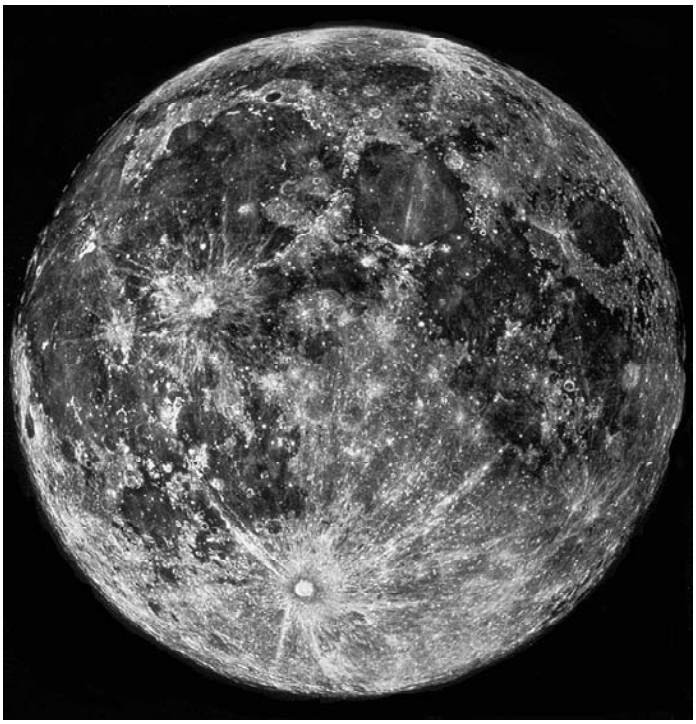
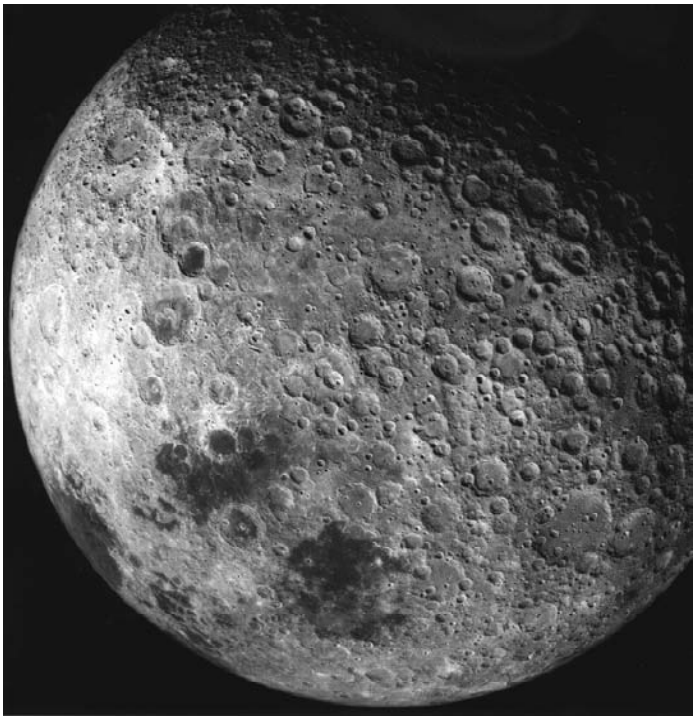
THE MOON

GATEWAY TO THE SOLAR SYSTEM

G. Jeffrey Taylor, PhD



WHEN ASTRONAUTS dug into the Moon's surface during the Apollo program, they were doing more than digging up dry, dark sediment. They were time travelers. The rocks and sediment returned by Apollo contain vital clues to how Earth and the Moon formed, the nature and timing of early melting, the intensity of impact bombardment and its variation with time, and even the history of the Sun. Most of this information, crucial parts of the story of planet Earth, cannot be learned by studying rocks on Earth because our planet is so geologically active that it has erased much of the record. The clues have been lost in billions of years of mountain building, volcanism, weathering, and erosion. Colliding tectonic plates



The Moon, front and back

The **top right** photograph is a telescopic image of the Earth-facing half of the Moon obtained at Lick Observatory in California. The one **below right** was taken during the Apollo 16 mission and shows mostly the farside, except for the dark areas on the left, which can be seen, though barely, from Earth. The two major types of terrain are clearly visible. The *highlands*, which are especially well displayed in the photograph of the farside, are light-colored and heavily cratered. The *maria* are darker and smoother; they formed when lava flows filled depressions. One of the mysteries about the Moon is why fewer maria occur on the farside than nearside. Note how many craters stand shoulder to shoulder on the farside. These immense holes chronicle the Moon's early bombardment, an intense barrage that probably affected the early Earth as well.

and falling rain have erased much of Earth history, especially the early years before four billion years ago.

The Moon was geologically active in its heyday, producing a fascinating array of products, but its geologic engine was not vigorous and all records of early events were not lost. Its secrets are recorded in its craters, plains, and rocks. This guide reveals the secrets that lunar scientists have uncovered since the Apollo missions returned 382 kilograms (843 pounds) of rock and sediment from the lovely body that graces the night sky.

The emphasis here is on geology. The samples returned by Apollo are the stars of the show. [See the "Lunar Disk" activity on Pages 39–42 and the "Apollo Landing Sites" activity on Pages 43–46.] Understanding the Moon, however, requires other geological approaches, such as geological mapping from high-quality photographs, the study of analogous features on Earth (for instance, impact craters), and experiments in laboratories.

THE LUNAR LANDSCAPE

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. Roses and morning glories do not sprout from its charcoal gray, dusty surface. Redwoods do not tower above its cratered ground. Dinosaur foot prints cannot be found. Paramecium never conjugated, amoeba never split, and dogs never barked. The wind never blew. People 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 Galilei, the first scientists to examine the Moon with telescopes. The names terrae and maria were given to lunar terrains by Hariot and Galileo's contemporary, Johannes Kepler. In fact, 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 the Moon has been bombarded by cosmic projectiles. The samples returned by the Apollo missions confirmed the pervasive role impact processes play in shaping the lunar landscape.

The term "meteorite impact" is used to describe the process of surface bombardment by cosmic object. The objects themselves are variously referred to as "impactors" or "projectiles."

