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 preforming 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.

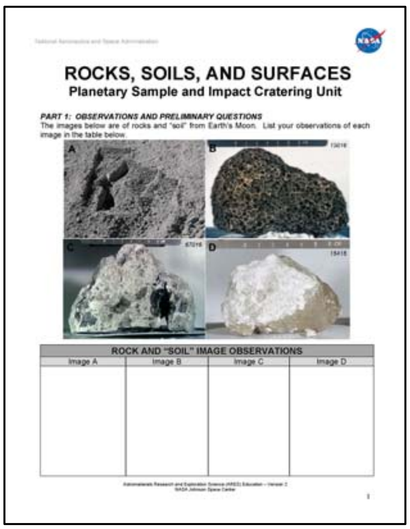
5-E Model of Inquiry: This set of activities is designed using the 5-E model of inquiry. This model of instruction is based on a constructive approach to learning where students learn by building or constructing new ideas by comparing new experiences to existing frameworks of knowledge. The 5-E model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

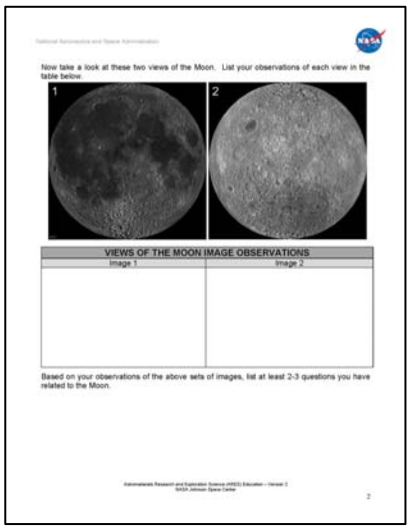
5-E Phase	General Description	Crater Comparison Activity
Engage	Teachers engage students using an activity, image, or discussion to focus students' thinking on the learning outcomes of an activity.	Students observe images of lunar rocks, "soils", and the surface. (Part 1)
Explore	Students actively explore 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)
Explain	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)
Elaborate	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)
Evaluate	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):	• *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:	• *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 asses 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*

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):	*Provide students with background knowledge and hands-on experience to gain an understanding of:* *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:	*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.*
Materials Needed:	• *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 craters, 1 rock, safety glasses (1 set per group/station)*

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



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)





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.

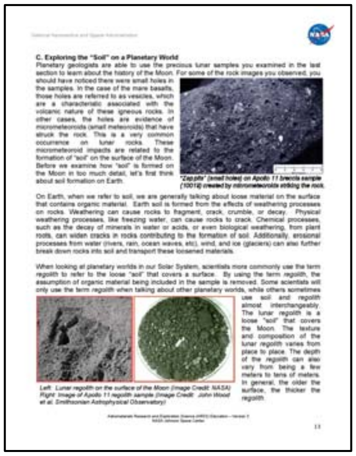
The *Student Guide* contains small images of the lunar samples for students to observe. Additional resources are available for you to choose from depending on the resources you have available. For example, you may choose to: a) Have students use the images on page 12 of the *Student Guide;* b) Print 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.

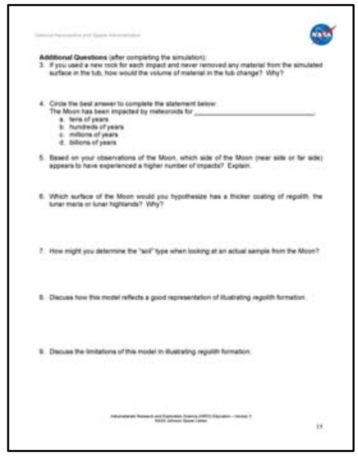
Sample answers*:

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)





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.

