



ROCKS, SOILS, AND SURFACES

Planetary Sample and Impact Cratering Unit

Teacher Guide

Goal: This activity is designed to introduce students to rocks, “soils”, and surfaces on planetary worlds, through the exploration of lunar samples collected by Apollo astronauts and the study of the most dominant geologic process across the Solar System, the impact process. Students will gain an understanding of how the study of collected samples and impact craters can help improve our understanding of the history of the Moon, Earth, and our Solar System.

Additionally, this activity will enable students to gain experience with scientific practices and the nature of science as they model skills and practices used by professional scientists.

Objectives: Students will:

1. Make observations of rocks, “soil”, and surface features
2. Gain background information on rocks, “soil”, and surface features on Earth and the Moon
3. Apply background knowledge related to rocks, soils, and surfaces on Earth toward gaining a better understanding of these aspects of the Moon. This includes having students:
 - a. Identify common lunar surface features
 - b. Create a model lunar surface
 - c. Identify the three classifications of lunar rocks
 - d. Simulate the development of lunar regolith
 - e. Identify the causes and formation of impact craters
4. Design and conduct an experiment on impact craters
5. Create a plan to investigate craters on Earth and on the Moon
6. Gain an understanding of the nature of science and scientific practices by:
 - a. Making initial observations
 - b. Asking preliminary questions
 - c. Applying background knowledge
 - d. Displaying data
 - e. Analyzing and interpreting data

Grade Level: 6 – 8*

**Grade Level Adaptations:* This activity can also be used with students in grades 5 and 9-12. Students in grades 9-12 should be able to work through the activity more independently than younger grade level students.

Grouping Suggestions: Have the class work in groups or teams of 4 or more students.

Time Requirements: This activity can be completed in 10 – 14 class periods. Class periods are based on a 45-minute session. You may consider facilitating individual part(s) of the activity rather than complete the entire unit. **Class Time Saver** suggestions are provided, where applicable, in the activity procedures section. These suggestions generally include having students complete minimal amounts of independent reading or web viewing at home.



Below are estimated time requirements for each section of the activity:

- PART 1: OBSERVATIONS AND PRELIMINARY QUESTIONS: ~20-30 minutes
- PART 2: WHY EXPLORE THE MOON?: ~1 class period
- PART 3: EXPLORING ROCKS, SOILS, AND SURFACES: ~4-6 class periods
 - A. Exploring the Surface of a Planetary World (~1-2 class periods)
 - B. Exploring the Rocks of a Planetary World (~1-2 class periods)
 - C. Exploring the “Soil” on a Planetary World (~1-2 class periods)
 - D. Utilizing Your Observations Skills: Exploring a Lunar Sample Disk (~30 minutes)
- PART 4: CLOSER LOOK AT IMPACT CRATERS THROUGH EXPERIMENTS: ~2-4 class periods
- PART 5: CRATER INVESTIGATORS: ~2 class periods
- PART 6: EVALUATE: ~20-30 minutes

(Procedures for each part of this activity are included in the ACTIVITY PROCEDURES Section of this guide.)

Materials:

- Rocks, Soils, and Surfaces *Student Guide* – 1 per student
- Surface Feature Images (Part 3A) – 1 per group
- Model Making Materials (Part 3A): Modeling clay or Play-Doh; sculpting materials such as pencils, popsicle sticks, toothpicks, round objects of varying sizes; ruler, post-its - 1 set per group/station
- Lunar Geologist Practice Images (Part 3B) – 1 per group
- Plastic tub, graham crackers (2-3 dark and 2-3 light), 1 rock, safety glasses (Part 3C) – 1 set per group/station
- Impact box materials, impact experiment materials (see Part 4 for additional details)
- Earth Impact Database Handout (Part 5) – 1 per group
- Rocks, Soils, and Surfaces Assessment (Part 6) – 1 per student
- Computers (optional)

NEXT GENERATION SCIENCE STANDARDS ALIGNMENT:

Disciplinary Core Idea

- ESS1B: Earth and the Solar System (MS-ESS1-2)
- ESS1C: History of Planet Earth (MS-ESS1-4)

Science and Engineering Practices

- Practice 1: Asking Questions and Defining Problems
- Practice 2: Developing and using Models
- Practice 3: Planning and Carrying Out Investigations
- Practice 4: Analyzing and Interpreting Data
- Practice 5: Using Mathematics and Computational Thinking
- Practice 6: Constructing Explanations and Designing Solutions
- Practice 7: Engaging in Argument from Evidence
- Practice 8: Obtaining, Evaluating, and Communicating Information

Cross Cutting Concepts

- 1. Patterns
- 2. Cause and Effect
- 3. Scale, Proportion, & Quantity
- 5. Energy and Matter
- 6. Structure and Function
- 7. Stability and Change



Nature of Science

- Scientific Investigations Use a Variety of Methods
- Scientific Knowledge is Based on Empirical Evidence
- Scientific Knowledge is Open to Revision in Light of New Evidence
- Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena
- Science is a Way of Knowing
- Scientific Knowledge Assumes an Order and Consistency in Natural System
- Science is a Human Endeavor
- Science Addresses Questions about the Natural and Material World

Common Core Key Connections

- Reading – Follow precisely a multistep procedure when carrying out experiments, taking measurements, or performing technical tasks.
- Writing – write arguments to support claims using evidence
- Research – Conduct short as well as more sustained research projects based on focused questions, demonstrating understanding of the subject under investigation.

TEACHER OVERVIEW AND INTRODUCTION:

To effectively prepare the nation's future Science, Technology, Engineering, and Mathematics (STEM) workforce, students in today's classrooms need opportunities to engage in authentic experiences that model skills and practices used by STEM professionals. Relevant, real-world authentic research experiences allow students to behave as scientists as they model scientific practices. This enables students to get a true sense of STEM-related professions and also allows them to develop the requisite knowledge, skills, curiosity, and creativity necessary for success in STEM careers. The importance of these skills is evident in the restructuring of science education standards into the Next Generation Science Standards. These standards require K-12 science educators to infuse activities into their standard curriculum that allow students to experience scientific practices.

This set of activities addresses the Next Generation Science Standards while recognizing that students potentially lack experience with scientific practices. These activities may challenge students to accept that there is not always a right or wrong answer to a question. The activities will help students learn to think critically, scientifically, and in such a way that they learn to defend answers using criteria and data-based justification.

Students begin the first activity by making observations and asking questions about rocks, soils, and surfaces. This sets the premise for the activity as a whole. Students continue learning and applying background knowledge about rocks, soils, and surfaces on planet Earth and Earth's Moon. This leads them to look more closely at the impact process, the most dominant geologic process seen across the Solar System as they design experiments to answer questions they develop. Students are then asked to think about how to attack a study on impact craters on Earth or on the Moon. The final aspect of the activity reinforces the importance of how studying collected samples and/or impact craters can help us better understand the history of Earth's Moon, Earth, and our Solar System.



Useful Websites:

- Astromaterials Research and Exploration Science Lunar Rocks & Soils: <http://curator.jsc.nasa.gov/lunar/index.cfm>
- ARES Petrographic Thin Sections: <http://curator.jsc.nasa.gov/education/lunar-thinsections.cfm>
- Lunar Sample Compendium: <http://curator.jsc.nasa.gov/lunar/lsc/index.cfm>
- NASA's Earth's Moon Website: <http://moon.nasa.gov/home.cfm>
- Lunar & Planetary Institute Lunar Exploration & Science: <http://www.lpi.usra.edu/lunar/>
- Digital Petrographic Slide Collection: http://ser.sese.asu.edu/cgi-bin/DPSC_Browse.pl
- Google Earth & Google Moon: <http://earth.google.com>; <http://www.google.com/moon/>
- Impact Cratering: http://www.lpi.usra.edu/education/explore/shaping_the_planets/impact_cratering.shtml
- Earth Impact Database: <http://www.passc.net/EarthImpactDatabase/index.html>
- International Observe the Moon Nights: <http://observethemoonnight.org/>

Extensions:

Suggested extensions for this activity include (but are not limited to) having students:

1. Complete a mini-research investigation on impact craters using the Crater Comparisons Activity. This activity enables students to gain experience conducting a structured investigation on impact craters on Earth, Earth's Moon, and other planetary worlds. (<http://ares.jsc.nasa.gov/interaction/eeab/CCA.cfm>)
2. Design and complete a unique student investigation focusing on samples from or surface features on the Moon or other planetary worlds.
3. Design a future human or robotic mission to visit and explore the Moon.

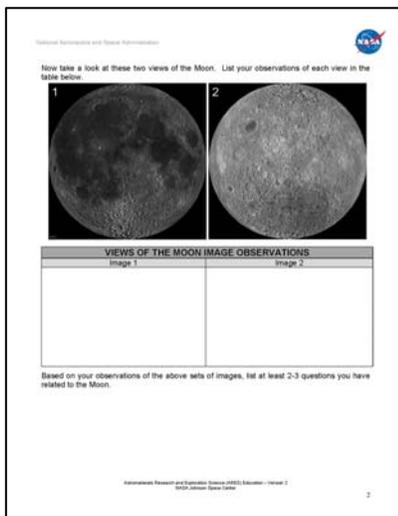
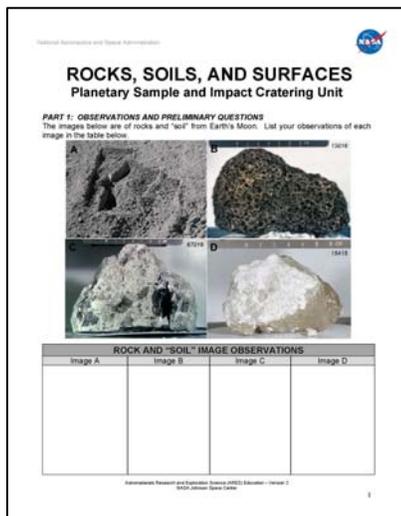
5-E Model of Inquiry: This set of activities is designed using the 5-E model of inquiry. This model of instruction is based on a constructive approach to learning where students learn by building or constructing new ideas by comparing new experiences to existing frameworks of knowledge. The 5-E model of instruction breaks this approach into 5 phases:

5-E Phase	General Description	Crater Comparison Activity
<i>Engage</i>	Teachers engage students using an activity, image, or discussion to focus students' thinking on the learning outcomes of an activity.	Students observe images of lunar rocks, "soils", and the surface. (Part 1)
<i>Explore</i>	Students actively explore and make discoveries about rocks, "soils", and surfaces using hands-on materials. Students develop concepts, processes, and skills to establish an understanding of content.	Students read background information and conduct a hands-on activity related to rocks, "soils", and surfaces. (Parts 2, 3, 4, & 5)
<i>Explain</i>	Students communicate and explain concepts they have been exploring. Students use formal language and vocabulary associated with content.	Students use formal language and vocabulary associated with content as they complete and discuss the hands-on activities. (Parts 3, 4, & 5)
<i>Elaborate</i>	Students extend conceptual understandings to new problems or experiences. Students reinforce and develop a deeper understanding of concepts and skills.	Students apply knowledge acquired as they consider conducting experiments and investigations on impacts. (Parts 4 & 5)
<i>Evaluate</i>	Teachers and students assess new knowledge and understanding of key concepts.	Students complete the Rocks, Soils, and Surfaces Assessment. (Part 6: Assessment)

ACTIVITY PROCEDURES:

This set of activity procedures provides a suggested guide for the *Rocks, Soils, and Surfaces* classroom activity. Estimated time frames for each section can vary depending on the level of students and time you feel is necessary for classroom discussions.

