ED 139 648 SE 022 486

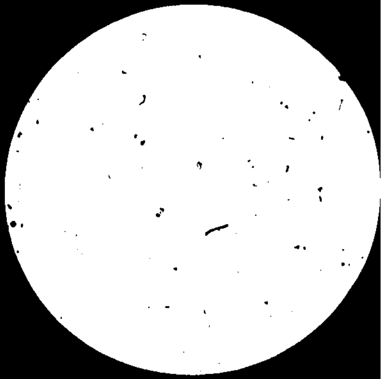
AUTHOR French, Bevan M.
TITLE What's New on the Moon?
INSTITUTION National Aeronautics and Space Administration, Washington, D.C.
REPORT NO NASA-EP-131
PUB DATE 76
NOTE 28p.; Photographs may not reproduce well
AVAILABLE FROM Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock Number 033-000-00653-5, $0.70; Minimum charge of $1.00 for each mail order)

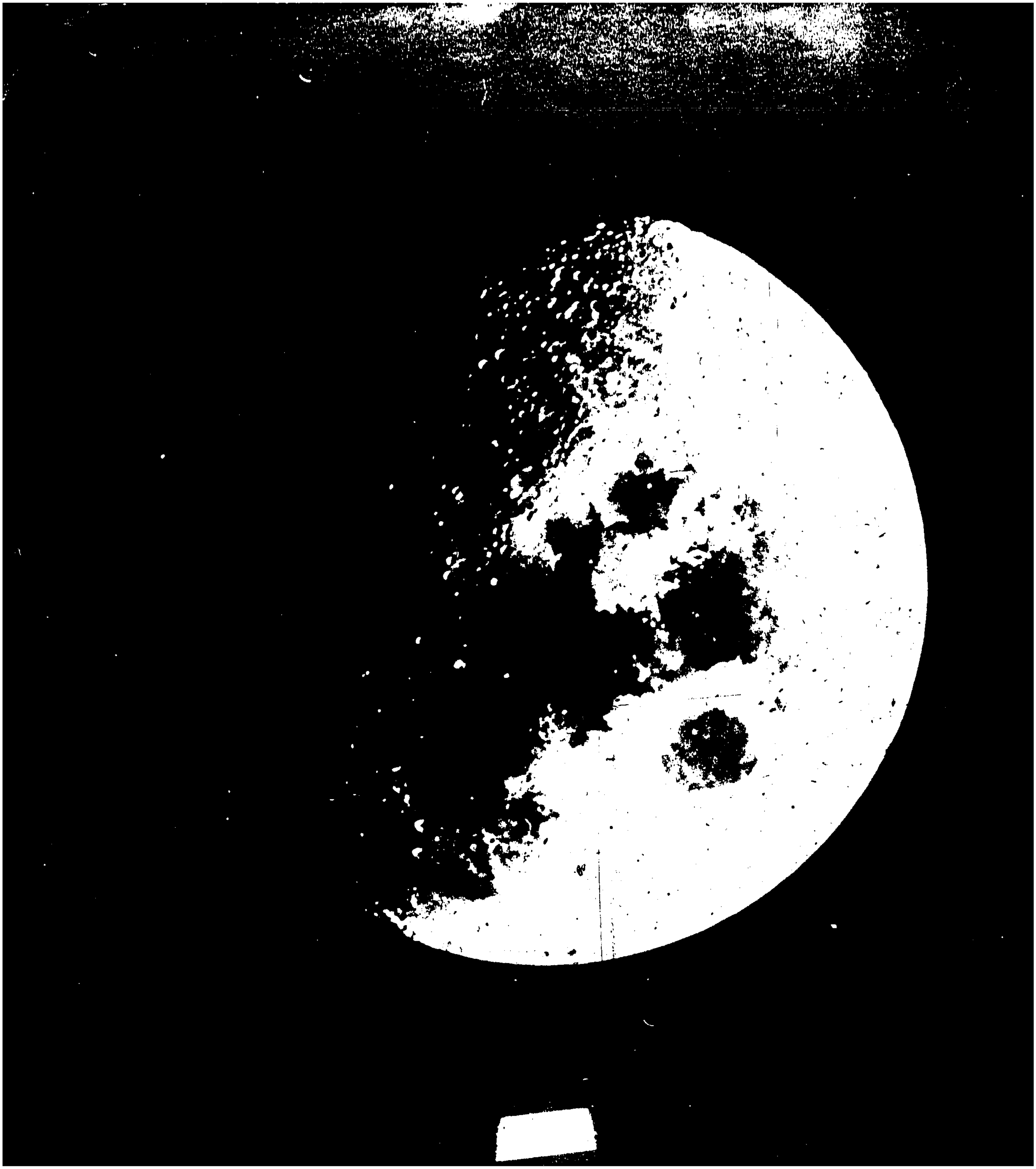
EDRS PRICE MF-$0.83 HC-$2.06 Plus Postage.
DESCRIPTORS *Aerospace Education; Aerospace Technology; *College Science; *Instructional Materials; *Lunar Research; Physical Sciences; Science Education; *Scientific Research; *Secondary School Science; *Space Sciences
IDENTIFIERS Apollo Program; Moon

ABSTRACT

This document presents an overview of knowledge gained from the scientific explorations of the moon between 1969 and 1972 in the Apollo Program. Answers are given to questions regarding life on the moon, surface composition of rocks on the moon, the nature of the moon's interior, characteristics of lunar "soil," the age, history and origin of the moon. Also discussed are answers to questions derived from lunar research about the Earth's creation and early history, the chemical composition of matter ejected by the Sun and the Sun's past history, and the early history of other planets. A section on unanswered questions about the moon includes topics such as chemical composition of the whole moon, reasons for its uneven shape, composition of the core, age of its youngest rocks. Several books for further reading are listed, and a source for educational materials from the Lunar Science Institute is given. (CS)

What's New on the Moon?





National
Aeronautics and
Space
Administration

What's New on the Moon?

by Dr. Bevan M. French,
Program Chief
NASA Extraterrestrial Materials
Research Program

Open for Inspection. Apollo 10 astronauts took this photo soon after leaving their lunar orbit. Terminator line at left runs at about 5 degrees west longitude. Sea of Tranquility is large dark area near center of photo.

BEVAN M. FRENCH has studied lunar samples and terrestrial meteorite craters for more than 10 years. The geologist manages NASA's programs for research on lunar samples, meteorites, and other extraterrestrial material while continuing work on ancient meteorite craters. In 1973, Dr. French helped discover a Brazilian impact crater 25 miles in diameter and 150 million years old.

In 1969 over half a billion people witnessed the "impossible" coming true as the first men walked on the surface of the Moon. For the next three years, people of many nationalities watched as one of the great explorations of human history was displayed on their television screens.

Between 1969 and 1972, supported by thousands of scientists and engineers back on Earth, 12 astronauts explored the surface of the Moon. Protected against the airlessness and the killing heat of the lunar environment, they stayed on the Moon for days and some of them travelled for miles across its surface in Lunar Rovers. They made scientific observations and set up instruments to probe the interior of the Moon. They collected hundreds of pounds of lunar rock and soil, thus beginning the first attempt to decipher the origin and geological history of another world from actual samples of its crust. (Figure 1).

The initial excitement of new success and discovery has passed. The TV sets no longer show astronauts moving across the sunlit lunar landscape. But here on Earth, scientists are only now beginning to understand the immense treasure of new knowledge returned by the Apollo astronauts.

