Module 2: Analysis of Lunar Features and Their Formation

In this module, students will investigate the Moon's geologic history by modeling the process of regolith formation and explore the roles of impact cratering, volcanic eruptions, and lava layering on the Moon. Additionally, they will continue their exploration of the properties of the Moon and will create their own hypotheses of the Moon's geological history. Finally, the students will assess the role that the Moon Mineralogy Mapper instrument plays in testing scientists' current understanding of the Moon's composition and geologic history.

Activity 2-1: Regolith Formation (30 minutes)

Students model the process of regolith formation and compare the process at work on Earth and on the Moon.

Activity 2-2: Impact Craters (60 minutes)

Students model factors affecting the formation of craters and ejecta on the Moon using everyday materials. They collect data on their observations and make inferences based on these data.

Activity 2-3: Lava Layering (40 minutes)

Students explore the stratigraphy of lava flows produced by multiple eruptions on the Moon. They observe patterns associated with these eruptions and use their observations to make conclusions about these processes occurring throughout the Moon's history.

Activity 2-1: Regolith Formation

Overview

In this activity, students model the process of regolith formation and compare the process at work on Earth versus the Moon.

Learning Objectives

The student will:

- Model the formation of regolith on the Moon
- Model the formation of regolith on Earth

Key Concepts

- Soil and regolith are not the same thing
- Soil is comprised of organic matter and so is non-existent on the moon
- Weathering processes create regolith on Earth
- Meteoric impacts create regolith on the Moon
- Moon's regolith is not disrupted by the most of the processes occurring on Earth due to the Moon's lack of an atmosphere
- Both the Moon and the Earth are at risk of future meteoric impacts

Materials

For each team of two to three students

- toasted white bread or light-colored crackers/cookies
- toasted golden wheat or dark-colored crackers/cookies
- bread
- small pan
- sand paper, nail file, or
- edge of ruler
- ice cube with sand inside
- tray
- fist-size rock

Preparation

1. Review and prepare materials listed on the student sheet.
2. Toast, crackers, or brittle cookies can be used in this activity. Toast is the least expensive but most time consuming choice. In any case, students will need two different colors of materials for procedure C; for example, vanilla and chocolate graham crackers. Invariably, students get hungry at the sight of food, so you may want to reserve some clean materials for consumption or use something other than a rock for the projectile.

Preparation continued on next page.

Preparation continued

3. To prepare bread: use a conventional oven, toaster, or sun-dry method to produce the most crisp and brittle toast. Toast one loaf of white bread and one loaf of golden wheat or rye bread. Note that whole wheat bread does not get brittle enough.
4. For procedure B, fill margarine containers (one for each group) with water and sand, then freeze. The more sand, the better the simulation of a real rock.
5. For procedure C, do not use glass pans. Large plastic tubs are preferred for this procedure. Recyclable aluminum roasting pans or shallow cardboard boxes work as well.

The Activity

1. Divide the students into cooperative groups and distribute materials.
2. Discuss the definition of regolith. Have students guess how regolith is formed on Earth and on the Moon. Ask students for justification.
3. If sand paper or nail files are not available, then students can use the edge of a ruler to illustrate the effects of sandblasting in procedure A. Caution students to use a collection tray in the sink in procedure B to avoid sand-clogged drains. An alternative to using a faucet is to have the students pour a steady stream of water from beakers onto their ice cube rocks to illustrate the effects of falling water.
4. Have students guess individually, then discuss in groups, what the surface of the Moon is like (hard rocks, fine dust, large boulders). Ask students for justification of their answers.
5. Refer to a photograph of an astronaut's bootprint on the surface of the Moon (included below). Give students the opportunity to change or confirm their guesses.
6. Procedure C is best done outside. Drop the rock from waist high. Sometimes the impacting rock causes the pan to bounce so you may want to secure the pan to the ground with tape. Students should stand back as a safety precaution.

