A geologist's-eye-view, in layman's language, of the results of the Apollo missions and what comes next—an adaptation of a Watson Lecture.

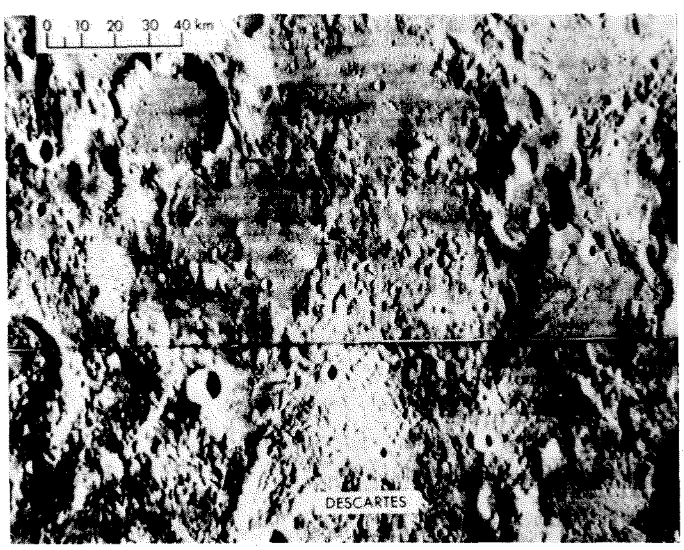
THE END OF EXPLORATION—

AND THE BEGINNING OF SCIENCE

by Leon T. Silver

Manned exploration of the moon, thrilling as it has been, represents only the opening phase of the scientific exploration of that planetary body. Scientists are now ready to begin making definitive studies of the Apollo crews' observations, photographs, lunar samples, and instrumental data. Their preliminary work indicates that important scientific yields will be the harvest of the immense effort we have put into the Apollo program.

From the beginning of the program, it was necessary for science to accommodate and adapt to the necessity of developing a technological capability to explore the moon. Although it wasn't as obvious, scientists were just as hard pressed as the builders of rockets and life-support systems to come up with adequate techniques and means to plan lunar-surface explorations, plot orbiting reconnaissance, and handle the samples. Thus, manned exploration of the moon involved some of the best and most hectic efforts of men in science, in engineering, and on the moon. But I want to emphasize that what remains to be done, now that the exploration phase of the Apollo program is over, is the main thrust of lunar science. That work—in its detail, its precision, and its depth—will go on for years.



From the earth, the moon seems to vary only between darker and lighter areas. Closer up, its variations also turn out to reflect the amount of cratering and differences in elevation. The Apollo 15 site (left) on a mare surface, though split by the sinuous Hadley Rille, is smooth by comparison with the rugged highlands near the crater Descartes (above), which was home base for Apollo 16.

Why did we want to go to the moon? As far as we could tell, it was so barren that there was nothing there to interest a man, unless he could look at it as a fascinating source of information about the universe of which it is a part. Perhaps if we came to understand how it was formed, we would be able to understand all the other planets better.

The moon is a striking example of a planet that apparently was frozen in the early stages of its development. In contrast to the variety and complexity of forces that continue to alter the face of the earth, the forces that have acted on the moon—at least for the last 3.2 billion years—have been relatively simple. This makes it possible for us to read its early record far more clearly than we can that of the earth.

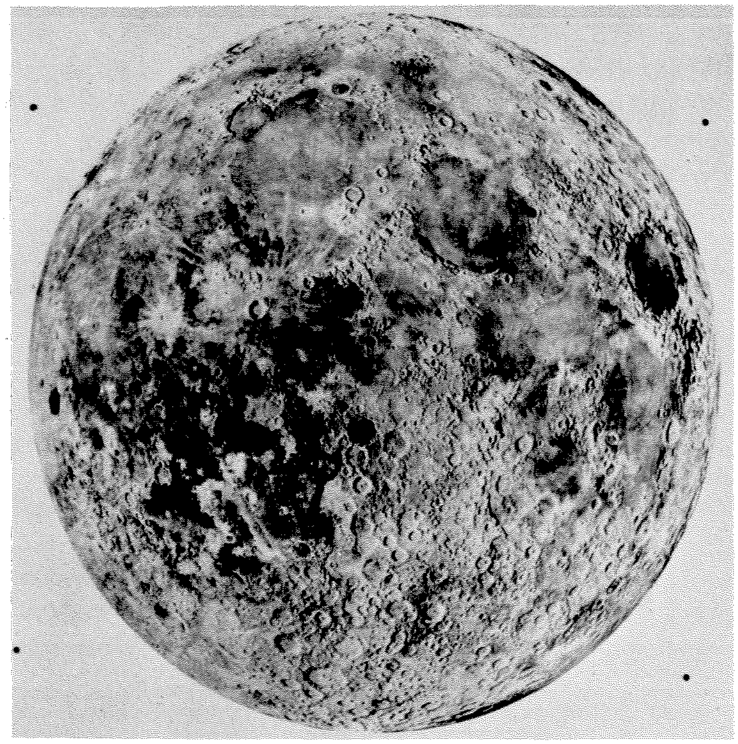
When ancient astronomers studied the moon with their primitive telescopes, they called the light-colored areas "terrae" or "highlands" and the darker ones "maria," the Latin word for "seas." We know now, of course, that there are no bodies of water on the moon, and that the highlands and the maria are quite different kinds of lands. They do have one feature in common, however: cratering. There are giant craters all over the moon's surface, and between them are somewhat smaller craters—with still smaller craters between *them.* Even the rocks are pitted with microscopic craters. We are not sure of the origin of all of these craters, but we think most of them are due to an external source of debris impacting upon the surface of the moon. And the debris ranged in size from giant asteroid-like masses of stone and iron down to very tiny charged particles, which smashed into the moon at velocities up to more than 15 miles per second. When they struck, their energy was immediately converted to surface explosions with production of intense heat, which caused the local melting that is a common phenomenon on the lunar surface.

