of debris such as asteroids and comets left over from the formation of the planets throughout the Solar System. Large impacts were more common then, and it appears that most objects in the Solar System with a solid surface show evidence for a heavy bombardment period early in their history. While large impacts are rarer today, they still occur on occasion, and small meteoroids continue to impact the various worlds in the Solar System even today.

The presence of an atmosphere influences the kind of cratering that takes place on a world. In a world with a substantial atmosphere (e.g., Earth), the impacting object has to fly through an atmosphere to reach the surface of a world, and during the flight, the object slows down and also burns up due to heating by the atmosphere. As a result, most of the small meteoroids are destroyed before they reach the surface. Larger objects, while slowing down and burning up some, may survive to the surface and create an impact crater. If the world has no atmosphere, meteoroids of all sizes can create impact craters on the surface.

CRATER PARTS

When an object falls onto a planet, a moon, or another solid body in the Solar System, it hits the surface hard and creates a crater on the surface. The object that strikes the planet is called an impactor. The impact vaporizes much of the impactor itself, and creates a shock wave that transmits the energy of the impacting object to the ground. The shock wave expanding from the point of 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. Small impactors excavate a crater only slightly larger than the impactor, while a large impactor can create much more havoc on the surface because of the high amount of energy transmitted by the shock wave. The parts of an impact crater are (see Fig. 1 for an illustration):

Floor – The bottom part of the crater. The floor may be shaped like a bowl, or it may be flat. This part is lower than the surrounding surface.

Walls – The sides of the crater. The walls can be very deep, depending on the severity of the impact. If a crater has shallow walls, the crater may have been filled or eroded somehow since its formation.

Rim – The edge of the crater; the top of the crater walls. The rim is usually the highest part of the crater.

Ejecta – Debris that is thrown out—ejected from—the impact site. The debris is created when the shock wave crushes, heats, and melts material at the impact site. Typically, the layer of ejecta is thick close to the crater, and thinner farther away.

Rays – Bright streaks that start at the rim of the crater and extend outward. Rays are created by fine ejecta coming from the crater and are usually found around craters on worlds where there is no significant atmosphere (e.g., they can be found around craters on the Moon but not on Earth.)

Central Peak – A small "mountain" that may form at the center of the crater in reaction to the force of the impact. Only large

> craters have central peaks. The size at which a crater can have a central peak depends on the size of the world. For example, on Earth, craters larger than 2-4 km (1.2-2.5 miles) in diameter may have central peaks, while on the Moon, the crater must be larger than 15-20 km (9-12 miles) in size.

The size of an impact crater depends on the amount of kinetic energy the impactor has at the time of impact. That is, crater size depends on the mass (m) and the velocity (v) of the impactor ($E_{kin} = 1/2 \times mv^2$). The more massive the impactor, the larger the crater. For two impactors of equal size, the crater is larger for the one that hits the surface with greater velocity.

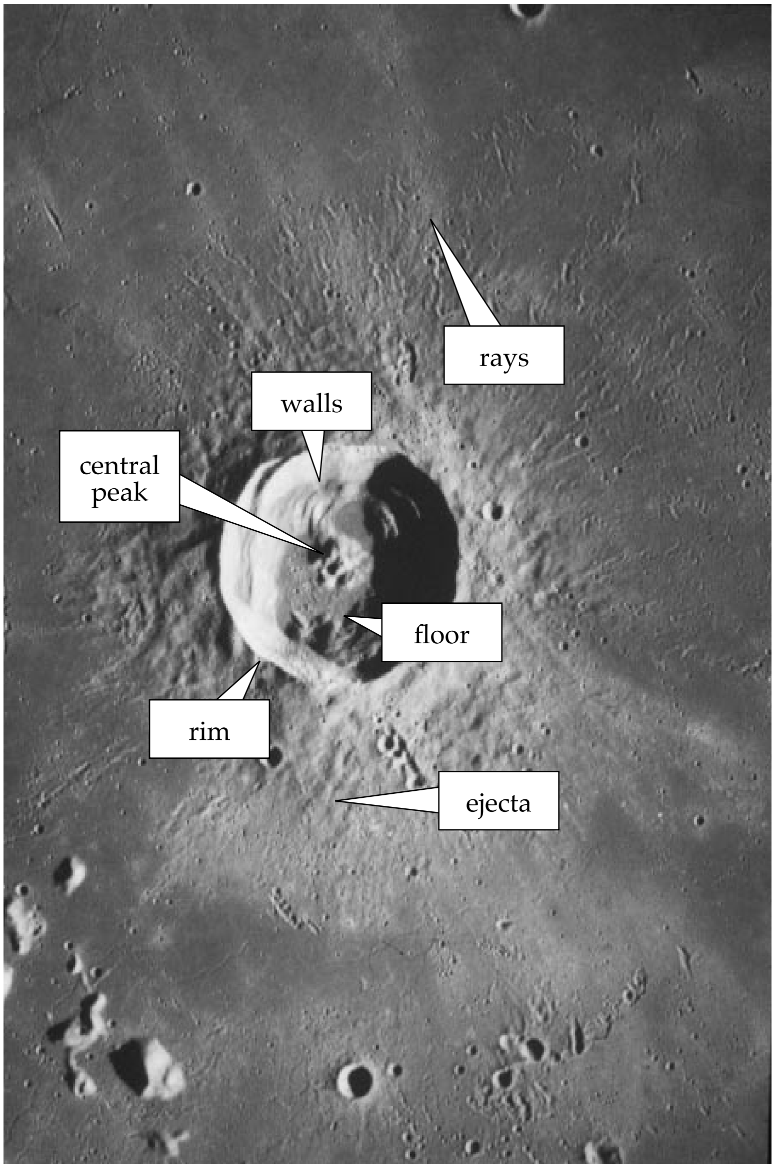

Figure 1. A crater on the Moon with crater parts labeled. (Image credit: Part of Apollo 17 Metric photograph AS17-2923.)

WHAT CHANGES THE SHAPE OF A CRATER?

Initially, impact craters have a crisp rim and clearly visible blankets of ejecta around the sides. However, there are many processes that may degrade the appearance of a crater. On Earth, the action of wind, water, lava flows (volcanoes), and plate tectonics can alter the appearance of a crater. Wind can blow away ejecta from around the crater. Water flows (rivers and floods) can erode the crater's walls and rim, or the crater may be filled with water to form a lake. Lava flows can fill the crater partially or completely and make the rim smoother. Plate tectonics may move the crater to the edges of the tectonic plate and bury it under the Earth's crust, or cause a tectonic fault to be formed through the crater. It is also possible that another impactor comes along and creates a new crater on top of the old crater, partially or completely destroying the older crater. Some of these effects also operate on other worlds in the Solar System, depending on the properties of the world. For example, there is no wind or water on the Moon to erode the craters formed there, but one can see craters on the Moon that have been filled with lava, or see instances where new craters have been created on top of old ones. It is even possible to deduce which of these processes might operate on a given world by looking at the properties of impact craters there.

A crater which clearly exhibits the different parts of a crater (has a sharp rim, a well-defined ejecta blanket and is relatively deep) is called a fresh crater. A degraded crater has been eroded over time and lacks some or all of the features of a fresh crater. A crater which has been almost completely eroded away and is just barely visible is called a ghost crater. Note that it may be difficult to tell whether a fresh crater was formed recently or if it is an old crater which has experienced little erosion.

CRATERS AND THE AGE OF A SURFACE

The older a surface is, the more time impactors have had to hit it. Very old surfaces have so many craters that it might even be difficult to notice if yet another impact occurred. As a result, little of the surface is smooth. If the surface of a world is renewed by one or more of the processes described above, the surface has fewer craters and larger smooth areas. This kind of surface is called young. For example, Earth has a young surface, while places like the Moon and the planet Mercury have heavily cratered, old surfaces. One world may also have areas where the surfaces are of different ages. As a result, the number and type of craters visible on the surface of the world can be used to determine the relative ages of the surfaces. Basically, the more craters a surface has, the longer it has been exposed to bombardment by meteoroids. Note, however, that it is not possible to determine the absolute age of the surface this way. To determine the absolute age of a surface, additional tests on samples of the surface (rocks or soil) must be performed. So far, scientists have been able to measure absolute ages for rocks from Earth and the Moon, as well as for meteorites that have been found on Earth. The oldest rocks on Earth are 4.0 billion years old, while the ages of oldest lunar rocks range from 4.4 to 4.5 billion years. This result agrees with the assessment that Earth's surface is younger than the Moon's surface. Note that these ages provide the times at which the rocks became solid from a molten state but does not say anything of the time before that. So, while the ages of the rocks give a good lower limit for the ages of the worlds on which they formed, additional information is required to get a better estimate of the ages of the worlds as a whole. For example, according to our current understanding of the Earth-Moon system, Earth as a planet is older than the Moon as a whole body; it is just the surface of Earth and the solid rocks on it that are younger than the Moon's surface. The ages of the oldest meteorites found on Earth are in the 4.5-4.6 billion year range. Since the oldest meteorites are thought to be some of the first solid material to have formed in the Solar System, the 4.6 billion year age is usually thought of as a good estimate for the age of the whole Solar System.