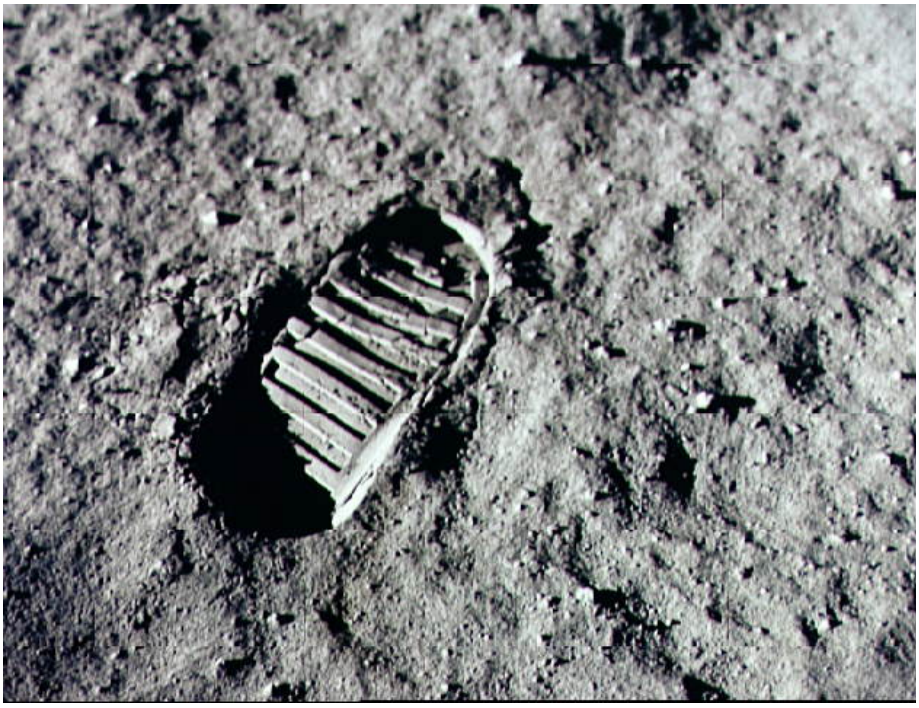

Image courtesy of NASA—Apollo 11 Bootprint

Analysis

1. After participating in the activity, have the whole class compare and contrast regolith formation and ask each small group to verify their original guesses.

Background

The loose, fragmental material on the Moon's surface is called **regolith**. This regolith, a product of **meteoritic bombardment**, is the debris thrown out of the **impact craters**. The composition and texture of the lunar regolith varies from place to place depending on the **rock** types impacted. Generally, the older the surface, the thicker the regolith. The regolith on young **maria** may be only 2 meters thick; whereas, it is perhaps 20 meters thick in the older lunar **highlands**.

By contrast, regolith on Earth is a product of **weathering**. Weathering encompasses all the processes that cause rocks to fragment, crack, crumble, or decay. These processes can be *physical* (such as freezing water causing rocks to crack), *chemical* (such as decaying of minerals in water or acids), and *biological* (such as plant roots widening cracks in rocks). The rock debris caused by weathering can then be loosened and carried away by **erosional** agents -- *running water* (fast-flowing rivers, rain, ocean waves), *high-speed wind* (by itself or sandblasting), and *ice* (glaciers).

In this activity, procedures A and B challenge the students to determine the effects of wind, sandblasting, and water on regolith formation and deposition on Earth. This is followed by procedure C in which the students simulate regolith formation on the Moon by meteoritic bombardment.

Regolith formation

Procedure A: What effect does wind have on regolith formation?

1. Imagine that the piece of toasted bread is a rock on Earth. Your hand is the wind. The sand paper is wind carrying particles of sand.
2. Predict the effects of rubbing just your hand and then the sand paper across the toasted bread.
3. Now try it. Rub your hand across the **toasted bread;** observe the bread and the pieces which fall from it onto the **pan**.
   Observations:
4. This time rub the **sand paper** across the toasted bread and observe the bread and the pieces which fall from it onto the pan.
   Observations:
5. How was the effect different?
6. How is this activity related to processes on Earth?

Procedure B: What effect does falling or fast flowing water have on regolith formation?

