NASA
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What We've Learned About The Moon

INTRODUCTION

From the day that Galileo saw the Moon through the first telescope until July 20, 1969, when Astronauts Neil A. Armstrong and Edwin E. Aldrin, Jr., walked on the Moon, we learned many things about the Moon. During those 300 years, we learned how to determine its size, shape, and weight, how to measure the temperature of the surface, to estimate the electrical properties from radar waves bounced off the Moon, and to do many others without leaving the planet Earth. We even sent automated spacecraft to the Moon's surface and analyzed the chemical composition!

We thus knew many facts about the Moon before Neil Armstrong and Buzz Aldrin landed their spacecraft. Yet their historic landing opened the way for us to visit the Moon, to bring back actual material from the Moon itself, and to leave scientific instruments on the surface of the Moon to operate by radio control for years. Just as Galileo's telescopic observations opened a new era in astronomy, Armstrong and Aldrin's voyage opened a new discipline in science — that of LUNAR SCIENCE!

This new science during its first decade has been filled with surprises. Now surprises in science are good. They usually mean that we have discovered something that was not expected, a scientific bonus.

There was intense excitement at the Lunar Receiving Laboratory in Houston when the Apollo 11 rock boxes were opened. The first samples of rocks and soil returned from the Moon!

The Apollo 11 samples are still being intensively explored today. The lunar samples are helping unravel some of the most important questions in lunar science and astronomy. They include: (1) How old is the Moon? (2) Where and how did the Moon originate? (3) What history and geologic features do the Moon and Earth have in common, and what are the differences? (4) What can the Moon tell us about the rest of the solar system, and of the rest of the universe?

To help solve these questions, NASA has used highly advanced and very sensitive scientific equipment, sometimes on samples almost too small to be seen by the unaided eye. Some of the equipment was designed and built specifically to work on the lunar material.

WHAT THE ROCKS ARE TELLING US

The rocks contain interesting, often exciting, stories. They reveal their stories through the scientist's experienced eyes and sophisticated instruments. The shape, size, arrangement and composition of the individual grains and crystals in a rock tell us about its history. Radioactive clocks tell us the age of the rock. Tiny tracks even tell us the radiation history of the Sun during the last 100,000 years. And so on. In some aspects, the appearance of lunar rocks resemble those of Earth rocks. The minerals are the same. The grain sizes are comparable. The shapes are familiar. But in other aspects, their appearances differ significantly. For example, the rock surfaces are pitted with many tiny craters. The rocks are extraordinarily free of weathering and appear from a terrestrial standpoint as fresh as though formed yesterday, although they are billions of years old.

For study of rocks with a microscope — lunar rocks as well as most Earth rocks — chips from them are cemented to glass slides and ground to paper thinness. These thin sections transmit light and can be studied under a microscope to learn about the sizes and shapes of the constituent grains, and how they fit together.

One kind of rock from the Moon shows the characteristics of igneous rocks on Earth. The term, igneous, means that the rock crystallized from a hot liquid, a fact that we infer from the minerals present, their arrangement and shape, and out of experience of seeing similar rocks cool from the molten lavas erupted from volcanoes on Earth.

In thin sections of basalt many of the individual mineral grains transmit light but others (the completely black grains) do not transmit light. The black grains (termed opaque) are the mineral ilmenite, which is rich in titanium dioxide. This mineral is common and composes a few percent of basalts on Earth. At the Apollo 11 and 17 landing sites on the Moon, however, ilmenite composes 10 % of the rocks. Since basalts come from lavas melted from materials hundreds of miles deep, these materials must be different inside of the Moon from what they are inside of the Earth.

Another feature common in lunar volcanic rocks is the occurrence of round holes called vesicles. On Earth similar holes are caused by gas, mostly steam, bubbling out of lavas as they cool and solidify. We can see these bubbles in lavas from the volcanoes on Hawaii. Because the Moon's gravity is too weak to have retained an atmosphere of gas, the way the Earth has, the nature of the gas from the bubbles is unknown. It cannot have been steam, though, because steam would have rusted the iron metal in the lunar lavas.