CRATERS ON EARTH

On Earth, craters are continually erased by weathering (wind, rain, and water flows), as well as by volcanic resurfacing and tectonic activity. Only about 175 terrestrial impact craters have been recognized, the majority in geologically stable areas of North America, Europe, southern Africa, and Australia. Spacecraft orbital imagery and other investigation methods using advanced techonology have helped identify craters that are in remote locations or are difficult to recognize as impact craters by sight. For example, scientists discovered the Chicxulub crater near Cancun in Mexico using seismic monitoring equipment designed to search for oil. Much of the crater lies under the ocean, and it is hidden under 65 million years' worth (or about 1 km; 0.6 miles) of sediment. The crater is 145-180 km (90-110 miles) wide. The impact that created the Chicxulub crater is generally thought to have triggered a mass extinction of living beings on Earth (including the dinosaurs) some 65 million years ago through large-scale, long-term environmental changes. Several mass extinctions of life forms on Earth seem to have occurred during our planet's history, though the cause has not always been a giant impact but environmental changes caused by other factors.

An example of a recently formed large impact crater is the Meteor Crater (also known as the Barringer Crater) in Arizona, a 1.2-kilometer (three-fourths of a mile) wide crater that was formed about 50,000 years ago. Small meteoroids impact the Earth daily, and while most of these small objects burn up completely in Earth's atmosphere, some of them survive and land on the surface as meteorites. Meteorites are highly prized by scientists, since a careful analysis of their composition can give important information on the conditions prevalent at the time of their formation. In some cases, meteorites that have provided crucial information on the properties of the Solar System during its formation.

CRATERS ON THE MOON

In contrast to Earth, the surface of the Moon is full of impact craters. Craters on the Moon range in size from over 300 km (190 miles) in diameter (larger than the state of Connecticut) to smaller than the head of a pin. Impact structures greater than 300 km (190 miles) are called impact basins, rather than craters. The dark regions of the Moon called maria are examples of these kinds of impact basins that were filled with lava after the impact; the lava later solidified to form the smooth basins visible on the surface. Because there is no weather on the Moon, and little geological activity today, the main way to erode an existing crater is to cover it with a new impact crater or debris landing on the crater from a nearby impact. Looking at the Moon through a pair of binoculars allows an observer to see numerous craters. In fact, it is hard to find any place on the Moon where there are not any craters.

IMPACTS ON EARTH IN THE FUTURE

While small meteoroids impact the Earth daily, the likelihood of a large impact today is small. Large impacts capable of causing large-scale devastation on our planet are thought to occur once or twice every million years. However, since this is just a probability estimate and it cannot say for sure when the next large impact on Earth might occur, and since large impacts are capable of causing significant damage, astronomers are tracking large meteoroids, asteroids and comets in the Earth's neighborhood to determine whether they could pose a danger to our planet at present or in the future.

CONDUCTING THE LESSON

WARM-UP & PRE-ASSESSMENT

Teachers will lead a discussion with the students about why there are hardly any craters easily visible on Earth, but many can be seen on the Moon.

TEACHER MATERIALS

- *The Earth and the Moon Transparency* (located at the back of the lesson)
- Overhead projector

PREPARATION & PROCEDURES

1. Make an overhead transparency of *The Earth and the Moon Transparency*. Project it onto a screen for the entire class to see.

2. Ask students to list ways in which the Moon looks different from the Earth. Some examples may be the lack of colors on the Moon, the lack of oceans and clouds on the Moon, and that the Moon has many craters. Make sure the students mention craters and understand what impact craters are.

3. Lead a discussion with the students as to why the two worlds look so different, even though they are located in the same neighborhood of the Solar System. Focus the discussion on craters. Ask students to hypothesize why there are craters on the surface of the Moon, but few visible on the surface of Earth. The students will examine the way impact craters are created in Activity 1, and why the number of impact craters may vary among different worlds in the Solar System in Activity 2.

NOTES:

ACTIVITY 1: CREATING CRATERS

Students will simulate crater impacts by dropping pebbles or marbles into a pan of flour and cocoa. The effect of increasing the energy of impact—by dropping the same object from a greater height—on crater appearance will be explored. Students then identify the basic characteristics of their impact craters, and compare their craters to the picture of a crater on the Moon.

STUDENT MATERIALS (PER PAIR OF STUDENTS)

- Student Worksheet 1
- Pie pan (approximately 23 cm, or 9 inches, in diameter)
- 2 pebbles or marbles of different masses
- 1 bag of flour or box of corn starch
- 5 dl (2 cups) powdered cocoa
- Sifter
- Scale to measure mass of marbles
- Meter stick
- Metric ruler
- Newspaper to cover the work surface
- Calculator (optional)

PREPARATION & PROCEDURES

1. Make copies of Student Worksheet 1, one per each pair of students.

2. Discuss with the class what an impact crater is and how it is formed. You can use the following questions to lead your discussion:
   There are a lot of pieces of rock floating around in space; do they ever hit anything? (*Desired answer: yes*) What evidence do we have that this has happened? (*Desired answer: we see impact craters, for example on the Moon*) What happens to the piece of rock (we call this the impactor) that hits the Moon when it impacts? (*Desired answer: it can hit with such a speed that it is vaporized*) What difference does it make if the impactor is big or small? (*Desired answer: a big impactor creates a larger crater*) What other property of the impactor could determine how large a crater is formed? (*Desired answer: the speed of the impactor*) So, it is not just the size (or mass) of the impactor but also its velocity; combined, we can say it's the energy of impactor that determines the size of the crater. If we examine a crater years after the impact, and there is no remnant of the impactor, just the crater, how could we tell how much energy the impactor had when

it hit the Moon? (*Desired answer: the impact craters might look different if they were formed by different impactors with varying energies*) How could we investigate what different kinds of impact craters might look like without having to leave the classroom? (*Desired answer: we can create a model to create impact craters, and examine them to see what they look like based on different kinds of impacts*) That's exactly what we're going to do!

3. Place students into pairs and hand out Student Worksheet 1 and the student materials. Have students conduct the activity and complete the Worksheet except for the last page (*Transfer of Knowledge* section.)

TEACHING TIP

If corn starch is used instead of flour in this activity it will store longer and can be used again.

REFLECTION & DISCUSSION

1. Discuss the features of impact craters with students. Discuss with students the formation of impact craters and their features (floor, walls, rim, ejecta, rays, central peak.)

2. Ask students to discuss how their craters looked different based on the amount of energy the impactor had when it hit.

3. Ask students to pretend that they are scientists who are seeing a crater on the Moon or another world for the very first time. Can they tell what the impactor was like based on what the crater looks like? (*Desired answer: not completely, because the size of the crater depends on the velocity and the size of the impactor, not just the mass. However, as a general rule, the larger and more massive the impactor, the larger the crater. Therefore, scientists can determine the approximate size of impactors based on crater size.*) Discuss with the students the difference between size (diameter, for example) and mass. Both are varied simultaneously in their experiment, but they are actually different factors. Crater size depends on both the mass and size of the impactor.

TEACHING TIP

What students do in this activity is different than real cratering events in some ways. When a crater is formed on a planetary surface, the energy of the impactor can break apart—even vaporize—the impactor. In addition, the energy of a crater is determined by its mass and its velocity when it reaches Earth, but in this activity students calculate the potential energy from the height dropped. You may want to make sure the students understand the differences between their model and real impact craters at the end of the activity.

Assessment Criteria for Activity 1

4 Points

- Student completed Student Worksheet 1 and gave appropriate reasons for the answers to the questions.
- Student answered the two *Transfer of Knowledge* questions correctly and gave appropriate reasons for the answers.

3 Points

- Student completed most of Student Worksheet 1 and gave appropriate reasons for the answers to the questions.
- Student answered one *Transfer of Knowledge* question correctly and gave appropriate reasons for both answers (this criterion places emphasis on supporting conclusions, no matter whether the conclusion itself is correct or incorrect).

2 Points

- Student completed some of Student Worksheet 1 and gave appropriate reasons for the answers to the questions.
- Student answered the two *Transfer of Knowledge* questions and gave appropriate reasons for their answers, even if the answers were incorrect.

1 Point

- Student completed some or all of Student Worksheet 1, but did not give appropriate reasons for the answers to the questions.
- Student answered the two *Transfer of Knowledge* questions correctly, but did not give appropriate reasons for their answers.

0 Points

- No work completed.

TRANSFER OF KNOWLEDGE

Have students complete the *Transfer of Knowledge* section in Student Worksheet 1. Here, they are asked to compare two impactors that caused two craters on the Moon.

PLACING THE ACTIVITY WITHIN THE LESSON

Have the students blow gently on their impact craters (or ask them to imagine what would happen if they were to blow on their impact craters). What happened? (*Desired answer: the craters erode away*) Ask students what kind of processes could do similar things to craters on Earth. Ask students to think about why we can see impact craters on the Moon if they are so easily destroyed on Earth. This activity helped students understand the basic nature of impact craters, but in Activity 2, they will be looking at pictures of surfaces on different worlds in the Solar System, and they will be asked why some impact craters are still around while others have disappeared.

EXTENSIONS

Have students create a graph of Energy vs. Size of Impact Crater. Help them analyze it to see that the correlation is positive. You can also create graphs of impactor mass vs. impact crater or impactor size vs. impact crater.

NOTES ON ACTIVITY 1:

ACTIVITY 2: CRATERS IN THE SOLAR SYSTEM

Students will examine impact craters on different worlds in the Solar System and discover that craters can reveal a great deal about the nature and history of the worlds' surfaces.