In the last century geologists, including especially our own Gene Shoemaker, have worked out a tentative sequence for the development of the major features on the moon. Most recently—i.e., for about the last 3 billion years—the lunar surface appears to have been modified only by a sequence of cratering events, and the largest features that were formed had diameters no greater than 100-150 km. Before that, in one of the major intervals in its history, the moon went through a stage when great areas of the surface were flooded with lava, and there was even more intense cratering. Prior to this, the moon underwent its most extreme cratering. This was the formative period—at least 4.6 billion years ago—when objects that represented the initial accumulation of planetary bodies in the solar system were impacting on the lunar surface.

In order to understand the evolution of the moon, we need to know how far back in time each of these events occurred, what kinds of materials were produced, and what happened to the preexisting materials that were subjected to such enormous temperatures and pressures. In the early development of the moon, pressures exceeded anything we can reproduce in the laboratory.

When we started planning the exploration of the moon, we didn't know whether or not its whole surface was covered with a uniformly mixed layer of debris produced by billions of years of impacts. It seemed unlikely because there were obvious color differences between the maria and the terrae, but we couldn't be sure. What we have found is that each of the Apollo landing sites not only had rocky debris apparently indigenous to it but also some exotic materials whose sources we couldn't immediately identify. One of my colleagues, Gerald Wasserburg, decided after the first Apollo mission to emphasize these mysterious materials by calling them the "magic component." This turned out to be no trivial attribution; it focused our attention on something we are just now beginning to understand.

One clue to the sources of the magic component lies in the light streaks that radiate in all directions from some of the more recent huge craters. Some of these streaks can be followed all the way around the visible side of the moon. It's quite clear that the energy of the impact that created those craters was in part transferred to the impacted material—and debris was thrown clear around the moon. It has also become clear that the exotic materials may come from great distances away from any given spot.

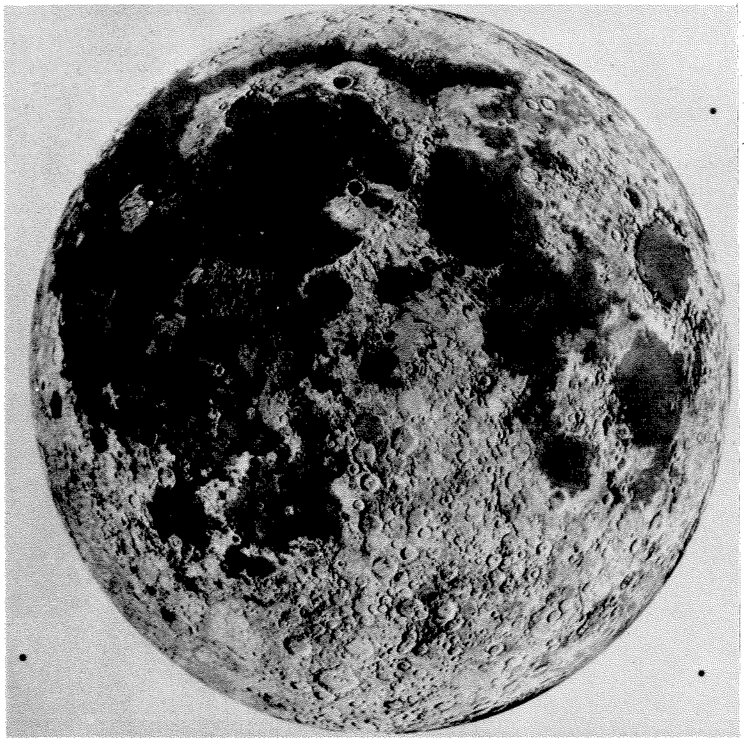


This mosaic of telescopic photographs of the moon as it looks today shows the familiar contrast between the dark maria and the lighter highlands. Slightly above the center and to the left, the giant crater Copernicus sits in the midst of rays of impact debris that radiate in all directions for hundreds of kilometers.

