

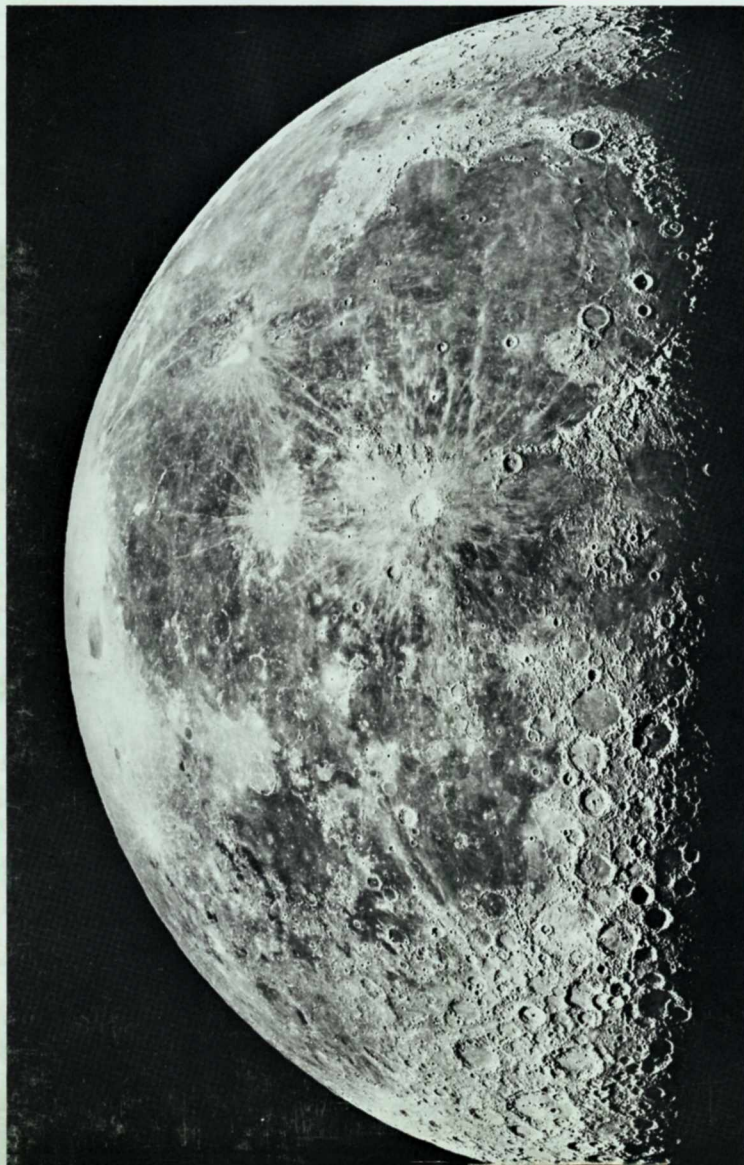
Moon Craters and Oregon Volcanoes

By Aaron C. Waters

Condon Lectures

Oregon State System of Higher Education

Eugene, Oregon □ 1967



The Condon Lectures

The Condon Lectureship was established in 1944 by the Oregon State Board of Higher Education upon the recommendation of the late Dr. John C. Merriam who was, at that time, a member of the faculty of the University of Oregon. The Lectureship was named in honor of Dr. Thomas Condon, the first professor of geology at the University.

The purpose of the lectures is to interpret the results of significant scientific research to the nonspecialist. The lectures, usually two annually, are delivered three times in the state, namely at Eugene, Corvallis, and Portland. They are then published in appropriately adapted form.

A list of Condon Lecture publications available is on page 69.

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Printed in the United States of America

Preface

Professor Thomas Condon, in whose honor the Condon Lectures were established, distinguished himself as a geologist who seldom missed an opportunity to share his knowledge and enthusiasm about Oregon's geology, whether his listeners were his church congregation, his friends and neighbors who accompanied him to the seashore or the mountains, or his students, to whom he was a great inspiration. Although he was known as "not merely a scholar and poet, but a seer," it is doubtful that Thomas Condon could have foreseen, even in his wildest reaches of fancy, that in 1966 a geologist would come to Oregon to lecture on the geology of the moon, using information obtained from photographs taken in space from close to the moon's surface and from data yielded by the most sophisticated of modern physical measurements.