PART 1: OBSERVATIONS AND PRELIMINARY QUESTIONS	
Main Goal(s):	<ul style="list-style-type: none"> • Engage students by having them make observations of lunar rocks, “soils”, and surface. • Have students formulate a set of initial questions; • Assess student prior knowledge.
Estimated Time:	~20-30 minutes
Class Time Saver:	Have students complete pages 1 & 2 at home
Materials Needed:	<ul style="list-style-type: none"> • Student Guide page 1 & 2



1. Divide the class into groups consisting of ~4 students.
2. Give students ~12-15 minutes to list their observations of the set of images provided. As students list their observations, informally assess their prior knowledge. Be cognizant of any student misconceptions.
3. Ask students to list 2-3 questions they have about the lunar rocks, “soil”, or surfaces (based on their observations) at the bottom of page 2.
4. Begin a class discussion acknowledging student observations. If you detected any misconceptions, bring those up as potential discussion points. Revisit these items at the end of the activity.
5. Briefly discuss student questions, validating that all questions are good questions. Let students know they may answer some of their questions as they work through the different portions of the activity.
6. Let students know that by the end of the activity they will be able to identify what they are looking at in these introductory images.



PART 2: WHY EXPLORE THE MOON	
Main Goal(s):	• Provide students with background information about the importance of lunar exploration.
Estimated Time:	~1 class period
Class Time Saver:	Have students read pages 3-4 for homework.
Materials Needed:	• Student Guide pages 3-4

PART 2: WHY EXPLORE THE MOON?

People from countries all around the world can share the beauty and intrigue of Earth's Moon. As a matter of fact, every year, generally in October, there are International Observe the Moon Nights (InOMN). These annual celebrations, held all around the world, are designed to encourage people to look up, observe the Moon, and participate in exciting activities that help celebrate our nearest planetary neighbor. After all, our Moon holds secrets that can help uncover some of the mysteries of the history of our Solar System.

If you haven't done so lately, step outside and look up at our Moon. What do you notice? What do you think the rocks, "soil," and surface really look like? Do you know how the Moon formed? Have you ever imagined what it would be like to walk on the Moon? There are so many questions scientists and the general public have wondered and asked about our Moon. Through human and robotic exploration, NASA and international space agencies all over the world have uncovered answers to many of these questions. But, just as quickly as questions are answered, new questions arise. This is simply the nature of science. It is human nature to wonder and curiously ask questions. That's one of the reasons humans explore.

Robotic lunar exploration began in 1959 and has continued throughout history. The images below are examples of four of the many different missions that have enabled scientists to study Earth's Moon. Just as we never stop learning about planet Earth, ongoing exploration of the Moon is also important. Through lunar exploration, studies conducted with the collection of lunar samples and remote sensing data of the surface help scientists explore the history of not only the Moon, but also the Earth and our Solar System.

Images of selected lunar exploration missions: Apollo 11 (July 1969), Apollo 16 (July 1968), Apollo 17 (December 1972), and Lunar Reconnaissance Orbiter (LRO) (May 2009).

While robotic spacecraft like the Lunar Orbiter (1966) and the Lunar Reconnaissance Orbiter (LRO) (2009) have provided invaluable remote sensing data for scientists to study, the six Apollo missions and astronauts from 1969 to 1972 brought back 382 kilograms (842 pounds) of lunar rocks, soil, samples, pebbles, sand, and dust from the lunar surface. The Apollo missions returned 2,200 separate samples from six different landing sites. These returned Apollo specimens returned an additional 200 grams (7.1 oz) of a pound), from three

other lunar sites. Specialized "clean rooms" at the Lunar Curatorial Facility at the NASA Johnson Space Center in Houston, Texas house these precious lunar samples. The samples are stored in glass and stainless steel containers filled with pure nitrogen. As pure nitrogen is not exposed to oxygen, water, or dust particles from Earth and can remain in pristine condition.

Today scientists continue to study rock and "soil" samples from the Moon in their laboratories. These continued studies have enabled progress in the understanding of the early history of the Moon, Earth, and the inner solar system. Among the useful contributions, one significant debate the lunar samples have helped settle is related to the formation of our Moon. There have been different scientific theories put forth about the formation of the Moon including that it is a captured object (planet or asteroid), or that it is part of a dual planet system, but the data have never completely supported these scientific theories.

Progress in lunar science, especially through research conducted on the collected lunar samples, has led scientists to formulate what is now considered to be the leading scientific theory about the formation of the Moon. Scientific data indicates that the Moon formed from a giant impact on Earth—4.5 billion years ago, by a planetary body about the size of Mars. The debris resulting from this impact is what accreted (gained together) through the force of gravity, and formed the Moon. This scientific theory is strongly supported by data including the chemical composition of the Moon derived from studies of lunar rocks. By studying the rock and "soil" samples, scientists have also learned that a crust formed on the Moon ~4.5 to 4.3 billion years ago. Lunar samples record crust formation, the intense meteorite bombardment occurring afterward, subsequent lava outpourings, and a permanent record of solar activity and radiation speeded out by the Sun.

Together, rocks, "soil" and remote sensing data of a planetary surface provide significant clues about its history. This applies to whether you are studying Earth, the Moon, or any other rocky world. The collected lunar samples, along with remote sensing imagery of lunar surface features, especially impact craters, have enabled scientists to answer important questions about our Moon and so much more. Are there still questions to answer? Absolutely! Robotic spacecraft will continue to provide data from the Moon that will enhance our understanding as new discoveries are made. Lunar missions such as LADEE (Lunar Atmosphere and Dust Environment Explorer), launched in 2013, are now helping scientists understand the tenuous atmosphere and the dust environment of the Moon. It is important to remember, the more we explore the Moon, the better scientists can piece together the history of our nearest planetary neighbor, and in turn, the history of Earth and our Solar System.

To help you gain your own perspective and understanding of rocks, "soil," and surfaces, let's take a closer look at the surface of the Moon, along with lunar rocks and "soil." For each section of this activity, we will touch upon what we know about Earth to help us better understand the Moon, which we can then apply to our planetary world in our Solar System.

Have students read over the information provided on pages 3-4 in the *Student Guide*. Have students pull out important information about why we explore the Moon. Sample questions you may provide and/or discuss with students include:

1. What are International Observe the Moon Nights?
2. When did lunar exploration begin?
3. Name four different lunar exploration missions?
4. Which set of lunar missions brought lunar samples back to Earth for scientists to study?
5. Where are lunar samples stored?
6. Based on the study of lunar samples, describe the leading theory as to the formation of the Moon?
7. Through studies of the Moon, collected lunar samples, and remote sensing imagery of the surface, what are we able to learn more about, aside from the Moon?

One very important aspect of this section is that through continued exploration of the Moon or any planetary world, you are able to progress the knowledge and understanding not only about the specific planetary world, but also the Earth and Solar System as a whole. The more we explore the Moon, the more we are able to understand about the history of our nearest planetary neighbor, and in turn, the history of Earth and our Solar System.

Additionally, each year, there is a celebration of the Moon with International Observe the Moon Nights (InOMN). Events around the world enable people to participate in exciting activities to help them understand not only the beauty, but the importance of exploring our Moon. For more information and to check out InOMN activities being held near your local area, visit: <http://observethemoonnight.org/>.



PART 3: EXPLORING ROCKS, SOILS, AND SURFACES	
Main Goal(s):	<p>Provide students with background knowledge and hands-on experience to gain an understanding of:</p> <ul style="list-style-type: none"> A) Features on a planetary surface (pp. 5-7) B) Rocks on a planetary surface (pp.8-12) C) “Soil” on a planetary surface (pp.13-15) D) Applying what they have learned to explore and identify lunar samples included on a Lunar Sample Disk. (pg.16)
Estimated Time:	~4-6 class periods
Class Time Saver:	<p>Have students read over information in Student Guide (pages 5 – 16) for homework before they come to class. Alternatively, assign a specific section (A, B, or C) to groups of students and have them be responsible to share the information with the rest of the class. Following the discussion of information, set up stations for student groups to experience sections A, B, and C.</p>
Materials Needed:	<ul style="list-style-type: none"> • Student Guide pages 5 - 16 • Section A Materials: Lunar Images (provide 1 image per group); Model Making Materials (1 set per group/station): Modeling clay or Play-Doh; sculpting materials (pencils, popsicle sticks, toothpicks, round objects of varying sizes); ruler, post-its (to enable students to include labels in their model) • Section B materials: Lunar Rock Images (1 set per group/station) • Section C materials: Plastic tub, light and dark graham crackers, 1 rock, safety glasses (1 set per group/station)

A: Exploring the Surface of a Planetary World (pages 5-7)

PART 3: EXPLORING ROCKS, SOILS, AND SURFACES
A. Exploring the Surface of a Planetary World
 If we wanted to get a sense of the different features that make up Earth as a whole, one way to do that is to look at a global image, globe, or map of our planet. By simply observing Earth from a global perspective, you can immediately start to notice the variety of features that make up our planet. The Google Earth screenshot (shown on the left) shows us to easily detect that Earth has ocean basins, land masses (continents), and even ice sheets. If we were to zoom in, we could detect additional details. The satellite photograph shows us high-resolution and high-contrast such as mountainous peaks. We could also identify low elevation areas such as flat plains. Zooming in also allows us to observe other bodies of water aside from Earth's oceans such as lakes and even river channels. Observing a planetary world from a global perspective and being able to zoom in to observe smaller detail and smaller features allows you to gain valuable insight into the planetary world as a whole.

What did you observe from the far view of the Moon from Part 1 of this activity? Perhaps you noticed two somewhat distinct regions of the Moon – one that appears brighter and the other that appears darker. Using telescopic observations of the Moon led early astronomers like Cassini, Galileo, and Johannes Kepler to refer to these regions as Maria, Latin for “sea” and maria (Latin for “sea’s”) Ocean Earth, however, the Moon does not have oceans and did never hold any flowing water on its surface. Do what do these darker and lighter regions of the Moon represent and what types of features exist on the surface of the Moon?

