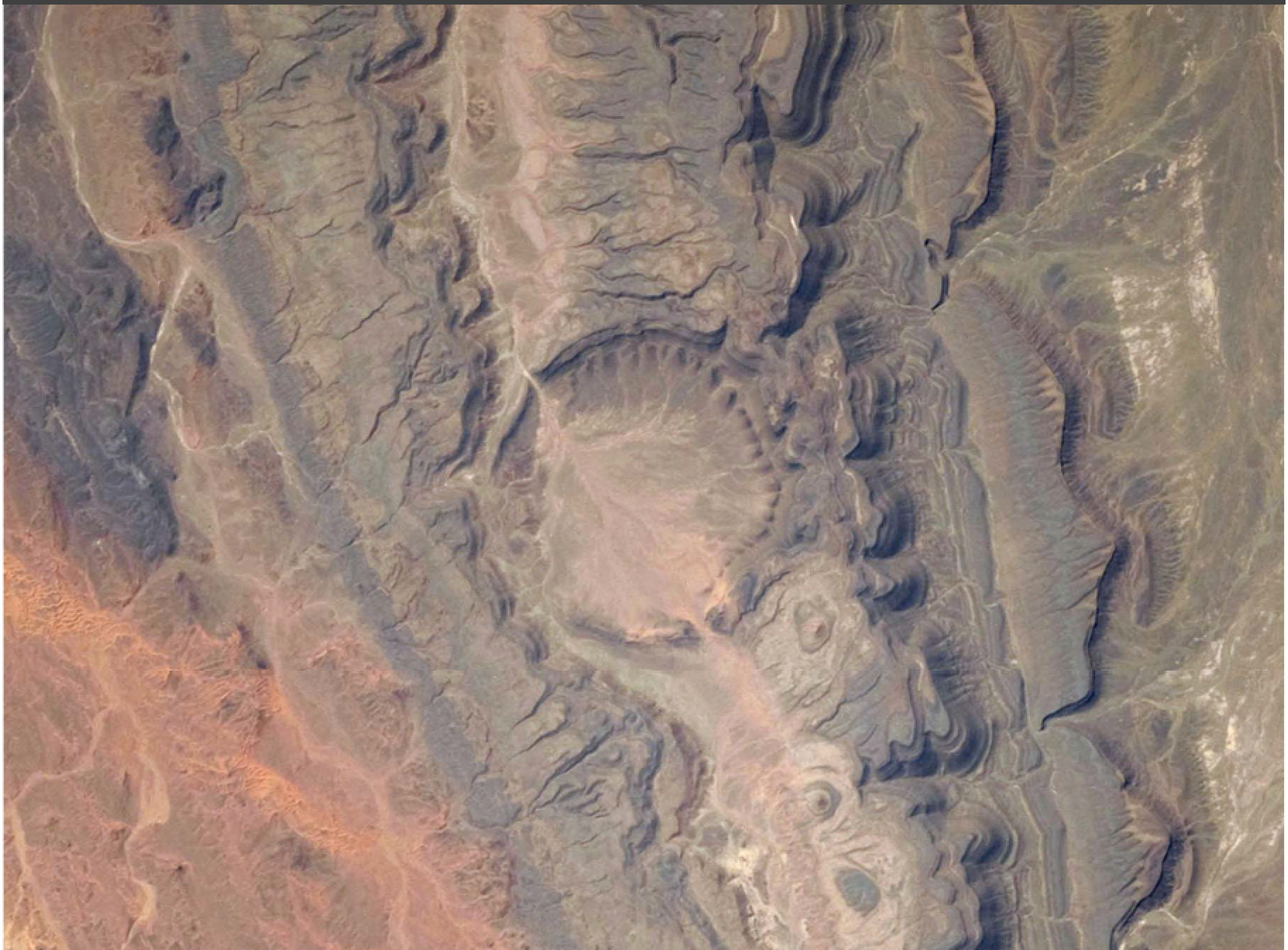
National Aeronautics and
Space Administration

CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds



STUDENT GUIDE

CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds

STUDENT GUIDE

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CRATER COMPARISONS

Investigating Impact Craters on Earth and Other Planetary Worlds

PART 1: OBSERVATIONS AND PRELIMINARY QUESTIONS

The images below are of impact craters from different planetary worlds in our Solar System. In the table below, list your observations of similarities and differences of the visible characteristics of these craters.

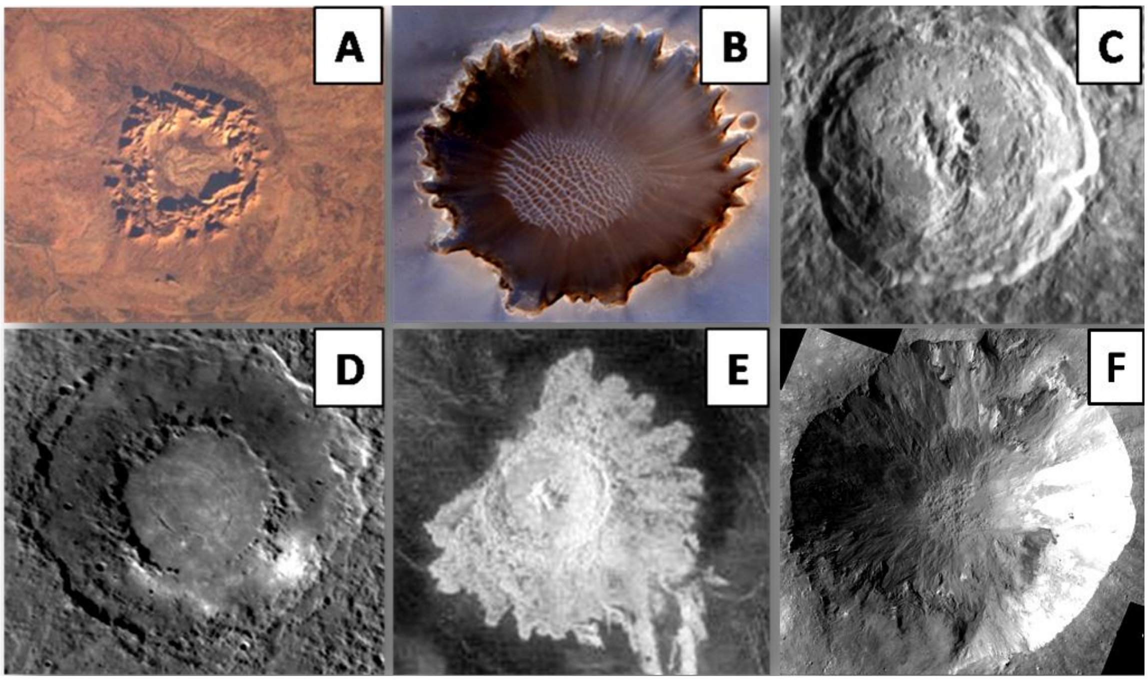


Image Credit: NASA

SIMILARITIES	DIFFERENCES

Based on your observations of the above images, list at least 1 question you have about impact craters in the space below?

PART 2: BACKGROUND INFORMATION ON IMPACT CRATERS

A. Causes of Impacts

Impact craters are features created on the surface of a planetary body when a meteoroid strikes the surface creating a bowl-shaped hole. Meteoroids can be particles of cosmic dust, parts of asteroids, planets, moons, leftover material from the formation of our Solar System, or even comets – objects made of rock and ice that travel through our Solar System. Small meteoroids burn up in our atmosphere. Those that are large enough to make it through the atmosphere, strike the surface creating an impact crater. The most common meteorites found on Earth are fragments of asteroids and other planets. The number and sizes of impact craters found on the surface of a planetary world vary.

> **Meteoroid:** A chunk of rock or ice orbiting the Sun inside the Solar System.
>
> **Meteor:** What we see when a meteoroid attempts to pass through Earth's atmosphere and burns up.
>
> **Meteorite:** Left over material that survives the trip through the atmosphere and is found on the surface.

Believe it or not, you have probably seen hundreds of impact craters! Every time you look up at the Moon you are looking at evidence of ancient collisions in our Solar System. Impact craters are found on almost all of the rocky (terrestrial) planetary worlds (including planets, moons, and asteroids) in our Solar System. The impact process is the most common geologic process seen across our Solar System.