Thomas Condon, whose pioneering studies of Oregon fossils carried him back a hundred million years, was able to bridge time. The 1966 Condon Lectures tell of the geologist's attempt to bridge space, over 200,000 miles of it, and to reach valid conclusions concerning the significance of moon features.

The surface of the moon with its maria and other features, long observed through the telescope, may now be studied in more detail, and it is evident that in some respects there is a striking resemblance to volcanic features well illustrated in Oregon. A corollary of the geologic truism, first stated by Hutton, that "the present is the key to the past" might be that the earth's volcanic terrain is one of the keys to understanding the perplexing terrain of the moon.

It is appropriate that the author of this volume, Dr. A. C. Waters, is a renowned geologist who has devoted a lifetime of study to volcanic features and, as a native of the Pacific North-

west, has made many significant contributions to the study of volcanoes in Oregon. These lectures permit the reader to see the moon and earth through the eyes of a scientist who brings together the known facts, skillfully interprets them, fills in some voids in our knowledge, and whets the appetite for the new knowledge that will come to us when geologists probe yet deeper into the earth's mysteries and when astronauts return to us with samples and firsthand observations of the surface of the moon.

Lloyd W. Staples, Head
Department of Geology
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THE AUTHOR

Born in Waterville, Washington, in 1905, Aaron Clement Waters was educated at the University of Washington (B.Sc. and M.Sc.) and at Yale (Ph.D.). He has spent most of his professional life in university teaching and field research on igneous rocks.

Dr. Waters has taught geology at Yale, Stanford and Johns Hopkins Universities and, since 1963, at the University of California, Santa Barbara. He will join the faculty of the University of California, Santa Cruz, in July 1967, to begin the program in geology and geophysics at this new campus.

Dr. Waters' principal scientific contributions have been investigations of the volcanic and plutonic rocks of the Pacific Northwest. His current studies concern the geology of the Columbia River gorge, of Newberry Caldera near Bend, and of certain maar-type volcanoes in south central Oregon and northeastern California. His active research and interest in the geology of the Moon began in 1964 when he was assigned a part in the geologic training of the astronauts, and in the formulation of the Apollo and Post-Apollo field geologic investigations.

Dr. Waters' professional honors include election to the National Academy of Sciences and to the American Academy of Arts and Sciences. He has been awarded Guggenheim and National Science Foundation Senior Postdoctoral fellowships.

Acknowledgments

In preparing this manuscript I have drawn on the work of many individuals; my debt to their printed contributions is indicated in part by the references cited and the credit lines beneath the illustrations. More intangible but of very great importance is the help and guidance I have received over the years from talking with numerous geologists engaged in volcanologic or astrogeologic research. It is not possible to name them all, nor to express in detail the special ways in which they have influenced the development of ideas, but I owe a particular debt of gratitude to E. M. Shoemaker, Charles A. Anderson, and Alfred H. Chidester. None of them, however, should be charged with any responsibility whatever for errors in fact or in judgment, nor for "outrageous hypotheses" that may be present herein; neither should the astronauts with whom I have spent happy hours on field trips, and in the classroom discussing various aspects of volcanic and impact geology.

Finally, I wish to express special appreciation to Professor Charles T. Duncan, Associate Dean of Faculties, University of Oregon, and Chairman of the Condon Lectures Committee. He not only had the task of arranging for the lectures in Eugene, Corvallis and Portland, but he also read the manuscript, suggested excellent editorial changes, and relieved me of many time-consuming details attending its publication.