1. How was the effect different?
2. How is this activity related to processes on Earth?
3. Imagine that the **ice cube with sand** is a rock.
   - Place this ice cube on a collection tray beneath the **water faucet**.
   - Adjust the water flow from the faucet so a medium stream hits the ice cube.
   - Observe what happens to the ice cube and the remaining particles.

4. What happened to the rock (ice cube)?

5. Describe the particles which remain.

Procedure C: Regolith Formation on the Moon

1. Do you think regolith on the Moon is formed in the same manner as on Earth? Why or why not?

Now we will investigate the effects of meteoritic bombardment on regolith formation.

2. In a small **pan**, place 2 slices of **toasted white bread** onto 3 slices of **toasted golden wheat bread**. This represents the Moon's crust.
3. Drop a **rock** onto the layers of toasted bread twice.

   Describe the bread slices and the crumbs.

4. Drop the rock 20 times onto the layers of toasted bread.

   Describe the bread slices and the crumbs.

5. Which crumbs can be seen at the surface? Why?

6. How does the thickness of the crumb layers compare after 2 hits and after 20 more hits?

Activity 2-2: Impact Craters

Overview

In this lesson, students will determine the factors affecting the appearance of impact craters and ejecta. Marbles or other spheres such as steel shot, ball bearings, golf, or wooden balls are used as impactors dropped from a series of heights onto a prepared "lunar surface."

Learning Objectives

The student will:

- Determine the factors affecting the formation of impact craters and ejecta

Key Concepts

- The Moon has been bombarded by meteorites in the past
- The meteorites have been various sizes and shapes, and have impacted at different speeds and angles
- The impacts have affected the appearance of the moon

Materials

For each team of two to three students

- Sieve, sifter, or colander
- Balance
- 3 impactors (marbles or other spheres)
- "Data Sheet" for each impactor
- 1 pan
- Meter stick
- Depression
- Lunar surface materials:
  - Flour
  - Cinnamon
  - Cocoa
- Ruler, plastic with middle
- Protractor
- Graph paper

Preparation

1. Review and prepare materials listed on the student sheet.
2. In this activity, marbles or other spheres such as steel shot, ball bearings, golf, or wooden balls are used as impactors dropped from a series of heights onto a prepared "lunar surface."
3. Using impactors of different mass dropped from the same height will allow students to study the relationship of the mass of the impactor to the crater size. Dropping impactors from different heights will allow students to study the relationship of velocity of the impactor to crater size.
4. The following materials work well as a base for the "lunar surface" topped with a dusting of cinnamon, cocoa, or other material in a contrasting color:
   - All purpose flour—reusable in this activity and keeps well in a covered container
   - Corn meal—reusable in this activity but probably not recyclable. Keeps only in freezer in airtight container.

- Baking soda—It can be recycled for use in the lava layer activity or for many other science activities. Reusable in this activity, even if colored, by adding a clean layer of new white baking soda on top. Keeps indefinitely in a covered container. Baking soda mixed (1:1) with table salt also works
- Sand and corn starch—Mixed (1:1), sand must be very dry. Keeps only in freezer in airtight container.
- Cinnamon or cocoa—Sift on top using a sieve, screen, or colander. A contrasting color to the base materials gives striking results.
- Pans should be plastic, aluminum, or cardboard. Do not use glass. They should be at least 7.5 cm deep. Basic 10"x12" aluminum dishpans or plastic tubs work fine, but the larger the better to avoid misses. Also, a larger pan may allow students to drop more marbles before having to resurface the target materials.
- A reproducible student "Data Chart" is included; students will need a separate chart for each impactor used in the activity.

The Activity

1. Begin by looking at craters in photographs of the Moon and asking students their ideas of how craters formed.
2. During this activity, the flour, baking soda, or cinnamon/cocoa may fall onto the floor and the baking soda may even be disbursed into the air. Spread a tarp or dark piece of plastic under the pan(s) to catch ejecta or consider doing the activity outside. Under supervision, students have successfully dropped marbles from second-story balconies. Resurface the pan before a high drop.