A photomicrograph (a photograph of a thin section taken through the microscope) of another type lunar rock contains three different kinds of minerals. One is completely dark, and has rather straight sides and sharp angles. This mineral is spinel and, when sufficiently large and flawless, is a beautiful gemstone. The second mineral stands out also, though not quite as sharply as the spinel, and also occurs as discrete grains. This mineral, olivine, also has sharp edges and angles and is probably better known as peridot, the birthstone for August. The third mineral, which transmits light very well and appears colorless in thin sections, constitutes the rest of the rock, filling the space around the other two minerals. It is termed feldspar and is the pink mineral in granite — a terrestrial rock commonly used for tombstones. Almost surely you have held feldspar in your hand. The familiar household cleansing and scouring powders, such as Ajax, are mostly feldspar.

And finally, there are a few dark spots that represent opaque grains, probably ilmenite; there may also be metallic iron with a small percentage of nickel.

There are two ways in which we "read" the history of a rock from the thin section. Because the grains of ilmenite, spinel, and olivine have their characteristic crystal shapes and are surrounded by the feldspar, we know that the feldspar crystallized last.

Secondly, the rock has a thin zone in which the individual grains are all smaller than elsewhere. This zone indicates that the bottom part of the rock was broken loose from the top part and displaced slightly.

One of the major surprises — though in retrospect the "surprise" should have been expected — was the discovery in the Apollo 11 samples of large quantities of glass. Why should glass surprise us? After all, we are extremely familiar with glass. We use glass every day. So what should be surprising? Even though we are literally surrounded with glass every day, all of that glass is artificial. It was manufactured. On the Earth, the occurrence of natural glass is exceedingly rare. (However, you may have seen obsidian, a black-to-brown volcanic glass.) Most people have never seen natural glass! On the other hand, its occurrence on the Moon is extremely common. Indeed, glass is abundant in the material from each lunar mission. It often sticks to the outside of rocks. The glass was formed by the high pressure and temperature produced when a meteorite struck the Moon. It was splashed from the impact site, much as mud is thrown from the impact point when a pebble is dropped into a mud puddle.

Glass also occurs inside some rocks often forming very beautiful swirls caused by the flow of the glass before it froze.

Another surprise about the glass in the lunar rocks is that is has survived so long. The lunar rocks are 3 to 4-1/2 billion-years-old. Yet, the glass has survived this large span of time. On Earth, the oldest known glass is very young in comparison, a mere 200 million years. Most terrestrial glasses are, in fact, younger than 50 million years. The glasses that formed on Earth before 200 million years, have long since changed into individual minerals, a process called devitrification. In fact, all glasses devitrify with time. So why is the process so much more rapid on Earth than it is on the Moon? Because no water is present on the Moon. Water greatly increases the rate of devitrification. Thus a glass can persist on the Moon for more than four billion years in the complete absence of water. Yet the same glass on Earth in the presence of water would devitrify within a few tens of millions of years.

Water is indeed very rare on the Moon. The widespread abundance of ancient glasses is very strong evidence. But in addition, none of the minerals of the lunar rocks contains water.

The absence of water on the Moon surprised most lunar scientists. Of course, we had known that at present, because of the extremely thin — almost nonexistent — lunar atmosphere, there could be no free water on the surface of the Moon. Yet because some lunar features such as the beautiful valley at Hadley-Apennine, the Apollo 15 site, we had expected that perhaps in the past there had been significant quantities of water on, and inside the Moon, But we now know that hypothesis to be completely false.

Incidentally, the absence of water on the Moon has great practical significance for us. It is expected that we will someday live in permanent colonies on the Moon. Thus the absence of water means that supplies of it must be either carried with the colonists (as the present-day astronauts), or manufactured on the Moon. In a sense, this lack of water also has immediate benefits to Apollo 17 science. It is exactly this absence of water that causes the electrical properties to be such that the surface electric properties (SEP) experiment will be able to "see deeply beneath the surface."