B. Formation of Craters

There are three main stages involved in the formation of craters:

- **Contact/compression stage:** A meteor (a meteoroid that has successfully made it through our atmosphere) traveling 10-15 kilometers per second strikes a planetary surface. As it strikes, shock waves compress the surface and cause rocky material to almost liquefy or melt.
- **Excavation stage:** Material gets ejected or thrown out of the newly formed hole in the ground.
- **Modification stage:** The ejecta settles out onto the surface and material in the walls of the newly formed crater slump. (Slump is when material moves a short distance down a slope.)

The entire crater formation process occurs in seconds. Usually much of the meteoroid is vaporized. Fragments that remain are called meteorites. The final crater will continue to be modified by gravity, erosion and/or other geologic processes shaping the surface.

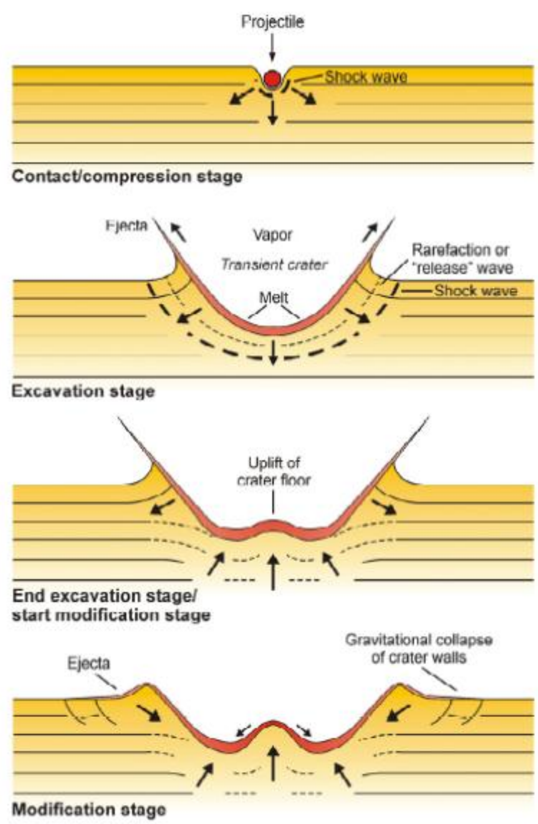


Image Credit: Planetary Science Institute

C. Crater Characteristics

There are 5 main parts or physical characteristics of a crater. These include:

- **Rim:** The raised area around the edge of the crater
- **Wall:** The sides of the crater
- **Floor:** The bottom of the crater
- **Central peak:** An uplifted mound in the floor of the crater. This peak is created when melted rock rebounds or gets uplifted during the impact event and then solidifies in that uplifted position.
- **Ejecta:** Material from inside the crater that is thrown out during the impact event. Ejecta can appear as rays or as a blanket of material surrounding the crater.

There are two general types of craters:

1. **Simple Crater:** (Crater A shown below)
   - Simple bowl shape
   - Generally smaller and younger than complex craters.

2. **Complex Crater:** (Craters B, C, and D shown below)
   - Much larger and older than simple craters.
   - Characteristics frequently include one or more of the following:
     - *Central peak* (visible in crater B)
     - *Ring of peaks* (visible in crater C)
     - *Multi-ring structure* (visible in crater D)
     - Material that has slumped along the walls giving them a terraced, step-like, or inner ring appearance.

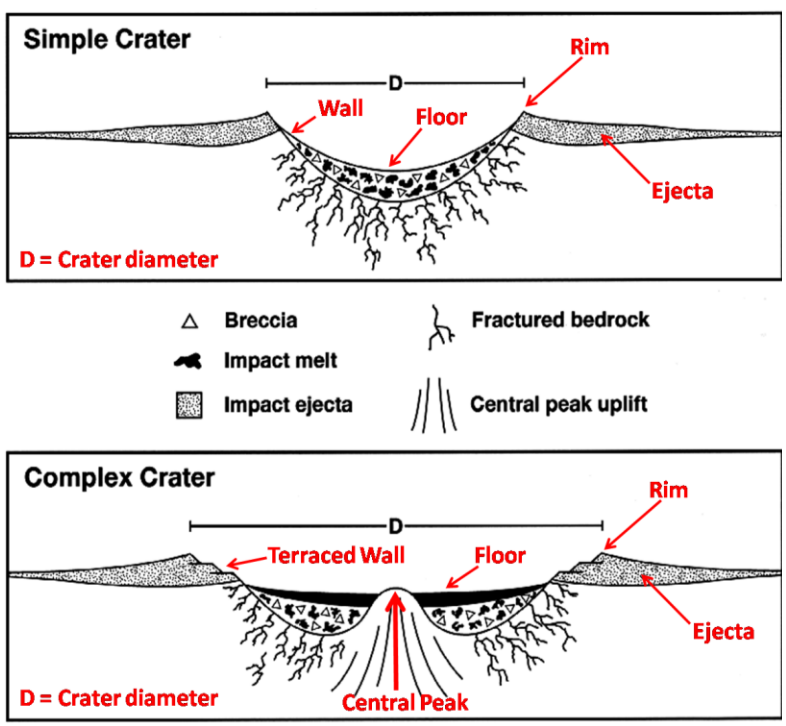


Image Credit: NASA/GSFC

Complex craters **are generally much** **<u>older</u>** **and larger than** ***simple craters*****.**

Very large craters (sometimes referred to as impact basins) are generally thought to be very old.

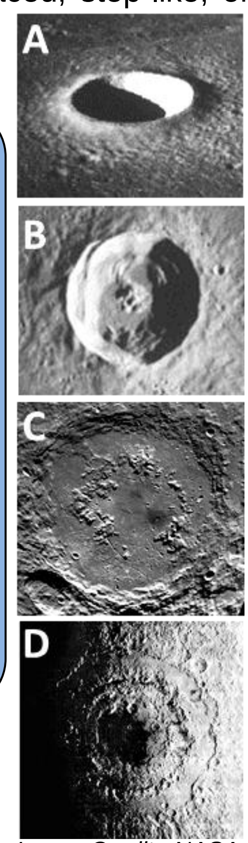


Image Credit: NASA

D. Using Craters to Reveal the Geologic History of a Surface

Impact craters and their physical characteristics open up a window into a planetary world's history and geology. Once a crater is formed, making observations of how it is modified or eroded tells us a lot about that planetary world. Craters can be modified by wind, water, tectonics, volcanic processes, or even other impacts. As part of these processes and others, craters can be covered or filled in by water, lava, sediments (sand, dust, etc), landslides, vegetation, or even ejecta from other craters.

When scientists examine the surfaces of planetary worlds, it is common for them to use relative terms for age dating. They will often refer to a surface as being *older* or *younger* relative to another. Additionally, they often refer to a process as having occurred *recently* or *long ago*. In geologic terms, *recent* may be 50,000 years ago, especially if you consider the Solar System as being 4.6 billion years old.

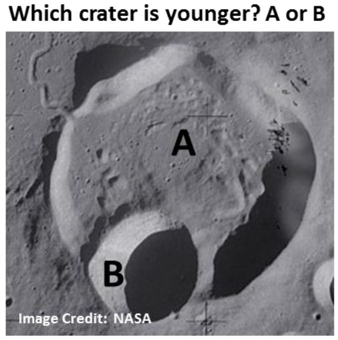
When looking at planetary surfaces, a *younger* surface is considered one that has been *recently* resurfaced by some process (wind, water, volcanics, or some other process). An *older* surface is one that has NOT been resurfaced by any process in a *long* time. Think of it this way…consider the street in front of your house. Over time, the street will become worn and will likely crack and even get pot holes. With every passing day, the street "ages". One day, the street gets repaved. That resurfaced street, if we think in relative terms, is now *younger*. The older street is still there – it is now under the newer surface. This works in a similar way with planets. A planet may be 4.6 billion years old, but if a volcano erupts lava onto the surface, that lava can fill in craters or even cover them up completely. That 4.6 billion year old surface basically just got "repaved" and this new surface is younger, with the older terrain underneath.