The Apollo Program has left us with a large and priceless legacy of lunar materials and data. We now have Moon rocks collected from eight different places on the Moon (Figure 2). The six Apollo landings returned a collection weighing 382 kilograms (843 pounds) and consisting of more than 2,000 separate samples. Two automated Soviet spacecraft named

Figure 1. The New Explorer. *Framed by the mountains around the Moon's Littrow Valley, Apollo 17 geologist-astronaut Harrison H. Schmitt sweeps with a special rake to collect lunar samples. As it passes through the lunar soil, the rake sieves and collects rock chips 1 to 2 cm (½ to one inch) in size. The chips were returned to Earth for analysis.*

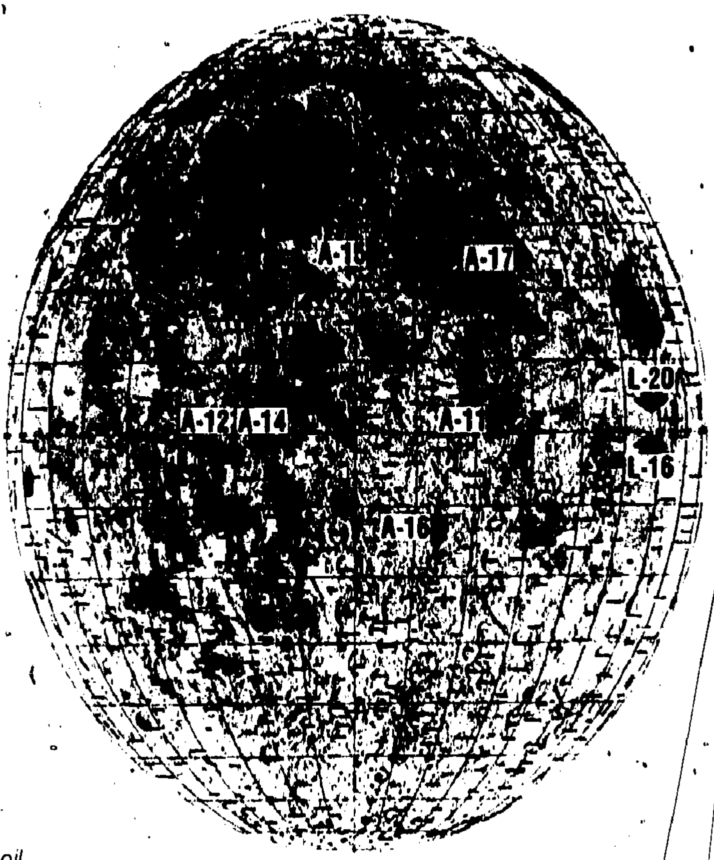


Figure 2. The Sampling of the Moon. *Arrows indicate the locations from which lunar samples have been returned to the Earth for scientific study. The "A" symbols mark the landing sites of the Apollo 11 through Apollo 17 missions. (The Apollo 13 mission did not land. Enroute to the Moon, an oxygen tank exploded; the crew returned safely to Earth.) The "L" symbols indicate the sites near the eastern edge of the Moon from which Russia's automated landers, Luna-16 and Luna-20, returned small samples of lunar soil.*

4 Luna-16 and Luna-20 returned small but important samples totalling about 130 grams (five ounces).

Instruments placed on the Moon by the Apollo astronauts as long ago as 1969 are still detecting moonquakes and meteorite impacts, measuring the Moon's motions, and recording the heat flowing out from the inside of the Moon. The Apollo Program also carried out a major effort of photographing and analyzing the surface of the Moon. Cameras on the Apollo spacecraft obtained so many accurate photographs that we now have better maps of parts of the Moon than we do for some areas on Earth. Special detectors near the cameras measured the weak X-rays and radioactivity given off by the lunar surface. From these measurements, we have been able to determine the chemical composition of about one-quarter of the Moon's surface, an area the size of the United States and Mexico combined. By comparing the flight data with analyses of returned Moon rocks, we can draw conclusions about the chemical composition and nature of the entire Moon.

Thus, in less than a decade, science and the Apollo Program have changed our Moon from an unknown and unreachable object into a familiar world.

WHAT HAS THE APOLLO PROGRAM TOLD US ABOUT THE MOON?

What have we gained from all this exploration? Before the landing of Apollo 11 on July 20, 1969, the nature and origin of the Moon were still mysteries. Now, as a result of the Apollo Program, we can answer questions that remained unsolved during centuries of speculation and scientific study.

(1) Is there life on the Moon?

Despite careful searching, neither living organisms nor fossil life have been found in any lunar samples. The lunar rocks were so barren of life that the quarantine period for returned astronauts was dropped after the third Apollo landing.

The Moon has no water of any kind, either free or chemically combined in the rocks. Water is a substance that is necessary for life, and it is therefore unlikely that life could ever have originated on the Moon. Furthermore, lunar rocks contain only tiny amounts of the carbon and carbon compounds out of which life is built, and most of this carbon is not native to the Moon but is brought to the lunar surface in meteorites and as atoms blasted out of the Sun.

(2) What is the Moon made of?

Before the first Moon rocks were collected, we could analyze only two types of bodies in our solar system: our own planet Earth and the meteorites that occasionally fall to Earth from outer space. Now we have learned that the Moon is chemically different from both of these, but it is most like the Earth.

The Moon is made of rocks. The Moon rocks are so much like Earth rocks in their appearance that we can use the same terms to describe both. The rocks are all *igneous*, which means that they formed by the cooling of molten lava. (No sedimentary rocks, like limestone or shale, which are deposited in water, have ever been found on the Moon.)

The dark regions (called "maria") that form the features of "The Man in the Moon" are low, level areas covered with layers of basalt lava (Figure 3), a rock similar to the lavas that erupt from terrestrial volcanoes in Hawaii, Iceland, and elsewhere. The light-colored parts of the Moon (called "highlands") are higher, more rugged regions that are older than the maria. These areas are made up of several different kinds of rocks that cooled slowly deep within the Moon (Figure 4). Again using terrestrial terms, we call these rocks gabbro, norite, and anorthosite.

Despite these similarities, Moon

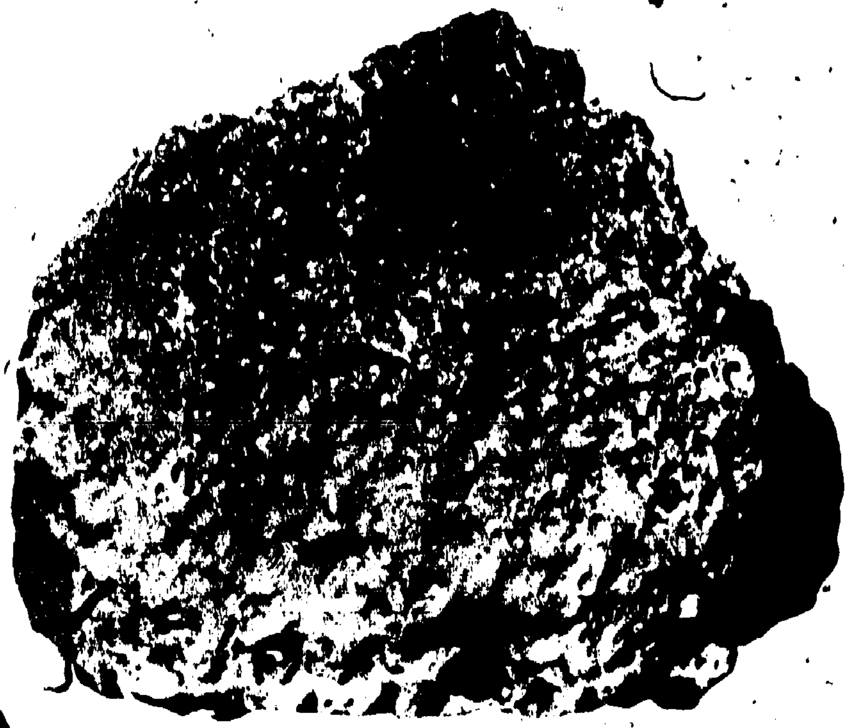


Figure 3. Frozen Lava from the Lunar Seas. *This chunk of lunar lava returned by the Apollo 15 astronauts still preserves bubbles produced as the lava poured out onto the surface of the Moon more than 3 billion years ago. The lava solidified so quickly that the bubbles, formed by escaping gas, were trapped in the solid rock. Because the Moon rocks contain no water, some other gas must have formed the bubbles. Possible gases are carbon dioxide, sulfur dioxide, or hydrochloric acid. The specimen is about 14 centimeters (6 inches) across.*