Scientists today refer to these two distinct regions of the Moon as the highlands and mare (lowlands). The highlands are the brighter (grayer) regions (see image 2), which are mostly found on the far side of the Moon, the side we do not see from Earth. These areas consist mostly of numerous overlapping craters. The craters formed when materials (space) projectiles such as asteroids and comets slammed into the surface creating bowl-shaped craters. They still look like these features more clearly than in this globe. The mare of mare (singular for maria), are much darker in elevation and are mostly found on the near side of the Moon, the side we always see from Earth (see image 1). These areas are lower in elevation than the far side of the Moon and are composed mostly of lava flows (a “magma ocean” – one can actually see where the lava has flowed) and “basalt” – dark silicate extrusion areas such as impact basins.

Although impact craters and lava flows are two of the most prominent features visible when looking at a global view of the Moon, there are other features that exist on the lunar surface. Randomly sampling images of the Moon allow us to zoom into the surface and identify other surface features that can help provide additional information about the Moon. The following surface features are commonly found on the Moon:

- **Impact Craters:** Bowl-shaped holes formed when materials (asteroid) projectiles strike the surface.
 - **Basins:** Long valleys that formed (1) as lava flowed across the surface; or (2) when lava flowed underground forming lava tubes that eventually collapsed.
 - **Crater Chains:** A pattern of roughly circular depressions that would be evidence of (1) a lava tube that has not completely collapsed (an intermediate formed flat); (2) a record of rocks that have broken out during an impact event that fell in a linear or arc-like pattern forming secondary craters (large secondary craters are not just smaller crater chains. They are often found alone, and some cannot be distinguished from primary craters).
 - **Mountains:** “Island” features found on the surface. These mountains can be identified as (1) the rims and other features of large craters; (2) a central mound (uplift) found in the center of some large craters; or (3) low, circular, scattered low-relief domes.

Check out the features in these images below:

1 & 2: Mountains
 3 & 4: Mare (Lava channels/lava tube)
 5: Impact crater
 6: Crater chain

Certainly there are multiple features that are visible in each of these images, but these annotated images at least give you an idea as to what some of the described surface features look like in remote sensing imagery. Perhaps you noticed that the feature labeled #3 looks similar to a river channel on Earth. Although it may look similar, the Moon has never had water flow across its surface. So, although you may be tempted to call these features river channels, they should be referred to as lava channels or lava tubes and are associated with flowing lava.

HANDS-ON ACTIVITY: CREATING A MODEL SURFACE OF THE MOON
 Now that you are aware of some of the features on the Moon, let's have you use your knowledge to create a labeled model surface. To prepare you will be assigned to create a model of 1 of the 5 images of the Moon below. Use modeling clay or Play-Doh, along with sculpting tools (pencil, popsicle sticks, toothpicks, round objects of varying sizes) to create your model.

To complete this exercise, do the following:

- Create your model and label at least 5 surface features.
- Include measurements as to 5 of surface features in your model. (NOTE: Use the scale bar provided on the image to help you figure out the sizes of features.)
- Check how closely the features in your model match surface features formed.

The information in this section is intended to cover the following aspects:

- Gaining a global perspective of Earth before “zooming in” to identify smaller-scaled features on the surface of the planet.
- Gaining a global perspective of the Moon before “zooming in” to identify smaller-scaled features on the surface of the planetary world.
- Hands-on Activity: Creating a Model Surface of the Moon



For this section, students start by thinking about and observing a snapshot image from Google Earth. Discuss with students the importance of having a global perspective of a planetary world in order to get an overall sense of the planet as a whole. Have them think about and discuss if they simply looked at the location on Earth where they currently live, would it provide a representative perspective of the planet as a whole? Discuss with students how useful it can be to have a global perspective of a planetary world to help you understand the finer details of a planetary surface as you zoom in and observe/identify additional features. In this portion (Part 3) of the activity, students will look at a global perspective of the Moon before they “zoom in” and look more closely at surface features, rocks, and “soil”. For this section (Section A) of the activity, students will focus on the surface features.

Ask students to think about the images from Part 1 of the activity. What did the global perspective of the Moon enable them to identify in general terms about the planetary world as a whole. If they do not bring up the idea of two distinct regions of the Moon, bring that to their attention. Have students again observe the two global views of the Moon and discuss the two distinct regions as described in the *Student Guide*.

Have students continue the discussion related to additional features commonly seen on the Moon. These additional features become evident as you zoom in and view smaller areas on the lunar surface in greater detail. Common surface features include impact craters, mountains, rilles and crater chains. Discuss each of these features and have students look at the images provided to gain a sense of what these features look like in remote sensing imagery. Remind students that rilles may look like river channels on Earth, but that there has been no liquid water that has ever flowed across the surface of the Moon. Rilles are indicative of areas where lava flowed across the surface or where lava flowed underground in lava tubes. When the top layer of a lava tube collapses, this enables you to observe evidence of where lava once flowed underground. Crater chains are either partially collapsed lava tubes (these tunnels collapse in a somewhat circular pit pattern) or features formed in conjunction with an impact event. Crater chains formed from an impact event can sometimes be evidence of secondary craters – craters that resulted from rocks being ejected from an initial impact. These ejected rocks sometimes strike the surface in a linear or arc-like pattern. Mountains may be related to one or more lunar features. These include 1) the rims of large craters, 2) a central mound (uplift) found in the center of some large craters and/or 3) low, circular, rounded hills called domes. Impact craters, circular features created when meteoroids strike the surface, will be discussed in more detail in Part 4.

To give students a tactile and visual sense of how these features formed, provide groups of students with modeling clay or Play-Doh and sculpting tools such as popsicle sticks, toothpicks, and round objects of varying sizes (golf ball, ping pong ball, tennis ball, etc.). Have students create a scale model of 1 of the 5 surfaces shown in the *Guide*. Provide them with a larger view of each area as necessary. Once students have created their model surface, they should label at least 5 features and include measurements of those features. Students should use the scale bar provided on the image to estimate the diameter of craters or the length and/or width of other features. In order to determine the height or depth of a feature, they would need to know information such as the sun angle. Although the sun angle is not provided, students could search for this information and use that along with the measured length of the shadow and some trigonometry to figure out the height or depth of a feature.



Aside from the visual model of the lunar surface, students can gain a sense of how these features form by the manner in which they create each feature on their modeled surface. For example, students can get a sense of the flow of lava as they use one of the tools provided and drag it along the modeled surface creating the long curvy flow. They could also gain a sense of the formation of the crater chains and almost imagine individual rocks striking the surface creating each “hole” or the collapse of a lava tube (which collapses in somewhat circular pits). Even when making a crater, the larger the impact, the larger the circular feature they will need to use to create that feature. With each movement students make to create each feature, they are, in a sense, modeling the formation of that feature as well as the order in which the features were created (providing information on the relative ages of features). Consider introducing concepts related to relative age dating such as the *Principle of Superposition* and *Cross-cutting principles*. Discuss these aspects with your students. (Note: Students will look at impact craters more in depth in Part 4 of the activity, so don't be concerned if you don't discuss them in great detail in this section.)

B: Exploring the Rocks on a Planetary World (pages 8-12)

8. Exploring the Rocks on a Planetary World

The rocks on Earth, or any other planetary world, are a product of the processes that exist or have existed throughout the history of that planetary world. For example, Earth is affected by wind, water, impact, volcanic, and tectonic processes. These geologic processes help create the rocks we find on our planet.

Rocks on Earth can be sorted into three general classifications:

- Igneous:** Rocks formed when molten rocks and minerals either below the surface (intrusive) or on the surface during volcanic events (extrusive) solidify.
- Sedimentary:** Rocks formed by the compaction and cementation of mineral particles, organic fragments, and sand. They can form from deposits accumulated through weathering brought in chemical processes (evaporation, salt crystallization).
- Metamorphic:** Rocks formed when heat and/or pressure deep within the crust cause a change in the mineral composition and grain size of existing rocks (gneiss, schist, marble).

Throughout its history, Earth's Moon has not experienced the same geologic processes as Earth. After the initial crust formation, the two dominant processes that have shaped the surface of the Moon are the impact and volcanic processes.

In thinking about the initial lunar crust formation, let's think about the lunar magma ocean concept. When the Moon formed, it was thought to be surrounded by a layer of molten rock (ocean of magma) hundreds of kilometers thick. As the magma crystallized, the minerals more dense than the magma sank, while those less dense (such as feldspar) floated. This process is known as differentiation and was instrumental in forming the anorthosite crust. The dense minerals (silica and pyroxene) later remained to produce the basalts that make up the lunar mare. As you will see, the rock types on the surface of the Moon are a reflection of these processes.

Now let's focus on the lunar rocks. Lunar rocks can be classified into three general categories: 1) primitive highland rocks (anorthosites), 2) mare basalts, and 3) impact breccias.

1) PRIMITIVE HIGHLAND ROCKS (ANORTHOSITES)

One type of lunar rock brought back by Apollo astronauts is known as primitive highland rocks or anorthosites. Although anorthosites did not collect many of the type of lunar rock, laboratory research on these samples has provided an abundance of information related to the formation of the Moon.

These igneous (intrusive) rocks were collected on the lunar highlands and contain minerals such as feldspar. Feldspar minerals float in a layer of molten lava (magma) and were thought to be part of the rocks that made up the original lunar anorthosite crust that formed between ~4.5 to ~4.3 billion years ago. These samples are considered to be "pristine" as they do not show evidence of being substantially altered by reheating since they were first formed. The most famous of these rocks (shown above) is the "Genesis Rock" collected by Apollo 15 astronauts.

Characteristics of Primitive Highland Rocks (Anorthosites):

- Brighter/lighter in color than the mare basalts
- Very friable (easily breakable)
- Generally coarse grained (see size individual minerals)

2) MARE BASALTS

The first samples from the Moon brought back by Apollo 11 astronauts were from a region called Mare Tranquillitatis. These igneous rocks were basic volcanic basalts. These mare basalts are located both at the surface as well as below the surface. On Earth, basalts are associated with volcanic activity. Laboratory research has shown that the lunar basalts are very similar to Earth basalts except for some minor chemical differences which have provided important clues into the history and formation of the Moon.

The mare basalts like the anorthosites, are igneous (intrusive) rocks. They contain dense minerals such as olivine and pyroxene. Mare basalts formed by remelting the dense materials that sank out of the magma ocean which erupted onto the surface as lava. This lava, in many cases, flowed up large impact basins of the Moon. The age of mare basalts range from ~3.9 to ~3.2 billion years old.

Characteristics of Mare Basalts:

- Dark gray to black in color
- Fine grained (you cannot easily see the individual minerals that make up the rock)
- Usually includes holes (vesicles) created by gases that escaped before the lava solidified into rock
- Rough texture
- Heat surface

3) IMPACT BRECCIAS

This type of lunar rock makes up the majority of samples collected by Apollo astronauts. Breccias are composite rocks made by the solidification of a mix of various irregularly shaped and sized pieces of rocks. They were formed by impact events, which first shattered and then consolidated pieces of rock from different places, fusing them together. Lunar breccias usually consist of grains of various sizes. They can have a wide variety of forms depending on the size fragments incorporated within them. The fact that most of the Apollo samples are breccias demonstrates how significant the impact process has been throughout lunar history.