3. Since the surface of the moon is not totally smooth, it is acceptable to have a hummocky or uneven surface. You may just shake the pan/tub to "smooth" the surface. The material need not be packed down. Be sure to reapply a fresh dusting of contrast material (cinnamon/cocoa) as needed.. Remind students that better experimental control is achieved with consistent handling of the materials. For instance, cratering results may vary if the material is packed down for some trials and not for others.
4. Allow some practice time for dropping marbles and resurfacing the materials in the pan before actually recording data.
5. Because of the low velocity of the marbles compared with the velocity of real impactors, the experimental impact craters may not have raised rims. Central uplifts and terraced walls will be absent.
6. The higher the drop height, the greater the velocity of the marble, so a larger crater will be made and the ejecta will spread out farther.
7. If the impactor were dropped from 6 meters, then the crater would be larger. The students need to extrapolate the graph out far enough to read the predicted crater diameter.

Analysis

1. Have the students sketch their impacts.
2. Have the students use their data sheets, where they measured crater depth (rim to floor), crater diameter (rim to rim), and drop height to analyze the impacts of drop height and speed to crater size.
3. Have the class compare and contrast their hypotheses on those things that affect the appearance of craters and ejecta.

Extensions

1. As a grand finale for your students, demonstrate a more forceful impact using a slingshot.
2. What would happen if you change the angle of impact? How could this be tested? Try it! Do the results support your hypothesis? If the angle of impact is changed, then the rays will be concentrated and longer in the direction of impact. A more horizontal impact angle produces a more skewed crater shape, or oblique crater.
3. To focus attention on the rays produced during an impact, place a paper bulls-eye target with a central hole on top of a large, flour-filled pan. Students drop a marble through the hole to measure ray lengths and orientations.
4. Use plaster of Paris or wet sand instead of dry materials.
5. Videotape the activity.
6. Some scientists think the extinction of the dinosaurs was caused by massive global climate changes because of a meteorite impact on Earth; some disagree. Summarize the exciting work that has been done at Chicxulub on the Yucatan coast of Mexico. (http://www.jpl.nasa.gov/news/news.php?feature=8)
7. Some scientists think Earth was hit by an object the size of Mars that caused a large part of Earth to "splash" into space, forming the Moon. Do you agree or disagree? Explain your answer. (http://starchild.gsfc.nasa.gov/docs/StarChild/questions/question38.html)

Image courtesy of NASA—Artist's rendering of the Chicxulub crater at the time of impact.

8. Physics students could calculate the velocities of the impactors from various heights. [Answers from heights of 30 cm, 60 cm, 90 cm, and 2 m should, of course, agree with the velocity values shown on the "Impact Craters - Data Chart".]

Background

The circular features so obvious on the Moon's surface are **impact craters** formed when **impactors** smashed into the surface. The explosion and excavation of materials at the impacted site create piles of rock (called **ejecta**) around the circular hole as well as bright streaks of target material (called **rays**) thrown for great distances.

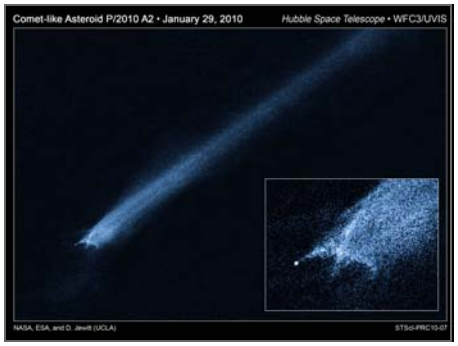

Image courtesy of NASA—Hubble Space Telescope sees suspected asteroid-asteroid collision

Two basic methods forming craters in nature are:

1. Impact of a **projectile** on the surface and
2. Collapse of the top of a **volcano** creating a crater termed *caldera.* By studying all types of craters on Earth, and by creating impact craters in experimental laboratories, geologists concluded that the Moon's craters are impact in origin.

The factors affecting the appearance of impact craters and ejecta are the size and velocity of the impactor, and the geology of the target surface.

Image courtesy of USGS—Crater Lake in Oregon created by the collapse of Mount Mazama Volcano

By recording the number, size, and extent of erosion of craters, **lunar geologists** can determine the ages of different surface units on the Moon and can piece together the geologic history. This technique works because older surfaces are exposed to impacting **meteorites** for a longer period of time than are younger surfaces.