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 (70,000 km/hour). 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, then decompressed. A little is vaporized, some melted, but most (a mass of about 10,000 times the mass of the impactor) is tossed out of the target area, piling up around the hole so produced. The bottom of the crater is lower than the original ground surface, the piled up material on the rim is higher. This is the characteristic shape of an impact crater and is different from volcanic calderas (no piled up materials) or cinder cones (the central pit is above the original ground surface). A small amount of the target is also tossed great distances along arcuate paths called rays.

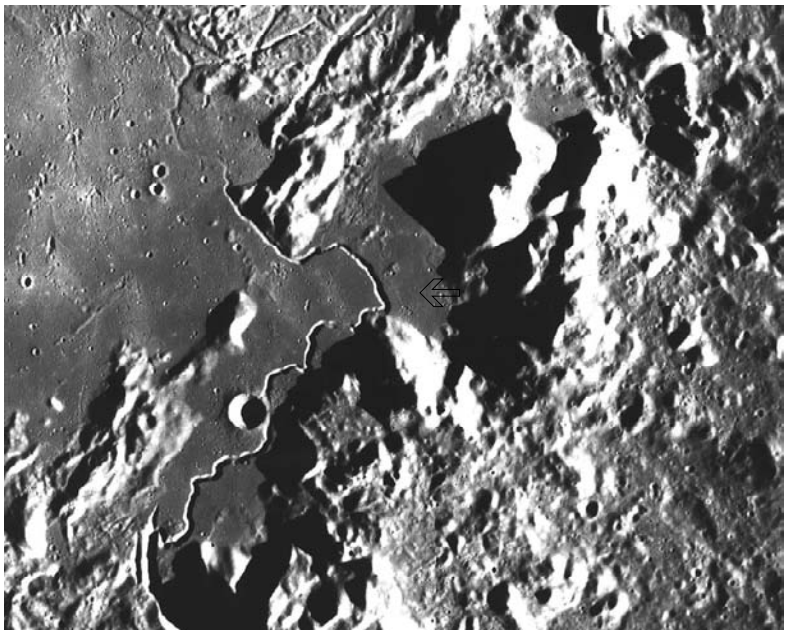
Real impacts cannot be readily simulated in a classroom. In fact, there are very few facilities where we can simulate high-velocity impacts. Nevertheless, classroom experiments using marbles, ball bearings, or other objects can still illustrate many important

points about the impact process. For example, objects impacting at a variety of velocities (hence kinetic energies) produce craters with a variety of sizes; the more energy, the larger the crater. [See the "Impact Craters" activity on Pages 61–70.]

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. Close examination of the relationships between the highlands and the maria shows that this activity took place after the highlands formed and after most of the cratering took place. Thus, the maria are younger than the highlands. [See the "Clay Lava Flows" activity on Pages 71–76 and the "Lava Layering" activity on Pages 77–82.]

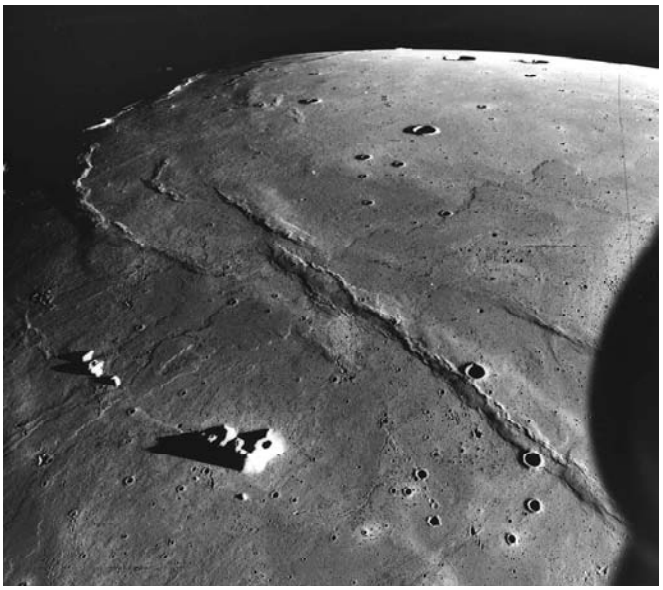
How do we know that the dark plains are covered with lava flows? Why not some other kind of rock? Even before the Apollo missions brought back samples from the maria, there were strong suspicions that the plains were volcanic. They contain some features that look very much like lava flows. Other features resemble lava channels, which form in some types of lava flows on Earth. Still other features resemble collapses along underground volcanic features 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.



Rivers or lava channels?

The origin of river-like valleys, called rilles, was debated before the Apollo 15 mission visited one of them, Hadley Rille, shown here from orbit (white arrow shows the landing site) and from the lunar surface. Some scientists argued that rilles were river valleys, implying that the Moon had flowing water at one time. Others thought that rilles resembled the channels that form in lava flows. Observations by the Apollo 15 crew and samples returned settled the argument: rilles are volcanic features.

The maria fill many of the gigantic impact basins that decorate the Moon's nearside. (The Moon keeps the same hemisphere towards Earth because Earth's gravity has locked in the Moon's rotation.) Some scientists contended during the 1960s that this demonstrated a cause and effect: impact caused not only the formation of a large crater but led to melting of the lunar interior as well. Thus, it was argued, the impacts triggered the volcanism. However, careful geologic mapping using high-quality telescopic images, showed that the mare must be considerably younger than the basins in which they reside. For example, the impact that formed the large Imbrium basin (the Man-in-the-Moon's right eye) hurled material outwards and sculpted the mountains surrounding the Serenitatis basin (the left eye); thus, Serenitatis must be older. The Serenitatis basin is also home to Mare Serenitatis. If the lavas in Mare Serentatis formed when the basin did, they ought to show the effects of the giant impact that formed Imbrium. They show no



Lava flows dribbling across Mare Imbrium

Long lava flows (lower left to upper right through center of photo) in Mare Imbrium. The flows are up to 400 kilometers long (the entire extent is not shown in this Apollo photograph) and have 30-meter high cliffs at their margins. The ridges running roughly perpendicular to the flows are called wrinkle ridges. The ridges formed after the flows because they did not impede the advance of the lava flow. The smooth plains surrounding the prominent lava flows are also lava, but older, so the margins are harder to see. The craters on the right along the ridge are about 5 kilometers in diameter.

signs of it. Furthermore, the maria contain far fewer craters than do basin deposits, hence have been around a shorter time (the older the surface, the greater the number of craters). The Apollo samples, of course, confirmed these astute geological observations and showed that the maria filling some basins formed a billion years after the basin formed.