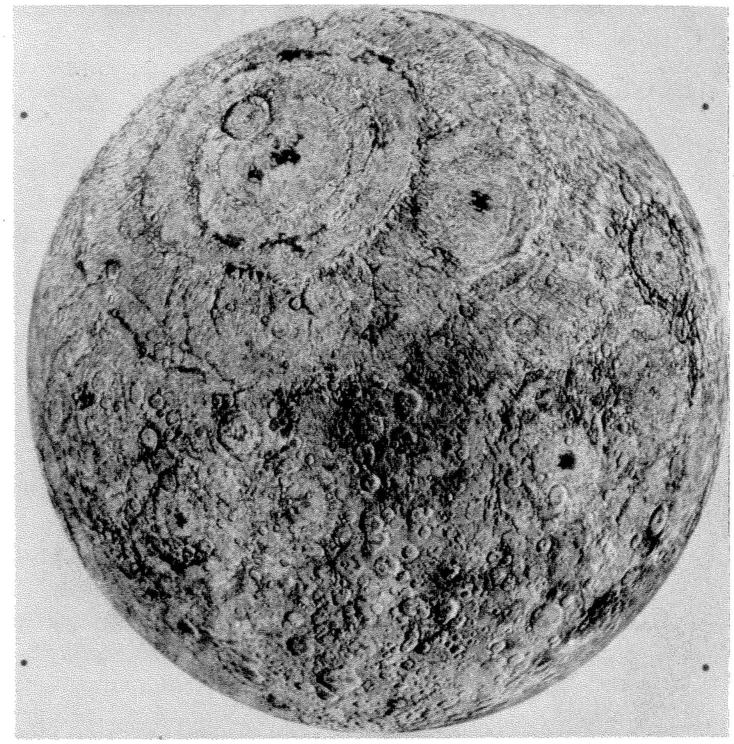
Men have now landed on the moon six times. They have explored the sites for increasing periods of time and at increasing distances from the landing modules. They have placed instruments on the moon, some of which have yielded immediate data and some of which will continue to collect and report information to earth for many years. They have given verbal accounts of their observations, and they have backed these up with photographs of everything from dust to panoramas. And they have collected and brought back to earth about 850 pounds of samples from the moon for earthbound scientists to analyze and build hypotheses from. The amount of material from any one of the missions is staggering; from all of them it is mountainous and will take years to understand.

Each of the Apollo missions answered some questions and created many more. It was only three and a half years ago that Apollo 11 landed at Mare Tranquilitatis. Astronauts Neil Armstrong and Buzz Aldrin found there a debris-strewn surface—a mixture of rocks, pebbles, sand grains, and dust. Pieces of ancient lava shocked us when we studied them, because they turned out to be at least 3.7 billion years old. No rock we knew of in the crust of the earth was that old. So, we immediately had to apply a different time perspective to the moon than we did to the earth.

The constituent minerals in one of these rocks are similar to minerals that we have on earth, but the ranges in composition are greater, and the rock has ten times as much titanium as comparable terrestrial rocks. This told



This is an artist's reconstruction of the lunar surface as it appeared about 3.3 billion years ago. Most of the mare material has been accumulated, but the "young" craters like Copernicus have not yet appeared. The maria look darker than they do today because such craters excavated the underlying light-colored material.

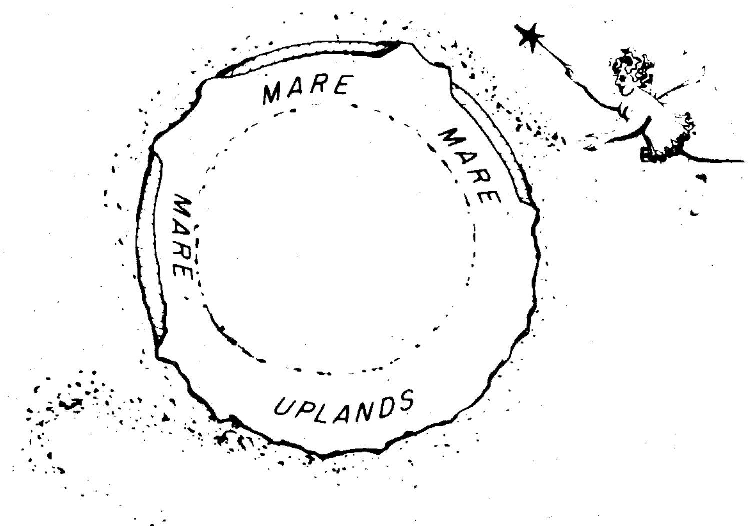


Around 4 billion years ago, the moon probably looked about like this. The great multiringed mare basins were formed—chief among them, at the top left, the giant Imbrium basin. Iridum, the sharply outlined crater perched on one of Imbrium's rings, was partly buried by later lava flooding and deposits of debris, but is still visible today.