Geologic Principles

Scientists use geologic principles or rules to help determine relative ages. By applying these rules you can gain insight into the sequence of geologic events that took place in a region. Three of these principles include:

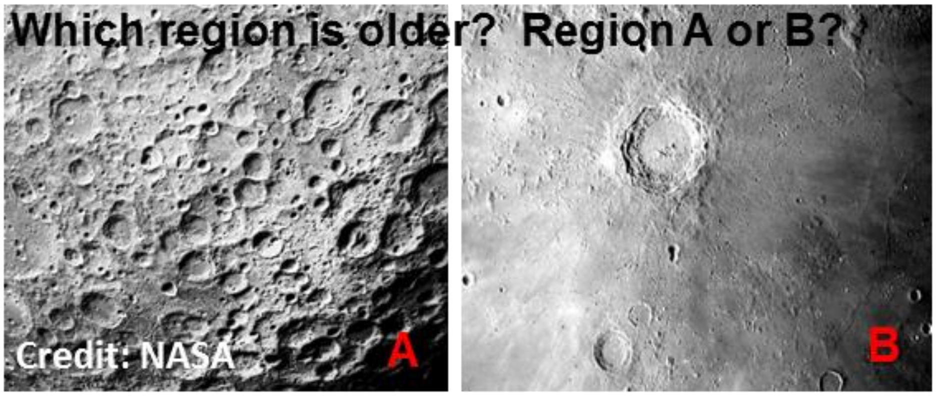
1. *Principle of Superposition:*
    - The order of layers or geologic features found on the surface provides information about which features are older or younger.
    - Features found on top are the youngest.
    - Relating to craters, if a crater is found on the floor of or overlapping the rim of another crater it must be younger. The crater on the bottom must have been there first, making it older.

Which crater is younger? A or B



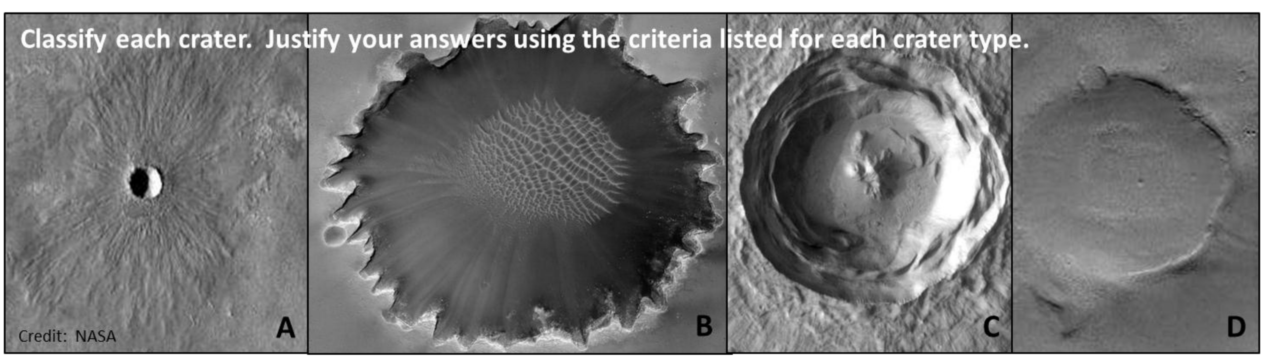
Answers: Layer A is younger; Crater B is younger.

2. *Crater Density:* When comparing areas of equal sizes, the more craters on the surface, the older that surface is.



Answer: Region A is older.

3. *Crater Classification:* The more modified a crater, the older it is. Craters generally flatten and lose shape with age. The relative ages of craters can be determined by classifying them into one of the following categories:
   - **<u>Preserved Craters:</u>** Youngest, best preserved craters
     - Circular craters
     - Raised rim
     - Look fresh
     - Can sometimes see ejecta blanket or rays of ejecta
   - **<u>Modified Craters:</u>** Middle aged craters with evidence of modification
     - Rim may appear uneven or somewhat irregular in shape
     - Floor may be partially filled in with sediment
     - Appear to be modified or eroded by wind, water, lava, or other process(es)
     - Can range from being slightly to severely modified
   - **<u>Destroyed Craters:</u>** Oldest craters that have been severely altered
     - Broken rims
     - Almost completely filled in by sediment, lava, or other material
     - Appear very flat and very worn away (severely eroded)



Sample Answers (Additional criteria may apply):
A = Preserved (circular, raised rim, looks fresh, can see ejecta blanket)
B = Modified (rim irregular in shape, crater shows modification by some process, floor filled in with sediment)
C = Modified (rim appears uneven, floor filled in with material, appears to be modified by some process)
D = Destroyed (broken rim, almost completed filled in by sediment; appears to be very worn away)

PART 3: GEOLOGIC HISTORY PRACTICE SCENARIOS

Scientists apply these geologic principles (and others) to study impact craters which can help them learn about the history of our Solar System. As the impact process is one of the most dominant processes that has affected terrestrial worlds, craters help provide clues about how our Solar System has changed over time. In addition to applying the geologic rules you just learned, other important aspects to pay attention to include:

- How the <u>frequency</u> of impacts has changed over time.
- How the <u>size</u> of material that has struck the surfaces of planets has changed over time.
- Evidence of <u>geologic</u> <u>processes</u> that may have modified craters such as wind, water, or volcanic processes. This helps scientists determine not only the types of geologic processes that have shaped (or continue to shape) the surface of a planet but also provides clues as to *when* those processes may have occurred.

It is important to note that the classification of craters can be useful in determining *when* processes may have occurred on a planetary surface. For example, preserved craters are considered relatively young craters. In addition to being relatively young, they can also help you make inferences about whether or not there are active geologic processes shaping the surface. The surface of the Earth, for example, is constantly being modified by Earth's active processes. Do you think there are many preserved craters on Earth? Probably not. Between weathering and erosion, even the youngest of craters on Earth would likely be classified as modified. The crater on the right is Barringer Crater in Arizona. This is one of the youngest craters on Earth (~50,000 years young). As the rim appears somewhat irregular in shape and there is evidence of wind erosion, it makes sense to classify this young crater as modified.

Credit: NASA JSC/ARES

Can we really state the actual age of a crater, as is mentioned with Barringer Crater above? For craters on Earth, we can. Scientists are able to use specialized dating techniques that allow them to examine rock samples collected from areas impacted to determine actual ages of craters on Earth. Based on these analyzed samples, Barringer Crater (1.2 km in diameter) is ~50,000 years old. One of the oldest craters on Earth is the Vredefort crater in South Africa. This complex crater is over 2 billion years old and is ~160 km in diameter. For most planetary worlds we do not have samples we can match as being from specific impact craters. Therefore scientists must rely on geologic principles to make inferences about relative ages.

Credit: NASA JSC/ARES

Let's see if you can apply what you have learned about craters and geologic principles to help make inferences about the geologic history of a planetary world. Two practice scenarios are given below. For each scenario you will be asked to think about two questions designed to help you gain practice in thinking about 1) the relative age of a planetary surface and 2) what you can infer about the geologic processes affecting the planet. As you answer each question, use the hints provided below to help guide your answers.

Question 1: Is the planetary surface relatively young or old? Explain.
Answer Hints: *Think about the following as you answer this question:*

- *Does the planetary surface have many or few impact craters on the surface?*
- *Does the planetary surface have many large impact craters?*

Question 2*:* What can you infer about the geologic processes affecting this planet? Explain.
Answer Hints: *Think about the following as you answer this question:*

- *Are the impact craters modified? This may mean there are (or were) active geologic processes shaping the surface.*
- *Are some impact craters preserved? This may mean there are not (or were not) any active geologic processes changing the surface when those craters formed.*

SCENARIO #1

- This planet has many impact craters. Craters range in size from relatively small (~1 km) to very large craters (~100+ km). Most of the larger craters are complex and some have visible central peaks, central rings of peaks, or look to be multi-ring basins. Most of the larger craters are modified. A few very large craters are destroyed. Smaller craters have raised rims and look preserved.

Question 1: Is the planetary surface relatively young or old? Explain.

Question 2*:* What can you infer about the geologic processes affecting this planet? Explain.

SCENARIO #2

- This planet has few impact craters. Craters range in size from relatively small (~1 km) to very large craters (~100+ km). All of the craters are modified or destroyed. Surface appears rugged in some areas; some areas appear to have evidence of water or ice; sand dunes are visible in other areas.

Question 1: Is the planetary surface relatively young or old? Explain.

Question 2*:* What can you infer about the geologic processes affecting this planet? Explain.

CHECK YOUR THINKING: Compare your answers with the sample answers provided below. Being able to recognize relevant clues to look for as you make inferences about the geologic history of a planetary world requires you to critically think and apply your knowledge.