Impact craters are not unique to the Moon. They are found on all the terrestrial planets and on many moons of the outer planets.

On Earth, impact craters are not as easily recognized because of weathering and erosion. Famous impact craters on Earth are Meteor Crater in Arizona, U.S.A.; Manicouagan in Quebec, Canada; Sudbury in Ontario, Canada; Ries Crater in Germany, and Chicxulub on the Yucatan coast in Mexico. Chicxulub is considered by most scientists as the source crater of the catastrophe that led to the extinction of the dinosaurs at the end of the Cretaceous period. An interesting fact about the Chicxulub crater is that you cannot see it. Its circular structure is nearly a kilometer below the surface and was originally identified from magnetic and gravity data.

Images courtesy of NASA Solar System and NASA Earth Observatory—from left to right, respectively, Meteor Crater in Arizona, U.S.A., Manicouagan in Quebec, Canada, and Ries Crater in Germany

STUDENT

Impact Cratering

Procedure

Making an hypothesis

1. After looking at photographs of the Moon, how do you think the craters were formed?

2. What do you think are factors that affect the appearance and size of craters and ejecta?

Preparing a "lunar" test surface

1. Fill a **pan** with **surface material** to a depth of about 2.5 cm. Gently smooth the surface, and then tap the pan to make the materials settle evenly. Do NOT pack it tightly.
2. Sprinkle a fine layer of **cinnamon or cocoa** evenly and completely over the surface. Use a **sieve** or **sifter** for more uniform layering.
3. What does this "lunar" surface look like before testing?

Cratering Process

1. Use the **balance** to measure the mass of each **impactor**. Record the mass on the "**Data Chart**" for this impactor.
2. Drop impactor #1 from a height of 30 cm (~knee height) onto the prepared surface.
3. **Measure** the diameter and depth of the resulting crater.
4. Note the presence of ejecta (rays). Count the rays, measure, and determine the average length of all the rays.
5. Record measurements and any other observations you have about the appearance of the crater on the Data Chart.
6. Repeat steps 2 through 5 for impactor #1, increasing the drop heights to 60 cm (~waist height), 90 cm (~shoulder height), and 2 meters (over the head). Complete the Data Chart for each of these heights. Note that the higher the drop height, the faster the impactor hits the surface.
7. Now repeat steps 1 through 6 for two more impactors. Use a separate Data Chart for each impactor.
8. Compute the average values.

Graphing Your Results

- **Graph #1:** Average crater diameter vs. impactor height or velocity.
- **Graph #2:** Average ejecta (ray) length vs. impactor height or velocity. Note: on the graphs, use different symbols (e.g., dot, triangle, plus, etc.) for different impactors.

Results

STUDENT

1. Is your hypothesis about what affects the formation and size of craters supported by test data? Explain why or why not.

2. What do the data reveal about the relationship between crater size and velocity of impactor?

3. What do the data reveal about the relationship between ejecta (ray) length and velocity of impactor?

4. If the impactor were dropped from 6 meters, would the crater be larger or smaller? How much larger or smaller? (Note: the velocity of the impactor would be 1,084 cm/s.) Explain your answer.

5. Based on the experimental data, describe the appearance of an impact crater.

The size of a crater made during an impact depends not only on the mass and velocity of the impactor, but also on the amount of kinetic energy possessed by the impacting object. Kinetic energy, energy in motion, is described as: KE = 1/2(mv2), where, m = mass and v = velocity. During impact, the kinetic energy of an asteroid is transferred to the target surface, breaking up rock and moving the particles around.

6. How does the kinetic energy of an impacting object relate to crater diameter?

7. Looking at the results in your Data Tables, which is the most important factor controlling the kinetic energy of a projectile, its diameter, its mass, or its velocity?

8. Does this make sense? How do your results compare to the kinetic energy equation?

9. Try plotting crater diameter vs. kinetic energy as Graph #3. The product of mass (in gm) and velocity (in cm/s) squared is a new unit called “erg.”