us that the rocks had grown, cooled, and crystallized in a way that was very different from anything we know on earth. These rocks could not have formed in the presence of any significant amount of water; the mineral assemblage would not have been stable. On earth this kind of rock is tremendously unstable, but on the moon it's as fresh as it was 3.7 billion years ago. So we learned something about conditions on the surface of the moon at the time of the crystallization of these lavas: Things were very dry and inhospitable.

The lunar lavas and rocks from the Apollo 11 mission were very much like similar rocks on the earth in terms of their oxygen isotope composition. Oxygen is extremely important in the solar system; it's probably the most abundant element in the planets. And its isotopic properties are considered to be a good indication of the original uniformity or non-uniformity of the materials of which the planets were made. In these rocks we find evidence of similarities between the earth and the moon. But our analysis of the oxygen isotope composition of these lunar lavas also revealed that while they resemble one class of meteorites, the chondrites, they are not like other classes of meteorites that have similar volcanic characteristics. No known meteorites appear to have the right bulk chemistry and oxygen isotopic composition to suggest that they have been derived from the moon. These findings are very important fingerprints in our developing model of the moon.

The Apollo 12 mission was designated to another mare surface region—the Ocean of Storms—which was known to be on one of the bright rays coming from the crater



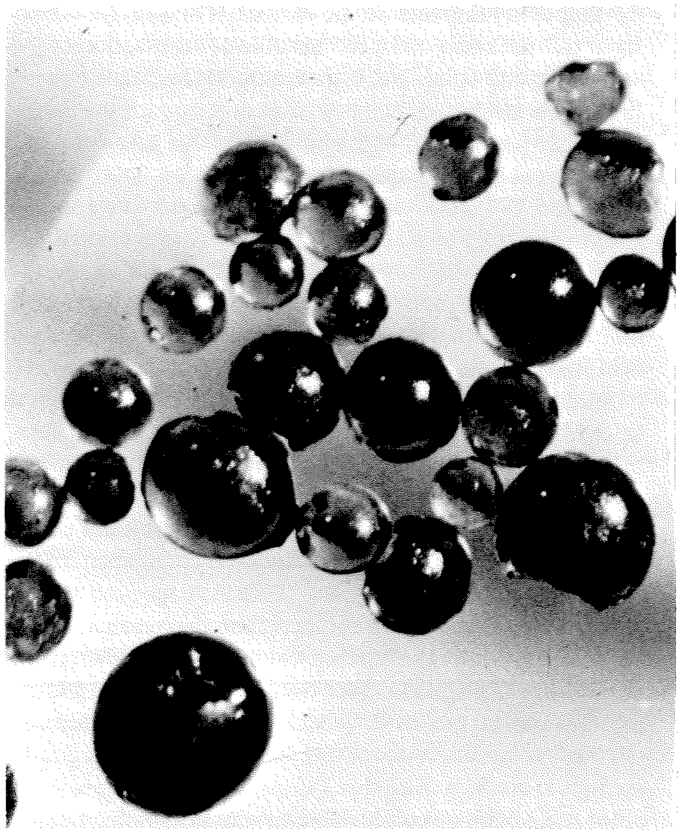
Whether this is the way it really happened or not, there is—in the words of Gerald Wasserburg, professor of geology and geophysics—a "magic component" in the mystifying mix of debris on the lunar surface.

Copernicus. One of the reasons for choosing this site was to revisit Surveyor III, and astronauts Pete Conrad and Alan Bean did a superb job of piloting the landing module to a site just a few hundred meters away. One of their jobs was to dismantle a few key parts of Surveyor and bring them home. In the interval between the landing of Surveyor III in April 1967 and that of Apollo 12 late in 1969, there had been a series of strong solar flares, and we wanted to know how the materials of which Surveyor was constructed had stood up. The moon, unlike the earth, is not shielded from the sun, so it takes all the sun's output directly. When we analyzed the Surveyor materials later, we learned more about the spectrum of energy and the kinds of particles that are thrown out of the sun than we had gained in any other single experiment.

Apollo 12 also ran into some unusual things, among them a very special little rock about as long as a finger and twice as wide, which was given the number 12013. That little rock is now famous in lunar science because it shook us up so completely. It is a very complex, highly evolved rock with a chemistry closely approaching that of terrestrial granite. It represents a degree of chemical evolution beyond what we had thought existed on the moon—a change about as extreme as any of the chemical changes or differentiations that have occurred on earth.