A. C. Waters

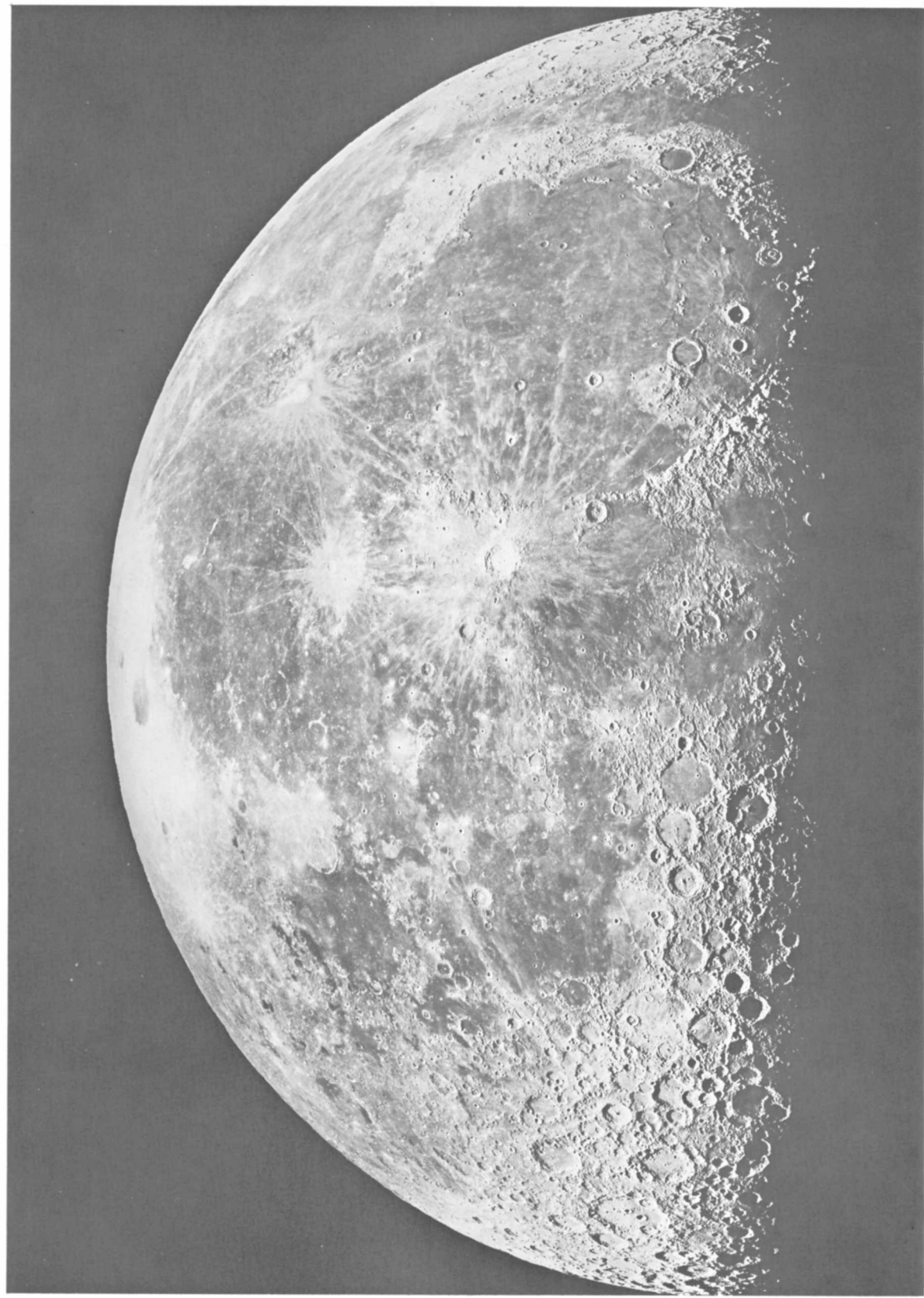


Figure 1

Introduction 13

Moon Craters 20

Impact Origin of Lunar Craters 27

Moon Maria 37

Volcanoes on the Moon 44

Permafrost on the Moon 53

Space Weathering on the Moon 57

Life on the Moon 62

References 65

Condon Lecture Publications 69

Contents

Figure 1. *The Moon at Last Quarter*. Sunlight illuminates the western half of the visible part of the moon's face, the eastern half is in shadow. Dark surfaced *maria* (*Latin*, seas) contrast with the cratered highlands or *terrae* (lands). The maria are barren plains, possibly underlain by dark-colored lava flows. The older *terrae* are a maze of overlapping impact craters. Radiating from Copernicus, the large crater near the center of the photograph, are light-colored feathery rays which spread radially hundreds of miles from the crater, but are best seen on the surface of Mare Imbrium, the large circular mare (pronounced *mar-ee*) that occupies much of the northern (top) half of the photograph. West of Copernicus is the smaller ray crater, Kepler, with its light-colored ejecta blanket from which radiate long thin rays like the radials of a spider web. The ray craters are among the youngest visible features on the moon.

Mount Wilson and Palomar Observatory photograph.