SCENARIO #1 ANSWERS

Question 1: Is the planetary surface relatively young or old? Explain.
Answer: *The surface of this planet is <u>relatively old</u>.*

- *We can base this on the observed number of impact craters on the surface. Crater density tells us more craters = older surface. Additionally, large complex craters are generally a sign of the surface being relatively old. As this planet has a wide range of crater sizes, and the larger craters are still visible, this infers this surface is relatively old.*

Question 2*:* What can you infer about the geologic processes affecting this planet? Explain.
Answer: *Geologic processes must have been <u>active early in the planet's history</u>.*

- *As many of the large (old) craters are modified and some are even destroyed, this provides evidence that there were likely active geologic processes early in this planet's history.*
- *As most of the large craters are modified and a few are destroyed, this perhaps indicates that the active geologic processes did not occur for a long enough period of time to further erode and destroy many of these large/old craters.*
- *As the newer/younger craters are preserved craters, these are younger craters that must have formed on the surface once those geologic processes were no longer active.*

SCENARIO #2 ANSWERS

Question 1: Is the planetary surface relatively young or old? Explain.
Answer: *This planetary surface is relatively young.*

- *The primary piece of evidence to infer this surface is young is that there are few impact craters on the surface. Although there is a range of sizes of craters on the surface, some of which are large (and likely old), overall, there is not a significant number of large impact craters.*

Question 2: What can you infer about the geologic processes affecting this planet? Explain.
Answer: *This planet has had active geologic process throughout its history and continues to have current active geologic processes.*

- *As all of the craters are modified or destroyed, this indicates there has been and continues to be active geologic processes shaping the surface of this planet.*
- *The appearance of the surface may provide clues as to what type of geologic processes may be shaping the surface. Rugged terrain may indicate volcanic processes. Evidence of ice or water may indicate fluvial and ice processes. Sand dunes likely indicate there are wind processes shaping the surface.*

Were you able to successfully determine details about the geologic history of the planetary worlds included in the two scenarios? It certainly requires you to critically think about many aspects and is not always completely straight forward. For example, while we can state that larger craters are generally more common early in the history of our Solar System, we must also realize that early in history there were craters of all sizes – both large and small. As you think about the geologic history of different planetary worlds, being prepared to justify your thinking is extremely important.

As you investigate planetary worlds within our Solar System, you may end up asking some of the same questions scientists have asked for years. Why are the planetary worlds in our Solar System different from one another? Aside from Earth, are there any other planetary worlds that may have once been able to support life? How has the Solar System changed over time? How have the sizes of impacts changed over time? In the future, will Earth be struck by a large object? Is there data to support the idea that material impacting planetary surfaces today is relatively small compared to material that has impacted surfaces in the past? Although you may not be able to answer all of these questions, these ideas are part of thinking about the bigger picture.

A global view of: Top Row: Earth, Mars, Earth's Moon; Bottom Row: Mercury, Venus, and asteroid Vesta. Planetary sizes not to scale. *Images courtesy of NASA.*

PART 4: INITIAL OBSERVATIONS AND THE BIG PICTURE

Now that you have some background knowledge, let’s look at the initial set of images from Part 1 of this activity. Crater images are of Earth (A), Mars (B), Earth’s Moon (C), Mercury (D), Venus (E), and an asteroid named Vesta (F).

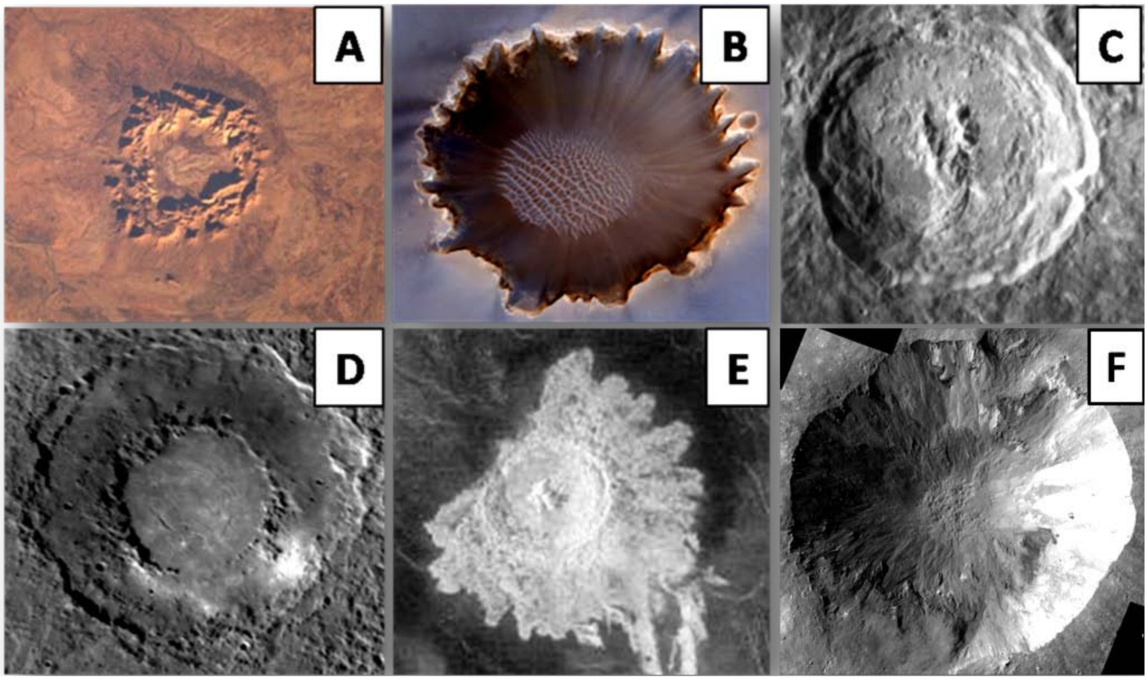


Image Credit: NASA

In the table below, use a check mark to select the type and classification of each crater:

	Image A	Image B	Image C	Image D	Image E	Image F
Simple Crater						
Complex Crater						
Preserved Crater						
Modified Crater						
Destroyed Crater						

As you completed this exercise, did you want to list comments or give an explanation to help justify your selections? Being able to list miscellaneous notes for this purpose (and others) can be very useful. You are encouraged to always have a place to list miscellaneous notes as you collect and log data.

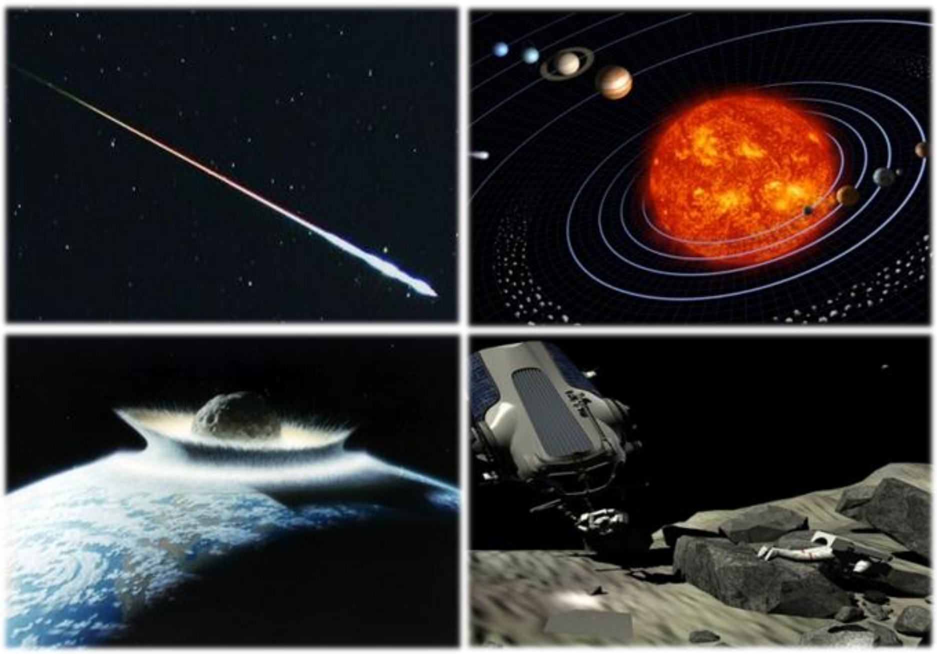
Do you think you have enough data to answer the question: **What do the characteristics of these craters reveal about the geologic history of these planetary worlds?** With just one image from each planet…definitely not. This activity will step you through an investigation to help you answer this question….but also allow you to think about the “big picture”.

