Dating the Moon: teaching lunar stratigraphy and the nature of science

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As our closest celestial neighbor, the Moon is a familiar and inspiring object to investigate using a small telescope, binoculars, or even photographs or one of the many high-quality maps available online (see "On the web"). The wondrously varied surface of the Moon--filled with craters, mountains, volcanic flows, scarps, and rilles--makes the Moon an excellent context for students to explore the methods scientists use to date geologic features, while learning about scientific observation and inference. This activity includes a unique application of the law of superposition that allows students to explore the relative ages of key lunar features and their origins.

Even with an unaided eye, two types of terrain seem to dominate the Moon's surface: the relatively light, very heavily cratered highlands and the dark, nearly smooth maria (Figure 1, page 36). The maria are extensive basaltic lava flows that cover about 16% of the lunar surface. As on Earth, the different types of terrain on the Moon have different ages. The relative ages of the Moon's highlands and maria can be determined by counting the number of craters per unit area superimposed on them (see sidebar at right). The older highlands have built up a larger number of impact craters than the smooth maria, which have not been exposed as long to bombarding meteoroids, asteroids, and comets (Wilhelms 1987).

Craters

Most craters on the Moon were caused by objects impacting the surface and explosively releasing their kinetic energy. In a typical collision, the impacting body burrows into the surface and is nearly instantly vaporized. The kinetic energy of the impactor is converted into shock waves that pulverize and launch the target material outward from the impact point, creating the crater (Shoemaker 1963). On the Moon, a typical impact crater is about 10 times the diameter of the impactor.

The material launched from the crater comes crashing down on the surrounding surface, creating a halo of debris called the ejecta blanket. Material launched higher on ballistic trajectories impacts the surface farther from the crater, creating secondary craters. In many cases, these secondaries cluster together, and the cluster may be oriented to point back to the primary crater.

Superposition/stratigraphy

An important tool of the geologist is the law of superposition: In general, younger formations are found atop older formations (see sidebar, page 37). While originally formulated for stratigraphy on Earth, the law of superposition can also help us understand the geologic history of many of the planets and moons
in our solar system. Just as the history of the Earth has been divided into geological eons, eras, periods, and so on by studying the layers of rocks found on Earth, geologic periods of the surface of the Moon can be discerned by studying the layers evident in photographs of the lunar surface (Shoemaker and Hackman 1962).

Until the mid-20th century, the history of the surface of the Moon was widely argued. Some believed the craters had a volcanic origin. Others said they were impact craters. Such debates are common in science when data are inconclusive, especially in the early stages of a research program. Eugene Shoemaker largely settled the debate in 1959 (Wilhelms 1993). Shoemaker had studied the geology of the Great Meteor Crater in Arizona and a number of large craters in Nevada carved by nuclear weapons. He realized that the similarity of the craters to those on the Moon demonstrated that most lunar craters resulted from impacts. Thus, observations about craters on Earth led to inferences about the origin of craters on the Moon.

In 1962, Shoemaker and Hackman were the first to define the five geologic periods of the surface of the Moon by studying its northwest quadrant (Figure 2, page 38). This activity allows your students to follow in Shoemaker's and Hackman's footsteps by using the law of superposition to determine the relative ages of some of the Moon's key features. There are six features whose relative ages we want to determine: The craters Copernicus (C ), Eratosthenes (E), Archimedes (Ar), and Autolycus (Au); the Apennine Mountains (Ap); and the Imbrium lava flows (Im).

The activity

We present this activity as a whole-class inquiry. Students use observations and inferences to interpret what they see in projected images of the moon (Figures 2 and 3 [p. 39]) with the teacher identifying important features and asking questions.

The key to classifying features by age is to determine which ones overlie the others. Geologists begin by looking for the most obvious relationships. In this case, have your students try to identify the youngest feature (a good exercise in noting layers). Using a projection of Figure 2, draw your students' attention to the crater Copernicus. Its ejecta blanket clearly overlies the Apennine Mountains and the Imbrium lava flows to the north. Ask students to infer the relative age of Copernicus from these facts. (Copernicus is younger than both.) The ray system around Copernicus seems undisturbed by the crater Eratosthenes. In higher resolution images of Eratosthenes (Figure 3), it is clear that secondary craters from Copernicus are superimposed on the ejecta blanket of Eratosthenes. With these observations your students may infer that Copernicus must be younger than Eratosthenes. In general, young, fresh craters have brighter ray systems.