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Figure 1.	The Moon at Last Quarter	8
Figure 2.	The Basin of Mare Imbrium	14
Figure 3.	The Ray Crater Copernicus	21
Figure 4.	Theophilus and Cyrillus	22
Figure 5.	Posidonius, a Pre-mare Crater	22
Figure 6.	Aristoteles and Eudoxus	23
Figure 7.	A Cluster of Secondary Craters	26
Figure 8.	Ariadaeus rille	28
Figure 9.	Crater Lake Caldera, Oregon	29
Figure 10.	Mt. Newberry Caldera, Oregon	32
Figure 11.	Oblique View into Mt. Newberry Caldera	32
Figure 12.	Astronaut Walter Cunningham Climbs Big Obsidian Flow	35
Figure 13.	Flows of Columbia River Basalt	40
Figure 14.	Rilles on the Floor of Crater Alphonsus	46
Figure 15.	Map of Crater Copernicus	46
Figure 16.	Craters and Rilles on the Floor of Alphonsus	47
Figure 17.	Cinder Cones Aligned along a Fissure	48
Figure 18.	Hole in the Ground	49
Figure 19.	Meteor Crater, Arizona	49
Map.	Through the Eyepiece of the Moon	inside back cover

Illustrations

Introduction

The greatest adventure of all time is rapidly unfolding and will soon be history. Man is about to travel across 239,000 miles of space and walk upon the surface of the moon. In the end this feat may turn out to be physically less demanding upon the astronaut than was Hillary's and Norkay's ascent of Mount Everest, or Roger Bannister's attainment of the 4-minute mile. The astronaut who first walks upon the moon, however, will have achieved far more than another demonstration of man's physical stamina, courage and insatiable urge to better a record, or to explore the unknown simply "because it is there." His disciplined mind must already have mastered the skills needed to control a rocket in flight, the navigational training required to rendezvous with an orbiting buddy in space, and the scientific knowledge demanded to make the observations, collect the samples and monitor the scientific experiments that will greatly further our knowledge of the universe, and ultimately pave the way to Mars and other planets.

Moreover, his observations and the samples he brings back will settle for all time many of the speculations and controversial questions about the morphological and geological features of the moon's surface—features which have excited men's imaginations ever since 1610 A.D. when Galileo built his telescope and first observed the moon's huge craters and dark "seas" (maria).

This paper, an outgrowth of my Condon Lectures, attempts to formulate and analyze some of the geologic questions, inferences, and speculations that arose from man's attempts to understand the moon on the basis of evidence he has been able to gain across the reaches of space while still chained to planet Earth.