Professor Wasserburg's group did detailed chemical analyses of the isotopic properties of 12013 and found that it was at least 4 billion years old. That showed us that very early in its history the moon had begun to develop the same kinds of materials in its crust that we find in the earth's continental crusts, which contain concentrations of elements of great use to man. But this rock turned out

Six Apollo missions reached the moon and took samples of the material at each of the landing sites, shown here by mission number. Rays fan out around several of the craters, particularly dramatically from Tycho (the large bright spot near the lower edge). Some of these rays can be followed across the whole lunar surface. The crater Autolycus or Aristillus (one above the other in Mare Imbrium north of the Apollo 15 site) may have been the source of the shocked rock round at that site.



In natural color, these microscopic glass spheres would be green. The rock sample in which they were found came from the Apollo 15 site in Mare Imbrium, though it was probably thrown there by an impact about a thousand kilometers away. Small amounts of identical material have also been found in samples from other landing sites.

to be much more radioactive than normal continental granite. In fact the whole Apollo 12 site was covered with a layer of this highly radioactive material that was deeper than we could penetrate in our sampling. We think it is foreign to this site. Apparently it is debris ejected from the crater Copernicus 300 km away. This kind of force is capable of introducing Wasserburg's magic component, and it demonstrates the tremendous impacts that could throw debris all over the surface of the moon.

Apollo 14 astronauts Al Shepard and Ed Mitchell brought back the first samples of big boulders that we had seen on the lunar surface. The landing site north of the crater Fra Mauro was chosen because it looked as if it would be underlain by material thrown out of the huge crater that we know as Imbrium. We thought we would be able to sample material thrown from more than 500 km away from the site and from very deep down in the moon. One sample of a boulder turned out to be a mixture of all kinds of broken particles. It's a kind of lunar concrete welded together by heat derived from the impact that pounded the lunar surface. It is radioactive and contains fragments similar to granite—just as material from Apollo 12 did. And it is about as old—on the order of 3.9 billion years. But it is very complex, containing billions of particles, each with a separate history. It will take a long time to understand it.

Apollo 15 landed in Mare Imbrium at the base of Mt. Hadley, one of the highest mountains on the moon, and beside a remarkable fracture called a rille. Having learned about the moon's traveling debris, we thought the site might have a little material from the craters Aristillus and Autolycus as well as that of local origin. We found—as we expected—some of the youngest lavas yet discovered on the moon (3.3 to 3.4 billion years old). On the other hand we found something we did not expect, and it turned out to make up most of the surface of the mare at the landing site. This was a blanket of shocked rock—a material in which shock pressures have produced such high temperatures that the rock had begun to melt. Many of us feel that this particular material was probably shocked when it was thrown south 150-250 km from Aristillus or Autolycus to this site, and we also think this happened quite recently—a billion years ago or less.

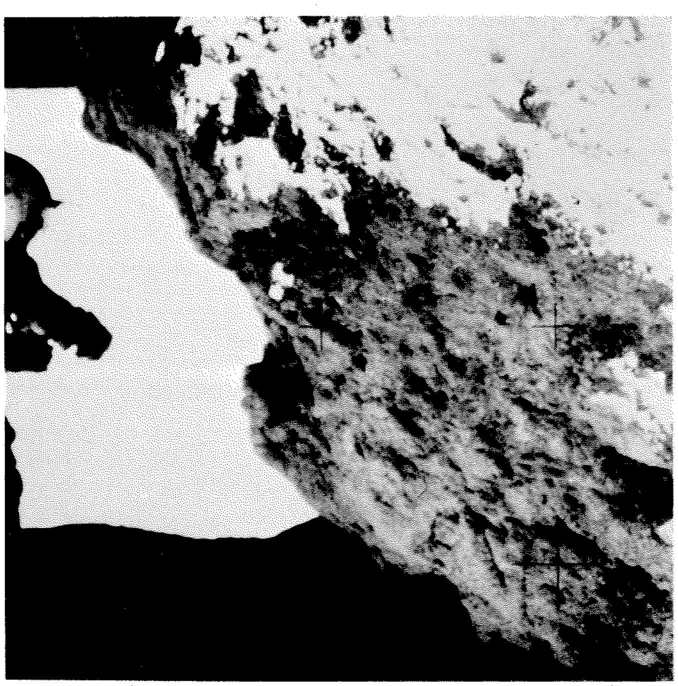
From the flank of the mountains, the crew brought back one of the most primitive materials we have found on the moon and one that we had speculated might be a constituent of the highlands. The Apollo 15 crew did a magnificent job of finding it for us. The rock is made up primarily of plagioclase feldspar. It is highly metamorphosed; i.e., it no longer has the original structure and crystals that formed it. It has been cooked up and recrystallized. We think the age of its metamorphism, which is about 4 billion years, is a minimum age for it, because it shows primitive abundance of strontium isotopes which contain almost no products of radioactive decay.