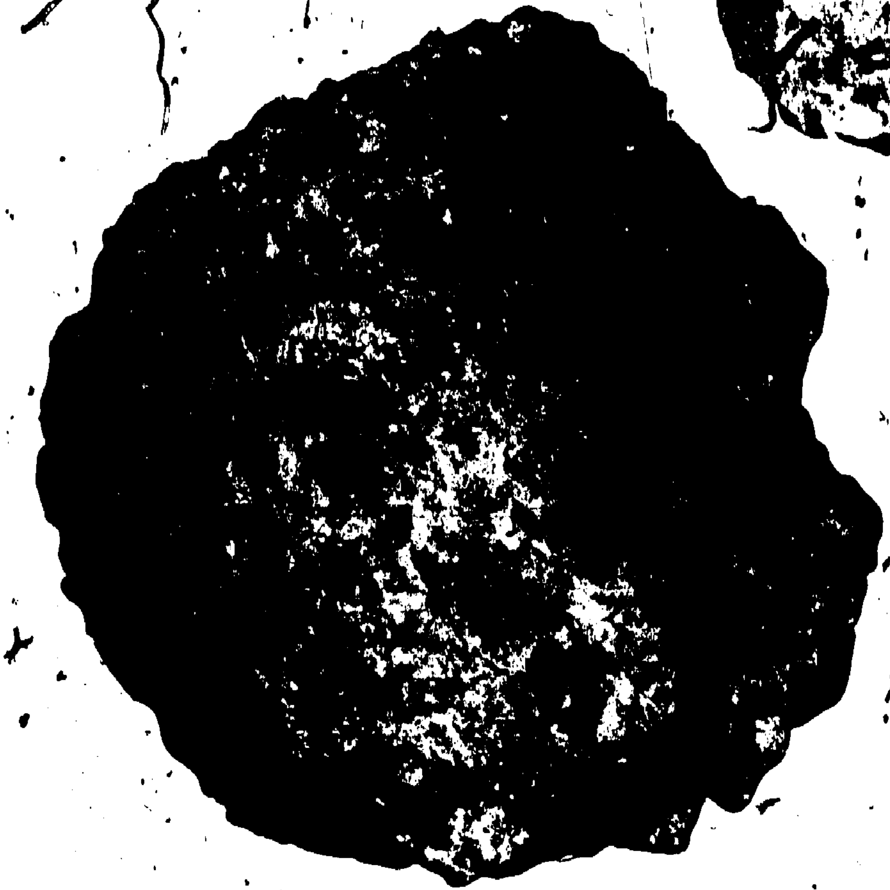
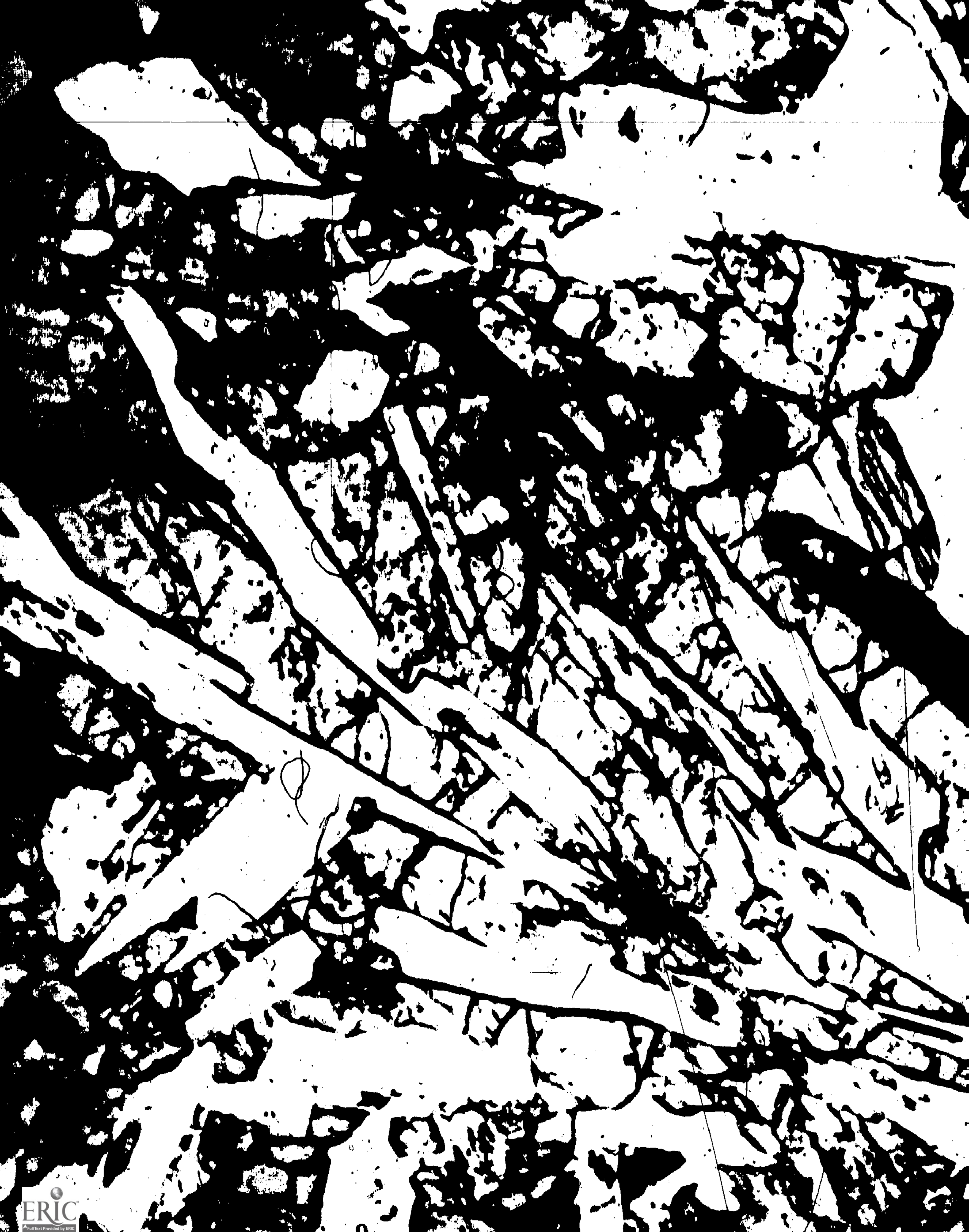


Figure 4. The ancient crust of the Moon. *A small rock fragment, collected by the Apollo 17 astronauts, holds the key to the earliest history of the Moon. The rock, called a troctolite, is composed mainly of two minerals, yellow-brown olivine and gray feldspar. The age of this specimen is measured at 4.6 billion years. It may have been some of the first material to solidify when the Moon was formed.*



rocks and Earth rocks are basically different, and it is easy to tell them apart by analyzing their chemistry or by examining them under a microscope (Figure 5). The most obvious difference is that Moon rocks have no water at all, while almost all terrestrial rocks contain at least a percent or two of water. The Moon rocks are therefore very well-preserved, because they never were able to react with water to form clay minerals or rust. A 3½ billion year old Moon rock looks fresher than water-bearing lava just erupted from a terrestrial volcano.