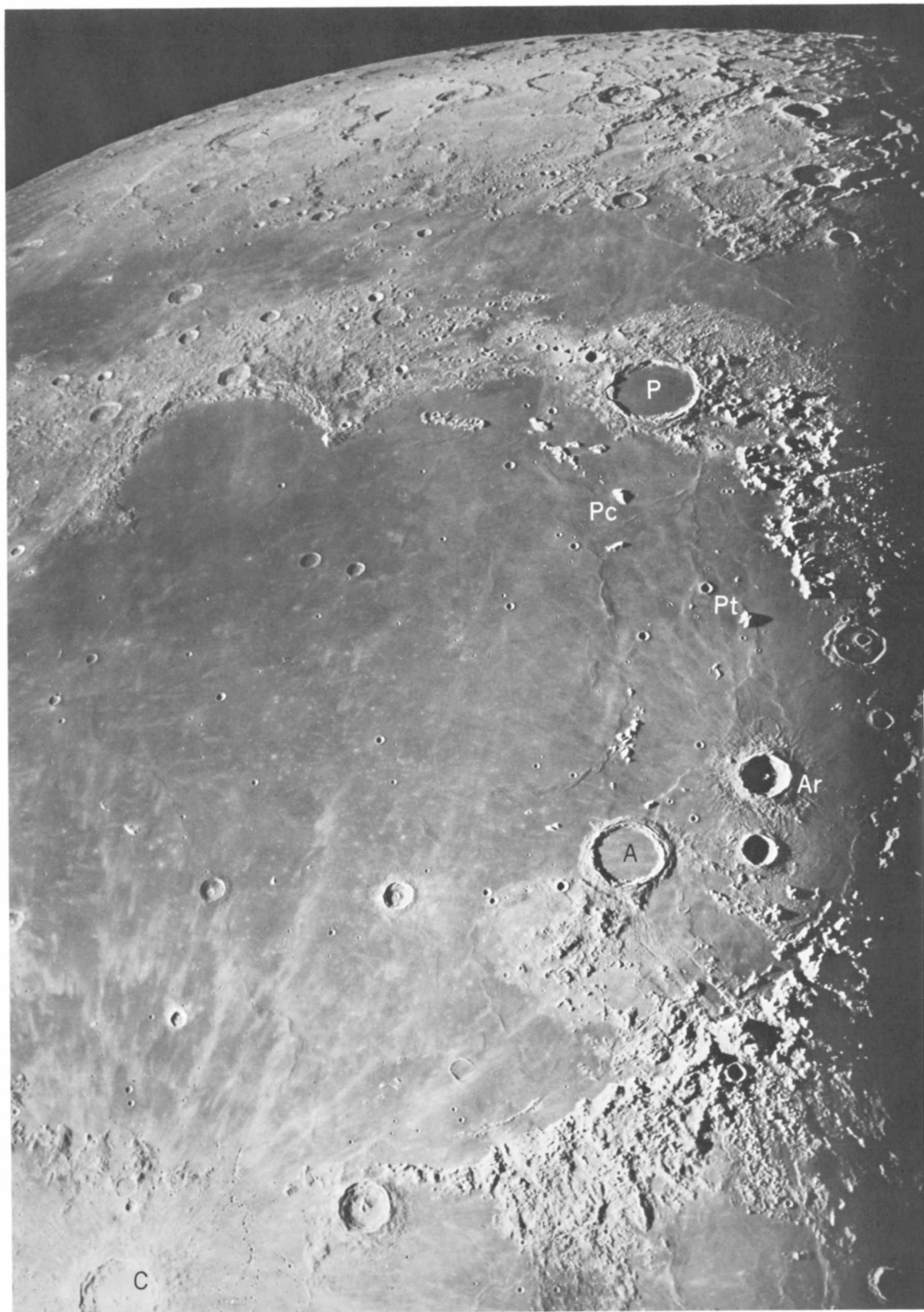


Figure 2

What do we know about the moon? Telescopes have been greatly improved since Galileo's day. The magnificent photographs of high quality taken in recent years at many astronomical observatories (see Figures 1 to 7), give the inquiring geologist an opportunity to scan the moon at his leisure and to make meaningful comparisons of the surface features of moon and earth for objects one-half kilometer or more in size. Examine the map in the pocket of this report and you will see that such comparisons yield surprisingly little in common: Earth's great systems of stream canyons and broad river plains, mountain ranges with their intri-

Figure 2. *The Basin of Mare Imbrium*, 700 miles in diameter, has been interpreted as having been formed by impact of a large planetesimal about 100 miles in diameter. On this interpretation the mountains that surround the basin are parts of the ejecta blanket, shot out by shock waves, and piled up around the crater rim. This ejecta blanket, and the radial fractures that extend outward from the Imbrium basin, are best seen in the lower-right part of the photo. After much inward slumping of the original steep crater walls a fluid (possibly lava) welled up from the moon's interior, filled the basin, and irregularly inundated its rims including the radial fractures and nearby smaller craters. Thus was produced the nearly flat surface of the mare, and its embayed shoreline.

Note that some large craters, such as Plato (P) and Archimedes (A) are older than the mare, because they have been inundated to the same level as the mare surface. Others such as Aristillus (Ar) and Copernicus (C), as well as many small ones scattered across the center of the mare, are younger. The meteors that formed them have dug deep pits in the mare filling, throwing ejecta out upon the mare surface. The light colored splashes in the lower-left part of the photograph are rays from Copernicus.

Note the stark black shadows cast by the walls of crater Aristillus, and by the two high peaks, Mt. Pico (Po) and Mt. Piton (Pn), which rise as islands above the mare surface between Plato (P) and Aristillus (Ar).

