

THE MOON

GATEWAY TO THE SOLAR SYSTEM BY G. JEFFERY 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 were 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, weather, and erosion. Colliding tectonic plates 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 sediments from the lovely body that graces the night sky.

THE LUNAR LANDSCAPE

The Moon is not like the 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 ever had any water), we still use the term *maria*, and the similar 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 2 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 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.

The maria

The maria covers 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.

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*.

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 Serenitatis formed when the basin did, they ought to show the effects of the giant impact that formed Imbrium. They show no signs of it. Furthermore, the maria contain 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 shows 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. 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, make 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 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 20km/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 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.

Lunar regolith is a mixed blessing. On the one hand, it has mixed local materials 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 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.

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 and the solar wind provided the rest. So, when the astronauts were digging up their 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 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.

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. 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 were 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, how did they get that way? 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 Hawaii developed a method to determine the iron content of the lunar surface from ratios 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. %. 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 with 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 breccias (rocks partly melted by an impact even), 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 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.

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. 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.