Characteristics of Impact Breccias include:

- Mixture of both fine and coarse grained rock and mineral fragments
- Appear to have features that look similar to basalts and/or primitive highland rocks
- Appear to have fragments (clasts) that have been "cemented together" to form the rock

HANDS-ON ACTIVITY: LUNAR GEOLOGIST PRACTICE

Now that you have had a chance to gain some information about the three general classifications of rocks on the Moon, let's have you and your lunar geologist skills to work. Examine the set of images of lunar samples. Use the characteristics provided (and create your own additional criteria) to identify the classification of each rock. Be sure to include your justification.

ROCK	ID#	CLASSIFICATION (Anorthosite, Basalt, Breccia)	JUSTIFICATION
A	71055	Basalt	Vesicles, rough texture, dark in color
B			
C			
D			
E			
F			
G			
H			
I			
J			
K			
L			
M			
N			
O			
P			

Lunar Geologist Practice Images

The information in this section is intended to cover the following aspects:

- The classification of rocks on Earth
- The classification of rocks on the Moon
- Hands-on Activity: Lunar Geologist Practice



For this section, students first read about the classifications of rocks on Earth. This allows them to gain an understanding of how the rocks on Earth are associated with the geologic forces and processes we have on Earth. The rocks on the Moon are also a result of processes that have affected the Moon. Two of the three classifications of lunar rocks are igneous, indicating the influence of magmatic and volcanic activity. The other classification of rocks is a result of the impact process, the other major process that has affected the lunar surface.

To help students understand how the lunar rocks have helped scientists piece together the story of the lunar surface, it is useful to introduce students the idea of the lunar magma ocean. The graphic in the *Student Guide* (page 8) along with completing a separate activity on differentiation (not included in this guide), can help students gain an understanding of the early history of the Moon. The lunar magma ocean concept explains how when the Moon formed it was thought to be surrounded by a layer of molten rock (ocean of magma) hundreds of kilometers thick. As the magma crystallized, the minerals more dense than the magma sank, while those less dense (such as feldspar) floated [this process is known as differentiation], forming the anorthosite crust. The dense minerals (olivine and pyroxene) later remelted to produce the basalts that compose the lunar maria.

Lunar rocks can be classified as follows:

- 1) **Pristine Highland Rocks or Anorthosites:** These lunar rocks are igneous and represent the earliest formation of the lunar crust that have not been altered by reheating. Astronauts retrieved far fewer of this type of lunar rock than the other rock types. The rock shown in the *Student Guide* is referred to as the “Genesis Rock” as it is ~4.5 to ~4.3 billion years old, as determined by specialized age-dating techniques conducted in laboratories. Anorthosites such as the one shown in the *Student Guide* (the Genesis rock), helped determine the age of the formation of the lunar crust, helping to piece together early lunar history.
- 2) **Mare Basalts:** These are volcanic (igneous) rocks. They look very similar to basalts on Earth as well, though they differ slightly in their chemical composition. Numerous lunar samples brought back by astronauts during the Apollo missions were mare basalts.
- 3) **Impact Breccias:** This is the most common type of rock picked up by astronauts. These rocks are made up of fragments of rocks that were broken by meteoroids striking the surface breaking the rocks into smaller irregular sized and shaped pieces. The heat of the impact cemented those irregular shaped pieces of rock together.

Typical characteristics of each rock type are provided in the *Student Guide*. Discuss these characteristics with students. In the hands-on activity portion of this section, students will use the characteristics provided, in addition to any others they may develop, as they gain practice using their lunar geologist skills to classify lunar rocks.

As students begin the hands-on portion of this activity, let them know that scientists have used the lunar samples to make discoveries about the Moon and its formation. These rocks hold many of the secrets of the lunar surface, and help contribute to the understanding of its formation and the history of Earth and our Solar System. Research on these lunar samples is



ongoing and has enabled a progression of lunar science in conjunction with remote sensing data provided by robotic spacecraft that have explored, or continue to explore the Moon. As scientists observe lunar samples as part of their research, one important task to complete is determining the classification of the rock they are observing.

Students will apply their knowledge and gain practice as lunar geologists using a set of images of lunar samples. Based on their observations and use of identification criteria, they will classify each rock. As part of their classification they will need to provide a suitable justification of their interpretation of the classification of their sample. Reinforce to students that classifying a sample is important, however, the justification they provide to support that classification is even more important.

The *Student Guide* contains small images of the lunar samples for students to observe. Additional resources are available for you to choose from depending on the resources you have available. For example, you may choose to: a) Have students use the images on page 12 of the *Student Guide*; b) Print sets of full page lunar rock images for students to use; c) Create a set of lunar rock activity cards by printing and cutting images in to ~3 X 5" activity cards; d) Display the full page images on a screen in the front of the room; or e) If you have individual laptops or tablets available for student groups, students can view the full page images on their mobile devices as they determine the classification of each rock.

Sample answers*:

ROCK	ID#	CLASSIFICATION	JUSTIFICATION
A	71055	Basalt	Vesicles, rough texture, dark in color
B	60025	Anorthosite	Justification will vary.
C	64535	Impact breccia	Justification will vary.
D	62275	Anorthosite	Justification will vary.
E	77017	Impact breccia	Justification will vary.
F	60215	Anorthosite	Justification will vary.
G	65315	Impact breccia	Justification will vary.
H	74275	Basalt	Justification will vary.
I	71565	Basalt	Justification will vary.
J	67955	Anorthosite	Justification will vary.
K	64435	Impact breccia	Justification will vary.
L	71135	Basalt	Justification will vary.
M	14307	Impact breccia	Justification will vary.
N	73255	Impact breccia	Justification will vary.
O	62275	Anorthosite	Justification will vary.
P	71036	Basalt	Justification will vary.

***NOTE:** These are sample answers based on the characteristics clearly visible in each image provided. As only one side of each lunar rock is shown, students may detect evidence of other characteristics that might alter their final classification of the sample. As long as students can justify their answers with evidence that make sense, alternative answers should be accepted.



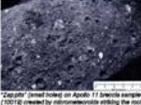
C: Exploring the “Soil” on a Planetary World (pages 13-15)

C. Exploring the “Soil” on a Planetary World
Planetary geologists are able to use the precious lunar samples you examined in the last section to learn about the history of the Moon. For some of the rock images you observed, you should have noticed there were small holes in the samples. In the case of the rock shown, these holes are referred to as vesicles, which are a characteristic associated with the volcanic nature of these igneous rocks. In other cases, the holes are evidence of micrometeoroids (small meteoroids) that have struck the rock. This is a very common occurrence on lunar rocks. These micrometeoroid impacts are related to the formation of soil on the surface of the Moon. Before we examine how “soil” is formed on the Moon in too much detail, let’s first think about soil formation on Earth.

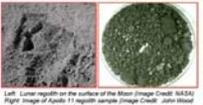
On Earth, when we refer to soil, we are generally talking about some material on the surface that contains organic material. Earth soil is formed from the effects of weathering processes on rocks. Weathering can cause rocks to fragment, crack, crumble, or decay. Physical weathering processes like freezing water can cause rocks to crack. Chemical processes, such as the decay of minerals in water or acids, or even biological weathering, from plant roots, can soften cracks in rocks contributing to the formation of soil. Additionally, erosional processes from water erosion, rain, ocean waves, wind, and ice (glaciers) can also further break down rocks into soil and transport these broken materials.

When looking at planetary worlds in our Solar System, scientists more commonly use the term regolith to refer to the loose “soil” that covers a surface. To using the term regolith, the association of organic material being included in the sample is removed. Some scientists will only use the term regolith when talking about other planetary worlds, while others sometimes use soil and regolith interchangeably.

The lunar regolith is a loose “soil” that covers the Moon. The texture and composition of the lunar regolith varies from place to place. The depth of the regolith can also vary from being a few meters to tens of meters. In general, the older the surface, the thicker the regolith.



Crater formed by micrometeoroid striking the rock, (FOOT) covered by micrometeoroid debris on the rock.



Left: Lunar regolith on the surface of the Moon (Image Credit: NASA). Right: Image of Apollo 11 regolith sample (Image Credit: John Wood at the Smithsonian Astrophysical Observatory).

So how did the regolith form on the Moon? The Moon is not affected by the same weathering and erosional processes that we have on Earth. Therefore, some other process has been responsible for the formation of the lunar regolith. That process is the impact process. Lunar regolith was actually created by the continuous impact of the lunar surface by meteoroids. As micrometeoroids and larger meteoroids slam into the surface of the Moon, they impact the rocks and actually break them down into “soil”. Lunar regolith is made up of a wide range of particle sizes and compositions. The main component reflects the most underlying rock. On the mare surfaces, the regolith is basaltic rich, while on the highland surfaces, there is a greater abundance of anorthite (highland crystalline fragments). Since impacts shed rock materials great distances and distribute broken rock from one part of the Moon to another, regolith is actually a mixture of the different rock types as you will see in the hands-on activity.

HANDS-ON ACTIVITY: REGOLITH FORMATION ACTIVITY
Making regolith on the Moon is an ongoing process that continues today. In this hands-on activity, you will gain an understanding of how regolith is formed.

In a large plastic tub your teacher will put some light and dark graham crackers. The graham crackers represent the surface of the Moon, made up of anorthite and basaltic rocks. Make sure you wear safety glasses as you use an actual rock (simulating a meteoroid) to impact the simulated surface of the Moon.

Before you begin, write your prediction to the following two questions. Once you have completed the simulation, write in the actual answers. Be prepared to discuss your predictions and actual results.

- How many times will you need to have the rock impact the graham crackers before you begin to create regolith?
 - Prediction: _____
 - Actual: _____
- The more the rock is dropped into the graham crackers, the more the particle size of the graham crackers will change. How do you predict the particle size of the graham crackers will change after dropping the rock into the plastic tub 5 times? How about after 15 times?
 - Prediction: _____
 - 5 drops: _____
 - 15 drops: _____
 - Actual: _____
 - 5 drops: _____
 - 15 drops: _____

Additional Questions (after completing the simulation):

- If you used a new rock for each impact and never removed any material from the simulated surface in the tub, how would the volume of material in the tub change? Why?
- Circle the best answer to complete the statement below:
The Moon has been impacted by meteoroids for _____
a. tens of years
b. hundreds of years
c. millions of years
d. billions of years
- Based on your observations of the Moon, which side of the Moon (near side or far side) appears to have experienced a higher number of impacts? Explain.
- Which surface of the Moon would you hypothesize has a thicker coating of regolith, the lunar mare or lunar highlands? Why?
- How might you determine the “soil” type when looking at an actual sample from the Moon?
- Discuss how this model reflects a good representation of illustrating regolith formation.
- Discuss the limitations of this model in illustrating regolith formation.

