Background Information for Teachers

Moon

The Moon is not like Earth. It does not have oceans, lakes, rivers, or streams. It does not have wind-blown ice fields at its poles. The wind has never blown. People have never lived there—but they have wondered about it for centuries, and a few lucky ones have even visited it.

Highlands and Lowlands

The major features of the Moon's surface can be seen by just looking up at it. It has lighter and darker areas. These distinctive terrains are the bright lunar highlands (also known as the *lunar terrae,* which is Latin for "land") and the darker plains called the *lunar maria* , Latin for "seas," which they resembled to Thomas Hariot and Galileo, the first scientists to examine the Moon with telescopes. The idea that the highlands and maria correspond to lands and seas appears to have been popular among ancient Greeks long before telescopes were invented. Although we now know they are not seas (the Moon never had any water), we still use the term *maria*, and its singular form, *mare.*

The Highlands and Craters

Closer inspection shows that the highlands comprise countless overlapping craters, ranging in size from the smallest visible in photographs (1 meter on the best Apollo photographs) to more than 1000 km. Essentially all of these craters formed when meteorites crashed into the Moon. Before either robotic or piloted spacecraft went to the Moon, many scientists thought that most lunar craters were volcanic in origin. But as we found out more about the nature of lunar craters and studied impact craters on Earth, it became clear that cosmic projectiles have bombarded the Moon. The samples returned by the Apollo missions confirmed the pervasive role impact processes play in shaping the lunar landscape.

The impact process is explosive. A large impactor does not simply bore its way into a planet's surface. When it hits, it is moving extremely fast, more than 20 km/sec. This meeting is not tender. High-pressure waves are sent back into the impactor and into the target planet. The impactor is so overwhelmed by the passage of the shock wave that almost all of it vaporizes, never to be seen again. The target material is compressed strongly, them decompressed. A little is vaporized, some melted, but most is tossed out of the target area, piling up around the hole produced.

The Maria

The maria cover 16% of the lunar surface and are composed of lava flows that filled relatively low places, mostly inside immense impact basins. So, although the Moon does not have many volcanic craters, it did experience volcanic activity.

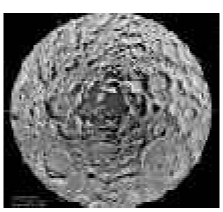
How do we know that the dark plains are covered with lava flows? Why not some other kind of rock? Even before the Apollo missions brought back samples from the maria, there were strong suspicions that the plains were volcanic. They contain some features that look very much like lava flows. Other features resemble lava channels, which form in some types of lava flows on Earth. Still other features resemble collapses along underground volcanic feature called lava tubes. These and other features convinced most lunar scientists before the Apollo missions that the maria were lava plains. This insight was confirmed by samples collected from the maria: they are a type of volcanic rock called *basalt*

Maria Mysteries.

Some mysteries persist about the maria. For one, why are volcanoes missing except for the cinder cones associated with dark mantle deposits? Second, if no obvious volcanoes exist, where did the lavas erupt from? In some cases, we can see that lava emerged from the margins of enormous impact basins, perhaps along cracks concentric to the basin. But in most cases, we cannot see the places where the lava erupted. Another curious feature is that almost all the maria occur on the Earth-facing side of the Moon. Most scientists guess that this asymmetry is cause by the highlands crust being thicker on the lunar far side, making it difficult for basalts to make it all the way through to the surface.

The Dusty Lunar Surface

Some visitors to Kilauea Volcano, Hawaii, have been overheard to say, upon seeing a vast landscape covered with fresh lava, “It looks just like the Moon!” Well, it doesn’t. The fresh lava flows of Kilauea and other active volcanoes are usually dark graying and barren like the Moon, but the resemblance ends there. The lunar surface is charcoal gray and sandy, with a sizable supply of fine sediment. Meteorite impacts over billions of years have ground up the formerly fresh surface into powder. Because the moon has virtually no atmosphere, even the tiniest meteorite strikes a defenseless surface at it full cosmic velocity, at least 20 km/sec. Some rocks lie strewn about the surface, resembling boulders sticking up through fresh snow on the slopes of Aspen or Vail. Even these boulders won’t last long, maybe a few hundred million years, before they are ground up into powder by the relentless rain of high-speed projectiles. Of course, an occasional larger impactor arrives, say the size of a car, and excavates fresh rock from beneath the blanket of powdery



sediment. The meteoritic rain then begins to grind the fresh boulders down, slowly but inevitably.

The powdery blanket that covers the Moon is called the lunar regolith, a term for mechanically produced debris layers on planetary surfaces. Many scientists also call it the "lunar soil", but it contains none of the organic matter that occurs in soils on Earth. Some people use the term "sediment" for regolith.