THE BIG PICTURE: What Can You Learn From Studying Impacts?

What can we learn about the Solar System by studying impact craters? Does comparing Earth to other planetary worlds help us gain an understanding of our Solar System as a whole? The answer is YES! By comparing Earth to other planetary worlds (comparative planetology), scientists are able to use what they know and understand about Earth to better hypothesize and draw conclusions about other planetary worlds and our Solar System as a whole. Making detailed observations and looking for patterns is extremely important. Scientists combine their observations and apply the knowledge they have about a planetary world to interpret what those observations mean. Knowledge that can help provide additional insight includes the composition of the planetary world, temperatures, the atmosphere (if one exists), the interior, the surface features, etc. This type of information can help you understand the geologic processes that may be or may have affected a planetary world. The more knowledge you have about a planetary world as a whole, the better you can draw conclusions about its history.

When conducting any investigation, whether you are a professional or student scientist, it is important to always keep the big picture in mind. What can you learn from studying impacts? Why is it important to study impact craters? Three major reasons include being able to:

1) better understand the history of our Solar System,
2) make predictions about potential future impacts, and
3) better understand factors that may influence future robotic or even human exploration.



This investigation will enable you to examine the geologic histories of different planetary worlds through a comparison of crater characteristics. Some of you may focus your attention on using impact craters to decipher the geologic history of Earth. Others may focus on other planetary worlds like Earth's Moon, Mars, Venus, Mercury or even an asteroid named Vesta. However your class works through this investigation, it will be useful to share/compare your findings. This will help provide a context in which you can think about those big picture questions.

Remember, by studying impact craters you can learn about the geologic history of a planetary world, which in turn can provide insight into the history of our Solar System, the future of potential impacts (especially important to us here on Earth), and can help you better understand factors that may drive the future robotic or even human exploration of other worlds.

Let's continue to explore and investigate…

PART 5: CONTINUING OUR CRATER INVESTIGATION

As you work through this investigation, you will be modeling the skills and practices used by professional scientists. The image below is an illustration of the process of science. Scientists generally follow a process similar to this when conducting investigations.

You have already started completing this process. You have asked a preliminary question (Step 1), made initial observations (Step 2), and gained background knowledge (Step 3) about craters.

Other steps you will complete include:

- Step 4: Creating an Experiment Design
- Step 5: Collecting and Compiling Data
- Step 6: Displaying Data
- Step 7: Analyzing and Interpreting Data
- Step 8: Drawing Conclusions
- Step 9: Sharing Research
  (Once your investigation is complete, consider who you might present your research to.)

At this point, we are ready to move into Step 4, creating an experiment design. An experiment design is a plan or the methods (procedure) you will use to conduct your research. Creating a solid plan is extremely important as it will allow you to consistently collect and compile data. It is important to have the same data to compare one planetary world to another. If you have consistent data collected for each planetary world you investigate, you will be better prepared to display, analyze, and interpret that data in order to draw conclusions.

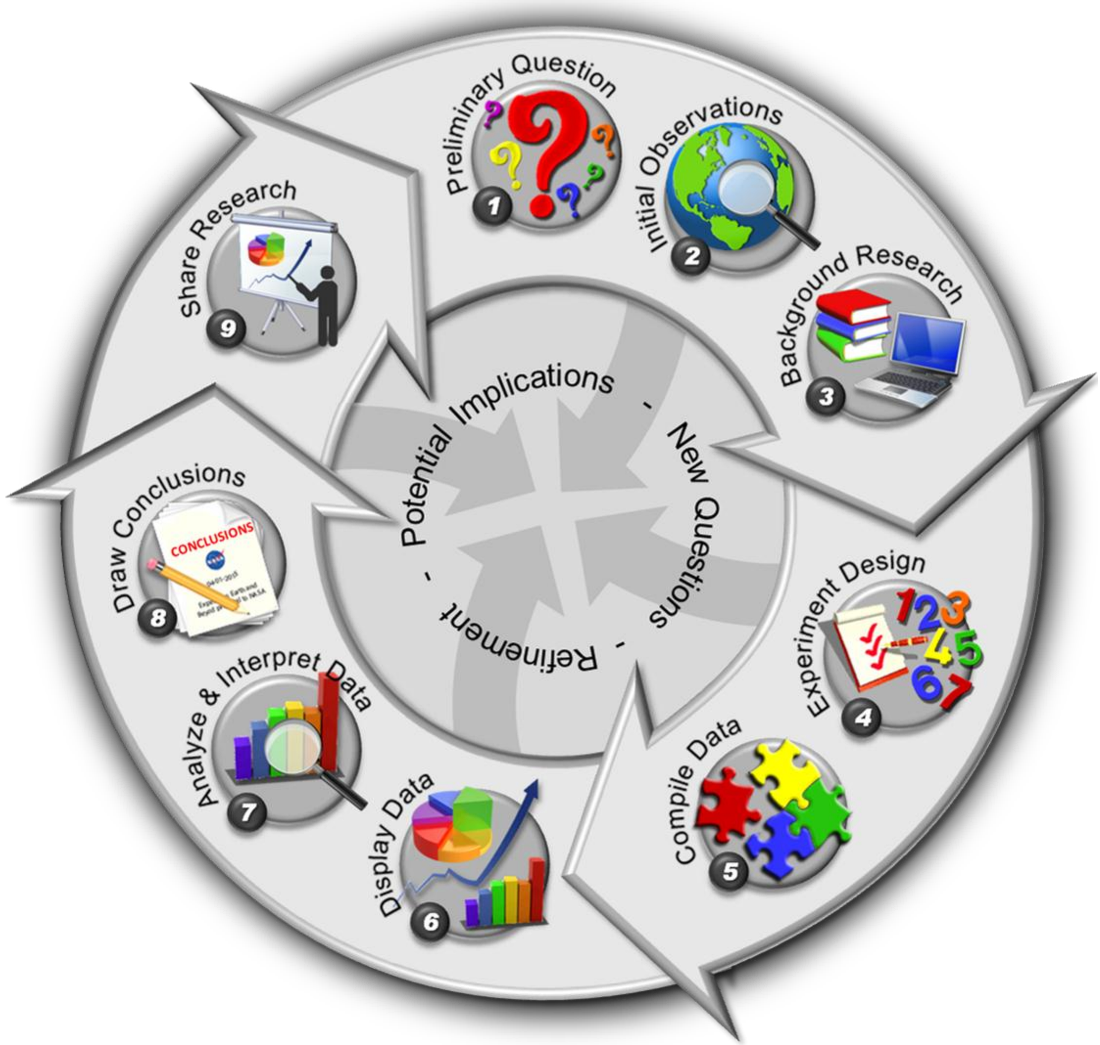


Image Credit: NASA/JSC/ARES/EEAB

PROCESS OF SCIENCE STEP 4: Experiment Design

The very first part of this step is to list your finalized research question. As you work through the first three steps of the process of science, you may find that as you gain more knowledge you may tweak or refine your question. By the time you are creating your experiment design, your question should be finalized. To help ensure this investigation can be successfully completed, a finalized research question has been created and is listed below.

The next part of this step is to list your current hypothesis/es. A hypothesis can be thought of as an educated guess. Ideally, a hypothesis should reflect your current understanding based on the patterns you have observed in preliminary images and background knowledge you may have. Again, to help guide your research, a set of hypotheses have been organized in the table below. Select the choice you feel best represents what you currently know. You are asked to hypothesize on the relative age of the surface and when (if at all) there were active processes shaping the surface. Focus on the planetary worlds you and your class will investigate.

Research Question: What do the characteristics of craters reveal about the geologic history of planetary worlds?

Hypothesis/es: Based on the images we have observed so far, and what we know about impact craters in our Solar System, we hypothesize the following…..		
	RELATIVE AGE OF SURFACE *Relatively young or old*	**ACTIVE GEOLOGIC PROCESSES** *Early in its history; throughout its history; currently; likely never existed*
EARTH		
EARTH'S MOON		
MARS		
VENUS		
MERCURY		
VESTA		

Perhaps the most challenging part of an experiment design is determining the specific details of your plan. There are certain considerations that must be addressed to ensure you can answer your science question and determine whether your hypothesis/es are supported or refuted. Below is a list of research considerations and how they are addressed for this investigation.