Mount Wilson and Palomar Observatory photograph.

cately folded rocks, lake-dotted tundra and ice-capped polar lands—these have no counterparts on the moon. Instead a maze of large and small craters—many more than 50 miles in diameter—form pock-marked highlands, the *terrae*, which occupy about two-thirds of the moon's visible surface. Even the flatlands, called *maria* because they were thought to be oceans by the early astronomers, turn out to be barren plains. The edges of the *maria* do, however, lap against the cratered highlands with embayed "shore-lines" like those of an ocean along a mountainous coast. Yet the *maria* cannot now be liquid; they are pocked by craters large and small, and dusted by streaks, hills and hummocks of loose debris. Large craters, however, are much fewer in number on mare surfaces than on the intensely cratered older highlands, thus affording another indication of the greater age of the *terrae*. (Figures 1 and 2).

Although this great difference in topography between earth and moon seems surprising at first, it is logical enough when we examine other evidence. The moon has no atmosphere and no water in its "seas." Thus there are no clouds of water vapor to be carried aloft, nor is there a wind to carry them. No rain falls on the atmosphere-less moon-world to collect into streams that erode canyons and valleys and fill the depressions with lakes and seas.

Astronomers can readily prove the absence of an atmosphere on the moon by the stark black shadows cast during an eclipse, or when crater rims and mountain peaks spread long shadows across the adjacent plains during the approach of lunar sunset. On earth our atmosphere diffuses the light, allowing some of it to spread into the shadow and partially highlight conspicuous objects; on the moon total blackness prevails the moment a shadow engulfs the surface, as clearly shown in the photographs (Figures 2 and 4).

Even more striking proof of the hard vacuum that surrounds the moon is afforded by temperature measurements. Our atmosphere serves as a warm blanket that conserves the sun's heat, protects us from great temperature changes between day and night (or between sunlight and shadow), and partially shields us from dangerous radiation and from electrically charged particles shot out from the sun. No such protection is afforded the moon's surface. When the sun is directly overhead the temperature rises to between 105 and 130 degrees Centigrade—well above that of boiling water on earth. During the long lunar night (nearly 14 of our days) it sinks to the abysmal cold of -150 degrees Centigrade.

Measurement of infrared emission enables us to determine not only the temperature but also the rate of fall of temperature. As a shadow spreads across the moon's surface an enormous drop in temperature occurs almost instantaneously. This proves not only the absence of an atmosphere capable of conserving and redistributing the heat but also that most of the rocks which make up at least the topmost meter of the moon's crust are very poor conductors of heat. According to Wright and others (1963) the temperature at a depth of a few meters below the moon's surface is near -25° Centigrade, and is affected little by the enormous change of surface temperature between day and night, or during lunar eclipses. Only rock material of a highly porous, minutely spongy structure, could possess this insulating capacity.

Other information obtained from moonlight (which is reflected sunlight), and from electromagnetic radiations beyond the range of wave-lengths characteristic of visible light, confirms this picture of a minutely rough and spongy structure. If a sphere with a good reflecting surface is examined in a strong light our eyes see its central area strongly illuminated, but progressively less light reaches us from the sloping surfaces toward the periphery of the visible sphere. The amount of reflected light that comes to our eyes is a function of the angle at which the light strikes the sphere and of the position of our eyes with respect to the direction of the incident light. This fading out of illumination around a bright center is not observed when we look upon the surface of the full moon; instead the whole disk appears about equally illuminated. Nor is there an appreciable change with time in the brightness of a particular crater or other surface feature on the moon's surface as the changing relative positions of sun, earth, and moon cause the spot to transit from one side to the other across the moon's visible disk. Not until shadows begin to obscure part of the surface as sunset approaches is there a marked drop in illumination. As Galileo pointed out more than 300 years ago, this peculiar nature of the moon's reflectivity can be explained if we assume that the surface is extremely rough at a scale somewhat larger than the wave lengths of light.

Basalt scoria—the frothy black and reddish cinders quarried for road surfacing from innumerable cinder cones (small basaltic volcanoes) that dot the plateaus of central and southeastern Oregon—is a spongy volcanic rock full of minute bubble-holes and irregular cellular cavities. It has reflecting properties almost identical to those of the maria on the moon. So do some kinds of lichen and moss. This does not necessarily mean that the maria

are covered with basaltic cinders—or with lichen—only that the moon's surface appears to possess the intricately rough and spongy character of these substances.