Another important difference is that the Moon rocks formed where there was almost no free oxygen. As a result, some of the iron in lunar rocks was not oxidized when the lunar lavas formed and still occurs as small crystals of metallic iron (Figure 6.)

Because Moon rocks have never been exposed to water or oxygen, any contact with the Earth's atmosphere could "rust" them badly. For this reason, the returned Apollo samples are carefully stored in an atmosphere of dry nitrogen, and no more of the lunar material than necessary is exposed to the laboratory atmosphere while the samples are being analyzed.

The Moon rocks are made of the same chemical elements that make up Earth rocks, although the proportions are different. Moon rocks contain more of the common elements calcium, aluminum, and titanium than

Figure 5. The Fabric of the Moon. *Under an optical microscope, the crystal structures of an Apollo 12 lunar basalt are revealed by shining polarized light through a polished slice of rock only a few hundredths of a millimeter thick. The rock contains crystals of three minerals: yellow-brown pyroxene, clear white feldspar, and black ilmenite. The intergrown character of the crystals is typical of molten lava that has solidified quickly. The largest crystals are about a millimeter long.*

Figure 6. Metal from the Moon. *Faceted like gems, tiny crystals of iron metal nestling in a cavity in a lunar rock are illuminated in this picture taken with a scanning electron microscope. The crystals, only a few thousandths of a millimeter in size, were probably deposited more than 3 billion years ago by a hot vapor that contained no free oxygen and no water. These fragile crystals have been preserved unchanged on the dry, airless Moon for billions of years; on Earth, they would be quickly destroyed by exposure to air and water if they were not carefully stored in a dry, nitrogen atmosphere.*

do most Earth rocks. Rarer elements like hafnium and zirconium, which have high melting points, are also more plentiful in lunar rocks. However, other elements like sodium and potassium, which have low melting points, are scarce in lunar material. Because Moon rocks are richer in high-temperature elements and contain less low-temperature elements, scientists believe that the material that formed the Moon was once heated to much higher temperatures than material that formed the Earth.

The chemical composition of the Moon also is different in different places. Soon after the Moon formed, various elements sorted themselves out to form different kinds of rock. The light-colored highlands are rich in calcium and aluminum, while the dark colored maria contain less of those elements and more titanium, iron, and magnesium.

(3) What Is the Inside of the Moon like?

Sensitive instruments placed on the lunar surface by the Apollo astronauts are still recording the tiny vibrations caused by meteorite impacts on the surface of the Moon and by small "moonquakes" deep within it. These vibrations provide the data from which scientists determine what the inside of the Moon is like.

About 3,000 moonquakes are detected each year. All of them are very weak by terrestrial standards. The average moonquake releases about as much energy as a firecracker, and the whole Moon releases less than one-ten-billionth of the earthquake energy of the Earth. The moonquakes occur about 600 to 800 kilometers (370 to 500 miles) deep inside the Moon, much deeper than almost all the quakes on our own planet. Certain kinds of moonquakes occur at about the same time every month, suggesting that they are triggered by repeated tidal strains as the Moon moves in its orbit around the Earth.

A picture of the inside of the Moon has slowly been put together from the records of thousands of moonquakes, meteorite impacts, and the deliberate impacts of discarded Apollo rocket stages onto the Moon. The Moon is not uniform inside, but is divided into a series of layers just as the Earth is, although the layers of the Earth and Moon are different. The outermost part of the Moon is a crust about 60 kilometers (37 miles) thick, probably composed of calcium- and aluminum-rich rocks like those found in the highlands. Beneath this crust is a thick layer of denser rock (the mantle) which extends down to more than 800 kilometers (500 miles) (Figure 7).

The deep interior of the Moon is still unknown. The Moon may contain a small iron core at its center, and there is some evidence that the Moon may be hot and even partly molten inside.

The Moon does not now have a magnetic field like the Earth's, and so the most baffling and unexpected result of the Apollo Program was the discovery of preserved magnetism in many of the old lunar rocks. One explanation is that the Moon had an ancient magnetic field that somehow disappeared after the old lunar rocks had formed.

One reason we have been able to learn so much about the Moon's interior is that the instruments placed on the Moon by the Apollo astronauts have operated much longer than expected. Some of the instruments originally designed for a one year lifetime, have been operating since 1969 and 1970. This long operation has provided information that we could not have obtained from shorter records.