The regolith consists of what you'd expect from an impact-generated pile of debris. It contains rock and mineral fragments derived form the original bedrock. It also contains glassy particles formed by the impacts. In many lunar regoliths, half of the particles are composed of mineral fragments that are bound together by impact glass.

One of the great potential bits of information stored in the complex pile atop the lunar surface is the history of the Sun. The nearest star puts out prodigious amounts of particles called the *solar wind.* Composed mostly of hydrogen, helium, neon, carbon, and nitrogen, the solar wind particles strike the lunar surface and are implanted into mineral grains. The amounts build up with time. In principle, we can determine if conditions inside the Sun have changed over time by analyzing these solar wind products, especially the isotopic composition of them.

The same solar wind gases may prove useful when people establish permanent settlements on the Moon. Life support systems require the life-giving elements: Hydrogen and oxygen (for water), carbon, and nitrogen. Plenty of oxygen is bound in the silicate, minerals of lunar rocks (about 50%by volume) and the solar wind provided the rest. So, when the astronauts were digging up lunar regolith for return to Earth, they were not merely sampling—they were prospecting!

Moon Rocks

Geologists learn an amazing amount about a planet by examining photographs and using other types of remotely sensed data, but eventually they need to collect some samples. For example, although geologists determined unambiguously from photographs that the maria are younger than the highlands, they did not know their absolute age, the age in years. Rocks also provide key tests to hypothesis. For instance, the maria were thought to be covered with lava flows, but we did not know for sure until we collected samples from them. Also, no method can accurately determine the chemical and mineralogical composition of a rock except laboratory analysis. Most important, samples provide surprises, telling us things we never expected. The highlands provide the best examined of a geological surprise, and one with great consequences for our understanding of what Earth was like 4.5 billion years ago.

The missions to mare areas brought back lots of samples of basalt. Basalts differ from the highlands rocks in having more olivine and pyroxene, and less plagioclase. The second mission, Apollo 12, returned basalts with lower titanium concentrations, so they were called “low-titanium” mare basalts. Subsequent missions, including an automated sample-return mission sent by the Soviet Union, returned some mare basalts with even lover titanium, so they were dubbed “very-low-titanium” basalts. Most scientists figure that mare basalts have a complete range in titanium abundance. Data from the U.S. Clementine Mission confirm this, and show that the high titanium basalts are not really very common on the Moon.

What’s Next?

Scientists are still working on the bounty returned by the Apollo missions. New analytical techniques and improved understanding of how geological processes work keep the field exciting and vibrant. Eventually we will need additional samples and some extensive fieldwork to fully understand the Moon and how it came to be and continues to evolve. These sampling and field expeditions will probably be done by a combination of robotic and piloted spacecraft.

In the meantime, Nature has provided a bonus: samples from the Moon come to us free of charge in the form of lunar meteorites. Thirteen separate meteorites have benn identified so far, one found in Australia and the rest in Antarctica. We are sure that they come from the Moon on the basis of appearance and chemical and isotopic composition, but of course we don not know from where on the Moon they come. Most important, knowing that meteorites can be delivered to Earth by impacts on the Moon lend credence to the idea that we have some meteorites from Mars. The Martian meteorites are collectively called SNC meteorites. If we did not know so much about the Moon we would never have been able to identify meteorites from the Moon, and therefore, would not have been able to argue as convincingly that some meteorites come from Mars.

Moonquakes, The Moon’s Interior, and the Mysterious Magnetic Field

The moon does not shake, rattle and roll as Earth does. Almost all moonquakes are smaller than Earth’s constant grumblings. The largest quakes reach only about magnitude 5 (strong enough to cause dishes to fall out of cabinets), and these occur about once a year. This is clear evidence that the Moon is not a present geologically active. No internal motions drive crystal plates as on Earth, or initiate hot spots to give rise to volcanic provinces like Hawaii. This seismic inactivity is a wonderful virtue in the eyes of astronomers. Combined with the lack of an atmosphere to cause stars to twinkle, the low moonquake activity makes the Moon an ideal place to install telescopes.

There are other mysteries about the Moon’s magnetism. Although the field was always weak and is extremely weak now, there are small areas on the Moon that have magnetic fields much stronger than the surrounding regions. These magnetic anomalies have not been figured out. Some scientists have associated them with the effects of large, basin-forming impacts. Others have suggested that the ionized gases produced when comets impact the Moon might give rise to strong magnetic anomalies in the crater ejecta. The jury is still out. The Lunar Prospector Mission will thoroughly map the distribution of magnetic anomalies, perhaps helping to solve this mystery.