Yet, to other electromagnetic radiations the moon's surface seems smooth. Radar reflections—with wave lengths of several meters—give us the impression of a smooth surface at the scale of meters and decimeters. These long-wave reflections also show the normal central area of strong reflecting power expected from a sphere. There is no inherent contradiction in accepting this picture of a surface that is intricately rough on a small scale but which appears to be smooth to remote sensors that make use of greater wave lengths. A sheet of polished steel one meter across will be recorded as smooth by the bubble in a 24-inch carpenter's level placed upon its surface, but a sheet of tightly packed steel wool of equal thickness is just as smooth to the carpenter's level. If we were to use a level only 1/1,000 inch long to examine the surfaces, however, the results would be very different.

Unfortunately sunlight and other electromagnetic radiations reaching us after reflection from the moon's surface give little information about the actual composition of moon material; most of their absorption spectral lines are those of the sun's incandescent atmosphere. The density of the moon is 3.43; that of the earth 5.55. On the moon—whose diameter is only a little more than half that of the earth—the gravitational force is about one-sixth as great. The moon's density and its gravitational constant are adequately explained if we assume that the moon is made of rocks like those of the earth's outer crust and mantle, but that the moon does not possess the heavy core—thought to be composed of nickel-iron—which extends from the center of the earth to about half its radius. From the data we have, there is no reason to reject the suggestion that the moon's maria may be composed of ordinary volcanic rocks—basalt, scoria, obsidian, pumice, ignimbrite—such as are common on many parts of the earth; for example, near Bend, Prineville, and Burns in central Oregon. But we cannot know whether this is actually so until the astronauts return with samples supplemented by on-the-site-observations.

Broken and shattered meteoric material also should be abundant on the moon, and particularly on the cratered highlands, if we accept the highly probable conclusion that its great craters were formed by large meteors and asteroids slamming into the moon from outer space. Indeed we have strong evidence that both

earth and moon were formed by the aggregation of meteoric debris swept up over the last four and one-half billion years as the two bodies spiraled continuously around the sun during its journey through space. Meteorites¹ are rarely found on the earth's surface today because those that fall on land are subjected to weathering and erosion—processes that depend upon the atmosphere and water of the earth. Thus meteorites that fall on land are slowly decomposed, and the debris is transported away and redeposited. Meteorites that fall in the sea or on river floodplains are eventually buried under new sediments. Furthermore the great heat of the earth's interior may long since have melted and recrystallized most of the earth's meteorites that fell during the early stages of the planet's aggregation. As these melts cooled and crystallized, the heaviest of the early crystallizing minerals would have sunk through the melt and segregated deep within the earth, thus forming the earth's heavy core, and the remaining less dense melt would float upward, bringing lighter material nearer the surface.

Thousands of small meteorites—most about the size of a grain of wheat—fall into the earth's atmosphere every day, but nearly all are burned to dust by the heat and friction of entry. These tiny meteorites, blazing up into incandescent splendor, are the “shooting stars” visible by the hundreds on any clear September night as you lie in your sleeping bag gazing up at the sky from a campsite on the Oregon plateaus. Such tiny meteors would fall unimpeded on the moon, splashing out small craters by the violence of their impact.

Because atmosphere and ocean are absent from the moon we expect meteoric material to be very much more abundant on its surface than on earth, but we do not expect moon rocks to include the shales and limestones so widespread on earth. These rocks have been formed by slow deposition of the debris produced by the physical, chemical and biologic activities made possible by the presence of water, wind and living organisms.

¹ The largest meteorite ever found in the United States was discovered in the Willamette Valley near West Linn in 1902, and can now be seen in the Hayden Planetarium in New York City. It weighs 15½ tons and is composed of nickel-iron.

Perhaps we can return to the difficult question of the moon's chemical composition, and the nature of the rocks that compose it, with a little more assurance after we have discussed the probable origin of its craters and maria. The true nature of moon rocks, however, can never be really evaluated until after return of samples to earth.

Moon Craters

The question of the origin of the moon's craters has fascinated observers since the time of Galileo. Several different kinds of craters can be recognized.

LARGE PRIMARY CRATERS. Large craters are the dominant topographic features of the moon's highlands, and are scattered sparsely upon the surface of the maria. In the highlands they are so thickly clustered that younger craters overlap and partially obliterate the older (Figures 1 and 4). Moon crater Clavius is 235 kilometers (145 miles) wide, and many lunar craters have diameters of more than 50 miles. Some of the moon's maria, for example Mare Imbrium and Mare Crisium, have rudely circular outlines. Do they occupy former giant craters which have been partly filled by lava or by frothy ash flows capable of welling up into the crater and leveling off to a nearly flat plain? Kopal (1962, p. 265) estimates that more than 300,000 craters with diameters exceeding 1 kilometer can be seen on the visible side of the moon alone. They range downward in size to craters not visible with the telescope—indeed, television cameras on the American Ranger and Surveyor probes and on Russia's Luna 9 prove that there are countless millions of primary craters on the moon's surface which are far too small to be seen by telescope from earth.