The long lifetime of the heat flow

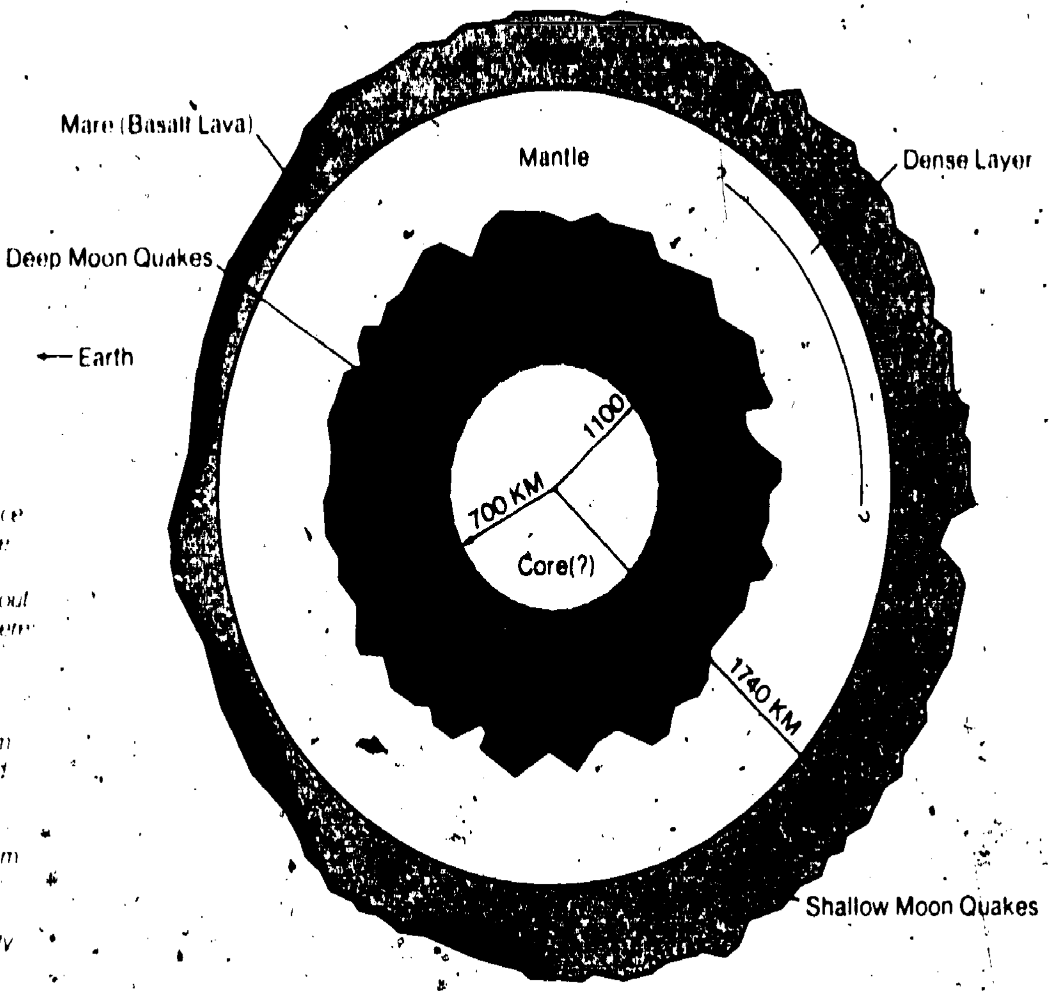


Figure 7. A Slice Through the Moon. *The interior of the Moon can now be divided into layers as scientists interpret data still being returned from instruments on the lunar surface. The Moon has an outer crust, an inner mantle and an innermost zone which may still be partly molten. Within this innermost zone, about 2200 kilometers (1400 miles) in diameter, there may exist a smaller metallic core (dashed circle). Most moonquakes (black squares) occur deep within the Moon.*

The lunar surface and crust are not uniform. The Earth-facing side is relatively smooth and shows large accumulations of lava (black). The far side is much more rugged, has a thicker crust and almost no lava. (The diagram is not to scale and the ruggedness of the Moon's far side has been exaggerated.

Adapted from data provided by A. M. Dainty, N. R. Goins and M. N. Toksöz.)

experiments set up by the Apollo 15 and 17 missions has made it possible to determine more accurately the amount of heat coming out of the Moon. This heat flow is a basic indicator of the temperature and composition of the inside of the Moon. The new value, about two-thirds of the value calculated from earlier data, is equal to about one-third the amount of heat now coming out of the inside of the Earth. As a result, we can now produce better models of what the inside of the Moon is like.

As they probed the lunar interior, the Apollo instruments have provided information about the space environment near the Moon. For example, the sensitive devices used to detect moonquakes have also recorded the vibrations caused by the impacts of small meteorites onto the lunar surface. We now have long-term records of how often meteorites strike the Moon, and we have learned that these impacts do not always occur at random. Some small meteorites seem to travel in groups. Several such swarms, composed of meteorites weighing a few pounds each, struck the Moon in 1975. The detection of such events is giving scientists new ideas about the distribution of meteorites and cosmic dust in the solar system.

The long lifetime of the Apollo instruments has also made several cooperative projects possible. For example, our instruments were still making magnetic measurements at several Apollo landing sites when, elsewhere on the moon, the Russians landed similar instruments attached to their two automated lunar roving vehicles (Lunokhods). By making simultaneous measurements and exchanging data, American and Russian scientists have not only provided a small example of international cooperation in space, but they have jointly obtained a better picture of the magnetic properties of the Moon and the space around it.

(4) What is the Moon's surface like?

Long before the Apollo Program scientists could see that the Moon's surface was complex. Earth-based telescopes could distinguish the level maria and the rugged highlands. We could recognize countless circular craters, rugged mountain ranges, and deep winding canyons or rilles.

Because of the Apollo explorations, we have now learned that all these lunar landscapes are covered by a layer of fine broken-up powder and rubble about 1 to 20 meters (3 to 60 feet) deep. This layer is usually called

Figure 8. The Smallest of Craters. *The bombardment of the lunar surface by cosmic particles of all sizes is graphically illustrated by Figures 8 and 9. Figure 8 (left) shows a cratered spherule of lunar glass less than a millimeter (1/25 inch) in diameter. The spherule, collected from the lunar soil, was once struck and shattered by an even smaller particle of cosmic dust that blasted a crater in the glass surface.*

the "lunar soil," although it contains no water or organic material, and it is totally different from soils formed on Earth by the action of wind, water, and life.

The lunar soil is something entirely new to scientists, for it could only have been formed on the surface of an airless body like the Moon. The soil has been built up over billions of years by the continuous bombardment of the unprotected Moon by large and small meteorites, most of which would have burned up if they had entered the Earth's atmosphere.

These meteorites form craters when they hit the Moon. Tiny particles of cosmic dust produce microscopic craters perhaps 1/1000 of a millimeter (1/25,000 inch) across, while the rare impact of a large body may blast out a crater many kilometers, or miles, in diameter (Figures 8 and 9). Each of these impacts shatters the solid rock, scatters material around the crater, and stirs and mixes the soil. As a result, the lunar soil is a well-mixed sample of a large area of the Moon, and single samples of lunar soil have yielded rock fragments whose source was hundreds of kilometers from the collection site.

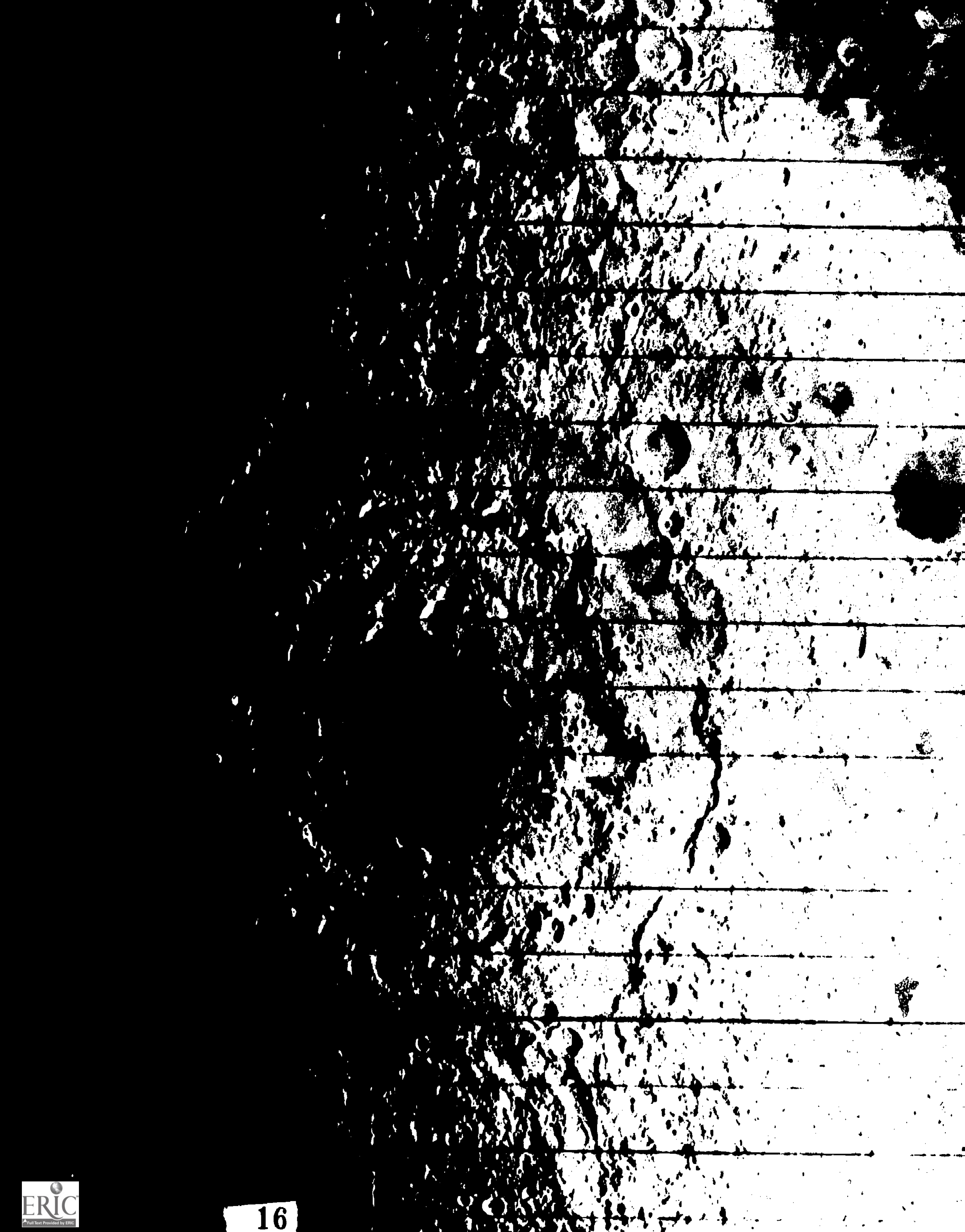
However, the lunar soil is more than ground-up and reworked lunar rock. It is the boundary layer between the Moon and outer space, and it absorbs the matter and energy that strike the Moon from the Sun and the rest of the universe. Tiny bits of cosmic dust and high-energy atomic particles that would be stopped high in the Earth's protective atmosphere rain continually onto the surface of the Moon.