STUDENT MATERIALS (PER PAIR OF STUDENTS)

- Student Worksheet 2
- 5 sheets of blank notebook paper

PREPARATION & PROCEDURES

1. Ask students to recall the *Warm-Up & Pre-Assessment* activity where they looked at the Moon and Earth and compared the two worlds. The Moon has more craters on its surface than Earth. Ask students why this might be the case; for example, could objects hit the Moon more than Earth, even though they are located at approximately the same place in the Solar System? (*Desired Answer: no. Some students may think that things actually do hit the Moon more often than the Earth. Ask them to explain why this would be the case and to back up their answer. Then move on and ask for other possibilities*)

   Are there any other explanations as to why there are not as many craters on the Earth as on the Moon? Is there anything that Earth has that would protect it from getting hit that the Moon does not have? (*Desired answer: an atmosphere*) In fact, many small objects burn up due to heating by Earth's atmosphere and they never reach the ground to make a crater. For this reason, do you think the craters that do appear on Earth are very big or very small? (*Desired answer: they tend to be very big, because the very small things that hit the Earth burn up in its atmosphere, while big objects that hit the Earth may burn partially, but they are big enough to make it through the atmosphere to the ground and form a large crater*)

   Is there anything that the Earth has that will not let the craters that are created stick around that the Moon does not have? (*Desired answer: Earth has weather that can erode the craters, like wind and rain, as well as lakes and oceans, volcanoes, and plate tectonics*)

   What other reasons could there be for why there are not as many craters on Earth? (*Desired answer: Earth has oceans; if something hits the ocean, a crater will not be visible on the surface but only on the ocean floor, and there, the crater may be quickly be eroded away by the water*)

2. Tell students that scientists describe surfaces like Earth as "young" and surfaces like the Moon as "old." Why do they think this is the case? (*Desired answer: there are few processes on the Moon to renew the surface, so the surface is old, craters tend not to get eroded, and, as a result, the surface is full of craters of all sizes and ages. The Earth's surface gets renewed all the time because of weather and geological activity, and as a result, the surface is young, and there are fewer craters on the surface.*) Some worlds may have very young surfaces, while others may be very old. Some worlds may have parts that are one or the other. (But remind the students that even though the surface of one world may be younger than the surface of another, it doesn't tell us much about the age of the worlds as a whole; just of their surfaces.)

3. Hand students copies of Student Worksheet 2, one per each pair of students, and explain that the students will be looking at cratering on several different worlds in the Solar System. The students will have to come up with conclusions about what those worlds are like, whether they have old or young surfaces, and what kind of processes capable of degrading craters (such as weather and geological processes) might operate on the worlds. If the students are not familiar with these processes, be sure to discuss them before starting work. Advise students to write their answers on notebook paper and stop before completing the last page of the Worksheet (the *Transfer of Knowledge* section.)

REFLECTION & DISCUSSION

1. Discuss with students how their conclusions about weathering and geological processes acting on the worlds examined in Student Worksheet 2 compare with the scientists' current understanding (see the *Teacher Answer Key* for details.) Remind students that the scientists may have had additional information from other regions of the worlds, as well as access to other data besides the pictures in the worksheet.

2. Discuss why the students have done this activity in terms of "relative age" instead of absolute age. We cannot know the absolute ages of the surfaces unless we can perform laboratory experiments on surface samples (such as rocks) to determine their actual ages.

TRANSFER OF KNOWLEDGE

Have students complete the *Transfer of Knowledge* section in Student Worksheet 2. In this section, the students are asked to place four surfaces in order by age.

Assessment Criteria for Activity 2

4 Points

- Student completed Student Worksheet 2 correctly and justifies his/her answers.
- Student completed *Transfer of Knowledge* correctly and justifies his/her answers.

3 Points

- Student completed Student Worksheet 2 and justifies his/her answers.
- Student completed *Transfer of Knowledge* and justifies his/her answers.

2 Points

- Student completed some of Student Worksheet 2 and justifies his/her answers.
- Student completed *Transfer of Knowledge* and justifies his/her answers.

1 Points

- Student completed some of Student Worksheet 2 and justifies his/her answers.
- Student completed some of *Transfer of Knowledge* correctly and justifies his/her answers.

0 Points

- No work completed.

Placing the Activity Within the Lesson

Students have now looked at various worlds in the Solar System and the nature of the impact craters on those worlds. Bring the discussion back to Earth and discuss why there are not very many visible impact craters on Earth. Ask students to hypothesize whether there were impact craters in the past, and whether Earth may change in the future. Ask students, if we were to look for life on other worlds, would we want to look at worlds with many or few impact craters? Why?

Notes on Activity 2:

Impact Craters:
A Look at the Past

Lesson at a Glance

Science Overview

Conducting the Lesson

Warm Up & Pre-Assessment

Activity 1: Creating Craters

Activity 2: Craters in the Solar System

Lesson Wrap-Up

Resources

LESSON WRAP-UP

TRANSFER OF KNOWLEDGE FOR THE LESSON

Students must use the knowledge they have accumulated in Activity 1 about the nature of craters, and the knowledge from Activity 2 about what craters can tell you about the age of objects in the Solar System, and decide the history of the surface in Student Worksheet 3.

LESSON CLOSURE

Discuss with students Student Worksheet 3 (*Transfer of Knowledge for the Lesson*.) In Activity 2, students decided whether surfaces were relatively young or old, but in this section, students had to decide the order of processes that occurred on one surface. Discuss how critical this technique could be in deciding what happened to a world in the Solar System long ago, and for being able to create a probable history of the world. For example, whether a world went through a phase where its surface was completely molten so that all traces of earlier cratering was erased could help determine the conditions prevalent at the time in the part of the Solar System where the world is located. Scientists can compare objects in the Solar System as pieces in a puzzle, and begin to put together the big picture of the history of the whole Solar System. In this way, there is a sequence of events at hand, and when the absolute ages for a few events are determined, it is possible to discuss the history of the various worlds in the Solar System in absolute ages rather than merely in relative ages.

EXTENSIONS FOR THE LESSON

- Have students research the current theory of how the Moon was formed—by a giant impact!
- Have students research the extinction of the dinosaurs and why scientists think that it was a massive impact that triggered it. Have students research other mass extinctions in Earth's history and see how many of them are thought to have occurred as a result of an impact.
- Discuss with students the possibility of an impactor hitting Earth today. Most students are interested in the dangers of a large impact. See the *Science Overview* and web sites listed in the *Internet Resources & References* section for details.
- Have students research for which objects in the Solar System scientists have been able to determine absolute ages. See the *Science Overview* and web sites listed in the *Internet Resources & References* section for details.

Assessment Criteria for the Lesson

4 Points

- Student justified his/her answer for parts A and B in Student Worksheet 3 (*Transfer of Knowledge for the Lesson*.)
- Student's answers for *Transfer of Knowledge for the Lesson* were both correct.

3 Points

- Student justified his/her answer for parts A and B in Student Worksheet 3 (*Transfer of Knowledge for the Lesson*.)
- One of student's answers for *Transfer of Knowledge for the Lesson* was correct.

2 Points

- Student justified one of his/her answers for parts A and B in Student Worksheet 3 (*Transfer of Knowledge for the Lesson*.)
- One of student's answers for *Transfer of Knowledge for the Lesson* was correct.

1 Point

- Student justified one of his/her answers for parts A and B in Student Worksheet 3 (*Transfer of Knowledge for the Lesson*.)
- Student's answers for *Transfer of Knowledge for the Lesson* were incorrect.

0 Points

- No work completed.

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Activity 1: Creating Craters
Activity 2: Craters in the Solar System
Lesson Wrap-Up
Resources

RESOURCES

INTERNET RESOURCES & REFERENCES

Student-Friendly Web Sites:
How Craters Age animation
clickworkers.arc.nasa.gov/training/how-craters-age.html
Interactive Map of Terrestrial Impact Craters
www.lpi.usra.edu/science/kring/epo_web/impact_cratering/World_Craters_web/intromap.html

Teacher-Oriented Web Sites
American Association for the Advancement of Science Benchmarks for Science Literacy
www.project2061.org/publications/bsl/online/bolintro.htm
Earth Impact Database
www.unb.ca/passc/ImpactDatabase/
Lunar and Planetary Institute: Chicxulub Impact Event (and the excinction of the dinosaurs)
www.lpi.usra.edu/science/kring/epo_web/impact_cratering/World_Craters_web/northamericacraters/Chicxulub.html
NASA Near Earth Object Program (tracks objects with a possibility of impacting the Earth)
neo.jpl.nasa.gov
National Science Education Standards
www.nap.edu/html/nses/
Planetary Science Institute: Origin of the Moon
www.psi.edu/projects/moon/moon.html
Terrestrial Impact Craters
www.solarviews.com//eng/tercrate.htm
U.S. Geological Survey – Geologic Time: Age of the Earth (and other absolute age determinations)
pubs.usgs.gov/gip/geotime/age.html
Voyage: A Journey through Our Solar System
www.voyagesolarsystem.org
Journey through the Universe
www.journeythroughtheuniverse.org

TEACHER ANSWER KEY

STUDENT WORKSHEET 1

Impact Table

Students' answers in the impact table will vary. Make sure their measurements and calculations were correct based on their materials and their data.

Questions & Conclusions

Questions about the experiment

1. There was an area where the marble hit the flour that became white because the impact blasted away the cocoa, leaving the flour exposed. There were lines of white, as well, coming away from the impact site.