One other type of deposit associated with the maria, though it blankets highlands areas as well, is known as dark mantle deposits. They cannot be seen except with telescopes or from spacecraft near the Moon, but are important nonetheless. Before Apollo, most scientists believed that the dark mantle deposits were formed by explosive volcanic eruptions known as pyroclastic eruptions (literally, "pieces of fire"). Some deposits seemed to be associated with low, broad, dark cinder cones, consistent with the idea that they were formed by pyroclastic eruptions—this is how cinder cones form on Earth. This bit of geologic deduction was proven by the Apollo 17 mission and its sampling of the "orange soil," a collection of tiny glass droplets like those found in terrestrial pyroclastic eruptions.

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 caused by the highlands crust being thicker on the lunar farside, making it difficult for basalts to make it all the way through to the surface. [See the "Moon Anomalies" activity on Pages 91–98.]

THE DUSTY LUNAR SURFACE

Some visitors to Kilauea Volcano, Hawai'i, 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 grayish 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 surfaces into powder. Because the Moon has virtually no atmosphere, even the tiniest meteorite strikes a defenseless surface at its 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. Be forewarned that the regolith samples in the Lunar Sample Disk are labeled "soil." Although it is everywhere, the regolith is thin, ranging from about two meters on the youngest maria to perhaps 20 meters in the oldest surfaces in the highlands. [See the "Regolith Formation" activity on Pages 47–52.]

Lunar regolith is a mixed blessing. On the one hand, it has mixed local material so that a shovelful contains most of the rock types that occur in an area. It even contains some rock fragments tossed in by impacts in remote regions. Thus, the regolith is a great rock collection. It also contains the record of impacts during the past several hundred million to a billion years, crucial information for understanding the rate of impact on Earth during that time. On the other hand, this impact record is not written very clearly and we have not come close to figuring it out as yet. The blanket of regolith also greatly obscures the details of the bedrock geology. This made field work during Apollo difficult and hinders our understanding of lunar history.

The regolith consists of what you'd expect from an impact-generated pile of debris. It contains rock and mineral fragments derived from 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; scientists call these objects agglutinates. The chemical composition of the regolith reflects the composition of the bedrock underneath. Regolith in the highlands is rich in aluminum, as are highland rocks. Regolith in the maria is rich in iron and magnesium, major constituents of basalt. A little bit of mixing from beneath basalt layers or from distant highland locales occurs, but not enough to obscure the basic difference between the highlands and the maria.

Raking moon dirt

One of the most useful ways of obtaining samples of Moon rocks was to drag a rake through the regolith. This allowed rock fragments larger than about one centimeter to remain on tines of the rake, while smaller fragments fell through. Note the large range in the sizes of rock fragments. One large boulder lies near the rake, a medium-sized one is visible between the astronaut's feet, along with countless other pebbles. Most of the regolith is smaller than fine sand. The astronaut's footprints are distinct because the regolith is composed of a large percentage of tiny particles (about 20% is smaller than 0.02 millimeters).

A geologist-astronaut does field work on the Moon

Geologist Harrison H. Schmitt examines a large rock at the Apollo 17 landing site. This large boulder contains numerous rock fragments that were smashed together by the huge impact event that made the 750-kilometer Serentatis basin on the Moon.

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 unambigously 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 hypotheses. 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 example of a geological surprise, and one with great consequences for our understanding of what Earth was like 4.5 billion years ago.

A fist-sized piece of the original lunar crust

This rock sample was collected during the Apollo 15 mission. It is an anorthosite, a rock composed of little else but the mineral feldspar. Anorthosites formed from the enormous magma system, the *lunar magma ocean,* that surrounded the newly formed Moon. Because of its importance in understanding the origin of the Moon's crust, the rock was nicknamed the "genesis rock."

Smash and mix, mix and melt

This rock returned by the Apollo 16 mission attests to the effects of impacts on a planet's crust. It is a hodgepodge of rock and mineral fragments, some of which themselves are complicated mishmashes of rock debris. Geologists call these complicated rocks *breccias.*

Highland rocks, the lunar magma ocean, and maybe a cataclysm

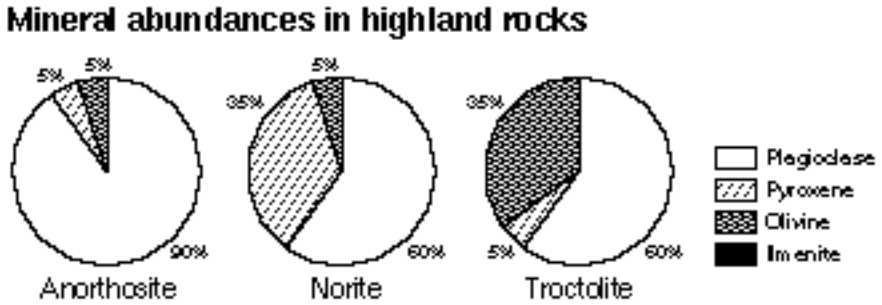
Strange as it may seem, the first highland rocks were collected during the first lunar landing, the Apollo 11 mission, which landed on a mare, Mare Tranquillitatis. Although most of the rocks collected were, indeed, basalts, some millimeter-sized rock fragments were quite different. They were composed chiefly of the mineral plagioclase feldspar; some fragments were composed of nothing but plagioclase. [See the "Rock ABCs Fact Sheet" on Page 19.] Such rocks are called anorthosites. Some scientists suggested that these fragments were blasted to the Apollo 11 landing site by distant impacts on highland terrain. Thus, they argued, the highlands are loaded with plagioclase. This was a bold extrapolation confirmed by subsequent Apollo missions to highland sites.

But this was not enough for some scientists. If the highlands are enriched in plagioclase, how did they get that way? One way is to accumulate it by flotation in a magma (molten rock). This happens in thick subterranean magma bodies on Earth. So, plagioclase floated in a magma. But if ALL the lunar highlands are enriched in plagioclase, then the magma must have been all over the Moon. The early Moon must have been covered by a global ocean of magma, now commonly referred to as the lunar magma ocean. Although some scientists still remain unconvinced about the veracity of the magma ocean hypothesis, nothing we have learned since has contradicted the idea that 4.5 billion years ago the Moon was covered by a layer of magma hundreds of kilometers thick. The idea has been extended to the young Earth as well, and even to Mars and some asteroids. And all this sprung forth because creative and bold scientists saw special importance in a few dozen white fragments of anorthosite strewn about in a pile of charcoal gray lunar regolith.