The Apollo 15 crew brought us back another surprise. The crews of the first missions reported seeing nothing but shades of black, white, and gray. But Dave Scott and Jim Irwin thought they saw green. They didn't believe their eyes, but when they brought a sample back, we found that it was indeed green. In fact, it turned out to be filled with tiny little spheres of green glass completely free of imperfections. It has clearly been raised to extraordinary temperatures. Its composition is very different from most of the materials at the Apollo 15 site, and its age is about 3.9 billion years. No natural glass anywhere near this old has survived on earth, but this lunar glass is perfectly preserved.

Once we had identified this glass and its unusual composition, we went back to samples from previous missions and checked them for the same thing. And here and there a few of them contained one or two spheres of an identical glass. We began to see the effect of material moving around on the moon—and this material has moved as far as 1,000 kilometers.

With the Apollo 16 mission, we made the first straightforward attempt to land in the center of the highlands—at the north end of the crater Descartes. This particular region has fresh-looking hills that we thought might be recently constructed lava mountains. It was chosen in the hope of finding relatively young material. We were wrong. We did not find any volcanic rocks, and the ages of the rocks that we did find are the oldest we have yet studied. But we are convinced that while the site is ancient—perhaps 4.1 to 4.2 billion years old—it is relatively young compared to the rest of the lunar uplands.

One very interesting sample brought back by the Apollo 16 crew, John Young and Charley Duke, was from a permanently shadowed area beneath the wide overhang of a boulder. In the lunar environment a permanent shadow is a cold place in which thermally excited gases that are generated in the lunar-vacuum environment are trapped. These gases may have escaped from the interior of the moon or they may have been boiled out by the temperatures developed by impacts on the surface. The sample taken from this area showed a remarkable concentration of lead, which is quite volatile at high temperatures. This confirmed our early suspicions that another contribution to the magic component in the lunar soils was gases produced by the great impact explosions.



Astronaut Charley Duke prepares to select an important sample—this boulder in the highlands near the crater Descartes which casts a permanent shadow on the moon, creating a kind of lunar refrigerator that traps thermally excited gases produced by the great impact explosions.

Apollo 17 landed on one of the great mare regions, chosen carefully by scientists to give maximum scientific yield. In trying for the greatest possible diversity, we chose a spot where we thought we could get samples of both highlands and maria material. There were giant blocks of lava from a crater, and a rock slide from a 7,000-foot mountain. The samples have only recently been distributed so there are few results yet announced. But photographs of the surfaces of great boulders that have rolled down the mountains show rock melted by impact to a point where it bubbled and frothed, though within it are unmelted fragments. And those unmelted fragments are very rich in the mineral plagioclase. This may turn out to be some of the most primitive material on the moon.

You may remember their great excitement when astronauts Gene Cernan and Jack Schmitt said they had found orange-colored material. (There was great excitement in the back room at Houston too, but our TV wasn't good enough to confirm the color.) Compared against a standard color scale back on earth, this material does indeed turn out to be orange. Now orange soil or rock on earth, especially in volcanic materials, is attributed to the action of hot water or steam gases modifying iron-rich rocks—literally rusting them. And we have not known of water or high-oxidizing materials on the moon. We don't know a great deal about this material yet, though we know it is of glass and of a unique composition. And, strangely enough, when we reexamine the fine debris from the Apollo 11 and 12 samples, we find a few grains with this same chemistry and composition.

It has turned out that the moon is not covered with a uniform well-mixed layer of debris. On the maria we find indigenous basalts and lavas—and also other materials. In the highlands we find materials that are characteristic of highlands, but we also find pieces of what look like mare basalt. So, it looks as if the moon has regional provincial characteristics, but all over its surface there may be bits and pieces of any other part of the moon. What this means is that unraveling the story is going to be a much more complicated job than we thought when we got our first samples back from Apollo 11. One of our main tasks right now is to sort out the extraordinary variety of material that is present in every sample.

We have been able to sample the moon directly only to a depth of about 3 meters, and indirectly—by use of craters—perhaps as much as a few kilometers. But we've been thumping it with explosive charges, listening to it for internal earthquakes, measuring the velocity with which sounds travel through it, measuring its temperatures, and developing a series of inferences about what kinds of materials the lavas could have been generated from. All of this gives us a preliminary picture.

We think that the interior of the moon may be quite warm—maybe 1000° Centigrade. We don't have any direct data for that, but we do know that at a depth of about 850 km we're getting moonquakes. And that means that some dynamic effect down there is sending signals. When those signals emerge, we measure their velocity, and this tells us something about the moon's density, which in turn makes it possible for us to draw some conclusions about its chemistry. What we are now deducing is that the moon's chemistry is very different from the models we had just three years ago for either the earth or the moon.