2. Because of its different color, the cocoa really helps to see how the surface is affected because you can see that more area is affected than just the surface where the marble hit.

3. The bigger the mass of the impactor, the larger the crater (when dropped from the same height.)

4. The higher the impactor is dropped from, the larger the crater (when using an impactor of the same mass.)

5. The energy is really the deciding factor in the size of the crater. No matter what, the higher the energy, the larger the crater.

6. This may or may not be true depending on the mass of the impactors the students used. Look at the Impact Table to check the accuracy of the answers.

Questions Using the Lunar Crater Image

1. It is fairly accurate in that it has most of the features from the Lunar Crater Image, except that it does not have a central peak.

2.

Walls	The walls are formed from the material that was not blasted out when the impactor hits the surface (and not from any indentation of the impactor—the walls are much farther out than the original impactor). They show the limit of the material blasted out of the crater.
Floor	The floor is formed because the material above it has been blasted up and out.
Rim	The rim is formed where the affected material meets the undisturbed material.
Ejecta	The ejecta is formed from the material that was blasted out from the crater when the impactor hit.
Rays	The ejecta can form rays of material. (Note: In real craters, rays form usually when there is no substantial atmosphere, which is not the case in the experiment. Be lenient in grading this section because rays may not form and therefore students may not understand how they form.)
Central Peak	The experiment did not form a central peak, but in the Lunar Image it was probably formed in reaction to the force of the impact. (Note: Be lenient in grading this section, because no central peak was not formed in the experiment, and therefore students may not understand how they form.)

Transfer of Knowledge

Impactor A hit the Moon with less energy than Impactor B. I can tell this is true because, even though Impact Crater A may look deeper than Impact Crater B (though this may also be just the effect of shadows covering most of the floor of the smaller crater), Crater B is definitely bigger than Crater A. From my experiment, I have found that the more energy an impactor has, the bigger the crater it creates.

STUDENT WORKSHEET 2

These answers are written with the assumption that the students' only evidence toward their conclusions are the pictures and the descriptions provided in the Student Worksheet. You may decide that students should have a more sophisticated understanding of what is actually going on in the pictures if they have past classroom experience. Some leeway should be given to the students' answers. If the students are basing their answers only on the pictures and the short descriptions provided, a lot of conclusions are possible. The current understanding of each process on each world is provided in parenthesis after each entry; the students cannot be expected to make all these conclusions based on the information available to them in the Worksheet, just the conclusions before the parenthesis.

1. **Mars** – The pictures and the short description can lead to the following conclusions:
   - *atmosphere with weathering (wind, rain, etc.)*: Wind and rain could have eroded crater rims. Wind could have filled crater floors with dust, causing old craters to become ghost craters. Some of the wave-like features could be dust blown by the wind. [Mars has a thin atmosphere with frequent dust storms.]
   - *oceans, rivers, or other bodies of water*: While there are no bodies of water visible in the pictures, if Mars had plentiful water on its surface in the past, this could have eroded older craters. Some of the wave-like features could be deposits of sand moved by water. [Mars had plentiful water on its surface in the form of rivers and seas in the past.]
   - *volcanoes*: There are no volcanoes visible in the pictures, but some of the wave-like features could be remnants of old lava flows. If lava flows were present, they could have degraded and filled old craters. [Mars had large-scale volcanic activity at least up to a few million years ago and may still have small-scale volcanic activity.]
   - *plate tectonics*: There is no evidence of large-scale horizontal or vertical motion in the pictures. There are no deep tectonic ridges, faults, or high mountains such as might be created at tectonic plate boundaries. The presence of plate tectonics appears unlikely. [Mars probably never had plate tectonic activity.]
   - *Final Conclusions*: It appears that the main processes eroding craters on Mars are an atmosphere with weathering (especially dust moved by winds), and possibly volcanic activity and the presence of water on the surface in the past. It also appears different parts of Mars have different types of surfaces: heavily cratered vs. less cratered.

2. **Venus –** The picture and the short description can lead to the following conclusions:
    - *atmosphere with weathering (wind, rain, etc.)*: Wind and rain could have eroded crater rims and filled crater floors with dust from the surrounding area, causing old craters to become ghost craters mentioned in the description; there is not much evidence for wind and rain in the picture. [Venus has a thick atmosphere with strong winds and acid rain.]
    - *oceans, rivers, or other bodies of water*: While there are no bodies of water visible in the pictures, if Venus had plentiful water on its surface in the past, it could have eroded older craters. Some of the channel-like features in the picture could be old river beds. [Venus is too hot to have liquid water on its surface today.]
    - *volcanoes*: There are no volcanoes visible in the pictures, but some of the channel-like features in the picture could be old lava flow channels. If lava flows are present, they could have degraded and filled old craters. [Venus has had lots of volcanic activity in the past and probably is active even today.]
    - *plate tectonics*: There seems to be evidence of buckling of the surface in some areas, but these could have been caused by other events besides plate tectonics. There are no deep tectonic ridges, faults, or high mountains such as might be created at tectonic plate boundaries. The likelihood of plate tectonics acting on Venus is unclear based on the information provided. [Venus probably never had much plate tectonic activity.]
    - *Final Conclusions*: The main processes eroding craters on Venus appear to be the presense of atmosphere with weathering and/or volcanic activity. There may have even been water on the surface in the past but it is uncertain based on available information.

3. **Ganymede and Callisto –** The pictures and the short description can lead to the following conclusions:
    - *atmosphere with weathering (wind, rain, etc.)*: Callisto seems to have lots of fresh craters on its surface, so the presence of an atmosphere with weathering activity is unlikely. Ganymede's surface is a bit more complicated, but most of the craters appear to be fresh or disturbed by geological activity rather than weathering. [Ganymede and Callisto have virtually no atmosphere.]
    - *oceans, rivers, or other bodies of water*: There is no evidence for the presence of water on Callisto. Some of the deep channel-like features on Ganymede's surface could be old river beds, and flowing water could have eroded old craters, resulting in degraded and ghost craters. [Ganymede and Callisto have no liquid water on their surfaces, though they have water ice, which might melt on occasion, such as during an impact.]

- *volcanoes*: There are no volcanoes visible in the pictures, but some of the grooved features on Ganymede could be remnants of old lava flows. The slightly smoother areas on Callisto could also be plains created by lava flows. If lava flows were present, they could have filled old craters, resulting in degraded and ghost craters. [Ganymede and Callisto do not have volcanic activity in the usual sense; they may have ice volcanoes, however.]
- *plate tectonics*: There are no deep tectonic ridges, faults, or high mountains such as might be created at tectonic plate boundaries on either Callisto or Ganymede. The grooved surface of Ganymede may show evidence for buckling of the crust, but the features may also have been created through some other process. As a result, the presence of plate tectonics remains uncertain based on the available information. [Callisto does not appear to have any plate tectonic activity, but Ganymede's icy crust appears to have broken into plates that could experience tectonic motions. The buckling may also be created by stresses caused by Jupiter's strong gravitational forces acting on Ganymede's crust.]
- *Final Conclusions*: It appears that there are not many processes capable of degrading craters on Ganymede and Callisto. On Ganymede, there is some evidence for presence of flowing water or perhaps volcanic activity at some point. There is no evidence for the presence of an atmosphere or weathering due to wind or rain. There is some suggestion of tectonic activity on Ganymede, but it remains uncertain based on the available information. There appears to be little activity to degrade craters on Callisto. [In fact, Callisto is thought to have perhaps the oldest surface of any world in the Solar System.]

4. **Mercury** – The picture and the short description can lead to the following conclusions:
   - *atmosphere with weathering (wind, rain, etc.)*: Mercury seems to have lots of fresh craters on its surface, so the presence of an atmosphere with weathering activity is unlikely. [Mercury has a very thin atmosphere that is little more substantial than a vacuum.]
   - *oceans, rivers, or other bodies of water*: There is no evidence for the presence of water on the surface of Mercury. There are a few channel-like features that could be old river beds but they may be created by something else. [There is no liquid water on Mercury's surface; it it too hot during the day and too cold at night.]
   - *volcanoes*: There are no volcanoes visible in the pictures, but some of the channel-like features in the picture could be old lava flow channels. Also, some of the smoother areas could be plains filled by lava flows. If lava flows are present, they could have filled

old craters, resulting in degraded and ghost craters. [Mercury had some volcanic activity in the past.]

- *plate tectonics*: There are some ridges and troughs on the surface (including one that goes through old craters), but these could have been caused by other geologic events besides plate tectonics. There are no high mountains such as might be raised at tectonic plate boundaries, so the likelihood of plate tectonics acting on Mercury appears unlikely. [Mercury probably never had plate tectonic activity, and the ridges and troughs are thought to be caused by the compression of the planet and the reaction of the surface to this process.]
- *Final Conclusions*: It appears that there are not many processes capable of degrading craters on Mercury, which is consistent with the planet featuring many fresh craters and few degraded and ghost craters. The most likely candidate may be volcanic activity. There is no evidence for the presence of an atmosphere or weathering due to wind or rain, and the suggestion of bodies of water on the surface is weak. There is some suggestion of tectonic activity, but it remains uncertain based on the available information.