This section is divided into three parts:

1. Soil formation on Earth
2. “Soil” (regolith) formation on the Moon
3. Hands-on Activity: Regolith formation activity

Students begin this section with somewhat of a continuation of observing lunar rocks. Looking closely at lunar samples, scientists identified what are referred to as “zap pits”. These zap pits were discovered to be evidence of micrometeoroids (small meteoroids) impacting the lunar rocks. These are commonly observed on lunar rocks and are closely associated with the formation of lunar “soil” as will be discussed in this section.

Students are first asked to think about the formation of soil on Earth. Just as is the case with the rocks, the “soil” on a planetary surface is associated with the processes affecting the surface. Soil is basically a breakdown of the planetary rocks. On Earth, physical, chemical, and biological processes all contribute to the formation of soil. As the Moon is not affected by these same processes, we must consider what process is responsible for the “soil” formation.

Students may be wondering why “soil” is in quotes. This is basically due to the idea that on Earth, soil is associated with organic material. On other planetary worlds, the “soil” does not contain organics. Therefore, scientists generally refer to the loose material on a planetary surface as *regolith*. The use of this term takes away the reference to organics, as is the case when using the term “soil”. Despite this, some scientists may use the terms regolith and “soil” interchangeably.

Lunar *regolith* is formed by a mechanical breakdown of the rocks through ongoing impacts to the rocks on the lunar surface. To help students gain experience in regolith formation they will complete a hands-on activity simulation. You may choose to provide each group with the set of materials for this exercise or set this up a station students can rotate through. The *Student Guide* contains questions for students to answer before and after the simulation.

1. How many times will you need to have the rock impact the graham crackers before you begin to create *regolith*?
 - Prediction: **Answers will vary.**
 - Actual: **Regolith is being formed on the first drop.**



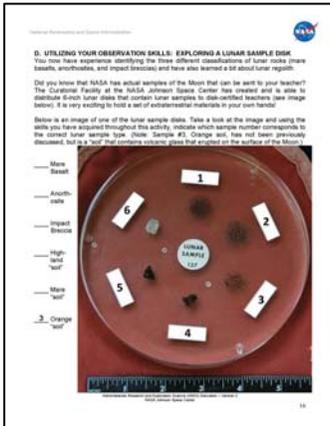
2. The more the rock slams into the graham crackers, the more the particle size of the graham crackers will change. How do you predict the particle size of the graham crackers will change after dropping the rock into the plastic tub 5 times? How about after 15 times?
 - Prediction:
 - 5 drops: **Answers will vary.**
 - 15 drops: **Answers will vary.**
 - Actual: **The more drops, the smaller the particle size of the graham crackers will be.**
 - 5 drops:
 - 15 drops:

Additional Questions (after completing the simulation):

3. If you used a new rock for each impact and never removed any material from the simulated surface in the tub, how would the volume of material in the tub change? Why?
The volume would increase. If no material is being removed from the tub and the rocks continue to be added to the tub, the volume of material will increase.
4. Circle the best answer to complete the statement below:
The Moon has been impacted by meteoroids for _____.
 - a. tens of years
 - b. hundreds of years
 - c. millions of years
 - d. **billions of years**
5. Based on your observations of the Moon, which side of the Moon (near side or far side) appears to have experienced a higher number of impacts? Explain.
The far side of the Moon appears to have experienced a higher number of impacts. Students should refer to the observations of the more heavily cratered surface on the far side of the Moon as seen in earlier sections of this activity. [NOTE: The near side of the Moon may have experienced just as many impacts as the far side (impacts are random and do not strike a region preferentially), however, modification/resurfacing of the surface through lava flows, for example, has “erased” evidence of those impacts. This allows scientists to relatively age date surfaces of a planetary world using crater density: more craters on a surface = older surface; fewer craters = younger surface.]
6. Which surface of the Moon would you hypothesize has a thicker coating of *regolith*, the lunar maria or lunar highlands? Why?
The lunar highlands would have a thicker coating of regolith. This is due to the number of impacts on these surfaces and the continued increase in volume of material.
7. How might you determine the “soil” type when looking at an actual sample from the Moon?
As the breakdown of the rocks creates the regolith, they can look at the color of the particles in the “soil” to determine the “soil” type.
8. Discuss how this model reflects a good representation of illustrating *regolith* formation.
Answers will vary.
9. Discuss the limitations of this model in illustrating *regolith* formation. **Answers will vary.**



D: UTILIZING YOUR OBSERVATIONS SKILLS: EXPLORING A LUNAR SAMPLE DISK (page 16)



This section of the activity gives students a view of a lunar sample educational disk. These specially made disks were created using pieces of lunar material collected by astronauts during the Apollo missions. Educators can be certified to check out these disks and bring actual lunar samples to the classroom. For additional information on the lunar sample disk certification process, go to <http://ares.jsc.nasa.gov/interaction/lmdp>. Giving your students the opportunity to hold extraterrestrial material in their hands can be quite inspiring. These 6-inch lucite disks include three lunar rock and three regolith samples. Students may think the samples are small, but let them know that when scientists request samples for their research, they too receive only a small portion of the original rock. Even a small sample allows scientists to conduct in-depth studies of the material. If you do check out a sample disk for your classroom, we encourage you to have your students view the different samples through a microscope. This will help students better observe the characteristics of each lunar sample.

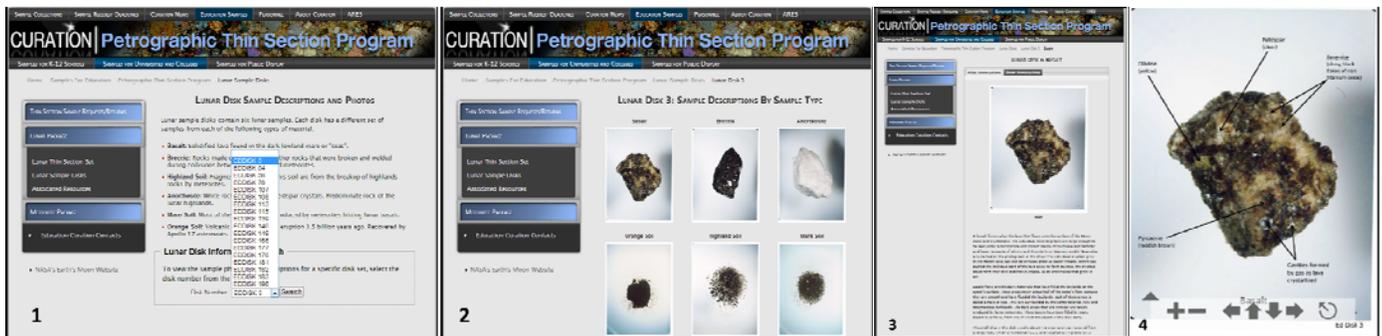
Even if you are not certified to check out a lunar sample disk, this portion of the activity can still be completed using the image provide in the *Student Guide*. Additionally, you and your students can explore other lunar samples and disks using the website listed below.

As students observe the image of the lunar sample disk in the *Student Guide*, have them identify the three different types of rocks (mare basalt, anorthosite, and impact breccias). With regards to the regolith samples, the disk contains highland “soil”, mare “soil” and orange “soil”. The orange “soil” was not discussed in the previous section and is therefore identified for the students. This orange “soil” is volcanic glass from explosive volcanic eruptions from early in lunar history.

If students want to make additional observations of lunar samples or even conduct a further investigation, encourage them to view additional lunar disk images of lunar samples at the following website: <http://curator.jsc.nasa.gov/education/lunar-disks.cfm>

The screen shots below show that you can use the above website to:

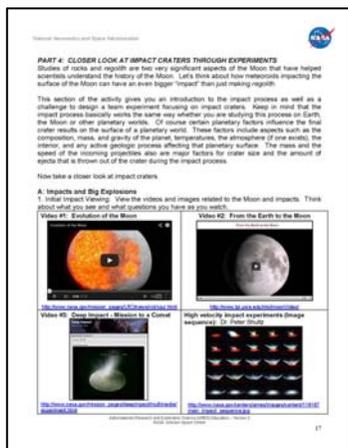
- 1: Select a lunar disk to observe
- 2: Observe the 6 samples included in lunar disk
- 3: View an individual sample & description
- 4: Observe an annotated view of a sample





PART 4: CLOSER LOOK AT IMPACT CRATERS THROUGH EXPERIMENTS	
Main Goal(s):	<p><i>Provide students with background knowledge and experiences to be able to design and conduct an impact experiment and analyze the data. Students will:</i></p> <ul style="list-style-type: none"> <i>View impact videos and images; document observations and questions; and share.</i> <i>Make impacts to gain experience and put the experience in context with their prior knowledge to help establish questions.</i> <i>Design and conduct an impact experiment to answer their questions.</i> <i>Compile experimental data; evaluate the process and the data.</i> <i>Report conclusions based on their data and defend conclusions.</i>
Estimated Time:	~ 2-4 class periods
Class Time Saver:	<i>Have students watch website videos and images at home and record observations and questions.</i>
Materials Needed:	<i>Student Guide pages 17-22, computer access for websites, set of impact box materials for each group of 8-10 students: plastic tubs or cardboard boxes, flour or baking soda, cocoa, marbles of various sizes, meter stick, safety glasses. Additional materials for student experiments and report guidelines (based on your requirements) may be needed. Details for specific materials are on pg.16 of this Teacher Guide.</i>

A: Impacts and Big Explosions (pages 17- 18)



This section is divided into two parts:

1. Initial impact viewing of videos and websites related to impacts that are intended to engage students with the topic. Students will view impact videos and record observations and questions. Ideally you can use a flipped classroom design and ask students to watch the impact videos at home and fill out the questions on the Impacts and Big Explosions *Student Guide* pages 17-18. If that is not possible then show the videos in class time and ask students to independently record observations and questions.



2. HANDS-ON ACTIVITY: MAKING CRATERS IN IMPACT BOXES

During this part of the activity, students gain experience with the cratering process by making craters, recording observations and questions, and reporting.

NOTE 1: Because of the high kinetic energy, an impact event is actually an explosion that excavates material from the surface. Experiments conducted at low kinetic energy, like what students will do in class, will be similar to, but not exactly like, those events that form actual craters.

NOTE 2: A common misconception is that only round objects can make round impact craters. This is not true. Additionally, most impact craters will be circular in shape unless the angle in which the impactor struck the surface was a very shallow angle.

Materials for Impact Boxes (1 impact box set per 8 students)

Items for 1 impact box set:

- Plastic tub or cardboard box - minimum of 18"x12" - cat litter box works well
- Dry white powdery material - baking soda is best, flour is also good - do not use diatomaceous earth. Sand does not generally form good crater models. About 2 pounds of flour per box is sufficient.
- Dry dark powder - cocoa is best or very fine colored sand may be used.
- Marbles - about 4 per student. The marbles may be different sizes if desired.
- Safety glasses
- Meter stick

Note: For a second use of the impact boxes, do not empty. Carefully remove marbles and resurface with thin coats of powdered materials.