Being forced to change our interpretation of the moon has shaken up our prejudices about what the inside of the earth is like. We don't really know very much about that either. We've gotten samples from only 100 to 150 miles down. So, we work on inferences about the chemistry of the earth too. It may be that what we learn about the moon is going to make us revise many of our planetary models.

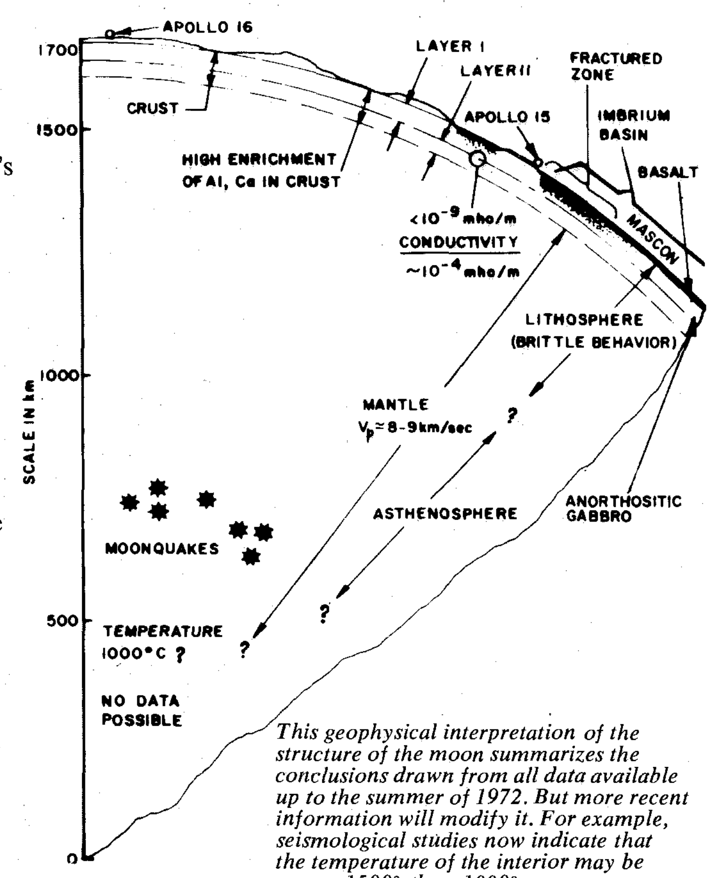
The moon has neither an atmosphere nor a strong magnetic field, both of which shield the earth. The massive atmosphere protects the earth's surface from much of the sun's radiation, and the strong magnetic field tends to divert the great variety of particles thrown at us by the sun in the form of solar wind. The moon is the place to go to find out what the sun is throwing out now and what its behavior has been like over the past 4 billion years.

In the last 15 years geologists have discovered that at intervals the earth's magnetic field drops to zero while it is reversing polarity. It has happened in the past, and it will happen again. When it does, for a time we will have only one shield instead of two. Perhaps some of the major changes in the history of the life cycle of the earth have been related to what happens in that case. It's important for us to know whether the intermittent exposure to the unshielded sun produces those changes.

One of the interesting things about the lava from the moon is that it shows evidence of once having had a distinct magnetic field. That's important because, if our models for our own magnetic field are correct, it is possible that the lunar magnetic field was produced by a hot, moving core in the moon. On the other hand, the moon may yet indicate how planetary magnetic fields may be created without a core dynamo.

The moon has not only been subjected to solar radiation but also to cosmic radiation, which comes from elsewhere in our galaxy—or maybe from outside our galaxy. The energies of cosmic rays are so great that they can penetrate any surface to great depths.

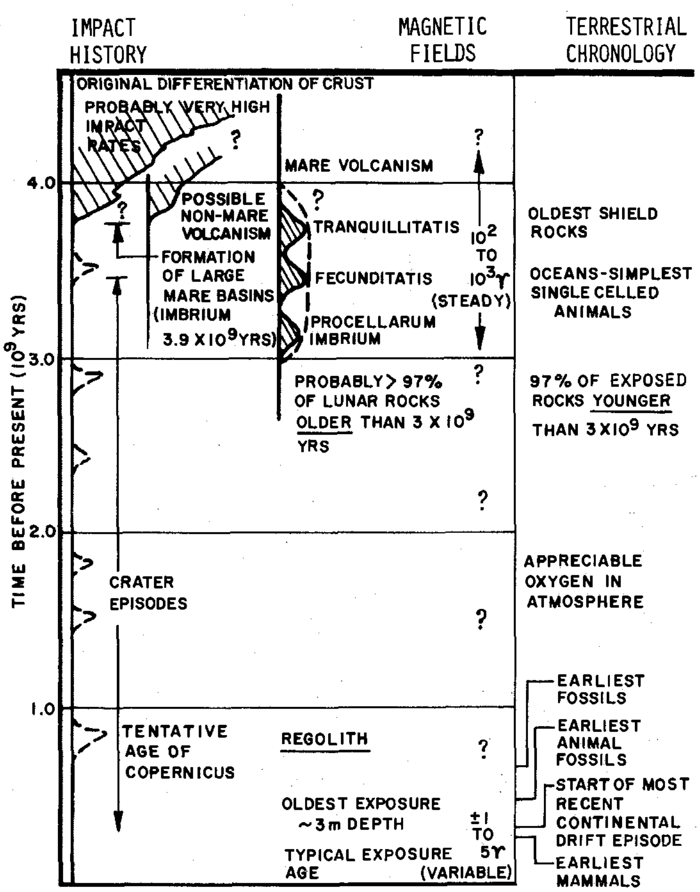
All of this particle bombardment on the unshielded surface of the moon produces effects, some of which are understandable as a measure of exposure. To some extent anything on the surface of the moon gets tanned, but the tanning is in a different form from what people get on a beach on earth. We measure the degree of solar exposure by measuring various isotopic effects. One of the experiments that has been carried out on each of the Apollo missions is called the Solar Wind Composition Experiment.