The magma ocean concept was tested by the 1994 U. S. Clementine Mission to the Moon. Clementine was in a pole-to-pole orbit for two months, during which it took thousands of photographs in several wavelengths. Scientists at the University of Hawai'i developed a method to determine the iron content of the lunar surface from ratioes of the intensity of light reflected in different wavelengths. The magma ocean hypothesis predicts that the lunar highlands should have low iron contents, less than about 5 wt. % (when recorded as iron oxide, FeO). According to Clementine measurements, the highlands average slightly under 5 wt. % FeO, consistent with the magma ocean idea. Further refinement of this test is underway using data from Clementine and the forthcoming U. S. Lunar Prospector Mission, scheduled for launch in early 1998.

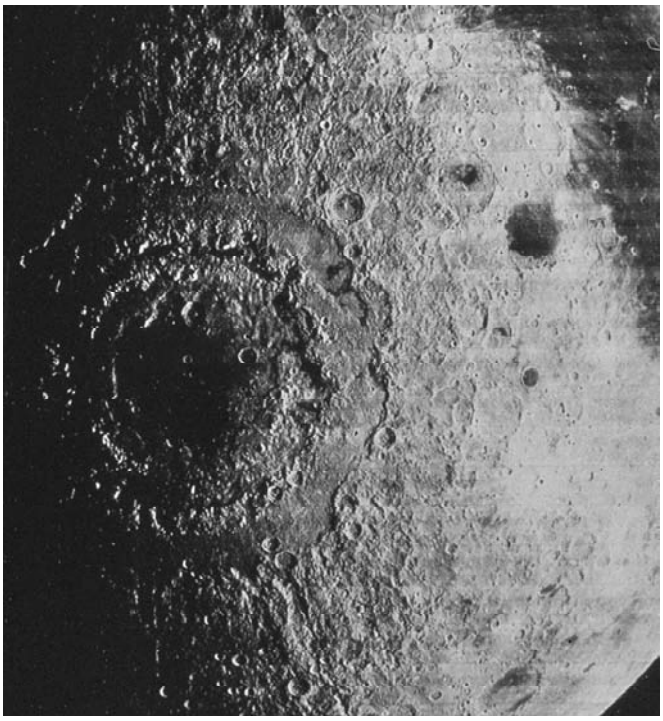
The highlands also contain other types of igneous rocks. The most abundant are called norites and troctolites, rocks composed of equal amounts of plagioclase and either olivine or pyroxene (both silicate minerals containing iron and magnesium). Age dating suggests that these rocks are slightly younger than the anorthosites and formed after the magma ocean had crystallized.

Highland rocks are difficult to work with because all that cratering, so evident in photographs of the highlands, has taken its toll on the rocks. Most highland rocks are complex mixtures of other rocks. The original igneous rocks have been melted, mixed, smashed, and generally abused by impacts during the Moon's first half billion years. We call these complicated rocks breccias. Some are so mixed up that they contain breccias within breccias within breccias. Most of the anorthosites, norites, and troctolites are actually rock fragments inside breccias. Separating them out is painstaking work.



An interesting thing about highland breccias, especially those we call impact melt breccias (rocks partly melted by an impact event), is that most of them fall into a relatively narrow span of ages, from about 3.85 to 4.0 billion years. This has led some scientists to propose (boldly again–lunar scientists don't seem to be timid!) that the Moon was

bombarded with exceptional intensity during that narrow time interval. If it happened, it probably affected Earth as well, perhaps leading to production of the first sedimentary basins, and possibly inhibiting the formation of the first life on this planet or harming whatever life had developed by four billion years ago. This idea of a cataclysmic bombardment of the Moon is not yet proven. It could be that the apparent clustering in rock ages reflects poor sampling—we may only have obtained samples from one or two large impact basins. The idea can be tested by obtaining samples from many more localities on the Moon.



Multi-ringed masterpieces

The Moon has about 35 multi-ringed, circular impact features larger than 300 km in diameter. The one shown here, the Orientale basin, has three very prominent rings. The diameter of the outer one is 930 km. These immense craters might all have formed in a narrow time interval between 3.85 and 4.0 billion years ago. Scientists do not know for sure how the rings form during the impact.

Many highland breccias and a few igneous rocks are enriched compared to other lunar samples in a set of elements not familiar to most of us. The elements are those that tend not to enter the abundant minerals in rocks. The result is that as a magma crystallizes the part that is still liquid becomes progressively richer in these special elements. The rocks that contain them are called KREEP, for potassium (chemical symbol K), rare-earth elements (abbreviated REE), and phosphorus (P). Most Moon specialists believe that KREEP represents the last dregs from the crystallization of the magma ocean. Huge impacts dug down to the lower crust of the Moon and excavated it, mixing it with other debris to form KREEPy breccias.

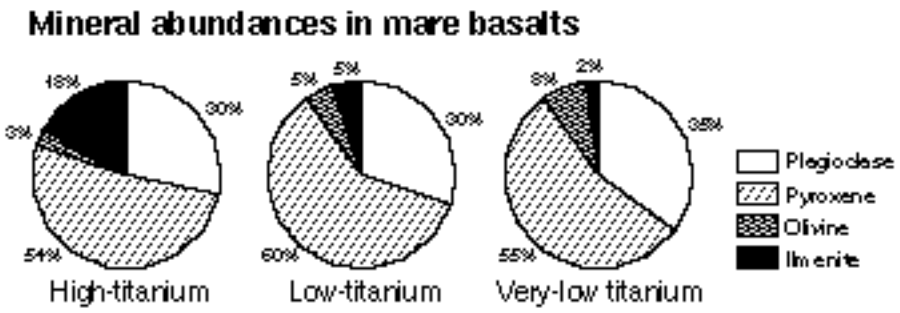
The maria: lava flows and fountains of fire

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

A piece of a lava flow

This typical sample of a mare basalt is composed mostly of brown pyroxene (grayish in the photo) and white feldspar. The holes in the sample are frozen gas bubbles. Some basalt samples have many such bubbles (called vesicles by geologists), whereas others have none.

plagioclase. Many of them also have surprisingly large amounts of an iron-titanium oxide mineral called ilmenite. The first batch had so much ilmenite (and some other related minerals) that they were called “high-titanium” mare basalts, in honor of the exceptional titanium contents compared to terrestrial basalts. 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 lower 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.