RESEARCH CONSIDERATIONS:

1. **Image Data Collection:** Where will you retrieve your imagery/data?
   This Investigation: This activity includes imagery and data for a variety of planetary worlds. Data/Imagery of Earth is Crew Earth Observation (CEO) Imagery; Data/Imagery of other planetary worlds includes a variety of data from remote sensing instruments on planetary spacecraft exploring these worlds.

2. **Specific Data to Collect:** What specific data will you collect?
   This Investigation: The following information will be logged from each image: 1) Image Identification #; 2) Crater name (if known); 3) Latitude (N); 4) Longitude (E); 5) Planetary Body; 6) Geographic location (country or region)
   Additional data that focus on visible observations include: 7) Crater diameter (km); 8) Crater Type (Simple or Complex) 9) Crater Classification (preserved, modified, destroyed); 10) Miscellaneous notes or observations; 11) Sketches.

3. **Number of Images:** How many images is enough for your study?
   This Investigation: Log data for a minimum of 8 different craters from each planetary world you are investigating.

4. **Geographic Regions:** Will you focus on a particular region?
   This Investigation: This investigation will not focus on any particular region.

5. **Other Data Sets:** Will you use other data sets as part of your investigation?
   This Investigation: No additional data sets are required. Supplemental data, however, was retrieved from the Earth Impact Database.

6. **Measurements:** How will you make measurements?
   This Investigation: Estimated measurements can be made based on scale bars/measurement lines provided on images.

7. **Sources:** What sources will allow others to retrieve the data you used (or find additional data)?
   This Investigation: Images and data were retrieved from the following sites: Gateway to Astronaut Photography of Earth (http://eol.jsc.nasa.gov); Earth Impact Database (http://www.passc.net/EarthImpactDatabase/index.html); JPL Planetary Photojournal (http://photojournal.jpl.nasa.gov/).

Once you have addressed these research considerations as part of the experiment design, you will now move into collecting and compiling your data. It is very important to log your data consistently. Notice on the data table sample provided (next page), the column headings provide specific details as to the information you should log. Gathering consistent data for each planetary world will allow you to make common comparisons. If you wish to make additions or changes to any of those details, feel free to do so. Just make sure your data collection is consistent.

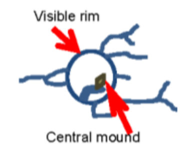
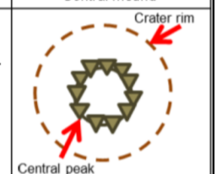
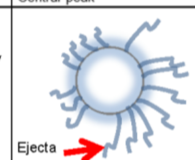
PROCESS OF SCIENCE STEP 5: Collect and Compile Data

Shown below is the recommended data table for you to use to collect data for craters you observe. Be sure to list the name of the planetary world you are collecting data for at the top of the table. The table shown here includes three data entries for three craters on Earth. Use these data entries as examples, or if you are collecting data on Earth, you now have three data points. The miscellaneous notes or observations column can be used to write in information that supports why you listed the crater as simple or complex or to list other observations or information you feel are important. Sketches are commonly used to help illustrate features you have observed.

DATA TABLE - CRATERS ON ____________________

Please note that latitudes are provided as North latitudes [Latitude (N)]. Latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. Longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.

The first three data logged here are of Earth. They can be used as examples, or if you are collecting data on Earth, you now have 3 data points.

Image Id#	Crater Name	Lat. (N)	Lon (E)	Planetary Body	Geographic Location	Crater Diameter *(km)*	CRATER TYPE *(Simple or Complex)*	CRATER CLASSIFICATION *(preserved, modified, or destroyed)*	Misc. Notes or Observations	Sketch(es)
ISS012-E-15881	Manicouagan	51.5	-68.5	Earth	Canada	65	Complex	Modified	Crater has central peak, though it is not easily detected. Diameter listed in Earth Impact Database as ~85 km. Only ~65km is actually visible in image. "Arms"/rivers extend out from the rim.	
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Complex	Modified	Crater has central peak. In reading information on NASA website about this crater, the well-defined bumpy circular feature is part of that central uplift. The faded outer rim is barely visible. This outer rim was used to determine the crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	Simple	Modified	Simple bowl shaped crater. The rim of this crater looks soft – the rim is not sharp and raised – likely due to erosion. There looks to be evidence of eroded ejecta around the rim. Ejecta extends out further on the right.	

As you log your observations, be sure to be as consistent as possible. If you are able to create a spreadsheet on a computer to log your data, this will allow you to more easily sort and display your data in the next step.

The first six columns on the data table are considered **metadata**. This is standard information from the images/data you observe. This includes the image identification number, the name of the crater (if known), the latitude, longitude, planetary body name, and the geographic location.

The remaining columns include your observations of the crater(s) in each image. By listing specific and consistent choices options, you will be able to make consistent comparisons of your observations of craters on different planetary worlds.

PROCESS OF SCIENCE STEP 6: Display Data

After you finish collecting and compiling data from at least 8 craters for each planetary world, it is time to display that data so you can make observations and later analyze the data. The three parts of Step 6 are to: 1) **Decide how to display your data** (Sorted Data Table(s), Graphs, Maps, Image Illustrations); 2) **Create your data displays**; and 3) **List observations**. Use the samples provided on the next few pages as examples.

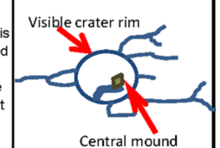
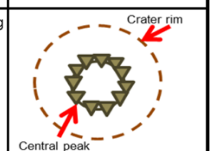
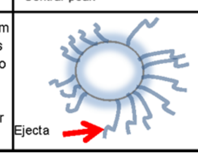
DATA TABLES

Your completed or master data table provides you with very useful information. Sorting your data is important as it allows you to look for patterns. Remember, with <u>each</u> data display be sure to list 2-3 observations.

The sample table below has been sorted by *crater diameter.* Observations are listed below the table.

DATA TABLE - CRATERS ON ____________________________

Please note that latitudes are provided as North latitudes [Latitude (N)]. A latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. A longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.
(The first three data logged here are of Earth. They can be used as examples, or if you are collecting data on Earth, you now have 3 data points.)

Image Identification #	Crater Name *(if known)*	Latitude (N)	Longitude (E)	Planetary Body	Geographic location *(country or region)*	Crater Diameter (km)	Crater Type *(simple or complex)*	Crater Classification *(preserved, modified, destroyed)*	Miscellaneous notes or observations	Sketch(es) of Craters *(optional)*
ISS012-E-15881	Manicoua-gan	51.5	-68.5	Earth	Canada	65	Complex	Modified	Crater has central peak, though it is not easily detected. Diameter listed in Earth Impact Database as ~85 km. Only ~65km is actually visible in image. "Arms"/rivers extend out from the rim.	
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Complex	Modified	Crater has central peak. In reading information on NASA website about this crater, the well-defined bumpy circular feature is part of that central uplift. The faded outer rim is barely visible. This outer rim was used to determine the crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	Simple	Modified	Simple bowl shaped crater. The rim of this crater looks soft – the rim is not sharp and raised – likely due to erosion. There looks to be evidence of eroded ejecta around the rim. Ejecta extends out further on the right.	

Observation #1: The larger the crater diameter, the more likely it is complex.
Observation #2: There smaller the crater, the more likely it is a simple crater.
Observation #3: Only two craters observed have a central uplift.

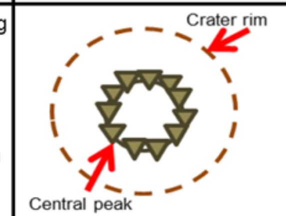
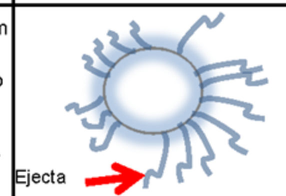
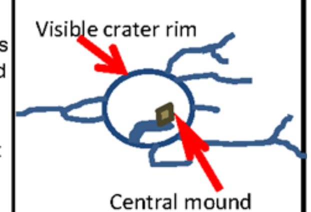
NOTE:

- Observations should state general patterns or notable information the data display is illustrating.
- Observations **do not** attempt to decipher what those patterns mean.
- Observations should generally not be questionable. Everyone should be able to agree on stated observations.

This sample table was sorted by *latitude.* Observations are listed below the table.