This geophysical interpretation of the structure of the moon summarizes the conclusions drawn from all data available up to the summer of 1972. But more recent information will modify it. For example, seismological studies now indicate that the temperature of the interior may be nearer 1500° than 1000°.

The only equipment required was a window shade of aluminum foil that was set up on the surface of the moon. In the short periods of exposure on each mission the foil captured evidence of the solar wind. Later analysis showed certain isotopes of rare gases and told us a great deal about the behavior of the sun.

Another experiment made it possible for Caltech professors Sam Epstein and Hugh Taylor to measure the ratio of two isotopes of hydrogen. They found material on the moon very depleted in the heavy hydrogen atom, deuterium. This depletion reflects the fact that the sun uses deuterium at a very great rate. And when it throws out its unburned debris in ash, it throws out a great deal of depleted hydrogen. At the same time it throws out a great deal of helium-3, which is a product of the solar furnace. The helium-3 enrichment in the lunar soil is a remarkable effect. With enough time we may be able to define this effect for many different samples and get a much more comprehensive look at what the sun is doing to the moon, what that means in the history of the sun, and what it may mean for the history of the earth.



In this summary, our present understanding of the history of the moon is compared with what was happening on the earth in the same billion-year periods. The most dynamic eras in the life of the moon occurred before 3 billion years ago, and there has been relatively little internal activity since. The early record of the earth has been obscured because of its subsequent very dynamic and complex behavior.

Professor Don Burnett was responsible for the lunar neutron probe experiment carried by Apollo 17. It was designed to measure the rates at which neutrons created by the impact of cosmic rays on the moon react with lunar material, and how depth causes these rates to vary. The data from this experiment should be helpful in our understanding the history of lunar samples more accurately. ["Probing for Neutrons on the Moon" — *E&S*, February].

We used to think we knew precisely when the moon formed, but we've become a bit more modest in our claims after half a dozen missions. We know that it's over 4 billion years old, and we know that early in its history it began to differentiate. When it differentiated, it produced rocks that are much like the beginning raw materials of our own continents. We know that enormous impacts were going on in its early history, producing tremendous ring structures. Starting perhaps 4 billion years ago and continuing until about 3.2 billion years ago, there were great outpourings of lava that filled the mare basins. Were there enormous impacts and similar outpourings of lava on earth? We are not sure, for the early history of the earth is obscure.

Postscript

Since writing this article, I had an opportunity to attend the Fourth Lunar Science Conference in Houston, Texas, in March. In the brief four days of these meetings, a number of basic premises of previous models for the evolution of the moon have been modified or overthrown. To begin with, materials from the Apollo 16 and 17 missions, including the orange soil, show evidence that there are regions in the moon where the volatile metals and other volatile elements are enriched to a much greater degree than observed before. The orange soil has been shown to be old (about 3.7 billion years), possibly volcanic material, recently exposed (20-30 million years ago) at the site where it was found. The orange soil is enriched in the isotope Pb-204 relative to the refractory element uranium. This enrichment approaches the levels that we know on the earth, and provides evidence that there may be regions on or within the moon that are not as different geochemically from the earth as we had thought.

At these meetings it was also reported that recent seismological studies of moonquakes and meteoroid impacts on the far side of the moon indicate that the lower 500-600 kms of the interior do not transmit shear waves as do the outer portions. This suggests that the deep interior of the moon may indeed be partially molten, which would imply temperatures perhaps as high as 1500° Centigrade or more and leads us to new estimates of the chemical nature of the interior of the moon. These new developments are characteristic of the possibilities for new discovery that lie in the tremendous quantities of materials brought back from the Apollo missions which still remain to be explored.