The Moon's Origin: A Big Whack on the Growing Earth

For a long time, the most elusive mystery about the Moon was how it formed. The problem baffled philosophers and scientists for hundreds of years. All of the hypotheses advanced for lunar origin had fatal flaws, even through partisans tried tenaciously to explain away the defects. The capture hypothesis, which depicts capture of a fully formed Moon by Earth, suffered from improbability. Close encounter with Earth would either result in a collision or fling the Moon into a different orbit around the Sun, probably never to meet up with Earth again. The fission hypothesis, in which the primitive Earth spins so fast that a blob flies off, could not explain hw Earth got to spinning so fast(once every 2.5 hours) and why Earth and the Moon no longer spin that fast. The double-planet hypothesis pictures Earth and Moon forming together, a two-body system for the start. This idea has trouble explaining Earth's rotation rate and how the moon-forming material got into orbit around Earth and stayed there, rather that falling to Earth. The problem was so frustrating that some scientists suggested that maybe science had proved that the Moon does not exist!

The annoying problems with the classical hypotheses of lunar origin led scientists to consider alternative. This search led to the seemingly outlandish idea that the Moon formed when a projectile the size of the planet Mars smashed into Earth when it had grown to about 90% of its present size. The resulting explosion sent vast quantities of heated material into orbit around Earth, and the Moon formed from this debris. This new hypothesis, which blossomed in 1984 from seeds planted in the mid-1970's, is called the *giant impact theory*. It explains the way Earth spins and why Earth has a larger metallic core than does the Moon. Furthermore, modern theories for how the planets are assembled from smaller bodies, which were assembled from still smaller ones, predict that when Earth was almost done forming, there would have been a body nearby with a mass about one-tenth that of Earth. Thus, the giant impact hypothesized to have formed the Moon is not an implausible event. The chances are so high, in fact, that it might have been unavoidable.

One would think that an impact between an almost Earth-sized planet and a Mars-sized planet would be catastrophic. The energy involved is incomprehensible - much more than a trillion trillion tons of material vaporized and melted. In some places in the cloud around the Earth, temperatures exceeded 10,000 C. A fledgling planet the size of Mars was incorporated into Earth, it metallic core and all, never to be seen again. Yes, this sounds catastrophic. But out of it all, the Moon was created and Earth grew to almost its final size. Without this violet event early in the Solar System's history, there would be no Moon in the Earth's sky, and Earth would not be rotating as fast as it is because the big impact spun it up. Days might even last a year. But then, maybe we would not be here to notice.

The Moon and Earth: Inexorably Intertwined

The moon ought to be especially alluring to people curious about Earth. The two bodies formed near each other formed mantles and crusts early, shared the same post-formational bombardment, and solar particles for the past 4.5 billion years. Here are a few examples of the surprising ways in which lunar science can contribute to understanding how Earth works and to unraveling it geological history.

Origin of the Earth-Moon System

No matter how the Moon formed, its creation must have had dramatic effects on Earth. Although most scientists have concluded that the Moon formed as a result of an enormous impact onto the growing Earth, we do not know much about the details of that stupendous event. We don not know if the Moon was made mostly from Earth materials or mostly projectile, the kinds of chemical reactions that would have taken place in the melt-vapor cloud, and precisely how the Moon was assembled from this cloud.

Early Bombardment History of the Earth and Moon

The thousands of craters on the Moon's surface chronicle the impact record of Earth. Most of the craters formed before 3.9 billion years ago., Some scientists argue that the Moon suffered a cataclysmic bombardment (a drastic increase in the number of impacting projectiles) between 3.85 and 4.0 billion years ago. If this happened and Earth was subjected to the blitzkrieg as well, then development of Earth's earliest crust would have been affected. The intense bombardment could also have influence the development of life, perhaps delaying its appearance.

Impacts, Extinctions, and the Evolution of Life on Earth

The mechanisms of evolution and mass extinctions are not understood. One possibility is that some mass-extinction events were caused by periodic increases in the rate of impact on Earth. For example, the mass extinctions, which included the demise of the dinosaurs, at the end of the Cretaceous period (65 million years ago), may have been caused by a large impact event. But the Moon has plenty of craters formed during the past 600 million years (the period for which we have a rich fossil record). These could be dated and the reality of spikes in the impact record could be tested.

How Geologic Processes Operate

The Moon is a natural laboratory for the study of some of the geologic processes that have shaped Earth. It is a great place to study the details of how impact craters form because there are so many well-preserved craters in an enormous range of sizes. It is also one of the places where volcanism has operated, but at lower gravity than on either Earth or Mars.

Exploring the Moon—A Teacher's Guide with Activities, *NASA EG-1997-10-116-HQ*
Images from http://eclipse99.nasa.gov/pages/MoonImages.html Available 18 June 2003.