(5) How old is the Moon?

Scientists now think that the solar system first came into being as a huge, whirling, disk-shaped cloud of gas and dust. Gradually the cloud collapsed inward. The central part became massive and hot, forming the Sun. Around the Sun, the dust formed small objects that rapidly collected together to form the large planets and satellites that we see today.

By carefully measuring the radioactive elements found in rocks, scientists can determine how old the rocks are. Measurements on meteorites indicate that the formation of the solar system occurred 4.6 billion years ago. There is chemical evidence in both lunar and terrestrial rocks that

__Figure 9. The Largest of Craters.__ This is the mammoth ringed bull's-eye of Mare Orientale as first seen by the U.S. Lunar Orbiter 4 in early 1968. The structure, about 750 kilometers in diameter, records the catastrophic effect of an asteroid some 25 kilometers (15 miles) in diameter that impacted about 4 billion years ago.



the Earth and Moon also formed at that time. However, the oldest known rocks on Earth are only 3.8 billion years old, and scientists think that the older rocks have been destroyed by the Earth's continuing volcanism, mountain-building, and erosion.

The Moon rocks fill in some of this gap in time between the Earth's oldest preserved rocks and the formation of the solar system. The lavas from the dark maria are the Moon's youngest rocks, but they are as old as the oldest rocks found on Earth, with ages of 3.1 to 3.8 billion years. Rocks from the lunar highlands are even older. Most highland samples have ages of 4.0 to 4.3 billion years. Some Moon rocks preserve traces of even older lunar events. Studies of these rocks indicate that widespread melting and chemical separation were going on within the Moon about 4.4 billion years ago, or not long after the Moon had formed.

One of the techniques used to establish this early part of lunar history is a new age-dating method (involving the elements neodymium and samarium) that was not even possible when the first Apollo samples were returned in 1969. The combination of new instruments and careful protection of the lunar samples from contamination thus make it possible to understand better the early history of the Moon.

Even more exciting is the discovery that a few lunar rocks seem to record the actual formation of the Moon. Some tiny green rock fragments collected by the Apollo 17 astronauts have yielded an apparent age of 4.6 billion years, the time at which scientists think that the Moon and the solar system formed. Early in 1976, scientists identified another Apollo 17 crystalline rock with the same ancient age. These pieces may be some of the first material that solidified from the once-molten Moon.

(6) What is the history of the Moon?

The first few hundred million years of the Moon's lifetime were so violent that few traces of this time remain. Almost immediately after the Moon formed, its outer part was completely melted to a depth of several hundred kilometers. While this molten layer gradually cooled and solidified into different kinds of rocks, the Moon was bombarded by huge asteroids and smaller bodies. Some of these asteroids were the size of small states, like Rhode Island or Delaware, and their collisions with the Moon created huge basins hundreds of kilometers across.

This catastrophic bombardment died away about 4 billion years ago, leaving the lunar highlands covered with huge overlapping craters and a deep layer of shattered and broken rock (Figure 10). As the bombardment subsided, heat produced by the decay of radioactive elements began to melt the inside of the Moon at depths of about 200 kilometers (125 miles) below its surface. Then, for the next half billion years, from about 3.8 to 3.1 billion years ago, great floods of lava rose from inside the Moon and poured out over its surface, filling in the large impact basins to form the dark parts of the Moon that we see today.

As far as we now know, the Moon has been quiet since the last lavas erupted more than 3 billion years ago. Since then, the Moon's surface has been altered only by rare large meteorite impacts and by atomic particles from the Sun and the stars. The Moon has preserved features formed almost 4 billion years ago, and if men had landed on the Moon a billion years ago, it would have looked very much as it does now. The surface of the Moon now changes so slowly that the footprints left by the Apollo astronauts will remain clear and sharp for millions of years.

This preserved ancient history of the Moon is in sharp contrast to the changing Earth. The Earth still be-

Figure 10. The Rubble of Ages. *This fragile white, feldspar-rich lunar rock, collected by the Apollo 16 astronauts, is a sample of the material that covers the light-colored highland regions of the Moon. This unusual specimen, called a breccia, is composed of numerous pieces of many kinds of rock with different sizes, shapes, colors, and compositions. The mixture of broken and crushed rocks in this specimen records the continuous bombardment of the Moon by large cosmic bodies more than 4 billion years ago, an event that left the Moon's surface covered with a thick layer of shattered rubble. The specimen is about 10 centimeters (4 inches) across.*

haves like a young planet. Its internal heat is active, and volcanic eruptions and mountain-building have gone on continuously as far back as we can decipher the rocks. According to new geological theories, even the present ocean basins are less than about 200 million years old, having formed by the slow separation of huge moving plates that make up the Earth's crust.

(7) Where did the Moon come from?

Before we explored the Moon, there were three main suggestions to explain its existence: that it had formed near the Earth as a separate body; that it had separated from the Earth; and that it had formed somewhere else and been captured by the Earth.

Scientists still cannot decide between these three theories. However, we have learned that the Moon formed as a part of our solar system and that it has existed as an individual body for 4.6 billion years. Separation from the Earth is now considered less likely because there are many basic differences in chemical composition between the two bodies, such as the absence of water on the Moon. But the other two theories are still evenly matched in their strengths and weaknesses. We will need more data and perhaps some new theories before the origin of the Moon is settled.

WHAT HAS THE MOON TOLD US ABOUT THE EARTH?

It might seem that the active, inhabited Earth has nothing in common with the quiet, lifeless Moon. Nevertheless, the scientific discoveries of the Apollo Program have provided a new and unexpected look into the early history of our own planet. Scientists think that all the planets formed in the same way, by the rapid accumulation of small bodies into larger ones about 4.6 billion years ago. The Moon's rocks contain the traces of this process of planetary creation. The same catastrophic impacts and widespread melting that we recognize on the Moon must also have dominated the Earth during its early,

Figure 11. An Ancient Impact Scar on the Earth. *Viewed from an altitude of 500 miles, the circular Manicouagan structure in Quebec, Canada, stands out clearly in this picture taken from NASA's Landsat-1 satellite. Geological studies have shown that this structure, formed about 200 million years ago by the impact of a large asteroid, was once a crater about 80 kilometers (50 miles) in diameter, about the size of many large lunar craters. Although deeply eroded since it formed, the central region (surrounded by the black-appearing waters of a reservoir) still preserves rocks that were shattered and melted by the catastrophic force of the impact.*

years, and about 4 billion years ago the Earth may have looked much the same as the Moon does now.