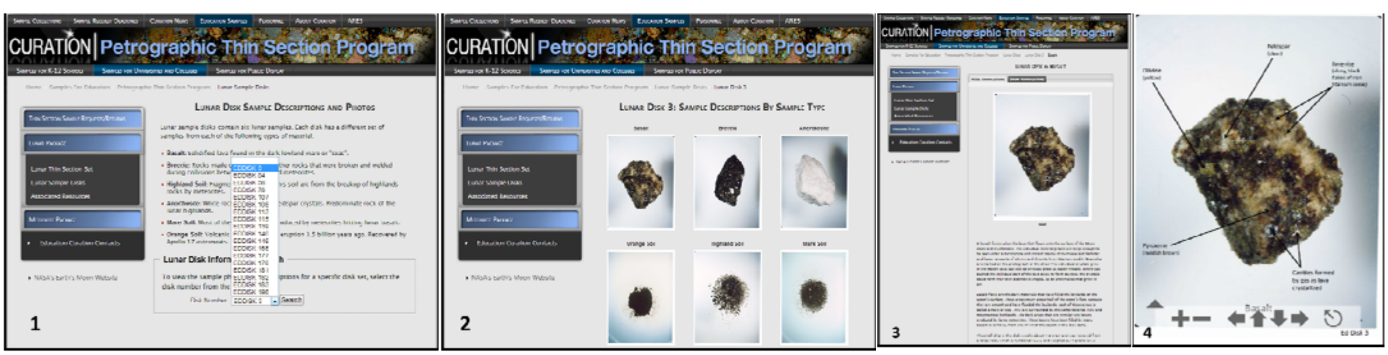
Even if you are not certified to check out a lunar sample disk, this portion of the activity can still be completed using the image provide in the *Student Guide.* Additionally, you and your students can explore other lunar samples and disks using the website listed below.

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

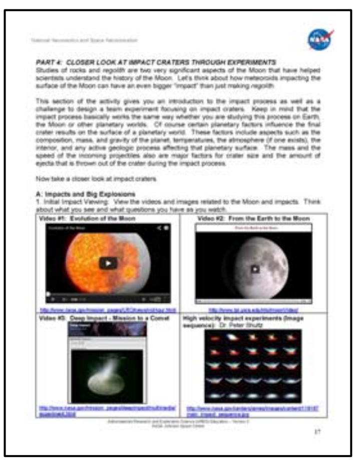
The screen shots below show that you can use the above website to:

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):	*Provide students with background knowledge and experiences to be able to design and conduct an impact experiment and analyze the data. Students will:* • *View impact videos and images; document observations and questions; and share.* • *Make impacts to gain experience and put the experience in context with their prior knowledge to help establish questions.* • *Design and conduct an impact experiment to answer their questions.* • *Compile experimental data; evaluate the process and the data.* • *Report conclusions based on their data and defend conclusions.*
Estimated Time:	*~ 2-4 class periods*
Class Time Saver:	*Have students watch website videos and images at home and record observations and questions.*
Materials Needed:	*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.*

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.

<u>Materials for Impact Boxes</u> (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.]

<u>Pre Class Preparation</u>

- 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 or 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:

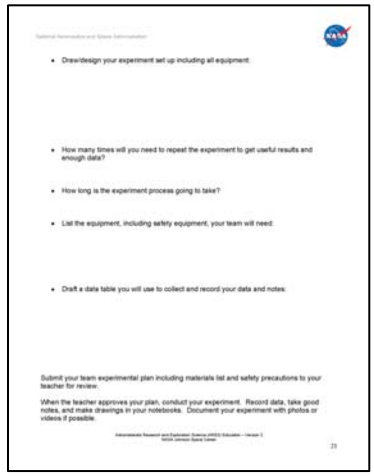
Safety Point: As students gather to make impacts, make sure they are standing up (not kneeling or sitting on the floor) when other students drop (throw) the marbles. Use safety glasses.

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.





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.

Note: If teams are having difficulty posing a question to investigate, you might ask leading questions that will help the students create their own testable question, such as: “Did you see a difference in the craters when you threw the marbles harder (more velocity)?”, “Did the craters look the same if the marbles were dropped from different heights?”, “Did the impact eject all the material from below?”, “Were the ejecta patterns all the same?”, “What happened when larger impactors hit?”, “Would mass of the impactor make a difference in the crater?”.

Make sure teams turn in their Experimental Plan to you. Check for safety, appropriateness and necessary equipment. Once approved, provide students with the necessary equipment to complete their experiments.

It is not a problem if several teams pursue the same or almost the same question. This will actually lead to good class discussions around data and experimental process.

C: Interpret Data and Report Conclusions (page 22)
Students interpret and evaluate data, draw conclusions, and report results.