DATA TABLE - CRATERS ON ______________________________

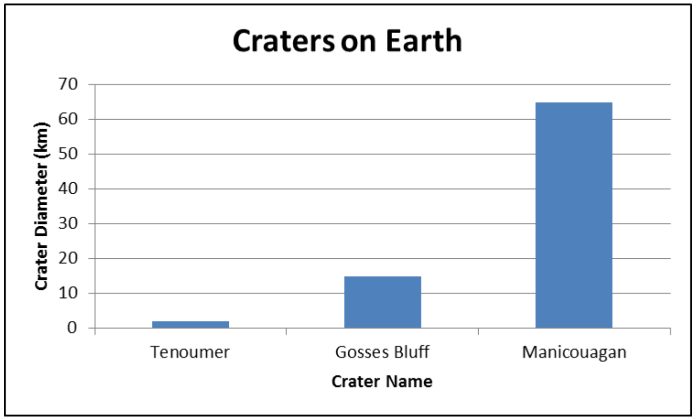
Please note that latitudes are provided as North latitudes [Latitude (N)]. A latitude with a (-) is a South latitude: Example: -27.8 is the same as 27.8S.
Also note that longitudes are provided as East longitudes [Longitude (E)]. A longitude with a (-) is a West longitude: Example: -68.5 is the same as 68.5W.
(The first three data logged here are of Earth. They can be used as examples, or if you are collecting data on Earth, you now have 3 data points.)

Image Identification #	Crater Name *(if known)*	Latitude (N)	Longitude (E)	Planetary Body	Geographic location *(country or region)*	Crater Diameter (km)	Crater Type *(simple or complex)*	Crater Classification *(preserved, modified, destroyed)*	Miscellaneous notes or observations	Sketch(es) of Craters *(optional)*
ISS015-E-17360	Gosses Bluff	-23.9	132.3	Earth	Australia	15	Complex	Modified	Crater has central peak. In reading information on NASA website about this crater, the well-defined bumpy circular feature is part of that central uplift. The faded outer rim is barely visible. This outer rim was used to determine the crater diameter.	
ISS018-E-14908	Tenoumer	22.9	-10.4	Earth	Mauritania	1.9	Simple	Modified	Simple bowl shaped crater. The rim of this crater looks soft – the rim is not sharp and raised – likely due to erosion. There looks to be evidence of eroded ejecta around the rim. Ejecta extends out further on the right.	
ISS012-E-15881	Manicoua-gan	51.5	-68.5	Earth	Canada	65	Complex	Modified	Crater has central peak, though it is not easily detected. Diameter listed in Earth Impact Database as ~85 km. Only ~65km is actually visible in image. "Arms"/rivers extend out from the rim.	

Observation #1: Craters located in both the southern and northern hemisphere of Earth are modified.
Observation #2: Craters located in both the southern and northern hemisphere of Earth have central uplifts.
Observation #3: Complex craters are located in both the southern and northern hemisphere of Earth.

GRAPHS

Graphs can allow you to visualize and illustrate your data, again allowing you to look for patterns. The graph below is showing the diameters of different craters on Earth.



Observation #1: Crater diameters on Earth, based on those observed, range from ~2km to ~65km.

Observation #2: There are not many craters of similar sizes on Earth

Observation #3: The range of craters sizes on Earth is wide.

Note: The more data you graph, the easier it is to make observations and look for notable patterns.

MAPS

Maps can allow you look for local, regional, or global patterns. The map shown here indicates the global distribution of impact craters (referred to as structures) on Earth.

Observation #1: Impact Craters are located on *most* continents on Earth.

Observation #2: The craters we observed are in North America, Africa, and Australia.

Observation #3: There are no impact craters found in Greenland or Antarctica.

World Impact Structures Sorted according to Location

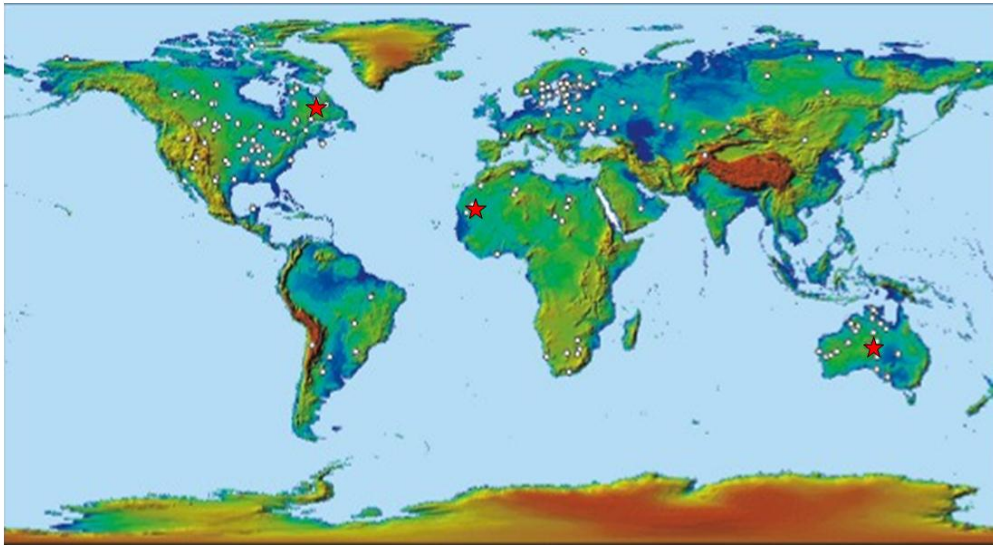


Image Credit: Earth Impact Database: http://www.unb.ca/passc/ImpactDatabase/CILocSort.html

★ = craters observed

IMAGE ILLUSTRATIONS

To help you illustrate your observations so readers of your research have a better understanding of your observations, image illustrations can be very powerful. See the two image illustration examples below.

IMAGE ILLUSTRATION #1: BARELY VISIBLE RIMS

Image Illustration #1: Most craters on Earth appear to be extremely modified (eroded) or destroyed. Rims like the one shown in the image above are oftentimes barely visible. (ISS028-E-14782: Shoemaker Crater)

IMAGE ILLUSTRATION #2: CRATER MODIFICATION

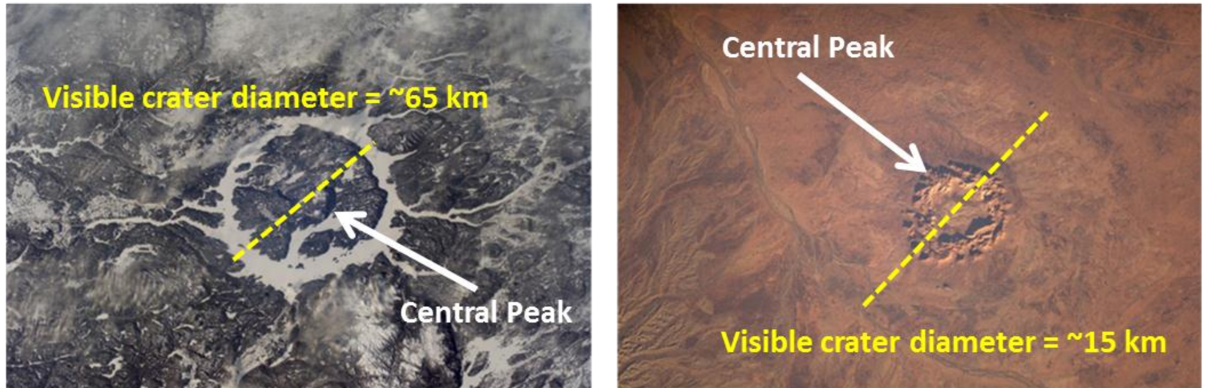


Image Illustration #2: Craters on Earth are modified by wind, water, ice, or volcanic processes. Oftentimes this modification makes it difficult to detect a central peak (if one exists). Additionally, the visible extent of the crater diameter may different from crater diameters indicated in the Earth Impact Database. For example, Manicouagan is listed as having a diameter of 85 km (~65 km visible here) and Gosses Bluff is listed as having a diameter of 22 km (~15 km visible here).

IMAGE ILLUSTRATION #1:

Observation #1: The rim of this crater is "broken" and barely visible.

Observation #2: This crater has been heavily modified by different processes, including water erosion.

Observation #3: The crater in this image is destroyed with hardly any visible detection of a wall, rim, or ejecta.