The shapes of the mineral grains and how they are intergrown in mare basalts indicate that these rocks formed in lava flows, some thin (perhaps a meter thick), others thicker (up to perhaps 30 meters). This is not unusual for basalt flows on Earth. Many lunar mare basalts also contain holes, called vesicles, which were formed by gas bubbles trapped when the lava solidified. Earth basalts also have them. On Earth, the abundant gases escaping from the lava are carbon dioxide and water vapor, accompanied by some sulfur and chlorine gases. We are not as sure what gases escaped from lunar lavas, although we know that water vapor was not one of them because there are no hints for the presence of water or water-bearing minerals in any Moon rock. The best bet is a mixture of carbon dioxide and carbon monoxide, with some sulfur gases added for good measure.

On Earth, when the amount of gas dissolved in magma (the name for lava still underground) becomes large, it escapes violently and causes an explosive eruption. In places such as Hawai‘i, for example, the lava erupts in large fountains up to several hundred meters high. The lava falls to the ground in small pieces, producing a pyroclastic deposit. This also happened on the Moon, producing the dark mantle deposits. One of these was sampled directly during the Apollo 17 mission. The sample, called the “orange soil,” consists of numerous small orange glass beads. They are glass because they cooled rapidly, so there was not enough time to form and grow crystals in them.

Small samples of pyroclastic glasses were also found at other sites. Some are green, others yellow, still others red. The differences in color reflect the amount of titanium they contain. The green have the least (about 1 weight percent) and the red contain the most (14 weight percent), more than even the highest titanium basalt.

Experiments conducted on mare basalts and pyroclastic glasses show that they formed when the interior of the Moon partially melted. (Rocks do not have a single melting temperature like pure substances. Instead they melt over a range of temperatures: 1000–1200°C for some basalts, for example.) The experiments also show that the melting took place at depths ranging from 100 to 500 km, and that the rocks that partially melted contained mostly olivine and pyroxene, with some ilmenite in the regions that formed the high-titanium basalts. An involved but sensible chain of reasoning indicates that these deep rocks rich in olivine and pyroxene formed from the lunar magma ocean: while plagioclase floated to form anorthosites in the highlands crust, the denser minerals olivine and pyroxene sank. So, although the anorthosites and mare basalts differ drastically in age and composition, the origins are intimately connected.

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 field work 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. (See companion volume *Exploring Meteorite Mysteries*.) Thirteen separate meteorites have been 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 do not know from where on the Moon they come. These samples have helped support the magma ocean idea. Most important, knowing that meteorites can be delivered to Earth by impacts on the Moon lends 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.

From the Moon, free of charge

The first lunar meteorite discovered in Antarctica hails from the lunar highlands and, like most highlands rocks, it is an impact breccia. The lunar meteorites prove that objects can be blasted off sizable objects without melting them, adding credence to the idea that a group of twelve meteorites comes from Mars.

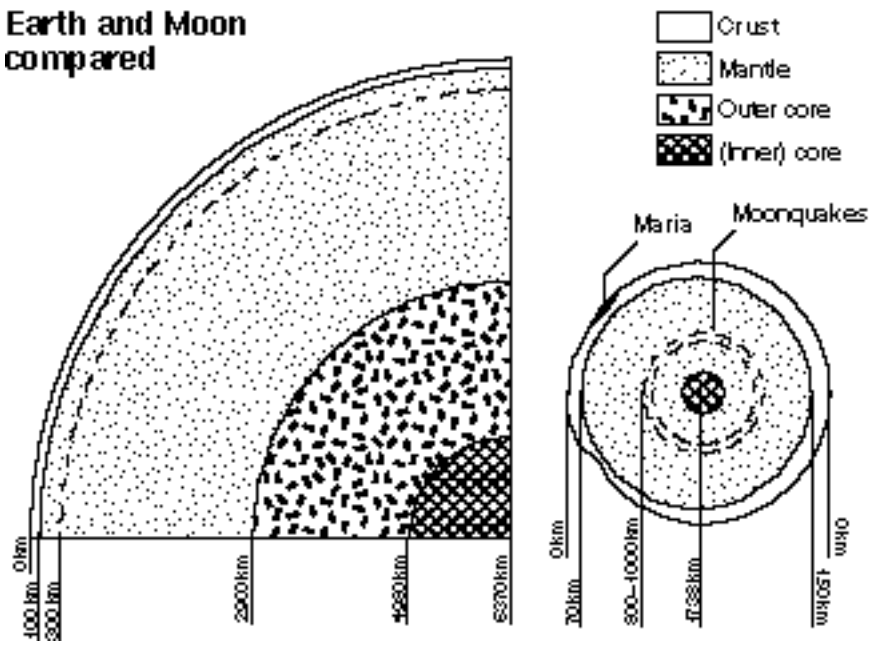
MOONQUAKES, THE MOON'S INTERIOR, AND THE MYSTERIOUS MAGNETIC FIELD

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 at present geologically active. No internal motions drive crustal plates as on Earth, or initiate hot spots to give rise to volcanic provinces like Hawai'i. 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.

We know about moonquakes from four seismometers set up by the Apollo missions. Besides telling us how many and how strong moonquakes are, the data acquired by the Apollo seismic network help us figure out something about the nature of the Moon's interior. On Earth, seismology has allowed us to know that the planet has a thin crust (20-60 km over continents, 8-10 km over ocean basins), a thick silicate mantle (down to 2900 km), and a large metallic iron core (2900 km to the center at 6370 km). The Moon is quite different. The crust is thicker than Earth's continental crust, ranging from 70 km on the Earth-facing side to perhaps 150 km on the farside. The mare basalts represent a thin veneer on this mostly plagioclase-rich crust, averaging only about 1 km in thickness (inferred mostly from photogeological studies). Evidence from samples collected on the rims of the large basins Imbrium and Serentatis and from remote sensing instruments carried onboard two Apollo missions, the Clementine Mission, and the forthcoming Lunar Prospector Mission suggest that the lower crust may not contain as much plagioclase as does the upper half of the crust. Beneath the crust is the lunar mantle, which is the largest part of the Moon. There might be a difference in rock types above and below a depth of 500 km, perhaps representing the depth of the lunar magma ocean. Beneath the mantle lies a small lunar core made of metallic iron. The size of the core is highly uncertain, with estimates ranging from about 100 km to 400 km.