National Aeronautics and Space Administration

C. Interpret Data and Report Conclusions
As you look at the data your team collected, it is important to discuss what the data can help you conclude about your question. It is also useful to reflect on your experiment and its application towards studying impacts throughout our Solar System.

- What does your data tell you? Discuss all interpretations of the data – there may be different interpretations.
- Do you have enough data to make a conclusion? Should you repeat the experiment to get more data?
- What conclusions can you draw about the answer to your question based on your experiment?
- What changes would you make to the procedure and experimental process if you conducted the experiment again?
- How can this experiment and results be applied to better understanding the impact process on Earth, the Moon, or other planetary worlds?
- Prepare a team report that includes your team question, experimental design, data, conclusions and recommendations for further experimental work. See your teacher for the proper format for the report and the report deadline. Be prepared to answer questions from other teams that may challenge your process or conclusions. Critical review by peers and courteous critique is a major part of the scientific process.

Astromaterials Research and Exploration Science (ARES) Education – Version 2
NASA Johnson Space Center

22

Student teams use their data analysis to make data interpretations and draw conclusion(s) regarding their experimental question. They assess their experimental plan and make suggestions related to how it could be changed or improved. They apply their experimental results to better understand the impact process on Earth and other planetary worlds.

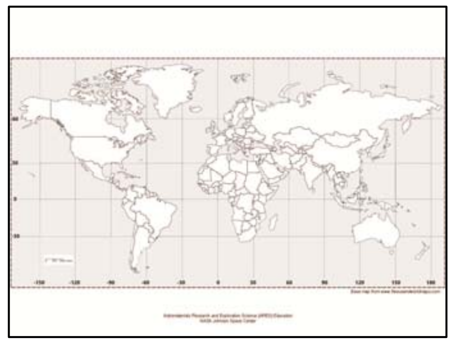
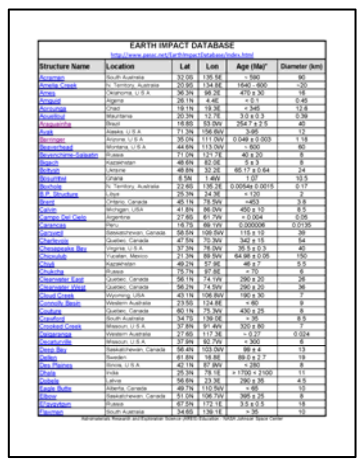
The teacher may have to coach the teams through this process by engaging the groups with gentle probing questions. The teams are working through a perhaps unfamiliar process that simulates the process scientific teams use as they work through the implications of their data.

The teams prepare and deliver a final report on their experiment. The report format is up to the teacher. It may be a short report or a major project that involves PowerPoint presentations for example. As the teams report, allow the other teams to question the experimental process and other aspects in the report. Teams should be ready to defend/explain their decisions and interpretations; this courteous but often critical exchange is a real aspect of the scientific process.

Use the final team reports as the assessment tool for the teacher to determine participation, depth of understanding of the science process, and skills.

PART 5: *CRATER INVESTIGATORS*	
Main Goal(s):	• *Introduce students to identifying and investigating craters on Earth.* • *Have students plot and analyze a subset of data to illustrate an aspect of their choice about craters on Earth.* • *Have students plan a potential lunar crater investigation.* • *Discuss the importance of studying rocks, "soils", and surfaces.*
Estimated Time:	*~2 class periods*
Class Time Saver:	*Have students read pages 23 for homework.*
Materials Needed:	• *Student Guide pages 23 - 27* • *Earth Impact Database Handout* • *Google Earth and Google Moon (optional)*



As students will have a good background on how impact craters form on a planetary surface, Part 5 of the activity will have them consider how they can identify craters in remote sensing imagery as well as how they can use collected data to conduct an investigation focusing on craters.

A. EARTH CRATER INVESTIGATORS

As you begin, have students discuss the questions on page 23 of the *Student Guide*. These questions will simply give your students the chance to reflect on what they may know (or think they know) about impact craters on Earth. Once you have discussed this information as a class, have students focus their attention on impact craters on Earth. Distribute a copy of the

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.