The Apennine Mountains provide a nice contrast with terrestrial geology. Whereas mountain ranges on Earth are usually created by plate tectonics, a different process formed the gently curving Apennines range on the Moon. Show your students the wide-field view of the Moon in Figure 1 again, pointing out the Apennine, Carpathian, and Alps ranges. What rough geometric shape do these features form? (A circle.) What features on the Moon are circular? (Craters.) Based on these observations, what can your
students infer about the origin of these three mountain ranges? (They form the uplifted rim of a huge crater, called an impact basin.)

The 1,160-km-diameter Imbrium impact basin was created when an object roughly 100 km in diameter struck the Moon. The tremendous impact would have obliterated all other features in Figure 2. Thus, we can infer that the Apennine Mountains must be the oldest feature in the field because their creation would have destroyed any older features.

At some point, lava flows filled the Imbrium Basin—obviously after the basin was created. Thus, your students can infer that the flows are younger than the Apennine Mountains. A close examination shows that the ejecta blanket and secondary craters from Eratosthenes lie over the nearby lava flows (Figure 3), so Eratosthenes must be younger than the lavas.

Next, direct your students' attention to the crater Archimedes. Ask how Archimedes differs from Copernicus and Eratosthenes. Students should notice that Archimedes shows no sign of an ejecta blanket and has a remarkably smooth floor. Clearly, when the Imbrium basin lavas began to flow, they buried the ejecta and flooded the floor of Archimedes. Ask your students to infer what this observation means regarding the relative age of Archimedes. (This could only happen if Archimedes formed before the lava flows.)

Finally, point out that Autolycus is surrounded by a clear blanket of ejecta and ask what your students can infer about its age relative to the Imbrium lava flows. (It must be younger than the flows because its ejecta blanket is visible on top of the lavas.)

To summarize, so far your students have used the Law of Superposition and their observations and inferences to determine the relative ages of the features: The Apennine Mountains (Imbrium Basin) are the oldest feature in the field; next comes Archimedes, which was then buried by the Imbrium lava flows; and then comes the younger craters Eratosthenes, Autolycus, and Copernicus, emplaced on top of the lava flows, in that order. Their relative ages can be determined by counting the number of smaller craters that have impacted on them and by examining the brightness of their ray systems. Clearly, observation and inference are powerful tools with which to explore the natural world (Murphy and Bell 2005; Bell 2008).

The Imbrium Basin

Now it's time to weave the above observations into a coherent story. Long ago, a large asteroid, probably about 100 km in diameter, impacted the Moon and created the Imbrium Basin. The basin did not immediately flood with lava. During a long period, comets and asteroids continued to strike the Imbrium Basin, creating many large craters, including Archimedes. Later, voluminous lavas filled the basin, flooding the floor of Archimedes and burying its ejecta blanket. Later, smaller bodies struck the Moon, leaving the craters Eratosthenes, Autolycus, and Copernicus superimposed on top of the lava flows.
The Imbrium Basin was produced by one of the largest basin-forming impacts on the near side of the Moon. Ejecta from its creation scarred craters across the Moon, allowing us to determine if the craters came before the Imbrium impact or after. Thus, Imbrium provides a moment in time, a horizon, when features on the Moon can be classified as pre-Imbrium or post-Imbrium.

Missing from this story is a quantitative estimate of the time that passed between the formation of these features. When did the Imbrium basin form? How much time passed before the lavas flowed? When was Copernicus, one of the youngest, freshest large craters on the Moon, created? Answers to these questions could come only from visiting these sites. Samples of rock from these locations could be dated (through the decay of radioactive elements and the length of time they have been exposed to cosmic rays on the surface) to infer the absolute ages of the features.

Samples collected from both the Apollo 14 and 15 missions indicate that the Imbrium Basin was created 3.85 billion years ago. Samples from the Apollo 11, 12, 15, and 17 missions indicate that the lavas flowed for hundreds of millions of years. Crater counting has shown that they may have continued to flow on some parts of the Moon until about a billion years ago. The Apollo 12 landing site may have been on one of the distant rays of Copernicus. A layer of light-colored debris, possibly ejecta from Copernicus, was used to estimate the age of the crater. Copernicus, one of the youngest, large craters on the Moon, is 800 million years old.

Just as we can use fossils to make inferences about the environments in which organisms lived, we can use the surface of the Moon to draw an important inference about the early solar system: It was a violent place of frequent and massive impacts. Consider the maria. Their smooth surfaces suggest that not much cratering happened in the solar system since their lava flowed about 3.8 billion years ago. The lunar highlands, though, show a massive amount of impact cratering. It must have happened in the 700 million years after the solar system formed but before the lavas were laid down. Those first 700 million years were exceedingly violent.