[Materials needed for Impact Experiments Section B will likely include many of the above materials. See additional possible materials listed in Section B.]

Pre Class Preparation

- Assemble equipment
- Prepare impact boxes with dry materials. 1 box per 8-10 students (minimum).

A) If possible, assemble the impact boxes where they will be used because the surface may change if the box is not carefully moved. Provide space for about 8 students to stand around each box for active impacting.

B) Place a 3-5cm even layer of dry white material in the bottom of impact boxes.

C) Sprinkle a thin layer of cocoa over the white material with a kitchen strainer – just enough to conceal the white layer.

Optional: Prior to covering the white material with cocoa, sprinkle a layer of cake sprinkles (colored sugar) on top of the white dry material – or cover only half of the white layer with cake sprinkles. Finish with cocoa. (Very fine craft glitter may be used in place of cake sprinkles for “sparkle” mineral effect.) The sprinkles layer shows a subsurface layer in this terrain.



Classroom Procedure:

Safety Point: As students gather to make impacts, make sure they are standing up (not kneeling or sitting on the floor) when other students drop (throw) the marbles. Use safety glasses.

Instruct students to take turns dropping marbles into the impact boxes. Encourage them to observe the process and the results – observe, wonder, question. Have students write their observations and questions in the *Student Guide*.

B: Impact Experiments (pages 19 – 21)

Students pose a question, design and conduct an experiment, and collect and compile data.

<p>National Aeronautics and Space Administration</p> <p>B. Impact Experiments</p> <p>Your teacher will assign the class into teams consisting of 4 students per team.</p> <p>1. In your team, discuss the observations and questions from the videos and the hands-on impact activity. Consolidate the team information and report the observations and questions to the class.</p> <ul style="list-style-type: none"> We observed: We wondered: <p>2. BACKGROUND INFORMATION ON IMPACTS AND CRATERS</p> <p>Impact craters form when meteoroids, including pieces of asteroids or comets strike the surface of a planetary body. There are craters on all the terrestrial planets, on Earth's Moon, and on all rocky objects in the solar system. Impacts occur everywhere in our Solar System – comets and asteroids even hit the Sun!</p> <p>Geological evidence in the lunar rocks returned by the Apollo missions indicates that about 3.9 billion years ago asteroid-size chunks of matter were abundant in the solar system. This was a time of intense bombardment of the young planets, affecting Earth by breaking up and melting parts of the crust. Mountain building, plate tectonics, weathering and erosion have largely removed the traces of Earth's early cratering period, but the near absence of weathering on the Moon has preserved much of the evidence of this ancient time.</p> <p>Impact craters form through the transfer of energy from a moving mass (asteroid fragment or comet) to a planetary world. Kinetic energy is the energy of motion. It is defined as one half the mass of an object, times the velocity of the object squared ($KE = \frac{1}{2} m \cdot v^2$). Objects in space have mass and move very fast, so there is a huge transfer of energy as objects smash into planetary worlds, causing huge explosions, and form craters! During an impact event, the kinetic energy of an incoming mass is transferred into heat and shock waves. This transfer of energy melts rocks, pulverizes and ejects or excavates rocks.</p> <p>As your team designs and conducts impact experiments, keep in mind that you will not be able to generate the same amount of kinetic energy involved in the actual impact process. Your experiments, however, will allow you to gain a better understanding of how the impact process works.</p> <p>Astromaterials Research and Exploration Science (ARES) Education – Version 2 NASA Johnson Space Center</p> <p>19</p>	<p>National Aeronautics and Space Administration</p> <p>3. Design and Conduct Your Team Experiment</p> <p>Your team challenge is to design a simple experiment that will allow you to gather data to help answer a question that you have about impact crater formation. Use your experience with watching impacts and making craters in the impact boxes to guide your question and experiment design.</p> <ul style="list-style-type: none"> What question will your team try to answer? Write a short summary of the experiment your team plans to conduct. How will this experiment give you results that you can use to answer your question? What variable will your team test and what controls do you need to make the data valid? (Controls are parts of the experiment that stay the same each time you conduct the experiment and a variable is the part that changes or is being tested.) How will you record and display your data? Write a procedure for the experiment, include all the steps needed and who will be responsible for each part. Record the experimental procedure on paper or on your computer. Be sure to include how you will address any safety concerns as part of your procedures. <p>Astromaterials Research and Exploration Science (ARES) Education – Version 2 NASA Johnson Space Center</p> <p>20</p>	<p>National Aeronautics and Space Administration</p> <ul style="list-style-type: none"> Draw/design your experiment set up including all equipment. How many times will you need to repeat the experiment to get useful results and enough data? How long is the experiment process going to take? List the equipment, including safety equipment, your team will need. Draft a data table you will use to collect and record your data and notes. <p>Submit your team experimental plan including materials list and safety precautions to your teacher for review.</p> <p>When the teacher approves your plan, conduct your experiment. Record data, take good notes, and make drawings in your notebooks. Document your experiment with photos or videos if possible.</p> <p>Astromaterials Research and Exploration Science (ARES) Education – Version 2 NASA Johnson Space Center</p> <p>21</p>
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Materials for Impact Experiments: The need will vary depending on what the student teams design. It is likely that they will need at least one impact box per team. Other possible materials: impactors of the same size but different mass (i.e. wood, plastic, glass, steel spheres of the same size), metric measuring sticks and rulers, sieve, cell phone video cameras, calculators, etc.

1. Regroup the class into teams consisting of 4 students per team. Ask the teams to discuss their observations and questions from both the videos and the hands-on impact activity. The teams will make consolidated team observations and questions using page 19 of the *Student Guide*. Ask each team to share their questions and observations with the class.

2. Instruct students to read the Background Information on Impacts and Craters on page 19.

3. Design and Conduct Your Team Experiment:

Provide the teams with a challenge to design a simple experiment that will allow them to gather data to help them answer a question they have about impact craters. Ask them to base their questions on the experience they have had with the videos and the impact box demonstration. Allow other questions to be posed if they can easily design an appropriate experiment. Allow student teams to discuss their questions and potential experiments. After they have a draft idea, be sure they fill out the information in the *Student Guide* on pages 20 and 21.



Earth Impact Database handout to each group. Have students scan the handout and indicate their observations of the following:

1. Number of craters found on Earth: **There are 182 craters on this list**
2. Size range of craters*: **Size of craters range from 0.0135km (13.5 meters) to 160 km**
3. Age range of craters*: **(Ma = millions of years) Age of craters range from 0.000006 million years old (6 years) to 2023 million years old (2.023 billion years old)**
4. Location of craters: **Answers may vary (Identified craters are located across all parts of the world --every continent except Antarctica. (Note: Antarctica is not included on the map provided.)**

**Students may need some assistance understanding the manner in which some numbers are written.*

Discuss this information with students. Ask students what surprised them about this information. For example, students may be surprised by the number of impact craters, the distribution of craters, or even how craters vary in size and age. Discuss with students how the *Earth Impact Database* handout contains quite a bit of data about craters on Earth. So much data can sometimes be overwhelming to work with. Let students know that professional scientists sometimes also have so much data to work with that they have to use a subset of that data as part of their research. This is perfectly suitable, provided that data selected to use does not show bias or lead to any potential misunderstandings about a particular topic.

In groups, students should discuss how they can use a subset of Earth impact crater data to plot on the map included in the *Student Guide* to illustrate something about craters on Earth. Tell students they must use at least 20 different craters to plot on their map. As student groups discuss their plan of what they want their map to illustrate about craters and how to plot their selected subset of data on the map, have them list information about their plan at the bottom of page 23. They should then plot their selected data on the map provided. [**OPTIONAL:** Depending on your availability of computers and your students' knowledge of inserting place marks on Google Earth, students can plot their data using Google Earth as an alternative to the hard copy map provided in the guide. If students are not already familiar with this process, encourage them to use the hard copy map. One additional option to consider would be to have students plot their data on Google Earth as an extra credit project.]

Have students observe each other's maps to see what data other groups plotted and what that data illustrates about impact craters on Earth. Discuss with students how by using a subset of data, this could lead someone to draw a conclusion about craters on Earth that is not quite complete or valid. This could lead to potential misinterpretations about, in this case, craters on Earth. Have students fill out the table on page 26 to consider this. Discuss as a class.

B. LUNAR CRATER INVESTIGATORS

Now that students have been briefly introduced to an investigation of craters on Earth, have them think about conducting an investigation focusing on craters on the Moon. As there are many more craters on the Moon compared to Earth, students would certainly need to use a subset of data if they were to conduct research focusing on lunar craters. Have students consider an aspect of lunar craters they could investigate and plot on a map. Students should discuss and write a brief overview of their investigation plan followed by sharing and discussing those potential plans with the class.



THE IMPORTANCE OF ROCKS, SOILS, AND SURFACES: TYING IT ALL TOGETHER

This last section of this activity aims to tie the importance of studying rocks, “soils”, and surfaces together. Students should realize that each of these aspects of a planetary world help reveal important information about the history of that world. The rocks and “soil” on a planetary surface are a reflection of the geologic processes that sculpt the surface of that planetary world. Of all the geologic processes that exist, the most dominant one throughout the inner Solar System is the impact process. Impact craters are found on all rocky worlds. This process has played a role in the formation and history of not only the Moon, but of Earth and the Solar System as well.

Based on what they have learned in this activity, ask students what they could do if they wanted to further investigate and gain a deeper understanding of the history of the Moon or even our Solar System. Potential answers include investigating additional lunar samples or investigating impact craters in more depth. Students could investigate impact craters on Earth, the Moon or even other planetary worlds. If they were to do this, they would begin to unlock the history of our Solar System as well as be able to think about the future of Earth and even influences on human and robotic exploration of our Solar System.

Want to have your students conduct an introductory investigation of impact craters? Check out the Crater Comparisons Activity (<http://ares.jsc.nasa.gov/interaction/eeab/CCA.cfm>). This activity provides an introductory and guided structure to help students gain experience with the process of science through the completion of a mini-research investigation. The activity includes all the resources students need to complete their investigation, including imagery of impact craters on Earth, Earth’s Moon, Mars, Venus, Mercury, and an asteroid named Vesta.



PART 6: <u>E</u>VALUATION	
Main Goal(s):	<i>Evaluate student mastery of objectives</i>
Estimated Time:	<i>~20-30 minutes</i>
Class Time Saver:	<i>No recommendations.</i>
Materials Needed:	• <i>Rocks, Soils, and Surfaces Assessment</i>

The *Rocks, Soils, and Surfaces Assessment* can be used to evaluate student general knowledge of information after the completion of this activity. You should evaluate student process skills and deeper understanding and application of content as they complete the individual activities included in each section of the activity.

This two-page assessment covers the broad concepts covered in the activity. See the answers and point values below.