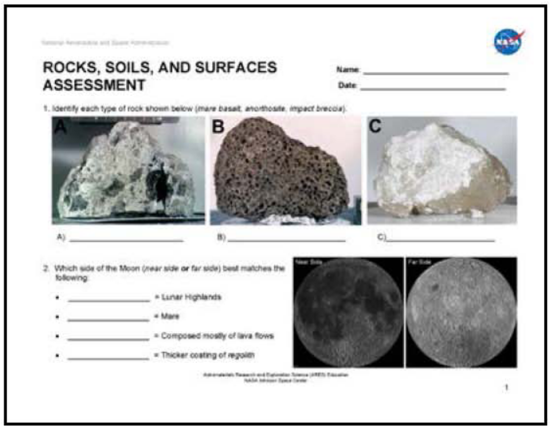
Based on what they have learned in this activity, ask students what they could do if they wanted to further investigate and gain a deeper understanding of the history of the Moon or even our Solar System. Potential answers include investigating additional lunar samples or investigating impact craters 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: *EVALUATION*	
Main Goal(s):	*Evaluate student mastery of objectives*
Estimated Time:	*~20-30 minutes*
Class Time Saver:	*No recommendations.*
Materials Needed:	• *Rocks, Soils, and Surfaces Assessment*

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.


ROCKS, SOILS, AND SURFACES ASSESSMENT

Name: ______

Date: ______

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

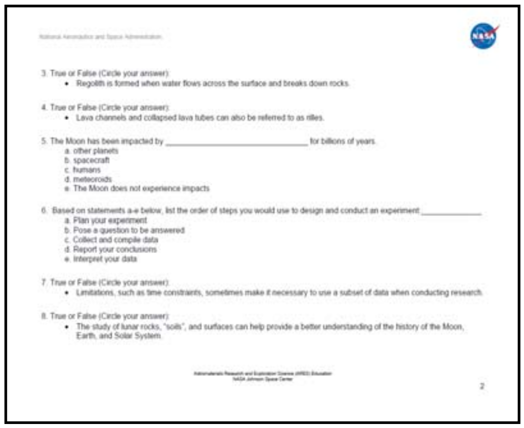
A B C

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

1


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.

2

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

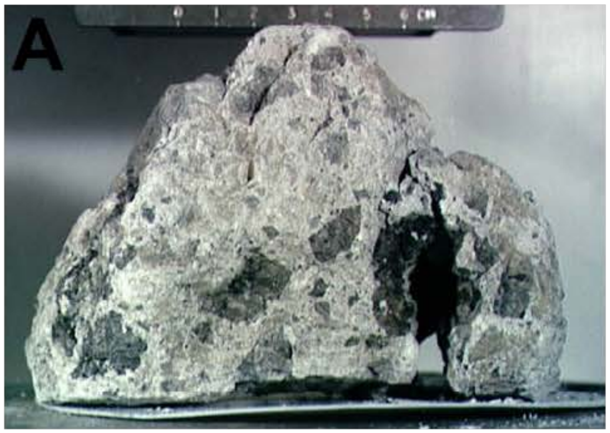
1. A) Impact Breccia B) Mare Basalt C) Anorthosite (1 point each answer)
2. Far Side (Lunar Highlands); Near Side (Mare); Near Side (Composed mostly of lava flows); Far Side (Thicker coating of regolith) (1/2 point each correct answer)
3. False (1 point)
4. True (1 point)
5. d. Meteoroids (1 point)
6.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

ROCKS, SOILS, AND SURFACES ASSESSMENT

Name: ______________________________

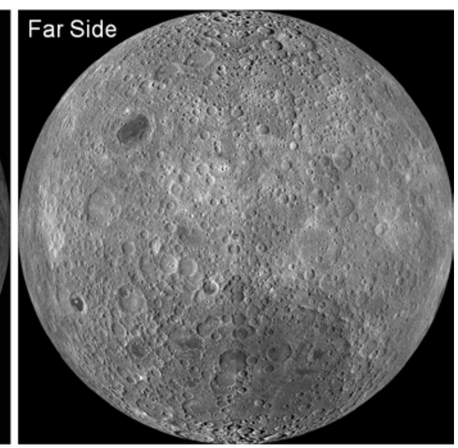
Date: ______________________________

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
Amguid	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
Araguainha	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
Boltysh	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
Kaluga	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
Keurusselkä	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
Ouarkziz	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'ile	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
Suavjärvi	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
Whitecourt	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