The two worlds then took different paths. The Moon became quiet while the Earth continued to generate mountains, volcanoes, oceans, an atmosphere, and life. The Moon preserved its ancient rocks, while the Earth's older rocks were continually destroyed and recreated as younger ones.

The Earth's oldest preserved rocks, 3.3 to 3.8 billion years old, occur as small remnants in Greenland, Minnesota, and Africa. These rocks are not like the lunar lava flows of the same age. The Earth's most ancient rocks are granites and sediments, and they tell us that the Earth already had mountain-building, running water, oceans, and life at a time when the last lava flows were pouring out across the Moon.

In the same way, all traces of any intense early bombardment of the Earth have been destroyed. The record of later impacts remains, however, in nearly 100 ancient impact structures that have been recognized on the Earth in recent years. Some of these structures are the deeply eroded remnants of craters as large as those of the Moon (Figure 11) and they give us a way to study on Earth the process that once dominated both the Earth and Moon.

Lunar science is also making other contributions to the study of the Earth. The new techniques developed to analyze lunar samples are now being applied to terrestrial rocks. Chemical analyses can now be made on samples weighing only 0.001 gram (3/100,000 ounce) and the ages of terrestrial rocks can now be measured far more accurately than before Apollo. These new techniques are already helping us to better understand the origin of terrestrial volcanic rocks, to identify new occurrences of the Earth's oldest rocks, and to probe further into the origin of terrestrial life more than 3 billion years ago.

WHAT HAS THE MOON TOLD US ABOUT THE SUN?

One of the most exciting results of the Apollo Program is that, by going to the Moon, we have also been able to collect samples of the Sun.

The surface of the Moon is continually exposed to the solar wind, a stream of atoms boiled into space from the Sun's atmosphere. Since the Moon formed, the lunar soil has trapped billions of tons of these atoms ejected from the Sun. The soil also contains traces of cosmic rays produced outside our own solar system. These high-energy atoms, probably produced inside distant stars, leave permanent tracks when they strike particles in the lunar soil (Figure 12).

By analyzing the soil samples returned from the Moon, we have been able to determine the chemical composition of the matter ejected by the

Sun and thus learn more about how the Sun operates. A major surprise was the discovery that the material in the solar wind is not the same as that in the Sun itself. The ratio of hydrogen to helium atoms in the solar wind that reaches the Moon is about 20 to 1. But the ratio of these atoms in the Sun, as measured with Earth-based instruments, is only 10 to 1. Some unexplained process in the Sun's outer atmosphere apparently operates to eject the lighter hydrogen atoms in preference to the heavier helium atoms.

Even more important is the fact that the lunar soil still preserves material ejected by the Sun in the past.

Figure 12. The Tracks of the Stars. *Short tracks made over millions of years by fast-moving charged atomic particles that were shot out of the Sun and other stars to eventually strike the surface of the Moon crisscross a tiny crystal collected from the lunar soil. The picture shows an area about a tenth of a millimeter across. The tracks, made visible by etching the crystal, are only a few hundredths of a millimeter long. Such grains, which may have trapped atomic particles for millions of years, preserve among other things, a unique record of the past activity of our Sun.*

(Photograph courtesy of Dr. R. L. Fleischer, from Science, *v. 167, p. 569, 30 January 1970 (c) The American Association for the Advancement of Science. Used by permission.)*

We now have a unique opportunity to study the past behavior of the Sun. Our very existence depends on the Sun's activity, and by understanding the Sun's past history, we can hope to predict better its future behavior.

These studies of the lunar soil are only beginning, but what we have learned about the Sun so far is reassuring. Such chemical features as the ratio of hydrogen to helium and the amount of iron in solar material show no change for at least the past few hundred thousand years. The lunar samples are telling us that the Sun, in the recent past, has behaved very much as it does today, making us optimistic that the Sun will remain the same for the foreseeable future.

As far as the ancient history of the Sun is concerned, the most exciting lunar samples have not yet been fully examined. During the Apollo 15, 16, and 17 missions, three long cores of lunar soil were obtained by drilling hollow tubes into the soil layer. These core tubes penetrated as much as three meters (10 feet) deep. The layers of soil in these cores contain a well-preserved history of the Moon and the Sun that may extend as far back as one and a half billion years. No single terrestrial sample contains such a long record, and no one knows how much can be learned when all the cores are carefully opened and studied. Certainly we will learn more about the ancient history of the Sun and Moon. We may even find traces of the movement of the Sun and the solar system through different regions of our Milky Way Galaxy.

WHAT ELSE CAN THE MOON TELL US?

Although the Apollo Program officially ended in 1972, the active study of the Moon goes on. More than 125 teams of scientists are studying the returned lunar samples and analyzing the information that continues to come from the instruments on the Moon. Less than 10 per cent of the lunar sample material has yet been studied in detail, and more results will emerge as new rocks and soil samples are examined.

The scientific results of the Apollo Program have spread far beyond the Moon itself. By studying the Moon, we have learned how to go about the business of exploring other planets. The Apollo Program proved that we could apply to another world the methods that we have used to learn about the Earth. Now the knowledge gained from the Moon is being used with the photographs returned by Mariners 9 and 10 to understand the histories of Mercury and Mars and to interpret the data returned by the Viking mission to Mars.

The Moon has thus become an

important key to solving several fundamental questions about the other planets:

(1) What is the early history of other planets?

The first half-billion years of the Moon's lifetime were dominated by intense and widespread melting; by catastrophic meteorite impacts, and by great eruptions of lava. Now close-up pictures of the planets Mercury and Mars show heavily-cratered regions and definite volcanic structures, indicating that these planets also have been affected by the same processes that shaped the Moon when it was young. Such episodes of early bombardment and volcanic eruption seem to be part of the life story of planets. Our own Earth must have had a similar history, even though the traces of these primordial events have been removed by later changes.

(2) How do planets develop magnetic fields?

We have known for centuries that the Earth has a strong magnetic field. However, we still do not know exactly how the Earth's field formed, why its strength varies, or why it reverses itself every few hundred thousand years or so.

One way to learn about the Earth's magnetic field is to study the magnetic field of other planets. In this respect, the Moon is surprising. It has no magnetic field today, but its rocks suggest that it had a strong magnetic field in the past. If the Moon did have an ancient magnetic field that somehow "switched off" about 3 billion years ago, then continued study of the Moon may help us learn how magnetic fields are produced in other planets, including our own.

(3) How did life originate?

Even the lifeless lunar soil contains simple molecules formed by reaction between the soil particles and atoms of carbon, oxygen, and nitrogen that come from the Sun. In a more favorable environment, these simple molecules might react further, forming the more complex molecules ("building blocks") needed for the development of life. The sterile Moon thus suggests that the basic ingredients for life are common in the universe, and further study of the lunar soil will tell us about the chemical reactions that occur in space before life develops.

WHAT MYSTERIES REMAIN ABOUT THE MOON?

Despite the great scientific return from the Apollo Program, there are still many unanswered questions about the Moon:

(1) What is the chemical composition of the whole Moon?

We have sampled only eight places on the Moon, with six Apollo and two Luna landings. The chemical analyses made from orbit cover only about a quarter of the Moon's surface. We still know little about the far side of the Moon and nothing whatever about the Moon's polar regions.

(2) Why is the Moon uneven?