Transfer of Knowledge

1. The most likely order is: 4,2,3,1. Picture 4 has a complicated surface with only one large crater clearly visible. This indicates that the surface has not been exposed to cratering activity for long after the surface was renewed last. The complicated patterns may be due to recent volcanic activity that filled old craters. The surface in picture 2 is smooth with a handful of craters visible, but mostly only in the lower part of the picture. This surface was probably recently renewed, as well, but the larger number of craters suggests the surface of picture 2 is older than picture 4. Picture 3 features many craters, some of them degraded, probably due to geological activity. The surface appears to have gone through some renewing, but not as much as 2 and 4; therefore, it is slightly older. The surface in picture 1 is heavily cratered and features craters of different sizes. The craters appear fresh, with just a few craters degraded (probably) by geological activity. Therefore, the surface in picture 1 appears to be the oldest of the four surfaces. The main point is to differentiate between the surface that appears to have been most recently renewed (4), the ones that show evidence for some renewing (2 and 3), and the one that is more heavily cratered (1).

2. You cannot be absolutely sure, since the only way to know the absolute ages of the surfaces would be to analyze samples of them in a laboratory. However, based on the way we understand craters

to be formed and degraded, you can be fairly confident with the relative ages, though there is always the possibility of something unexpected having occurred at a given site.

3. Picture 1 could be Mercury or the Moon because there are many craters, and the surface looks like the images of these two objects seen previously during this lesson. [The picture is an image of Mercury.]
   Picture 2 is probably Mars because it exhibits smooth plains such as those seen in the pictures of Mars during the lesson, with just a few fresh craters visible. [The picture is an image of Mars.]
   Picture 3 is probably Ganymede because it exhibits grooved terrain such as was seen in the picture of Ganymede during the lesson. [The picture is an image of Ganymede.]
   Picture 4 is probably Venus because it looks like the image of Venus seen previously during the lesson. The smooth surface has a lot of channels (remnants of lava flows) flowing through the surface, with just one large crater in view.

4. No. The characteristics (an atmosphere with weathering, oceans or other bodies of water, volcanoes, and plate tectonics) noted at the beginning of Activity 2 play a large part in determining the age of the surface, but the world is much older than its surface. The amount of cratering on a world does give an indication of the age of the surface, but only of the surface.

STUDENT WORKSHEET 3

Part A: The youngest to the oldest: C, A, B. The river has eroded away the edge of crater B, and you can see the river flowing through it, so the crater must have formed before the river flowed through it. Crater C appears to be on top of the old riverbed (A) and has not eroded away, so it must have formed after the river had dried up.

Part B: Answers will vary. The basic idea is that Mars went through a history of heavy cratering, with craters of all sizes being formed. Later, plentiful water was present on the surface in the form of rivers and the rivers flowed through and degraded old craters. There probably were dust storms and perhaps even rain to further degrade the craters. Craters were still being formed, though not as many. Later, the river beds dried up and the liquid water disappeared from the surface. Mars continued to be impacted by meteoroids, and new craters were created, though the impacts seem to be less frequent and the created craters smaller.

(Image credit: photojournal.jpl.nasa.gov)

Student Worksheet 1
Creating Craters

Name ____ Date __________

Student Materials (Per pair of students)

- Pie pan (approximately 23 cm, or 9 inches, in diameter)
- 2 pebbles or marbles of different masses
- 1 bag of flour or box of corn starch
- 5 dl (2 cups) powdered cocoa
- Sifter
- Scale
- Meter stick
- Metric ruler
- Newspaper
- Calculator (optional)

Directions

1. Use the scale to measure the mass of your two impactors (pebbles or marbles) and record the data in the Impact Table on the next page.

2. Cover your work area on the floor with newspaper.

3. Fill a pie pan with a thick layer of flour. Smooth out the flour so that it is as flat as possible.

4. Cover the flour with a light dusting of cocoa. Use a sifter to make sure the layer of cocoa is evenly spread on top of the flour.

5. Place the pie pan on the floor. Be sure not to disturb the surface when moving the pan.

6. Place the meter stick vertically on the floor next to the pan, and measure a distance of 30 cm above the pan.

7. Drop one of the impactors into the pan from the 30 cm height.

8. Remove the impactor from the pan, and repeat steps 5-7 with a different mass impactor, creating a second impact site in a slightly different location in the pan so that the second site is not too close to the first. Remove the impactor, and draw a picture of the craters in the Impact Table.

9. Measure the sizes of your impact craters and record their diameters in the Impact Table.

10. Remove as much of the cocoa powder from the pan as you can, smooth out the flour, sift on a new layer of cocoa, and repeat steps 5-9 for impacts from the height of 20 cm. Repeat the process again for impacts from the height of 10 cm.

11. Calculate the amount of energy for each impact and write the results in the Impact Table. The amount of energy (E) of the impactor at the time of impact is equal to the impactor mass (m) times the gravitational constant ($g = 9.8\ m/s^2$) times the height at which you dropped the impactor (h). This is a good way to characterize how strong each impact is.

    Energy (measured in joules) = mass (measured in kilograms) x gravitational constant x height (measured in meters)

Impact Table

Height	Impactor Mass	Energy * (E = mgh)	Size of crater	Draw a picture
30 cm (0.3 m)	Impactor 1: ______ kg			
30 cm (0.3 m)	Impactor 2: ______ kg			
20 cm (0.2 m)	Impactor 1: ______ kg			
20 cm (0.2 m)	Impactor 2: ______ kg			
10 cm (0.1 m)	Impactor 1: ______ kg			
10 cm (0.1 m)	Impactor 2: ______ kg			

QUESTIONS & CONCLUSIONS

Questions about the Experiment

1. How did the appearance of the surface of the flour change after it had been hit by the impactor?

2. Why is the layer of cocoa useful for revealing how impacts change the surface?

3. How does the mass of the impactor affect the crater?

4. How does the height from which the impactor is released affect the crater?

5. How does the overall energy of the impactor affect the crater?

6. Are there any cases where a big impactor created a smaller crater than a small impactor, depending on where they were dropped from?

Questions Using the Lunar Crater Image
Examine the *Lunar Crater Image* on the next page, and answer the questions below.

1. Compared to the *Lunar Crater Image*, was your model an accurate representation of lunar craters? Explain why or why not.

2. Examine the *Lunar Crater Image*. Examine each part of the image that is listed, and write a description about how each feature occurs, based on your findings from this activity.

Walls	
Floor	
Rim	
Ejecta	
Rays	
Central Peak	

Lunar Crater Image

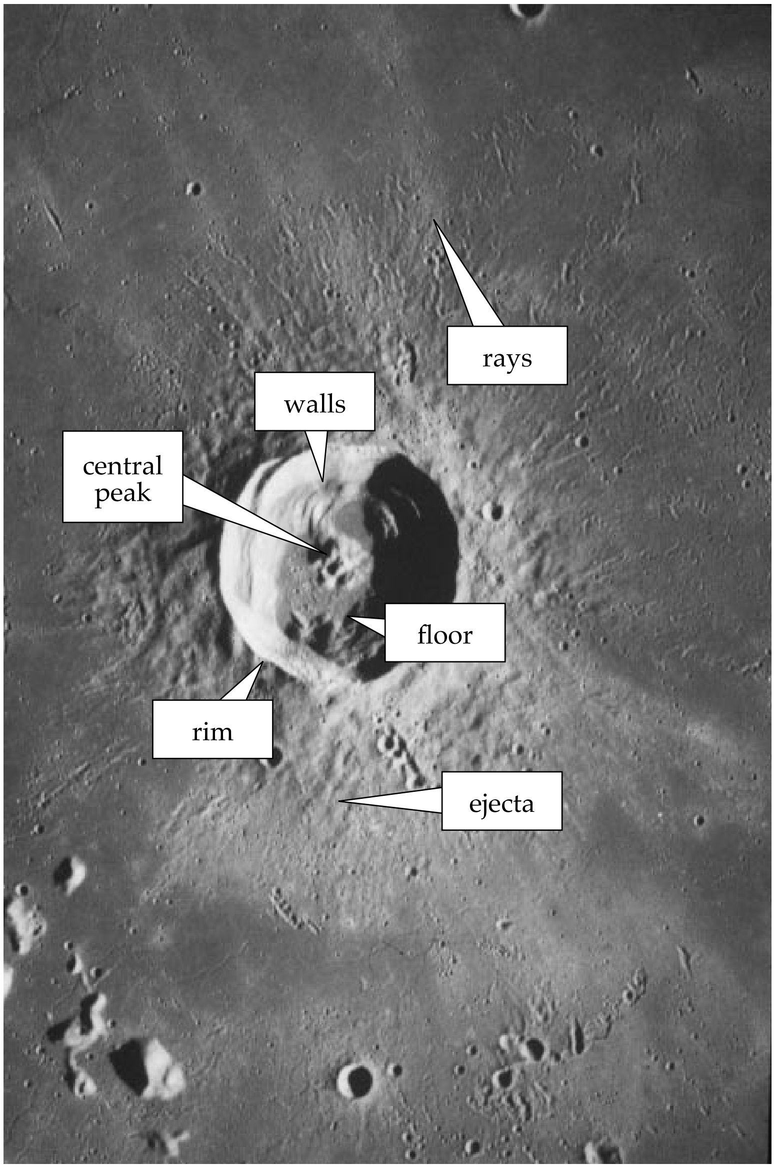


Figure 1.(Image credit: Part of Apollo 17 Metric photograph AS17-2923.)