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ROCKS, SOILS, AND SURFACES ASSESSMENT

Name: _____
Date: _____

1. Identify each type of rock shown below (mare basalt, anorthosite, impact breccia).



A) _____



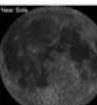
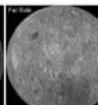
B) _____



C) _____

2. Which side of the Moon (near side or far side) best matches the following:

- _____ Lunar Highlands
- _____ Mare
- _____ Composed mostly of lava flows
- _____ Thicker coating of regolith

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3. True or False (Circle your answer)

- Regolith is formed when water flows across the surface and breaks down rocks.

4. True or False (Circle your answer)

- Lava channels and collapsed lava tubes can also be referred to as rilles.

5. The Moon has been impacted by _____ for billions of years.

- a. other planets
- b. spacecraft
- c. humans
- d. meteoroids
- e. The Moon does not experience impacts

6. Based on statements a-e below, list the order of steps you would use to design and conduct an experiment _____

- a. Plan your experiment
- b. Pose a question to be answered
- c. Collect and compile data
- d. Report your conclusions
- e. Interpret your data

7. True or False (Circle your answer)

- Limitations, such as time constraints, sometimes make it necessary to use a subset of data when conducting research.

8. True or False (Circle your answer)

- The study of lunar rocks, "soils", and surfaces can help provide a better understanding of the history of the Moon, Earth, and Solar System.

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The grading rubric is as follows:

- A = 18-20 points
- B = 15-17 points
- C = 12-14 points
- D = 9-11 points
- F = Below 9 points

ANSWER KEY

1. **A) Impact Breccia B) Mare Basalt C) Anorthosite** (1 point each answer)
2. **Far Side** (Lunar Highlands); **Near Side** (Mare); **Near Side** (Composed mostly of lava flows); **Far Side** (Thicker coating of regolith) (1/2 point each correct answer)
3. **False** (1 point)
4. **True** (1 point)
5. **d. Meteoroids** (1 point)
6. **b, a, c, e, d** (1 point)
7. **True** (1 point)
8. **True** (2 points)

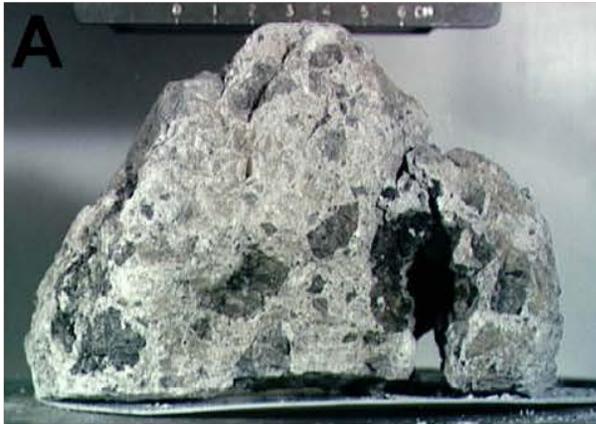


ROCKS, SOILS, AND SURFACES ASSESSMENT

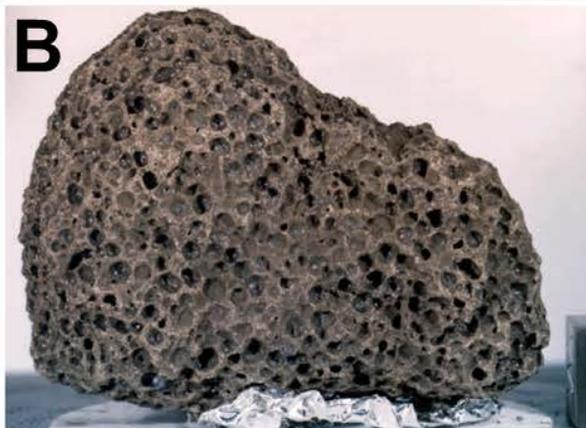
Name: _____

Date: _____

1. Identify each type of rock shown below (*mare basalt*, *anorthosite*, *impact breccia*).



A) _____



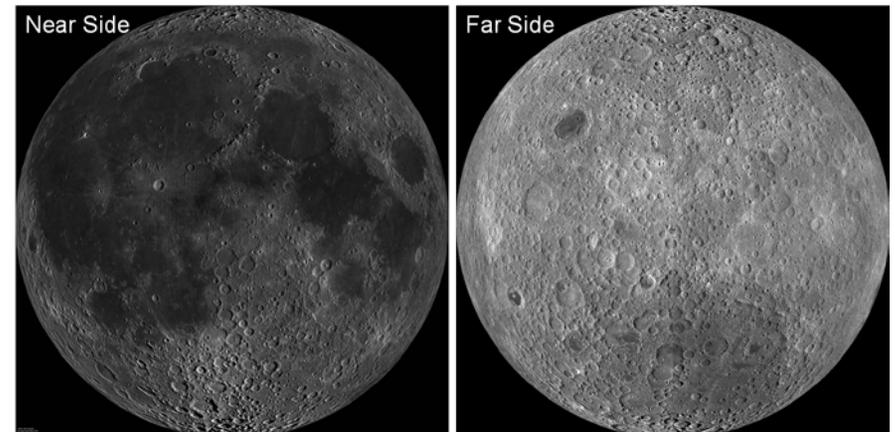
B) _____



C) _____

2. Which side of the Moon (*near side* **or** *far side*) best matches the following:

- _____ = Lunar Highlands
- _____ = Mare
- _____ = Composed mostly of lava flows
- _____ = Thicker coating of *regolith*





3. True or False (Circle your answer):
 - Regolith is formed when water flows across the surface and breaks down rocks.

4. True or False (Circle your answer):
 - Lava channels and collapsed lava tubes can also be referred to as rilles.

5. The Moon has been impacted by _____ for billions of years.
 - a. other planets
 - b. spacecraft
 - c. humans
 - d. meteoroids
 - e. The Moon does not experience impacts

6. Based on statements a-e below, list the order of steps you would use to design and conduct an experiment: _____
 - a. Plan your experiment
 - b. Pose a question to be answered
 - c. Collect and compile data
 - d. Report your conclusions
 - e. Interpret your data

7. True or False (Circle your answer):
 - Limitations, such as time constraints, sometimes make it necessary to use a subset of data when conducting research.

8. True or False (Circle your answer):
 - The study of lunar rocks, “soils”, and surfaces can help provide a better understanding of the history of the Moon, Earth, and Solar System.

EARTH IMPACT DATABASE

<http://www.passc.net/EarthImpactDatabase/index.html>

Structure Name	Location	Lat	Lon	Age (Ma)*	Diameter (km)
Acraman	South Australia	32.0S	135.5E	~ 590	90
Amelia Creek	N. Territory, Australia	20.9S	134.8E	1640 - 600	~20
Ames	Oklahoma, U.S.A.	36.3N	98.2E	470 ± 30	16
Amquid	Algeria	26.1N	4.4E	< 0.1	0.45
Aorounga	Chad	19.1N	19.3E	< 345	12.6
Aouelloul	Mauritania	20.3N	12.7E	3.0 ± 0.3	0.39
Araquainha	Brazil	16.8S	53.0W	254.7 ± 2.5	40
Avak	Alaska, U.S.A.	71.3N	156.6W	3-95	12
Barringer	Arizona, U.S.A.	35.0N	111.0W	0.049 ± 0.003	1.18
Beaverhead	Montana, U.S.A.	44.6N	113.0W	~ 600	60
Beyenchime-Salaatin	Russia	71.0N	121.7E	40 ± 20	8
Bigach	Kazakhstan	48.6N	82.0E	5 ± 3	8
Boltysch	Ukraine	48.8N	32.2E	65.17 ± 0.64	24
Bosumtwi	Ghana	6.5N	1.4W	1.07	10.5
Boxhole	N. Territory, Australia	22.6S	135.2E	0.0054± 0.0015	0.17
B.P. Structure	Libya	25.3N	24.3E	< 120	2
Brent	Ontario, Canada	45.1N	78.5W	>453	3.8
Calvin	Michigan, USA	41.8N	86.0W	450 ± 10	8.5
Campo Del Cielo	Argentina	27.6S	61.7W	< 0.004	0.05
Carancas	Peru	16.7S	69.1W	0.000006	0.0135
Carswell	Saskatchewan, Canada	58.5N	109.5W	115 ± 10	39
Charlevoix	Quebec, Canada	47.5N	70.3W	342 ± 15	54
Chesapeake Bay	Virginia, U.S.A.	37.3N	76.0W	35.5 ± 0.3	40
Chicxulub	Yucatan, Mexico	21.3N	89.5W	64.98 ± 0.05	150
Chiyli	Kazakhstan	49.2N	57.9E	46 ± 7	5.5
Chukcha	Russia	75.7N	97.8E	< 70	6
Clearwater East	Quebec, Canada	56.1N	74.1W	290 ± 20	26
Clearwater West	Quebec, Canada	56.2N	74.5W	290 ± 20	36
Cloud Creek	Wyoming, USA	43.1N	106.8W	190 ± 30	7
Connolly Basin	Western Australia	23.5S	124.8E	< 60	9
Couture	Quebec, Canada	60.1N	75.3W	430 ± 25	8
Crawford	South Australia	34.7S	139.0E	> 35	8.5
Crooked Creek	Missouri, U.S.A.	37.8N	91.4W	320 ± 80	7
Dalgaranga	Western Australia	27.6S	117.3E	~ 0.27	0.024
Decaturville	Missouri, U.S.A.	37.9N	92.7W	< 300	6
Deep Bay	Saskatchewan, Canada	56.4N	103.0W	99 ± 4	13
Dellen	Sweden	61.8N	16.8E	89.0 ± 2.7	19
Des Plaines	Illinois, U.S.A.	42.1N	87.9W	< 280	8
Dhala	India	25.3N	78.1E	> 1700 < 2100	11
Dobele	Latvia	56.6N	23.3E	290 ± 35	4.5
Eagle Butte	Alberta, Canada	49.7N	110.5W	< 65	10
Elbow	Saskatchewan, Canada	51.0N	106.7W	395 ± 25	8
El'gygytgyn	Russia	67.5N	172.1E	3.5 ± 0.5	18
Flaxman	South Australia	34.6S	139.1E	> 35	10