Another kind of lunar rock, also extremely common, is a breccia (pronounced brek' sha), which is a rock that contains broken, angular pieces of other rocks. On the Moon, breccias are formed under the intense pressure and temperature produced by meteorite impacts. Thus the rocks that existed before an impact, as well as the soils, are welded together under the high pressures and temperatures. In the breccia, a darkish material is glass that "cements" individual mineral grains as well as individual rock particles. The event that produced the glass was undoubtedly the last of several events. At least two other events are also recorded in this type rock. They contain other mineral grains, as well as pieces of other preexisting rocks. What about the minerals present in the Moon rocks? Most of them are similar to the ones with which we are familiar on Earth though with notable exceptions. The common minerals are feldspar (familiar to you from Ajax), olivine (in gem form, peridot), pyroxene (a mineral composed chiefly of iron, magnesium, calcium, silicon, and oxygen), and spinel. Quartz (silicon dioxide), an extremely common terrestrial mineral, is very rare on the Moon. And finally, shiny iron metal is present, though in small quantities, in most of the lunar rocks. Rusty iron occurs in some Apollo 16 samples, but this rusting happened after the rocks were brought to Earth by reaction of iron chloride with the trace amounts of oxygen and water in the nitrogen gas that is being used for storing the rocks.

Still another kind of rock consists almost entirely of a single mineral, feldspar. The stripes across the grains, characteristic of feldspar, are caused by the individual sections having a special orientation with respect to the rest of the mineral grain. A very small amount of another mineral, olivine, is also present. The recognition that such rocks as this, termed anorthosites, form the highlands region of the Moon, is one of the most exciting chapters in Lunar Science. This conclusion is supported by the previous discovery by two scientists at the Jet Propulsion Laboratory in Pasadena, California, William Sjogren and Paul Muller, that the rocks beneath the lunar highlands are less dense than the rocks beneath the lunar mare. Anorthosites were known to be less dense than basalts. Large samples of anorthosite have been found on both the Apollo 15 and Apollo 16 missions. And finally, an Apollo 15 orbital experiment, the X-ray fluorescence experiment showed that the elements aluminum and silicon are in the proper ratio in the highlands for anorthosite.

Anorthosites are very special rocks. The observation that anorthosite consists almost entirely of a single mineral is very important. The chemical processes that lead from the ordinary igneous rocks — like basalt — to an anorthosite are very complex. An anorthosite is a "highly refined product." The processes are similar to the ones used on Earth in petroleum refineries to change crude oil to such diverse products as asphalt for roads, lubrication greases, motor oil, kerosene, jet fuel, automobile gasoline, aviation gasoline, and dozens of other products. Like aviation gasoline, the anorthosite is the final product of a series of very complex chemical processes.

All the lunar rocks are very, very old. Their ages range from three to over four and one half billion years. The oldest known terrestrial rock is about three and one-half billion years old, but rocks older than two billion years are rare. How are such ages measured? By radioactive clocks. The rocks contain radioactive elements, such as uranium, that change slowly at a known rate into other elements such as lead. From the ratio of the product element to the parent radioactive element, measured with highly sensitive instruments, the time the process has been going on can be determined; this gives the age of the rock.

What about life on the Moon? We have found no chemical evidence that living things (except 12 very lively astronauts!) have ever been on the Moon. No fossils. No micro-organisms. No traces of biologically formed chemicals. Nothing. Yet, there do appear to be extremely small amounts of amino acids and possibly other related organic compounds in some of the lunar soil. Recently, such molecules as formaldehyde, ammonia, and methyl alcohol have been detected as clouds in remote space. Such findings have led many to speculate that even though there is no evidence of life on the Moon, life, even intelligent life, must exist elsewhere in the universe. Undoubtedly, this question will remain a major one for future investigations.