IMAGE ILLUSTRATION #2:

Observation #1: Central peaks in these craters on Earth are difficult to identify.

Observation #2: The terrain/environment of these two impact craters appear to be very different.

Observation #3: The original crater diameters (retrieved from the Earth Impact Database) are larger than the crater diameter measured using the measurement reference lines provided with each image. Manicouagan has a visible measured diameter of ~65km; diameter of Gosses Bluff is ~15km.

PROCESS OF SCIENCE STEP 7: Analyze & Interpret Data

Once you display your data **and** have listed observations of those data displays, you are ready to do one of the most important steps of your research – analyze and interpret the data. Analysis and interpretation of data are done by thinking about how specific observations and knowledge you have directly relate to your question. Your goal is to be able to draw conclusions about your research with supporting evidence.

As you analyze your data, focus on your research question and hypothesis/es.

Research Question: What do the characteristics of craters reveal about the geologic history of planetary worlds?

Hypothesis/es: *[This should be the original set of hypotheses you made earlier.]*		
	RELATIVE AGE OF SURFACE *Relatively young or old*	**ACTIVE GEOLOGIC PROCESSES** *Early in its history; throughout its history; currently; likely never existed*
EARTH		
EARTH'S MOON		
MARS		
VENUS		
MERCURY		
VESTA		

As part of Step 7, each group should fill out the *Analysis and Interpretation of Data* table (page 22) for the planetary world you observed. As you analyze and interpret data, focus on: 1) Specific/listed observations from Data Displays; 2) Interpretation of what those observations mean with respect to your question/hypotheses; and 3) Evidence that support your interpretations.

Consider including information that focuses on each observation category you logged on your data tables. For example, you made observations of the following characteristics: 1) crater diameter, 2) crater type, and 3) crater classification. You should be able to use the information you displayed, observed, and analyzed to draw conclusions about what these overall characteristics reveal about the geologic history of these planetary worlds.

The table on the next page provides starting information on two of these categories: *crater diameter* and *crater classification*. Your finished table should reflect your overall analysis and interpretation of data, related to each category, for whichever planetary world you observed. As you look at the sample table, notice how the information listed in column 1 is an observation directly from Step 6 (the specific data display and observation are listed in parenthesis). As you complete this step, you should revisit your data displays and listed observations and look for specific observations that are especially relevant to your research. As previously mentioned, observations are very important in that they basically state patterns or notable information illustrated in a data display. In Step 7, as you think about how those observations apply to your research, you are analyzing and interpreting the data. Your interpretation (column 2) of a listed observation compared to someone else's interpretation can vary. This is why it is important to have supporting evidence (column 3) to back up your interpretations. This will also help as you draw conclusions.

In Step 7 you will: 1) Fill out an *Analysis and Interpretation of Data* table; and 2) Share your analysis with the class.

Sample table focusing on data collected from Earth craters. This same table structure would be used for *each* planetary world:

ANALYSIS AND INTERPRETATION OF DATA **Planetary World: EARTH**		
Specific Observation from Data Display	**Interpretation(s) of What Observation Means with Respect to Your Question and/or Hypothesis**	**Evidence That Supports Your Interpretation** (from specific data displays and/or background knowledge)
IMPORTANT: Be sure to list a relevant observation you listed with one of your data displays.	*IMPORTANT: Describe how this observation can be interpreted – what does it reveal about the age of the planetary surface or the processes affecting the surface.*	*IMPORTANT: Provide additional evidence that supports your interpretation. Did you illustrate this point in another data display; did you read something about this in the text provided or somewhere else?*
1. CRATER CLASSIFICATION: Example: This crater is being modified by different processes, including water erosion. (Image Illustration #1, Observation# 2)	Example: Impact craters on Earth are mostly modified and are therefore middle-aged to old. Not observing any preserved craters allows us to infer that Earth has not been impacted by any significant object recently. As all observed craters are modified, this can be interpreted to mean there are active processes currently modifying craters on Earth.	Example: Earth has current and active weathering and erosion processes that continually modify/shape the surface of the planet. (Source: Crater Comparison Student Guide pg. 6)
2. CRATER DIAMETER: Example: Crater diameters on Earth, based on those observed, range from ~2km to ~65km. (Earth Graph, Observation #1)	• What does this observation lead you to infer about the age of the planetary surface? • What does this observation lead you to infer about the geologic processes affecting the surface and when those processes may have occurred?	• Is there another data display you created that supports this interpretation? • Is there text provided in this guide (or some other source you have researched – textbook, internet, etc.) that supports this interpretation?
3. CRATER TYPE: (simple versus complex) • Include a specific and relevant observation you listed with one of your data displays.	• What does this observation lead you to infer about the age of the planetary surface? • What does this observation lead you to infer about the geologic processes affecting the surface and when those processes may have occurred?	• Is there another data display you created that supports this interpretation? • Is there text provided in this guide (or some other source you have researched – textbook, internet, etc.) that supports this interpretation?

Fill out this *Analysis and Interpretation of Data Table* for the planetary world you investigated. (Use additional paper, as necessary.)

ANALYSIS AND INTERPRETATION OF DATA: **Planetary World: ______________________**		
Specific Observation from Data Display	**Interpretation(s) of What Observation Means with Respect to Your Question and/or Hypothesis**	**Evidence That Supports Your Interpretation** (from specific data displays and/or background knowledge)

SHARING YOUR ANALYSIS:
Be prepared to share information you have included in you *Analysis and Interpretation of Data* table. As you present your information: 1) Be prepared to discuss your information related to all 3 crater characteristics, 2) Be prepared to show any related data displays that allow you to illustrate your specific observations and help support your interpretations, and 3) Be prepared to discuss any limitations related to your research (not enough data, needed more area to be shown in images, something else?).

As you listen to each group's presentation, be prepared to contribute additional information as you see fit. In the table below, fill in the names of the planetary worlds you have investigated. Take notes so you can later draw conclusions about this research.

SUMMARY TABLE (use additional paper, as necessary)

	Earth	______________	______________	______________
Crater Diameter				
Crater Type				
Crater Classification				
Other Notes or Limitations				

PROCESS OF SCIENCE STEP 8: Draw Conclusions

Now that you have completed all the above steps, you are now ready to draw conclusions about your question and hypothesis/es. This is an essential part of your investigation as it allows you to synthesize your overall research and state your results. It also allows others to expand or build on your research in the future.

1**. RESEARCH QUESTION:** What do the characteristics of craters reveal about the geologic history of planetary worlds? Based on your research and analysis of data, what do you think is the answer to your question? Provide specific details.

2. **HYPOTHESIS/ES:** Based on your research and analysis of data, indicate whether your hypothesis/es were supported or refuted? Summarize pertinent evidence. [Be sure to list your original set of hypotheses. If a hypothesis was refuted, include a hypothesis revision statement to indicate your new understanding.] Use additional paper as necessary.

	RELATIVE AGE OF SURFACE *Rel. young or old*	**Supported** or **Refuted**	**Summary of pertinent evidence**	**ACTIVE PROCESSES** *Early in its history; throughout its history; currently; likely never existed*	**Supported** or **Refuted**	**Summary of pertinent evidence**
EARTH						
EARTH'S MOON						
MARS						
VENUS						
MER-CURY						
VESTA						

WHAT DOES IT ALL MEAN?

In addition to looking at the geologic history of planetary worlds using the characteristics of craters, as mentioned earlier, an important part of any research investigation is to think about the bigger picture. The research you have conducted provides you with useful information related to one of the most dominant processes within our Solar System – the impact process. What are the potential implications of this research? Why is it important? What does it all mean? Your research should allow you to address aspects related to the “bigger picture”. You should be able to 1) reflect on and better understand the history of our Solar System, 2) make predictions about potential future impacts, and 3) consider future robotic or even human exploration of other worlds.

Based on your investigation, discuss the answers to the following questions. Make additional observations as necessary:

1. Which are older: large complex craters or small simple craters? What does that tell you about the size of materials that may be have impacted planetary worlds early in the history of the Solar System versus the size of materials that have more recently impact surfaces? What does this tell you about how our Solar System has changed over time? Explain your answer.

2. If the Earth or other planetary worlds were impacted by an object in the future, do you think this object would likely be relatively large or small? Explain your answer.

3. NASA plans to send astronauts to visit another planetary world in the future to help us better understand our Solar System. If you had the opportunity to choose which planetary world to visit, which would you choose and why?