CRATER PARTS

Floor – The bottom part of the rater. The floor may be shaped like a bowl, or it may be flat. This part is lower than the surrounding surface.

Walls – The sides of the crater. The walls can be very deep, depending on the severity of the impact. If a crater has shallow walls, the crater may have been filled or eroded somehow since its formation.

Rim – The edge of the crater; the top of the crater walls. The rim is usually the highest part of the crater.

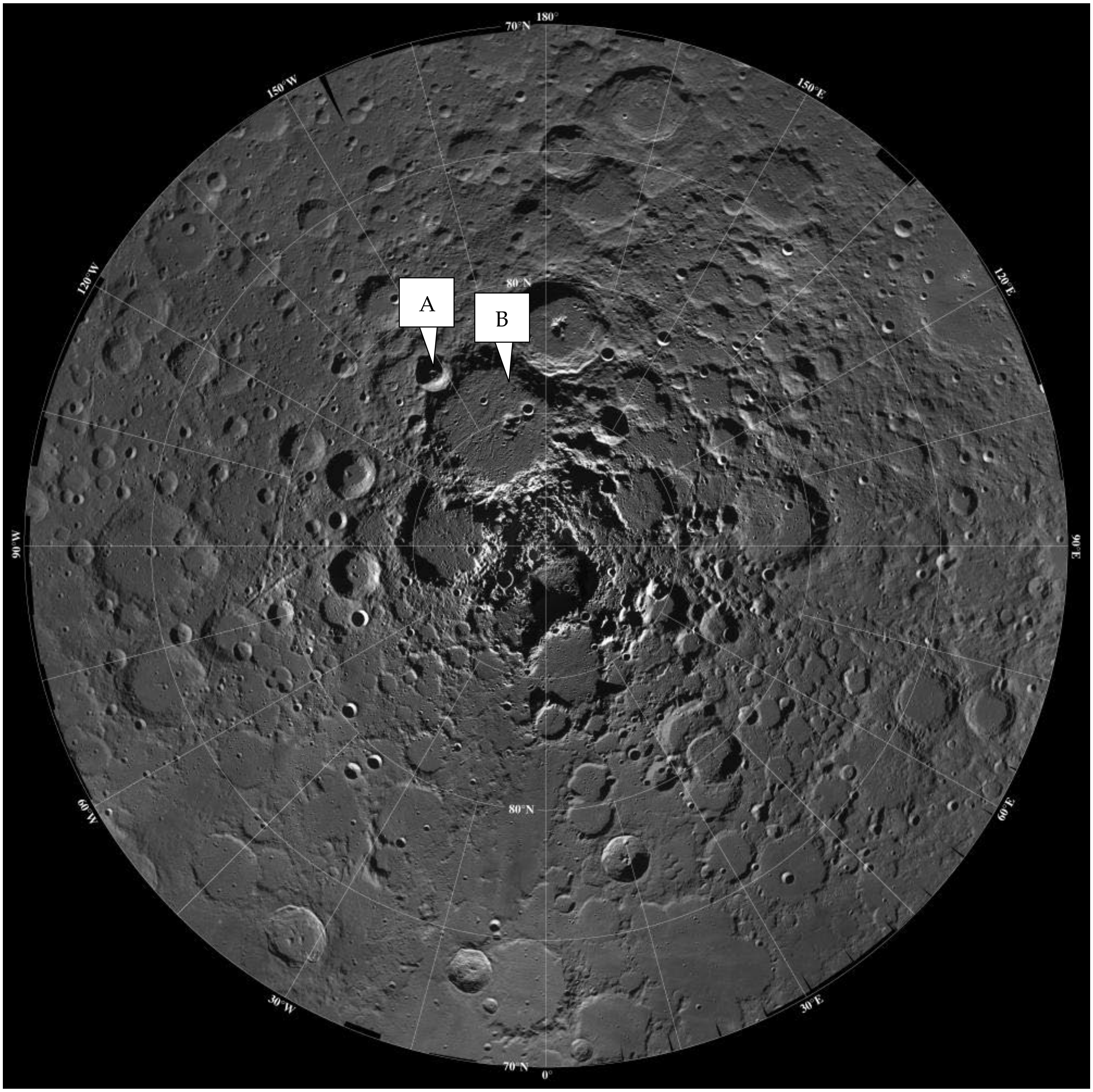
Ejecta – Debris that is thrown out—ejected from—the impact site. The debris is created when the shock wave crushes, heats, and melts material at the impact site. Typically, the layer of ejecta is thick close to the crater, and thinner farther away.

Rays – Bright streaks that start at the rim of the crater and extend outward. Rays are created by fine ejecta coming from the crater and are usually found on worlds where there is no significant atmosphere (e.g., they can be found around craters on the Moon but not on Earth).

Central Peak – A small "mountain" that may form at the center of the crater in reaction to the force of the impact. Only large craters have central peaks. The size at which a crater can have a central peak depends on the size of the world. For example, on Earth, craters larger than 2-4 km (1.2-2.5 miles) in diameter may have central peaks, while on the Moon, the crater must be larger than 15-20 km (9-12 miles) in diameter.

Transfer of Knowledge

Let's assume that a long, long time ago, Impactor B hit the Moon and created Impact Crater B. A little later, Impactor A hit the Moon and created Impact Crater A. Now, scientists want to know something about the impactors that created these craters, but the only thing they have to go on is what the impactors left behind—their craters. Look at the picture below of Impact Craters A and B. Based on the impact craters, compare the differences between the two impactors (A and B) that created these craters.



Impactor A hit the Moon with (more, less, the same amount of) energy than Impactor B had when it hit the Moon. I can tell this is true because:

Student Worksheet 2: Craters in the Solar System

Name ____ Date __________

If the surface of a world is young, it may be because the surface has been renewed by:

- an atmosphere allowing weathering by wind, rain, etc.;
- oceans, rivers, or other bodies of water;
- volcanic activity; or
- plate tectonics.

In different worlds, some, all, or none of these processes may be present and cause the surface to be renewed. As a result of the renewal of the surface, old craters may be degraded or even destroyed. Based on the amount of degrading they have experienced, craters can be divided into three groups:

- *fresh craters*, which have sharp rims, clear ejecta blankets, and central peaks (if the crater is large enough for a central peark to have formed);
- *degraded craters*, which have eroded over time and lack some or all of the features of fresh craters;
- *ghost craters*, which have degraded so severely that they are barely visible remnants of old craters.

See the images of Mars on the next page (Figs. S1-S3) for examples of the different types of craters.

Investigate the pictures and the descriptions of impact craters on the various worlds depicted in the following pages to determine which surface renewing processes migh be acting on the world. Hint: Look for clues such as:

- atmosphere with weathering:
    - dust carried by wind, covering old craters,
    - signs of frequent rain,
    - dunes,
    - wave-like patterns in sand or dust created by wind;
- oceans, rivers, or other bodies of water:
    - ocean basins,
    - river channels or gullies;
- volcanic activity:
    - volcanoes,
    - smooth areas covered with lava that has solidified,
    - lava channels,
    - wavy patterns where lava outflows have solidified on top of each other;
- plate tectonics:
    - subduction zones where one plate is moving on top of another
    - ridges that spread apart at tectonic plate boundaries,
    - deep faults or high mountains created at the edges of tectonic plates.]

1. Examine the three pictures below (Figs. S1-S3) taken of the surface in different regions of Mars. Mars has craters of different sizes and types (fresh, degraded, and ghost craters.) The number and the types of craters vary from one region to another. There are also surfaces with very few, if any, craters. What can you conclude of the likelihood of each of the different surface renewing processes acting on Mars?

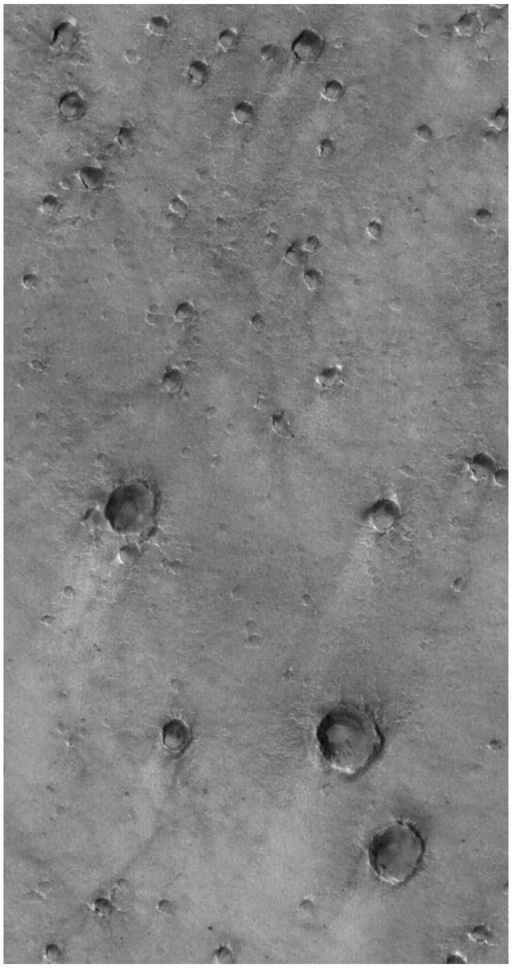


Figure S1. Fresh craters on Mars. This part of Mars in general has many impact craters.