That little core is important, though. The Moon does not have much of a magnetic field, so the lunar core is not generating magnetism the way Earth's core is. Nevertheless, it did in the past. Lunar rocks are magnetized, and the strength of the magnetic field has been measured by special techniques. Also, older rocks have stronger magnetism, suggesting that the Moon's magnetic field was stronger in the distant past, and then decreased to its weak present state. Why this happened is unknown. What is known is this: you cannot navigate around the Moon using a compass!

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



Inside the Moon and Earth

Scientists have learned what Earth and the Moon are like inside by several techniques, the most important of which is seismology, the study of earthquake (and, of course) moonquake waves. Earth has a much larger metallic core than does the Moon.

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 though 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 how Earth got to be 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 the Moon forming together, a two-body system from 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 than falling to Earth. (These problems with total amount of spinning involve both Earth's rotation and the Moon's motion around Earth. The amount of rotation and revolving is quantified by a physical property called angular momentum.) 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 alternatives. This search led to the seemingly outlandish idea that the Moon formed when a projectile the size of the planet Mars (half Earth's radius and one-tenth its mass) 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-1970s, 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, its metallic core

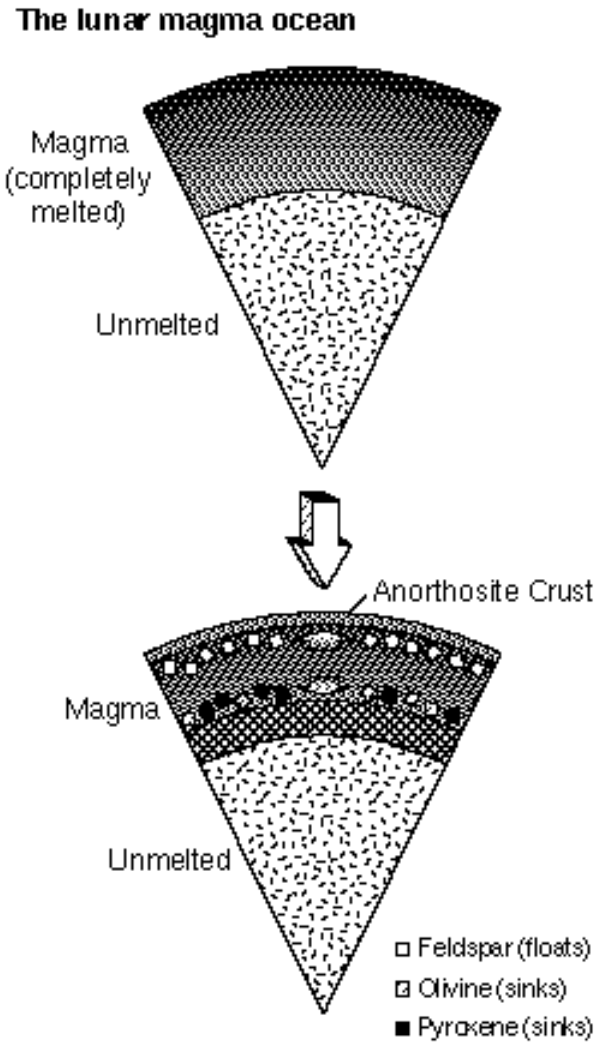
and all, never to be seen again. Yes, this sounds catastrophic. But out of it all, the Moon was created and Earth grew to almost its final size. Without this violent event early in the Solar System's history, there would be no Moon in Earth's sky, and Earth would not be rotating as fast as it is because the big impact spun it up. Days might even last a year. But then, maybe we would not be here to notice.

WHACK!

The Moon may have formed when an object the size of the planet Mars smashed into Earth when our future home was about 90% constructed. This fierce event made Earth larger and blasted off vaporized and melted material into orbit. The Moon formed from this debris. This painting was created by William K. Hartmann, one of the scientists who invented the giant impact hypothesis for lunar origin.

A BRIEF HISTORY OF THE MOON

We know the general outlines of what happened to the Moon after it was formed by a giant impact. The first notable event, which may have been a consequence of the giant impact, was the formation and crystallization of the magma ocean. Nobody knows how deep it was, but the best guess is that it was at least 500 km deep. The first minerals to form in this mind-boggling magmatic system were the iron and magnesium silicates olivine and pyroxene. They were denser than the magma, so they sank, like rocks in a pond, though not as fast. Eventually, plagioclase feldspar formed, and because it was less dense than the magma, began to float to the top, like bubbles in cola. It accumulated and produced mountains of anorthosite, producing the first lunar crust. The magma ocean phase ended by about 4.4 billion years ago. [See the "Differentiation" activity on Pages 57–60.]



Sinking and floating in an ocean of magma

Soon after it formed, the Moon was surrounded by a huge shell of molten rock called the lunar magma ocean. As crystals formed in it, the denser ones such as olivine and pyroxene sank and the less dense ones, such as feldspar, floated upwards, forming the original anorthosite crust on the Moon. Dropping toothpicks and pennies into a glass of water shows the process: the toothpicks (representing feldspar) float and the pennies (olivine and pyroxene) sink.

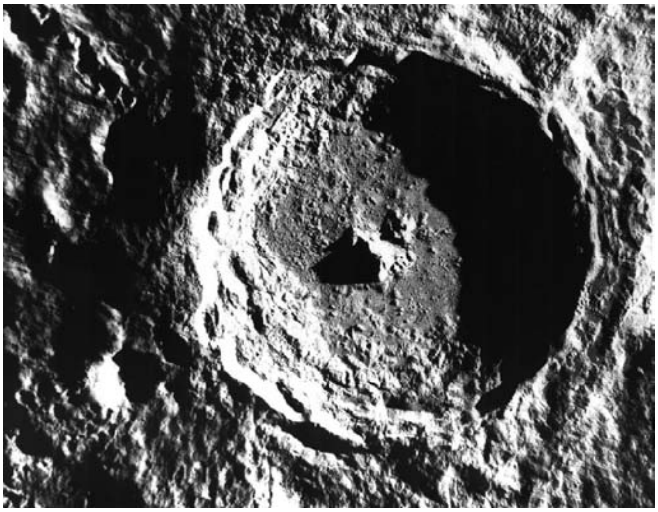
Almost as soon as the crust had formed, perhaps while it was still forming, other types of magmas that would form the norites and troctolites in the highlands crust began to form deep in the Moon. A great mystery is where inside the Moon and how deep. Many lunar specialists believe the magmas derived from unmelted Moon stuff beneath the magma ocean. In any case, these magmas rose and infiltrated the anorthosite crust, forming large and small rock bodies, and perhaps even erupting onto the surface. Some of the magmas reacted chemically with the dregs of the magma ocean (KREEP) and others may have dissolved some of the anorthosite. This period of lunar history ended about 4.0 billion years ago.