Impactor #		STUDENT
	Approximate Size	
	Approximate Weight	Student Name: _____ Date: _____ Class:_____

		Trial 1	Trial 2	Trial 3	Total	Average
Drop Height = 30 cm Velocity = 242 cm/s	Crater Diameter					
	Crater Depth					
	Average Length of All Rays					
Drop Height = 60 cm Velocity = 343 cm/s	Crater Diameter					
	Crater Depth					
	Average Length of All Rays					
Drop Height = 90 cm Velocity = 420 cm/s	Crater Diameter					
	Crater Depth					
	Average Length of All Rays					
Drop Height = 2 m Velocity = 626 cm/s	Crater Diameter					
	Crater Depth					
	Average Length of All Rays					

Graph Your Results

STUDENT

Activity 3-3: Lava Layering

Overview

The focus of this activity is on the patterns of lava flows produced by multiple eruptions. We use a short cup (or plastic soda cap) to hold the baking soda because we are looking at the flows and not constructing an actual volcano model. Volcanoes, like those with which we are familiar, are not present on the Moon. Three well-known areas on the Moon interpreted as important volcanic complexes are: Aristarchus Plateau, the Marius Hills, and Rumker Hills (both located in Oceanus Procellarum). These areas are characterized by sinuous rilles (interpreted as former lava channels and/or collapsed lava tubes) and numerous domes.

Learning Objectives

- Model the stratigraphy of lava flows produced by multiple eruptions

Key Concepts

- The Moon has experienced volcanic activity with multiple lava flow events
- Meteoric bombardment causes erosion of the regolith which makes interpreting lava flows difficult
- The study of the layering of the rock is called “stratigraphy”
- Younger flows tend to cover older ones and are thus located closer to the surface of the Moon

Materials

For each team of two to three students

- Small paper cups (some cut to 2.5cm in height) or plastic soda caps
- Cafeteria tray or cookie sheet, 1 for each eruption source
- Tape
- Tablespoon
- Baking soda
- Measuring cup
- Vinegar
- Food coloring, 4 colors;
  - for example, red, yellow, blue, green
- Playdough or clay in the same 4 colors as the food coloring
- Plastic knife, string, or dental floss: to slice through the layers
- Student Sheets duplexed

Preparation

- Baking soda-vinegar solutions and playdough are used to model the basaltic lavas.
- Different colors identify different eruption events; this activity calls for 4 colors.
- Students will be asked to observe where the flows traveled and to interpret the resulting stratigraphy.
- Students will be asked to create a map of their lava flows.
- Cover the work area and be prepared for spills!

You may use store-bought play-dough or homemade recipes.

Play Dough (stove-top recipe):

Best texture and lasts for months when refrigerated in an air tight container.

- 2 cups flour
- 1/3 cup oil, scant
- 1 cup salt
- 2 cups cold water
- 4 teaspoons cream of tarter
- food colorings (20 drops more or less)

Make this large batch one color or divide ingredients in half to make 2 colors. You will need 4 colors total. Combine ingredients and cook mixture in a large sauce pan, stirring constantly, until the dough forms a ball. Turn dough out onto a floured surface to cool. Then kneed until smooth and elastic. Cool completely; refrigerate in air tight containers.

Play Dough (no-cooking recipe)"

- 2 cups flour
- 2 Tablespoons oil
- 1 cup salt
- 1 cup cold water
- 6 teaspoons alum or cream of tartar food colorings (as above)

Make this large batch one color or divide ingredients in half to make 2 colors. You will need 4 colors total. Mix ingredients and kneed until smooth and elastic. Store in air tight containers.

In Class

This activity can be done individually or in cooperative teams. Making a vertical cut through the flows reveals, quite dramatically, the stratigraphy of the section.

Background

Dark, flat **maria** (layers of **basaltic lava** flows) cover about 16 percent of the Moon's total surface. They are easily seen on a full Moon with the naked eye on clear nights from most backyards. The maria, quite similar to Earth's basalts, generally flowed long distances ultimately flooding low-lying areas such as **impact** basins. Yet, the **eruption sources** for most of the lunar lava flows are difficult to identify. The difficulty in finding source areas results from burial by younger flows and/or erosion from meteoritic bombardment.