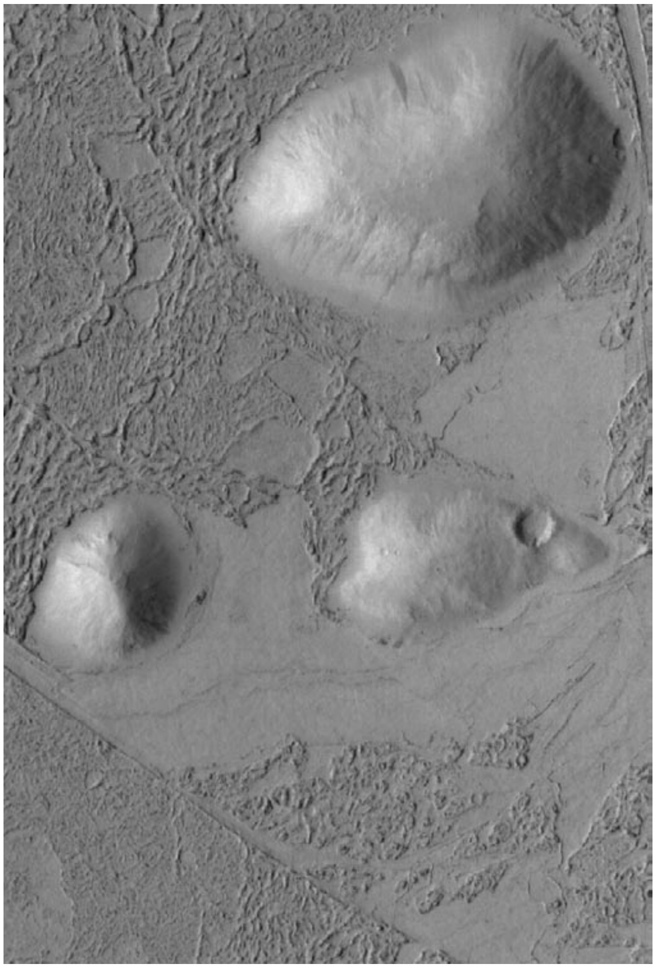


Figure S2. Degraded craters on Mars.

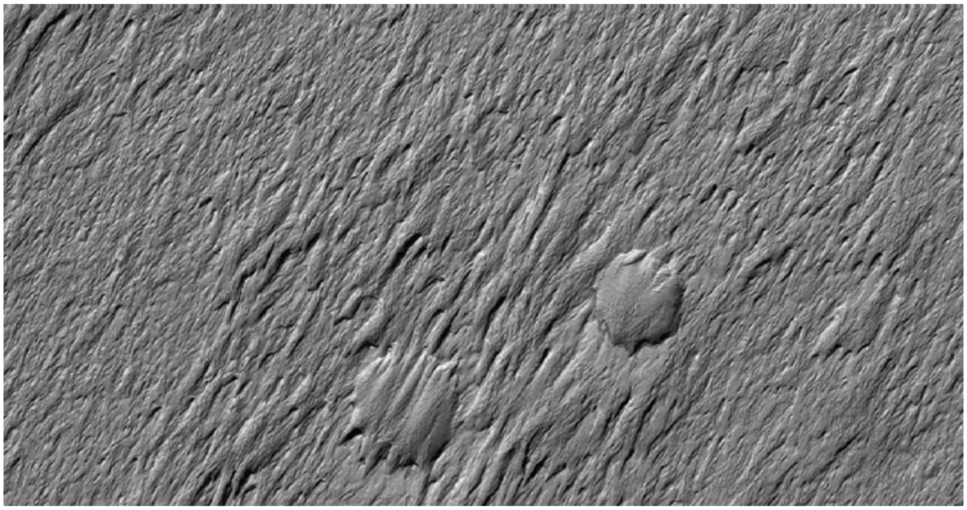


Figure S3. Ghost craters on Mars. This part of Mars in general does not have many impact craters.

(*Image credits: NASA/JPL/Malin Space Science Systems)*

2. Examine the picture below (Fig. S4) of the surface of Venus. Venus has mostly large craters, but the number of craters varies across the surface. Venus has a number of fresh, degraded, and ghost craters, but also surfaces with no craters whatsoever. What can you conclude of the likelihood of each of the different surface renewing processes acting on Venus?

Figure S4. Surface of Venus. (Image credit: NASA)

3. Examine the pictures below (Figs. S5 and S6) of two moons of Jupiter, Ganymede and Callisto. These moons have many craters of all sizes and types (fresh, degraded, and ghost craters.) What can you conclude of the likelihood of each of the different surface renewing processes acting on Ganymede and Callisto?

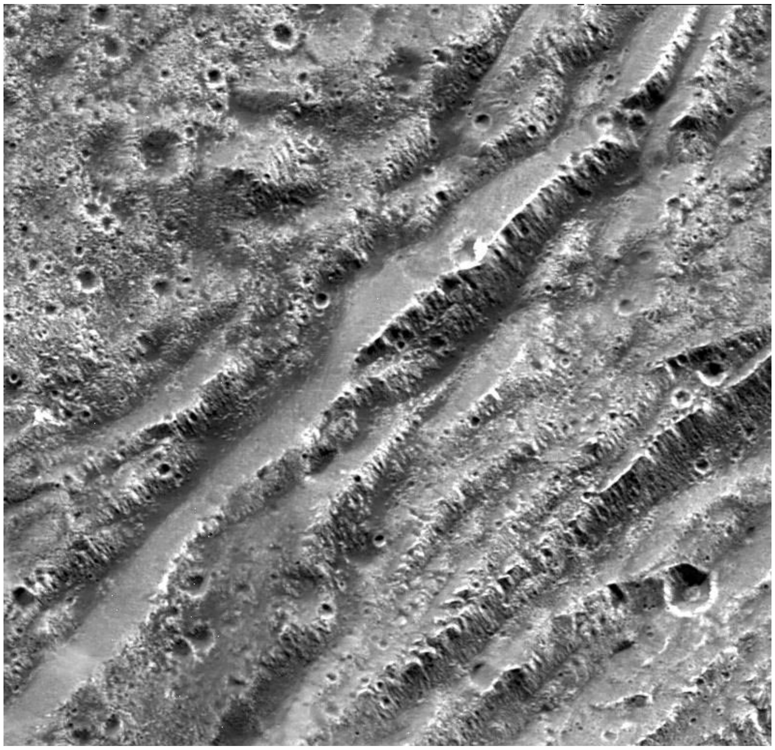


Figure S5. Surface of Ganymede. (Image credit: NASA/JPL)

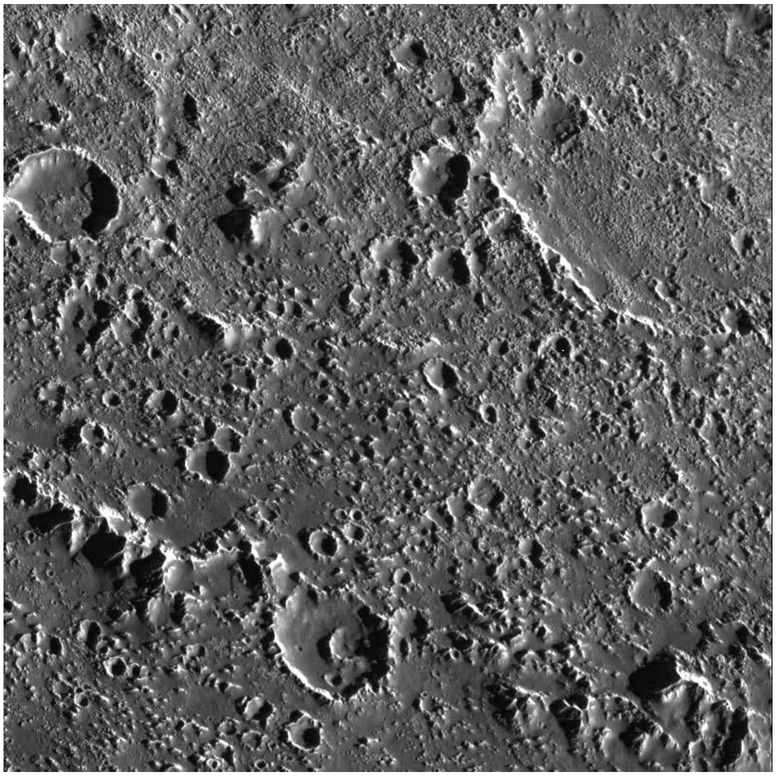


Figure S6. Surface of Callisto. (Image credit: NASA/JPL)

4. Examine the picture below (Fig. S7) of the surface of Mercury. This planet has many craters covering its surface, and they are mostly fresh, although there appear to be some degraded and ghost craters. What can you conclude of the likelihood of each of the different surface renewing processes acting on Mercury?