All during these first epochs, left-over projectiles continued to bombard the Moon, modifying the rocks soon after they formed. The crust was mixed to a depth of at least a few kilometers, perhaps as much as 20 km, as if a gigantic tractor had plowed the lunar crust. Though not yet proven, the rate of impact may have declined between 4.5 and 4.0 billion years ago, but then grew dramatically, producing most of the large basins visible on the Moon. This cataclysmic bombardment is postulated to have lasted from 4.0 to 3.85 billion years ago. [See the "Impact Craters" activity on Pages 61–70, and the "Regolith Formation" activity on Pages 47–52.]

Once the bombardment rate had settled down, the maria could form. Basalts like those making up the dark mare surfaces formed before 3.85 billion years ago, but not as voluminously as later, and the enormous bombardment rate demolished whatever lava plains formed. However, between 3.7 and about 2.5 billion years ago (the lower limit is highly uncertain), lavas flowed across the lunar surface, forming the maria and decorating the Moon's face. Along with the basalts came pyroclastic eruptions, high fountains of fire that launched glowing droplets of molten basalt on flights up to a few hundred kilometers.

Since mare volcanism ceased, impact has been the only geological force at work on the Moon. Some impressive craters have been made, such as Copernicus (90 km across) and Tycho (85 km). These flung bright rays of material across the dark lunar landscape, adding more decoration. In fact, some of the material blasted from Tycho caused a debris slide at what would become the Apollo 17 landing site. Samples from this site indicate that the landslide and some associated craters formed about 110 million years ago. This, therefore, is the age of the crater Tycho. It is a triumph of geological savvy that we were able to date an impact crater that lies over 2000 km from the place we landed!

The impacts during the past billions of years also have mixed the upper several meters of crust to make the powdery lunar regolith. The Sun has continued to implant a tiny amount of itself into the regolith, giving us its cryptic record and providing resources for future explorers. And recently, only seconds ago in geologic time, a few interplanetary travelers left their footprints here and there on the dusty ground.



Anatomy of an impact crater

The crater Tycho in the southern highlands on the lunar nearside is 85 kilometers across. Its terraced walls rise 3 to 4 kilometers above its floor. Its rim rises above the surrounding terrain, and its floor sits below it. Smooth material on the floor of the crater consists of impact-melted rock that flowed like lava across the growing floor in the later stages of excavation. In response to the huge increase then decrease in pressure, mountains two kilometers high rose from its floor, bringing up material from as much as ten kilometers in the crust. The blanket of material surrounding the crater is called the ejecta blanket; this pile of debris becomes progressively thinner away from the crater (especially evident on the left of the photo).

Although not visible on this photograph, large craters like Tycho also have rays emanating from them. Rays form when materials thrown out of the crater land and excavate more of the lunar landscape along arcuate paths. The Tycho event caused a landslide and several secondary impacts at the Apollo 17 landing site, over 2000 kilometers away. Analysis of samples collected during the Apollo 17 mission indicates that these events took place 110 million years ago. Thus, Tycho formed 110 million years ago.

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 have been bathed in the same flux of sunlight 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 its 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 do 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.

Magma oceans. The concept that the Moon had a magma ocean has been a central tenet of lunar science since it sprung from fertile minds after the return of the first lunar samples in 1969. It is now being applied to Earth, Mars, and asteroids. This view of the early stages of planet development is vastly different from the view in the 1950s and 1960s. Back then, most (not all) scientists believed the planets assembled cold, and then heated up. The realization that the Moon had a magma ocean changed all that and has led to a whole new way of looking at Earth's earliest history.

Early bombardment history of 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 influenced the development of life, perhaps delaying its appearance.

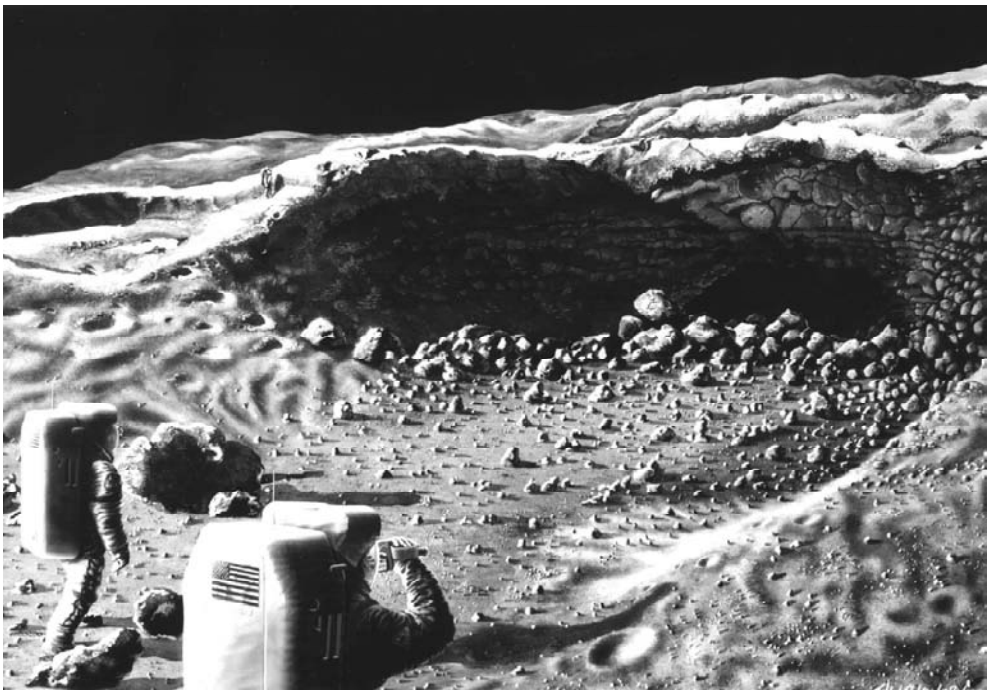
Impacts, extinctions, and the evolution of life on Earth. The mechanisms of evolution and mass extinctions are not understood. One possibility is that some mass-extinction events were caused by periodic increases in the rate of impact on Earth. For example, the mass extinctions, which included the demise of the dinosaurs, at the end of the Cretaceous period (65 million years ago), may have been caused by a large impact event. Attempts to test the idea by dating impact craters on Earth are doomed because there are too few of them. 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.