About 200 scientists in the United States and 10 foreign countries are still studying the lunar samples today. Even though about 840 pounds of lunar samples have been brought to Earth, NASA is still being very conservative in how much is used. Those who study the samples usually receive a piece smaller than one-fourth inch on a side; a very few receive larger pieces. All material (except that which is used in experiments that consume the material) is returned to NASA when the work is finished for use in new studies. Only 2 percent of the total samples have been consumed in analysis during a decade of study; another 10 percent is in use being studied in scientific laboratories, on exhibit in museums, in educational sets that are circulated among schools and universities; 88 percent is being carefully preserved for scientific studies in future years, which will use new and more powerful analytical tools not yet known today. These samples will be a priceless scientific and educational heritage as well as a special kind of enduring monument to the memory of the astronauts and to the many scientists, engineers, taxpayers, and others who made the Apollo missions possible. Small quantities of lunar material have been given to each of the States in the U. S. and to the Governments of foreign countries.

WHAT THE LUNAR SURFACE EXPERIMENTS TOLD US

The scientific experiments left on the Moon by the astronauts sent data to Earth over microwave radio links for four years. It is hoped that they will continue to operate for several more years. A complete listing of these experiments is given in the Appendix. A few of those experiments that have helped us understand the interior of the Moon have given many surprises.

Very sensitive instruments, termed seismographs, measure extremely small vibrations of the Moon's surface. These instruments are similar to the familiar ones used by doctors to listen to your heartbeat. With them, we can listen back on Earth to the vibrations on the Moon. Some of those vibrations are caused by naturally occurring events, others by impacts on the Moon of parts of spacecraft, still others by meteorites.

The spacecraft impacts were especially valuable to studies of the Moon's interior. NASA scientists now believe that the Moon has a crust of rocks that differ greatly from the rocks deeper in the Moon. This crust is roughly 30 to 60 miles thick. Its existence implies that the early geological history of the Moon resembles that of the Earth which also developed a similar crust. (Relative to their different sizes, however, the Earth's crust is much thinner than the Moon's.)

By comparison with the Earth, the Moon is extremely quiet. More than one million earthquakes occur on the Earth each year, while there are only a few hundred small moonquakes during the same time.

The seismic properties of the lunar crust were greatly surprising. Very small signals from the impact of each spacecraft caused the Moon to ring like a bell for several hours. Such behavior of the Earth occurs only with the largest of earthquakes. Similar signals on the Earth would have died completely after a few minutes. Perhaps this difference in behavior is caused by the absence of water in the Moon, and the lower temperature of the Moon's crust.

Another surprise, as well as some exciting implications, was provided by measurement of the Moon's magnetic field. Now the magnetic field of the Moon (and also the Earth) has two parts, one that changes with time and one that is steady and does not change rapidly with time.

The steady part of the Earth's magnetic field is about 50,000 gamma (the usual unit of magnetic field employed by Earth scientists). It causes compasses to point approximately north-south. The steady part of the lunar magnetic field, measured at the Apollo 12 site, was about 35 gamma, somewhat more than 1,000 times smaller than the Earth's field. Yet the 35 gamma field was several times larger than expected. Values measured at the Apollo 14 and 16 site were even larger! The steady part of the lunar magnetic field is undoubtedly due to the presence of natural magnetism that was frozen into the lunar rocks. This magnetism was probably inherited early in the Moon's history (several billion years ago) when the magnetic field was many times larger than today. Now the magnetic field is much too small to affect a compass.

The other part of the lunar magnetic field, that which varies with time, is influenced greatly by the electrical properties of the interior of the Moon. Therefore, a study of the variations with time of the magnetic field revealed the electrical properties of the Moon as a function of depth.

Because the electrical properties of rocks are influenced by the temperature, we hope to use such data to measure indirectly temperatures in the interior of the Moon.