Orbiting Apollo spacecraft used a laser device to measure accurately the heights of peaks and valleys over much of the lunar surface. From these careful measurements, scientists have learned that the Moon is not a perfect sphere. It is slightly egg-shaped, with the small end of the egg pointing toward the Earth and the larger end facing away from it.

There are other major differences

between the two sides of the Moon. The front (Earth-facing side), which is the small end of the egg, is covered with large dark areas which were produced by great eruptions of basalt lava between 3 and 4 billion years ago. However, the far side of the Moon is almost entirely composed of light-colored, rugged, and heavily cratered terrain identical to the highland regions on the front side, and there are only a few patches of dark lava-like material. Furthermore, the Moon's upper layer (the crust), is also uneven. On the front side, where the maria are, the lunar crust is about 60 kilometers (37 miles) thick. On the back side, it is over 100 kilometers (62 miles) thick (Figure 7).

We still do not know enough to explain these different observations. Perhaps the Moon points its small end toward the Earth because of tidal forces that have kept it trapped in that position for billions of years. Perhaps lava erupted only on the front side because the crust was thinner there. These differences could tell us much about the early years of the Moon, if we could understand them.

(3) Is the Moon now molten inside?

We know that there were great volcanic eruptions on the Moon billions of years ago, but we do not know how long they continued. To understand the Moon's history completely, we need to find out if the inside of the Moon is still hot and partly molten. More information about the heat flow coming out of the Moon may help provide an answer.

(4) Does the Moon have an iron core like the Earth?

This question is critical to solving the puzzle of ancient lunar magnetism. At the moment, we have so little data that we can neither rule out the possible existence of a small iron core nor prove that one is present. If we can determine more accurately the nature of the Moon's interior and make more measurements of the magnetism on the lunar surface, we may find a definite answer to the baffling question.

(5) How old are the youngest lunar rocks?

The youngest rocks collected from the Moon were formed 3.1 billion years ago. We cannot determine how the Moon heated up and then cooled again until we know whether these eruptions were the last or whether volcanic activity continued on the Moon for a much longer time.

(6) Is the Moon now really "dead"?

Unexplained occurrences of reddish glows, clouds, and mists have been reported on the Moon's surface for over 300 years. These "lunar transient events," as they are called, are still not explained. It is important to determine what they are, because they may indicate regions where gases and other materials are still coming to the surface from inside the Moon.

WHAT DO WE DO NOW?

For all we have learned about the Moon, the exploration of our nearest neighbor world has only just begun. Much of the returned lunar sample material remains to be studied, and we will continue to analyze the data from the instruments on the Moon as long as they operate.

From what we have learned, we can now confidently plan ways to use the Moon to help us understand better the behavior of our own planet. One such project involves using several reflectors that were placed on the Moon by Apollo astronauts. By bouncing a laser beam off these reflectors and back to Earth, we can measure variations in the Earth-Moon distance (about 400,000 kilometers or 250,000 miles) with an accuracy of a few centimeters (a few inches, or one part in 10 billion). Continued measurement of the Earth-Moon distance as the Moon moves in its orbit around us will make it possible to recognize tiny variations that exist in the Moon's motions. These variations occur because the Moon is not quite a uniform sphere, and these minor movements contain important clues about what the inside of the Moon is like.

The laser reflectors, which need no power, will last on the Moon for more than a century before being covered with slow-moving lunar dust. Long before that, continuous measurements should make it possible to understand the internal structure of the Moon. It may even be possible to use the Moon to measure the slow movements of the Earth's continents and oceans as they converge and separate.

To further explore the Moon itself, we can send machines in place of men. An unmanned spacecraft could circle the Moon from pole to pole, measuring its chemical composition, radioactivity, gravity, and magnetism. This mission would carry on the tasks begun by the Apollo Program and would produce physical and chemical maps of the whole Moon. Such an orbiter could also serve as a prototype for later spacecraft and instruments to be put into orbit around Mars or Mercury to map and study those planets as we have mapped and explored the Moon.

Other spacecraft, like the Russian Luna-16 and Luna-20 landers, could return small samples from locations never before visited: the far side, the poles, or the sites of the puzzling transient events. Because of the Apollo Program, we now know how to analyze such small samples and how to interpret correctly the data we obtain. Each landing and sample return would have a double purpose: to teach us more about the Moon, and to help us design the machines that might return samples from the surfaces of Mars, Mercury, or the moons of Jupiter.

Finally, we may see man return to the Moon, not as a passing visitor but as a long-term resident, building bases from which to explore the Moon and erecting astronomical instruments that use the Moon as a platform from which to see deeper into the mysterious universe that surrounds us.

SUGGESTIONS FOR FURTHER READING

Lewis, Robert S. (1974). **The Voyages of Apollo: The Exploration of the Moon.** New York, Quadrangle (The New York Times Book Co.), 308 p., price $12.50. A history of the entire Apollo program and the scientific discoveries made about the Moon, from the first steps of Apollo 11 to the splashdown of Apollo 17.

Collins, Michael (1974). **Carrying the Fire: An Astronaut's Journeys.** New York, Ballantine Books, 488 p., paperback, price $1.95. A biographical memoir by an Apollo 11 astronaut, describing his progress from test pilot through the Gemini and Apollo missions. An entertaining presentation of the personalities and technicalities involved in going to the Moon.

Taylor, S. R. (1975). **Lunar Science: A Post-Apollo View.** New York, Pergamon Press, 372 p., paperback, price $9.50. An extensive textbook that describes in detail the scientific results from the Apollo program and the state of present knowledge about the nature, origin, and history of the Moon. For scientists and advanced science students.

Short, Nicholas M. (1975). **Planetary Geology.** Englewood Cliffs, N.J., Prentice-Hall, Inc., 361 p., price $17.95. A college-level textbook that summarizes the application of terrestrial geology to lunar studies, the scientific results from the Apollo program, and the new knowledge obtained about other planets by automated spacecraft.

King, Elbert A. (1976). **Space Geology.** New York, John Wiley and Sons, Inc., 349 p., price $16.95. A text for the advanced geology student, this book presents in detail our current knowledge about the geology of the solar system without discussing the history and technical details of space exploration. The chapters on meteorites, impact craters, the moon, Mars, and the asteroids are excellent summaries of the exciting scientific discoveries that have been made in the last few years.

(SP 350) **Apollo Expeditions to the Moon.** Washington, D.C., Superintendent of Documents, U.S. Government Printing Office, 326 p., price $8.90. Stock Number 033-000-00630-6. A history of Apollo as told by the Apollo astronauts and key NASA personnel. Four-color illustrations.

NOTE FOR SCIENTISTS AND EDUCATORS.

The Lunar Science Institute in Houston, Texas can provide further information about lunar science and about data resources that are available for scientific and educational purposes. In particular, the Institute maintains lists of available books, articles, photographs, maps, and other materials dealing with the Moon and the Apollo missions. For further information, contact:

Lunar Science Institute
Data Center, Code L
3303 NASA Road #1
Houston, TX 77058
Phone (713) 488-5200

Inquiries about participation in NASA-supported programs of research on lunar samples and other aspects of lunar science should be addressed to:

Deputy Director
Lunar and Planetary Programs Office
Code SL
NASA Headquarters
Washington, DC 20546
Phone (202) 755-3730.

Earthrise. *Photograph by Apollo 12 crew captured a crescent Earth rising above the lunar horizon*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 70 cents
tock No. 033-000-00653-5
here is a minimum charge of $1.00 for each mail order

☆ U.S. GOVERNMENT PRINTING OFFICE : 1976 O—219-361