Structure Name	Location	Lat	Lon	Age (Ma)*	Diameter (km)
Flynn Creek	Tennessee, U.S.A.	36.3N	85.7W	360 ± 20	3.8
Foelsche	N. Territory, Australia	16.7S	136.8E	> 545	6
Gardnos	Norway	60.7N	9.0E	500 ± 10	5
Glasford	Illinois, U.S.A.	40.6N	89.8W	< 430	4
Glikson	Western Australia	24.0S	121.6E	< 508	~19
Glover Bluff	Wisconsin, U.S.A.	44.0N	89.5W	< 500	8
Goat Paddock	Western Australia	18.3S	126.7E	< 50	5.1
Gosses Bluff	N. Territory, Australia	23.8S	132.3E	142.5 ± 0.8	22
Gow	Saskatchewan, Canada	56.5N	104.5W	< 250	5
Goyder	Northern Territory	13.5S	135.0E	< 1400	3
Granby	Sweden	58.4N	14.9E	~ 470	3
Gusev	Russia	48.4N	40.5E	49.0 ± 0.2	3
Gweni-Fada	Chad, Africa	17.4N	21.8E	< 345	14
Haughton	Nunavut, Canada	75.4N	89.7W	39	23
Haviland	Kansas, U.S.A.	37.6N	99.2W	< 0.001	0.015
Henbury	N. Territory, Australia	24.6S	133.1E	0.0042 ± 0.0019	0.157
Holleford	Ontario, Canada	44.5N	76.6W	550 ± 100	2.35
Ile Rouleau	Quebec, Canada	51.7N	73.9W	< 300	4
Ilumetsä	Estonia	58.0N	27.4E	~ 0.0066	0.08
Ilyinets	Ukraine	49.1N	29.1E	378 ± 5	8.5
Iso-Naakkima	Finland	62.2N	27.2E	> 1000	3
Jänisjärvi	Russia	62.0N	30.9E	700 ± 5	14
Jebel Waqf as Suwwan	Jordan	31.1N	36.8E	56 - 37	5.5
Kaalijärv	Estonia	58.4N	22.7E	0.004 ± 0.001	0.11
Kalkkop	South Africa	32.7S	24.4E	0.250 ± 0.050	0.64
Kaluqa	Russia	54.5N	36.2E	380 ± 5	15
Kamensk	Russia	48.4N	40.5E	49.0 ± 0.2	25
Kamil	Egypt	22.0N	26.1E	?	0.045
Kara	Russia	69.1N	64.2E	70.3 ± 2.2	65
Kara-Kul	Tajikistan	39.0N	73.5E	< 5	52
Kärdla	Estonia	59.0N	22.8E	~ 455	4
Karikkoselkä	Finland	62.2N	25.3E	~ 230	1.5
Karla	Russia	54.9N	48.0E	5 ± 1	10
Kelly West	N. Territory, Australia	20.0S	134.0E	> 550	10
Kentland	Indiana, U.S.A.	40.8N	87.4W	< 97	13
Keuruselkä	Finland	62.1N	24.6E	< 1800	~30
Kgagodi	Botswana	22.5S	27.6E	< 180	3.5
Kursk	Russia	51.7N	36.0E	250 ± 80	6
La Moinerie	Quebec, Canada	57.4N	66.6W	400 ± 50	8
Lappajärvi	Finland	63.2N	23.7E	73.3 ± 5.3	23
Lawn Hill	Queensland, Australia	18.7S	138.7E	> 515	18
Liverpool	N. Territory, Australia	12.4S	134.1E	150 ± 70	1.6
Lockne	Sweden	63.0N	14.8E	455	7.5
Logancha	Russia	65.5N	95.9E	40 ± 20	20
Logoisk	Belarus	54.2N	27.8E	42.3 ± 1.1	15
Lonar	India	20.0N	76.5E	0.052 ± 0.006	1.83
Luizi	Dem. Republic of Congo	10.2S	28.0E	< 573	17

Structure Name	Location	Lat	Lon	Age (Ma)*	Diameter (km)
Lumparn	Finland	60.2N	20.1E	~ 1000	9
Macha	Russia	60.1N	117.6E	< 0.007	0.3
Manicouagan	Quebec, Canada	51.4N	68.7W	214 ± 1	85
Manson	Iowa, U.S.A.	42.6N	94.6W	73.8 ± 0.3	35
Maple Creek	Saskatchewan, Canada	49.8N	109.1W	< 75	6
Marquez	Texas, U.S.A.	31.3N	96.3W	58 ± 2	12.7
Matt Wilson	Northern Territory	15.5S	131.2E	1402 ± 440	7.5
Middlesboro	Kentucky, U.S.A.	36.6N	83.7W	< 300	6
Mien	Sweden	56.4N	14.9E	121.0 ± 2.3	9
Mishina Gora	Russia	58.7N	28.1E	300 ± 50	2.5
Mistastin	Newfoundland/Labrador, Canada	55.9N	63.3W	36.4 ± 4	28
Mizarai	Lithuania	54.0N	23.9E	500 ± 20	5
Mjølnir	Norway	73.8N	29.7E	142.0 ± 2.6	40
Montagnais	Nova Scotia, Canada	42.9N	64.2W	50.50 ± 0.76	45
Monturaqui	Chile	23.9S	68.3W	< 1	0.46
Morasko	Poland	52.5N	16.9E	< 0.01	0.1
Morokweng	South Africa	26.5S	23.5E	145.0 ± 0.8	70
Mount Toondina	South Australia	28.0S	135.4E	< 110	4
Neugrund	Estonia	59.3N	23.7E	~ 470	8
Newporte	North Dakota, U.S.A.	49.0N	102.0W	< 500	3.2
New Quebec	Quebec, Canada	61.3N	73.7W	1.4 ± 0.1	3.44
Nicholson	NW Territories, Canada	62.7N	102.7W	< 400	12.5
Oasis	Libya	24.6N	24.4E	< 120	18
Obolon'	Ukraine	49.6N	32.9E	169 ± 7	20
Odessa	Texas, U.S.A.	31.8N	102.5W	< 0.0635	0.168
Ouarkiz	Algeria	29.0N	7.6W	< 70	3.5
Paasselkä	Finland	62.0N	29.1E	< 1800	10
Piccaninny	Western Australia	17.5S	128.4E	< 360	7
Pilot	NW Territories, Canada	60.3N	111.0W	445 ± 2	6
Popigai	Russia	71.7N	111.2E	35.7 ± 0.2	90
Presqu'île	Quebec, Canada	49.7N	74.8W	< 500	24
Puchezh-Katunki	Russia	57.0N	43.7E	167 ± 3	40
Ragozinka	Russia	58.7N	61.8E	46 ± 3	9
Red Wing	North Dakota, U.S.A.	47.6N	103.6W	200 ± 25	9
Riachao Ring	Brazil	7.7S	46.7W	< 200	4.5
Ries	Germany	48.9N	10.6E	15.1 ± 0.1	24
Rio Cuarto	Argentina	32.9S	64.2W	< 0.1	4.5
Ritland	Norway	59.2N	6.4E	520 ± 20	2.7
Rochechouart	France	45.8N	0.9E	201 ± 2	23
Rock Elm	Wisconsin, U.S.A.	44.7N	92.2W	< 505	6
Roter Kamm	Namibia	27.8S	16.3E	3.7 ± 0.3	2.5
Rotmistrovka	Ukraine	49.0N	32.0E	120 ± 10	2.7
Sääksjärvi	Finland	61.4N	22.4E	~ 560	6
Saarijärvi	Finland	65.3N	28.4E	> 600	1.5
Saint Martin	Manitoba, Canada	51.8N	98.5W	220 ± 32	40
Santa Fe	New Mexico , U.S.A.	35.8N	105.9W	< 1200	6-13

Structure Name	Location	Lat	Lon	Age (Ma)*	Diameter (km)
Serpent Mound	Ohio, U.S.A.	39.0N	83.4W	< 320	8
Serra da Cangalha	Brazil	8.1S	46.9W	< 300	12
Shoemaker (formerly Teague)	Western Australia	25.9S	120.9E	1630 ± 5	30
Shunak	Kazakhstan	47.2N	72.7E	45 ± 10	2.8
Sierra Madera	Texas, U.S.A.	30.6N	102.9W	< 100	13
Sikhote Alin	Russia	46.1N	134.7E	0.000066	0.027
Siljan	Sweden	61.0N	14.9E	376.8 ± 1.7	52
Slate Islands	Ontario, Canada	48.7N	87.0W	~ 450	30
Sobolev	Russia	46.3N	137.9E	< 0.001	0.053
Söderfjärden	Finland	63.0N	21.6E	~ 600	6.6
Spider	Western Australia	16.7S	126.1E	> 570	13
Steen River	Alberta, Canada	59.5N	117.6W	91 ± 7	25
Steinheim	Germany	48.7N	10.1E	15 ± 1	3.8
Strangways	N. Territory, Australia	15.2S	133.6E	646 ± 42	25
Suavijärvi	Russia	63.1N	33.4E	~ 2400	16
Sudbury	Ontario, Canada	46.6N	81.2W	1850 ± 3	130
Suvasvesi N	Finland	62.7N	28.2E	< 1000	4
Tabun-Khara-Obo	Mongolia	44.1N	109.7E	150 ± 20	1.3
Talemzane	Algeria	33.3N	4.0E	< 3	1.75
Tenoumer	Mauritania	22.9N	10.4W	0.0214 ± 0.0097	1.9
Ternovka	Ukraine	48.1N	33.5E	280 ± 10	11
Tin Bider	Algeria	27.6N	5.1E	< 70	6
Tookoonooka	Queensland, Australia	27.1S	142.8E	128 ± 5	55
Tswaing (formerly Pretoria Saltpan)	South Africa	25.4S	28.1E	0.220 ± 0.052	1.13
Tvären	Sweden	58.8N	17.4E	~ 455	2
Upheaval Dome	Utah, U.S.A.	38.4N	109.9W	< 170	10
Vargeao Dome	Brazil	26.8S	52.1W	123±1.4	12
Veevers	Western Australia	23.0S	125.4E	< 1	0.08
Vepriai	Lithuania	55.1N	24.6E	> 160 ± 10	8
Viewfield	Saskatchewan, Canada	49.6N	103.1W	190 ± 20	2.5
Vista Alegre	Brazil	26.0S	52.7W	< 65	9.5
Vredefort	South Africa	27.0S	27.5E	2023 ± 4	160
Wabar	Saudi Arabia	21.5N	50.5E	0.00014	0.116
Wanapitei	Ontario, Canada	46.8N	80.8W	37.2 ± 1.2	7.5
Wells Creek	Tennessee, U.S.A.	36.4N	87.7W	200 ± 100	12
West Hawk	Manitoba, Canada	49.8N	95.2W	351 ± 20	2.44
Wetumpka	Alabama, U.S.A.	32.5N	86.2W	81.0 ± 1.5	6.5
Whitcourt	Alberta, Canada	54.0N	115.6W	<0.0011	0.036
Wolfe Creek	Western Australia	19.2S	127.8E	< 0.3	0.875
Woodleigh	Western Australia	26.1S	114.7E	364 ± 8	40
Xiuyan	China	40.4N	123.5E	> 0.05	1.8
Yarrabubba	Western Australia	27.2S	118.8E	~ 2000	30
Zapadnaya	Ukraine	49.7N	29.0E	165 ± 5	3.2
Zeleny Gai	Ukraine	48.1N	32.8E	80 ± 20	3.5
Zhamanshin	Kazakhstan	48.4N	61.0E	0.9 ± 0.1	14