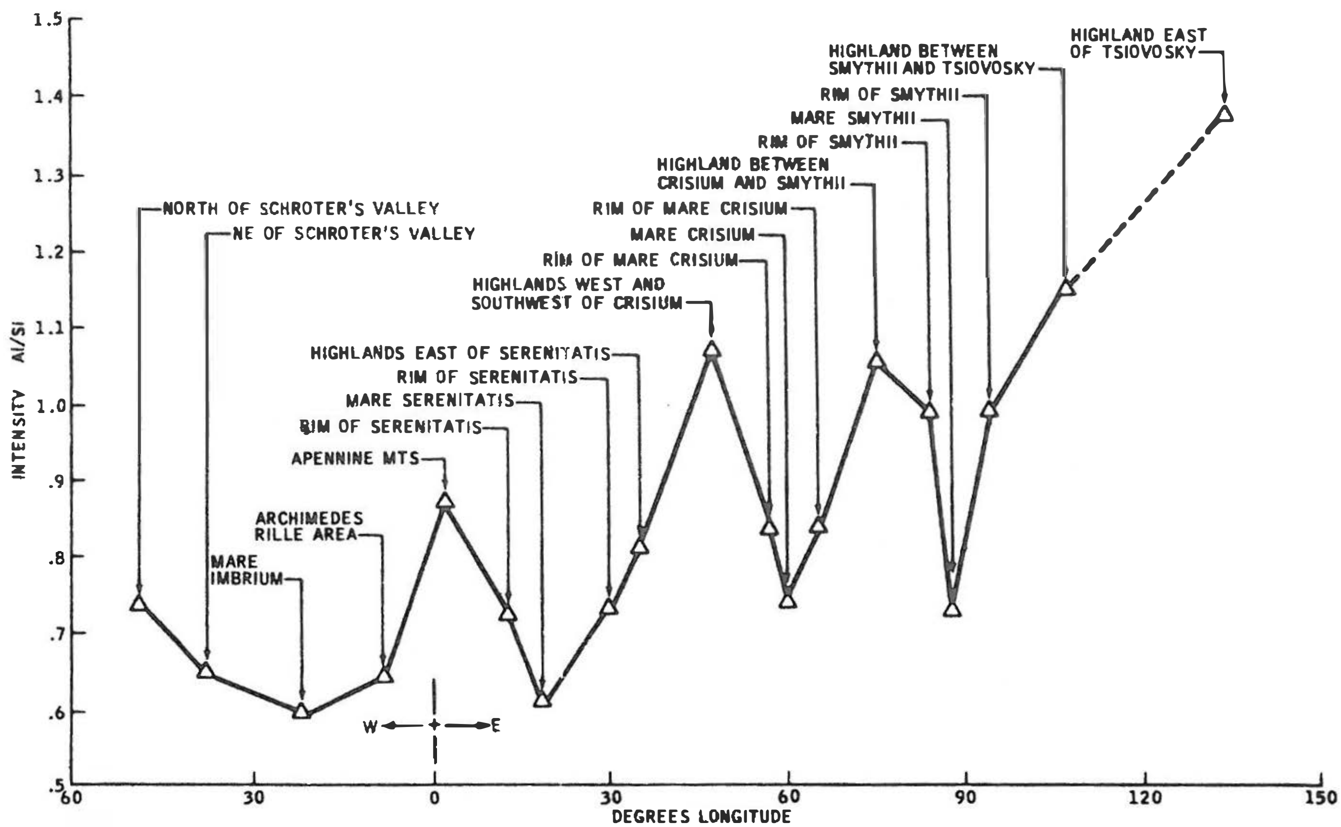
WHAT THE ORBITAL EXPERIMENTS TOLD US

While the surface experiments told about the interior of the Moon, or about some phenomenon in the vicinity of the landing site, and the lunar rocks also tell mainly about events that happened near the landing sites, the orbital experiments gave information along a path completely around the Moon. Thus, the orbital experiments allow us to extend the information collected at those few landing spots on the Moon to much larger regions. For example, from the chemical group of orbital experiments — the X-ray Fluorescence Experiment, the Alpha-particle Spectrometer, and the Gamma Ray Spectrometer we know the chemical differences between the highlands and maria and that the highlands material is closely akin to anorthosite.