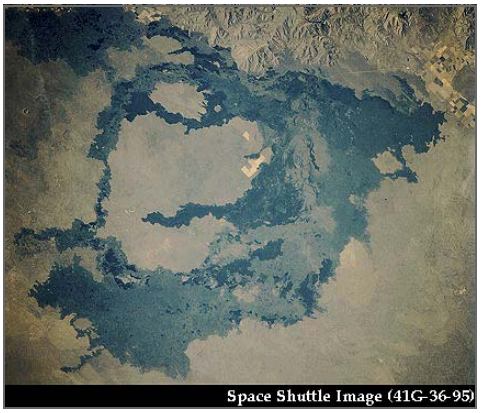

Image courtesy of NASA—Lava field at Craters of the Moon in Idaho; there are over 60 lava flows, a few of which you can discern in the image.

Generally, the overall slope of the surface, local topographic relief (small cliffs and depressions), and eruption direction influence the path of lava flows. Detailed maps of the **geology** of the Moon from photographs reveal areas of complicated lava layering. The study of rock layering is called **stratigraphy**.

Image courtesy of NASA—The Galileo spacecraft sent back this image of the moon on its way to the outer solar system. Tycho Impact Basin is the bright crater at the bottom of the image.

On the Moon, older flows become covered by younger flows and/or become more pocked with impact craters. On Earth, older lava flows tend to be more weathered (broken) and may have more vegetation than younger flows. Field geologists use differences in roughness, color, and chemistry to further differentiate between lava flows. They also follow the flow margins, **channels**, and **levees** to try to trace lava flows back to the source area.

The focus of this activity is on the patterns of lava flows produced by multiple eruptions. We use a short cup to hold the baking soda because we are looking at the flows and not at constructing a volcano model. Volcanoes, like those so familiar to us on Earth and Mars, are not present on the Moon. Three well-known areas on the Moon interpreted as important volcanic complexes are: Aristarchus plateau, and the Marius Hills and Rumker Hills (both located in Oceanus Procellarum). These areas are characterized by sinuous rilles (interpreted as former lava channels and/or collapsed lava tubes) and numerous domes.

Lava Layering

Procedure

1. Take one **paper cup/soda cap** and secure it onto the tray. (You may use a small loop of tape on the outside bottom of the cup.) This short cup is your eruption source and the tray is the original land surface.
2. Place one **Tablespoon of baking soda** in this cup.
3. Fill 4 tall paper cups each with **1/8 cup of vinegar**.
4. To each paper cup of vinegar add 3 drops of **food coloring**; make each cup a different color. Set them aside.
5. Set aside small balls of **playdough**, one of each color.
6. You are now ready to create an eruption. Pour red-colored vinegar into your source cup and watch the eruption of "lava."
7. As best you can, use red playdough to cover the areas where red "lava" flowed.
8. Repeat steps 6 and 7 for each color of vinegar and playdough. You may add fresh baking soda to the source cup or spoon out excess vinegar from the source cup as needed.

Results

1. After your four eruptions, can you still see the original land surface (tray)? Where?

2. Describe what you see and include observations of flows covering or overlapping other flows. Sketch in the box on the following page.

3. Where is the oldest flow?

4. Where is the youngest flow?

5. Did the flows always follow the same path? (be specific)

6. What do you think influences the path direction of lava flows?

7. If you had not watched the eruptions, how would you know that there are many different layers of lava? Give at least 2 reasons:

Results continued

Sketch:

8. Which of the reasons listed in answer 7 could be used to identify real lava layers on Earth?

9. What are other ways to distinguish between older and younger layered lava flows on Earth?

10. Which of the reasons listed in answer 9 could be used to identify lava layers on the Moon?

11. What are other ways to distinguish between older and younger layered lava flows on the Moon?

12. Make a vertical cut through an area of overlapping playdough "lava" layers. Draw what you see in the vertical section. Color your sketch and add these labels: **oldest flow, youngest flow**.

Vertical section

through the flows