LIFE AND WORK AT A MOON BASE

People will someday return to the Moon. When they do, it will be to stay. They will build a base on the Moon, the first settlement in the beginning of an interplanetary migration that will eventually take them throughout the Solar System.

There will be lots to do at a lunar base. Geologists will study the Moon with the intensity and vigor they do on Earth, with emphasis on field studies. Astronomers will make magnificent observations of the universe. Solar scientists will study the solar wind directly and investigate past activity trapped in layers of regolith. Writers and artists will be inspired by a landscape so different from Earth's. Life scientists will study how people adapt to a gravity field one-sixth as strong as Earth's, and figure out how to grow plants in lunar greenhouses. Engineers will investigate how to keep a complex facility operating continuously in a hostile environment. Mining and chemical engineers will determine how to extract resources from Moon rocks and regolith. The seemingly dry lunar surface contains plenty of the ingredients to support life at a Moon base (oxygen and hydrogen for water, nitrogen and carbon for the growth of plants), including the construction



Geology at a Moon Base

The best geology is done in the field. To understand rocks we must examine them up close, map their distributions, see the structures in them, and chip off samples when necessary. The field geology done during the Apollo missions was hampered by the lack of time the astronauts could devote to it. But that will change when people live permanently on the Moon. Geologists will be able to spend as much time as they need to decipher the story recorded by lunar rock formations. This painting shows three astronauts (one in the distance) examining the outside of a lava tube, an underground conduit that carried red-hot lava to an eruption site perhaps hundreds of kilometers away.

materials to build and maintain the base (regolith can be molded into bricks; iron, titanium, and aluminum can be smelted and forged into tools and building materials). It will be an exciting, high-tech, faraway place inhabited by adventurous souls. [See the Unit 3 activities beginning on Page 99.]

WHERE MOON ROCKS HANG OUT

Since arrival on Earth, lunar samples have been treated with the respect they deserve. Most of the treasure of Apollo is stored at the Lunar Curatorial Facility at the Johnson Space Center, Houston, Texas. A small percentage is stored in an auxiliary facility at Brooks Air Force Base near San Antonio, Texas, placed there in case a disaster, such as a hurricane, befalls Houston and the samples are destroyed. Many small samples are also in the laboratories of investigators around the world, where enthusiastic scientists keep trying to wring out the Moon's secrets.

The Curatorial Facility is one of the cleanest places you'll ever see. To go inside, you must wear white suits, boots, hats, and gloves, outfits affectionately known as "bunny suits." Wipe a gloved hand on a stainless steel cabinet and you will not find a trace of dust because the air is filtered to remove potential contaminating particles.

The samples are stored in a large vault, and only one at a time is moved to a glove box. You can pick up the rocks by jamming your hands into a pair of the black rubber gloves, allowing you to turn a rock over, to sense its mass and density, to connect with it. A stereomicroscope allows you to look at it closely. If you decide you need a sample, and of course you have been approved to obtain one, then expert lunar sample processors take over. The sample is photographed before and after the new sample is chipped off. This is time consuming, but valuable to be sure we know the relationships of all samples to each other. In many cases, we can determine the orientation a specific part of a rock was in on the surface of the Moon before collection.

A select small number of pieces of the Moon are on display in public museums, and only three pieces can actually be touched. These so-called lunar "touchstones" were all cut from the same Apollo 17 basaltic rock. One touchstone is housed at the Smithsonian Air and Space Museum in Washington, D.C. Another touchstone is at the Space Center Houston facility adjacent to the Johnson Space Center. A third touchstone is on long-term loan to the Museo de Las Ciencias at the Universidad Nacional Autonoma de Mexico. Visitors to these exhibits marvel at the unique experience of touching a piece of the Moon with their bare hands.

Safe haven for precious rocks

NASA stores the lunar sample collection in a specially constructed facility called the Lunar Curatorial Facility at the Johnson Space Center in Houston, Texas. The priceless materials remain in a nitrogen atmosphere, which is far less reactive chemically than normal oxygen-rich air. Scientists working in the facility wear lint-free outfits affectionately known as "bunny suits," and handle the samples in glove boxes. In this photograph, Roberta Score is examining a piece of an Apollo 16 rock, while Andrea Mosie (left) looks on.

SCIENTISTS AS POETS

Scientists do not view the world in purely objective ways. Each has biases and a unique way of looking at the world. Science is not done solely with piles of data, hundreds of graphs, or pages of equations. It is done with the heart and soul, too. Sometimes a scientist is moved to write about it in elegant prose like that written by Loren Eisley or in poetry, like the poem written by Professor Carlé Pieters of Brown University. Dr. Pieters holds her doctorate from MIT and is an expert in remote sensing of planetary surfaces. She is especially well known for her telescopic observations of the Moon. The poem first appeared in the frontispiece of Origin of the Moon, published by the Lunar and Planetary Institute.

The Original Moon

Four and a half æons ago
a dark, dusty cloud deformed.
Sun became star; Earth became large,
and Moon, a new world, was born.

This Earth/Moon pair, once linked so close,
would later be forced apart.
Images of young intimate ties
we only perceive in part.

Both Earth and Moon were strongly stripped
of their mantle siderophiles.
But Moon alone was doomed to thirst
from depletion of volatiles.

Moon holds secrets of ages past
when planets dueled for space.
As primordial crust evolved
raw violence reworked Moon's face.

After the first half billion years
huge permanent scars appeared;
ancient feldspathic crust survived
with a mafic mantle mirror.

But then there grew from half-lived depths
a new warmth set free inside.
Rivers and floods of partial melt
resurfaced the low 'frontside'.

Thus evolved the Original Moon
in those turbulent times.
Now we paint from fragments of clues
the reasons and the rhymes:

Sister planet;
Modified clone;
Captured migrant;
Big splash disowned?

The Truth in some or all of these
will tickle, delight,
temper, and tease.

— Carlé Pieters