Figure S7. Surface of Mercury. (Image credit: NASA/JPL/Northwestern University)

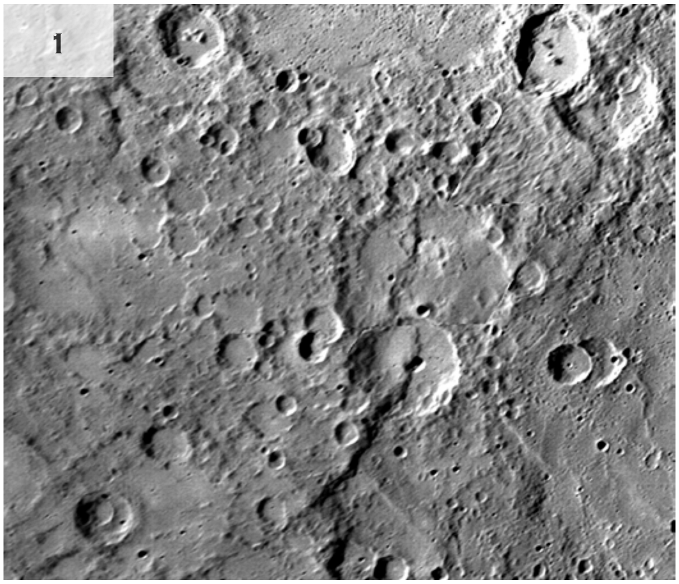
Transfer of Knowledge

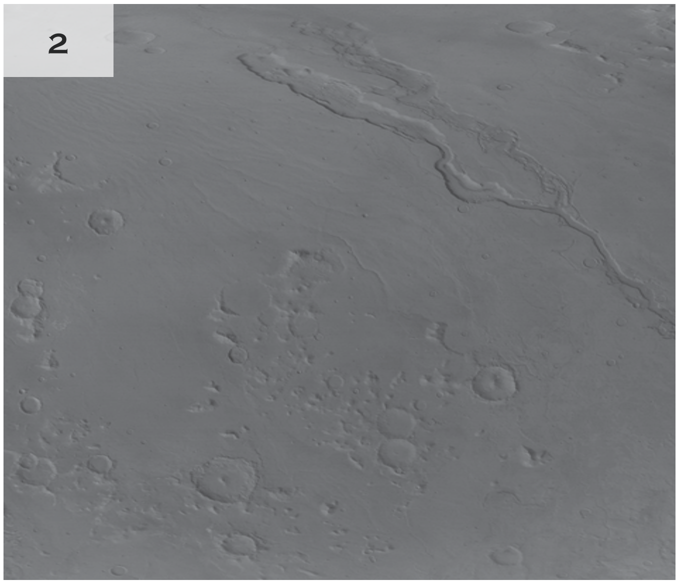
1. Place the following surfaces (images 1-4 below) in order from the youngest to the oldest.

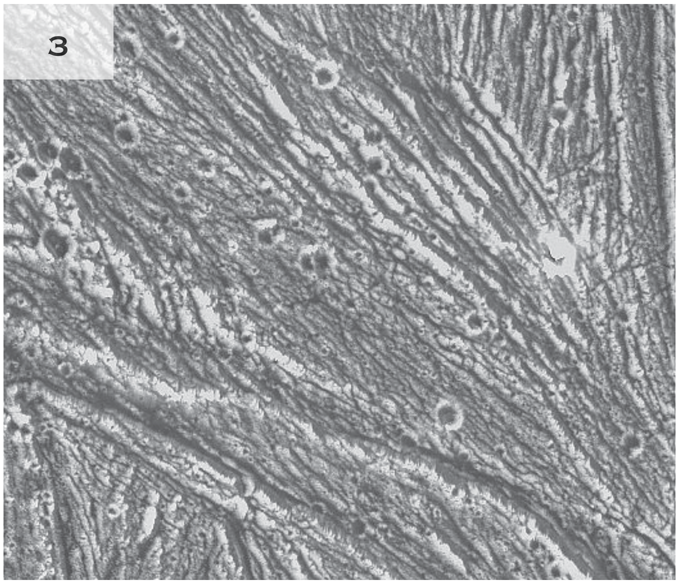
2. Can you be sure of the order you picked?

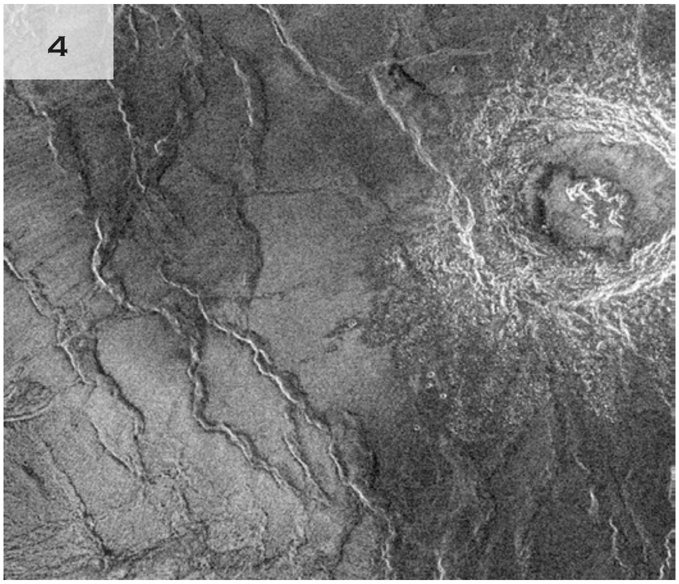
3. Based on the images of the surfaces of different worlds you have seen during the lesson, which worlds might the images be of?

4. Does an older surface mean that the world is older than other worlds? Why or why not?


1


2


3


4

(Image credits: NASA, Carnegie Institution of Washington, Johns Hopkins University Applied Physics Laboratory, Malin Space Science Systems)

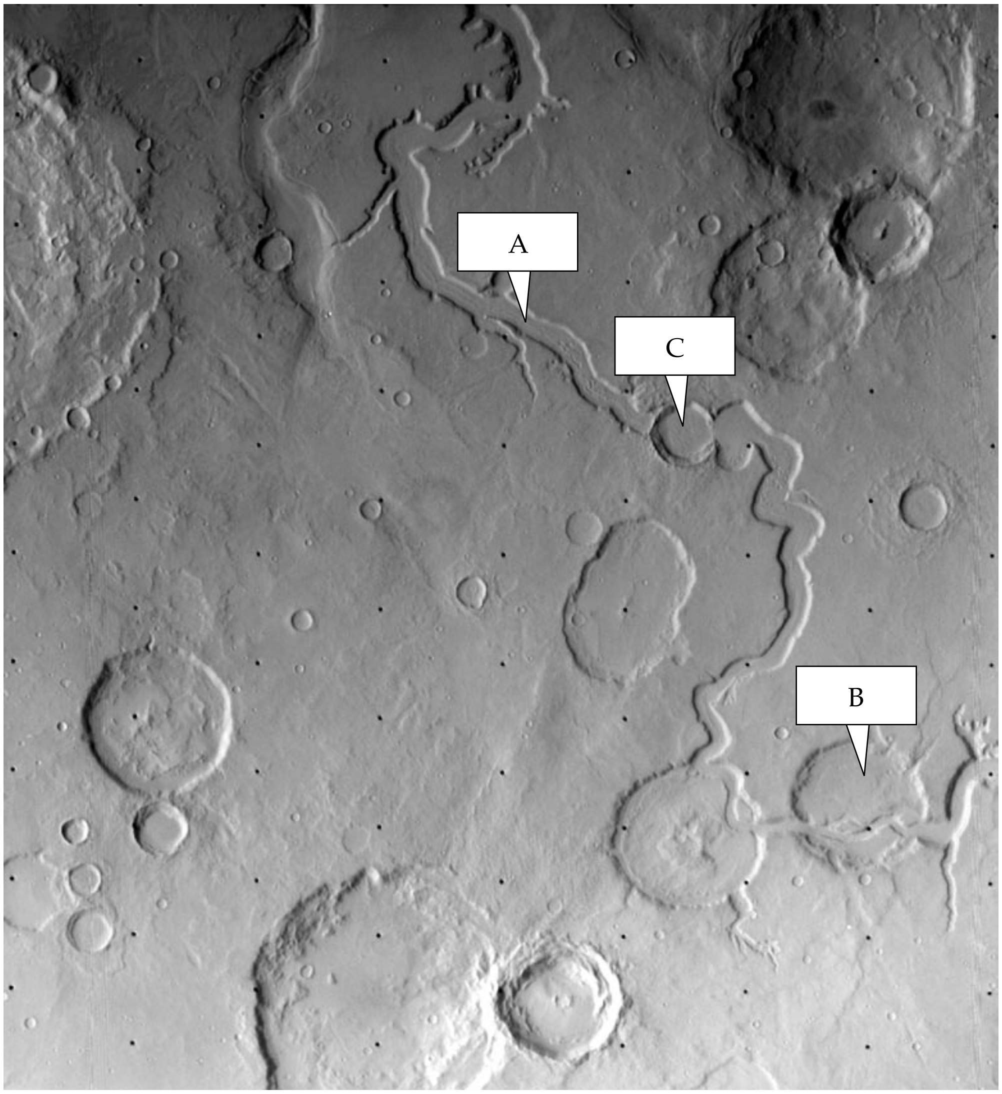
Student Worksheet 3:
Sequence of Events on a Surface

Name ____ Date ___________

The picture below shows craters and river beds on the surface of Mars. Examine the picture carefully to answer the following questions.

Part A. Put the features A, B, and C in order of age from the youngest to the oldest, and explain why you think this is the case. Be sure to look at the crater rims to tell you if there has been any erosion.

Part B. Based on the picture below, write a description of the environment in this region of Mars through time. Explain your answer.



(Image credit: NASA/Viking 1 Orbiter) (Note that the regularly spaced black dots in the image are not real, but an artifact of the way the image was created)