Besides teaching about the conditions of the early solar system and Earth's place in time, this lesson lets students experience the interplay between observation and inference in the creation of scientific knowledge. Our research indicates that students know much about how scientists use observations but very little about the role of inferences (Bell, Mulvey, and Maeng 2012). By completing this lesson with your explicit guidance, your students can better understand the role that inference plays and thus be one step closer to understanding the nature of science.

On the web

CosmoQuest Terraluna Activities: http://cosmoquest.org/ Educator_Resources

Google Moon: www.google.com/moon/

Lunar and Planetary Institute Moon Images and Geologic Maps: www.lpi.usra.edu/resources/
The Moon appears to be covered in craters. The Earth, by comparison, appears to have few. Asked why, your students would likely offer a variety of answers, including: "The Earth's atmosphere burns up meteorites before they hit the ground," and "The Moon protects the Earth." A scale model of the Earth-Moon system should dispel the second of these misconceptions. If the Earth is represented by a standard 12-inch (30.5 cm) classroom globe, then the Moon is about the size of a large orange 30 feet (9 m) away. Build that model, and your students will see that the Moon--so distant and relatively small--provides almost no protection for the Earth.

What about Earth's atmosphere? Surprisingly, although small meteoroids do burn up before they hit the ground, our atmosphere has little effect on large asteroids. The Southern Highlands of the Moon (Figure 1) have hundreds of craters with diameters of 50 km or more. These were created by asteroids with a rough diameter of five km or larger. Such large bodies would strike Earth with almost the same mass and speed they would have if we had no atmosphere.

The Earth doesn't look like the Moon mostly because of erosion. Long ago, the Earth's surface probably did have many impact craters. Today, few are left because they have been worn down by wind, rain, ice, and plate tectonics. Nevertheless, a careful examination of the older parts of the Earth, using a map or Google Earth, will show features believed to have resulted from impacts, such as the Clearwater Lakes (Canada), Ries Crater (Germany), and the Great Meteor Crater (Arizona).

On the Moon, the relative ages of terrains can be determined by counting the number of craters of a given size per unit area, because no substantial erosion (except other impacts) have worn old craters away. For example, the smooth maria, with few large impact craters, must be young relative to the old highlands and far side of the Moon, which are completely covered in craters. Students can count craters to determine the age of parts of the Moon surface using the CosmoQuest Terraluna Activities (see "On the web").

FIGURE 1

Using a picture to determine the relative ages of lunar features.
The moon presents a wonderfully varied surface when viewed through binoculars, a small telescope, or even as a photograph. The two most obvious features are the light, heavily cratered highlands and the dark, relatively smooth maria. The activity described in the text focuses on the highlighted region.

Superposition and scientific laws

The Law of Superposition, developed in the 17th century by Nicolas Steno, posits that in undisturbed sedimentary or volcanic layers of rock laid down sequentially, the oldest strata will be at the bottom.

Like all scientific laws, the Law of Superposition has exceptions—like when rock layers are washed away or folded by crustal movement. Hence, the caveat "in undisturbed rock." Still, the law provides a useful generalization that helps geologists tell the story of the Earth (and other solid bodies in the solar system).

Steno's Law is not the only one with exceptions. Even laws as fundamental as the Law of Conservation of Matter and Newton's Laws of Motion were subsequently changed to reflect new evidence and understandings. In fact, every scientific law comes with caveats, and many have changed in light of new evidence. Scientific laws are not absolute (Bell 2008).

FIGURE 2

Data for the inquiry activity.

This close-up of the northwest quadrant of the Moon from Figure 1 serves as data for the inquiry activity. The six features whose relative ages we want to determine are the craters Copernicus (C), Eratosthenes (E), Archimedes (Ar), and Autolycus (Au); the Apennine Mountains (Ap); and the Imbrium lava flows (Im).

FIGURE 3

Ejecta blanket and secondary craters.

Lunar Orbiter IV image of the crater Eratosthenes. Note how the ejecta blanket and secondary craters from Eratosthenes are superimposed on the Apennine Mountains and the surrounding Imbrium lava flows. Along the western (left) and southern (bottom) sides of Eratosthenes, likely secondary craters from Copernicus (some circled) can be seen superimposed on the ejecta from Eratosthenes, showing that Copernicus is younger.

References


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