But not only have the orbital experiments let us extrapolate the site data, but also they have provided new information about the Moon that was not otherwise available. We have obtained very high quality photographs that are being used to provide a geodetic reference system for locations on the Moon that are comparable to the best yet developed for the Earth. Geologic analysis of a few of those photos has revealed the presence of several features on the Moon that had previously been suggested on the basis of less evidence. The photos of the Taurus-Littrow site have been interpreted by two geologists, Jim Head and Tom McGetchin, to indicate the presence near the Apollo 17 site of volcanic debris similar to that on Earth blown out of the volcanoes Stromboli and Etna. Head and McGetchin used slow-motion photography of the eruptions of these two volcanoes, aerodynamic theory, and the effect of one-sixth gravity, to show the kind of deposits that these volcanoes would have built on the Moon. They then compared the predicted features with those shown on the lunar photos.

Dr. Isadore Adler recognized that materials on the Moon bombarded with X-rays from the Sun fluoresced and allowed him to perform an orbital experiment to detect and measure fluorescent X-rays from the Moon. Under favorable conditions, his experiments measured the amounts. The most common of these elements in lunar rocks, as well as terrestrial, are magnesium, aluminum, and silicon.

Results obtained in the diagram below from the Apollo 15 flight are shown. The ratio of aluminum to silicon (denoted Al/Si) is plotted against longitude for one revolution. Shown also are the locations of various features of the Moon in relation to the data. Adler and his team observed that the ratios are generally low over mare regions and high over the Highlands. Such systematic variations are clearly related to the distribution of rock types over the surface of the Moon.



There were several other orbital experiments. Each experiment has revealed many important and exciting things about the Moon.

APPENDIX

APOLLO SCIENCE EXPERIMENTS

The science experiments carried on each Apollo mission were more numerous and also more complex than those carried on the preceding Apollo mission.

Number	Experiment	Mission and landing site						
		A-11 Sea of Tranquility	A-12 Ocean of storms	A-13 Mission aborted	A-14 Fra Mauro	A-15 Hadley-Apennine	A-16 Descartes	A-17 Taurus-Littrow
	Orbital experiments							
S—158	Multi-Spectral Photography		X					
S—176	Cm Window Meteoroid				X	X	X	X
S—177	UV Photography—Earth and Moon					X	X	
S—178	Gegenschein from Lunar Orbit			X	X	X		
S—160	Gamma-Ray Spectrometer					X	X	
S—161	X-Ray Fluorescence					X	X	
S—162	Alpha Particle Spectrometer					X	X	
S—164	S-Band Transponder (CSM/LM)			X	X	X	X	X
S—164	S-Band Transponder (Subsatellite)					X	X	
S—165	Mass Spectrometer					X	X	
S—169	Far UV Spectrometer							X
S—170	Bistatic Radar			X	X	X	X	
S—171	IR Scanning Radiometer							X
S—173	Particle Shadows/Boundary Layer (Subsatellite).					X	X	
S—174	Magnetometer (Subsatellite)					X	X	
S—209	Lunar Sounder							X
	Surface experiments							
S—031	Passive Seismic	X	X	X	X	X	X	
S—033	Active Seismic				X		X	
S—034	Lunar Surface Magnetometer		X			X	X	
S—035	Solar Wind Spectrometer		X			X		
S—036	Suprathermal Ion Detector		X		X	X		
S—037	Heat Flow			X		X	X	X
S—038	Charged Particle Lunar Env.			X	X			
S—058	Cold Cathode Ion Gauge		X		X	X		
S—059	Lunar Field Geology	X	X	X	X	X	X	X
S—078	Laser Ranging Retro-Reflector	X			X	X		
S—080	Solar Wind Composition	X	X	X	X	X	X	
S—151	Cosmic-Ray Detection (Helmets)	X						
S—152	Cosmic Ray Detector (Sheets)						X	
S—184	Lunar Surface Closeup Photography		X	X				
S—198	Portable Magnetometer				X		X	
S—199	Lunar Gravity Traverse							X
S—200	Soil Mechanics				X	X	X	X
S—201	Far UV Camera/Spectroscope						X	
S—202	Lunar Ejecta and Meteorites							X
S—203	Lunar Siesmic Profiling							X
S—204	Surface Electrical Properties							X
S—205	Lunar Atmospheric Composition							X
S—207	Lunar Surface Gravimeter							X
M—515	Lunar Dust Detector		X	X	X	X		
S—229	Lunar Neutron Probe							X

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