Figure 3. *The Ray Crater Copernicus*, about 55 miles in diameter, is the largest on the photograph. The large crater to its right is Eratosthenes. Copernicus shows a flat floor with central peaks, and has steep inner walls lined by slump terraces caused by inward caving of the oversteepened slopes. The raised crater rim towers more than 11,000 feet above the crater floor but is only about 3,000 feet higher than the adjacent mare surface. The rim is mostly ejecta blanket, expelled from the crater and piled in hummocky confusion near the crater rim. Note the thousands of small secondary craters clustered in and near the ejecta blanket, the low radial ridges grading outward from the ejecta blanket, and the light-colored feathery splashes of crushed rock (rays) shooting out radially for more than 200 miles. All of these features are typical of craters formed by meteor impact.

The small craters neatly arranged along straight and sinuous fissures, seen midway between Copernicus and Eratosthenes, are probably moon volcanoes of the maar-type.

Mount Wilson and Palomar Observatory photograph.



Figure 3



Figure 4



Figure 5

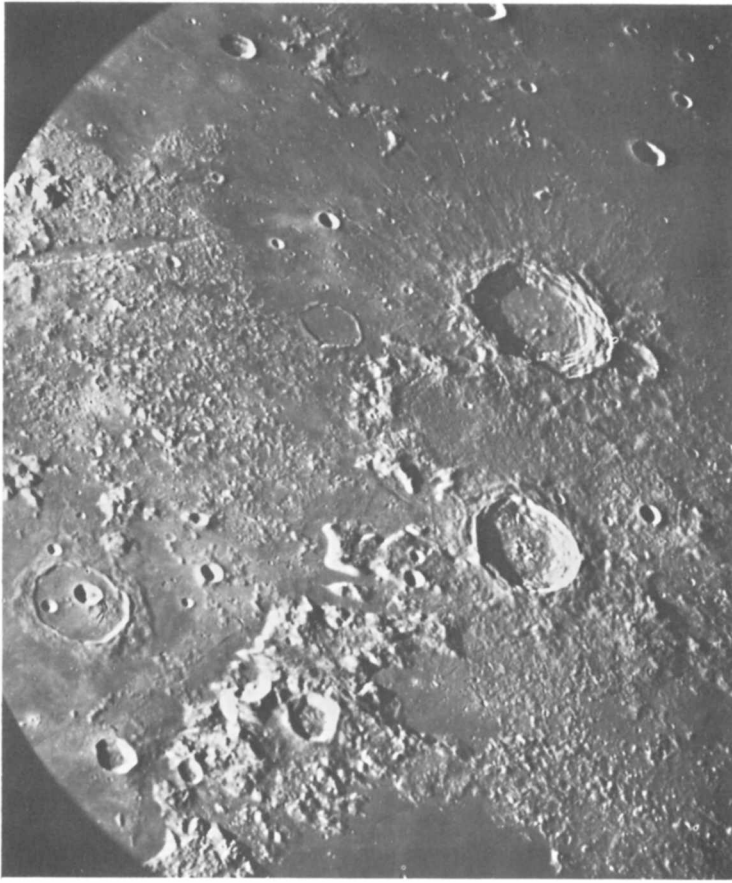


Figure 6

Figure 4. *Theophilus and Cyrillus*, two large impact craters, side by side. Note that Theophilus is the younger and has obliterated part of the rim and ejecta blanket of the older Cyrillus.

Lick Observatory photograph.

Figure 5. *Posidonius, a Pre-mare Crater*. The floor of Posidonius, an old crater about 55 miles in diameter, has been more than half inundated, and its western (left) rim nearly overtopped by the filling (possibly lava) of Mare Serenitatis. Another crater, Le Monnier, lies on the mare shoreline 60 miles to the southeast (center—right). It has been completely engulfed on its western side and now forms a crescent-shaped bay.

Note several small cup-shaped craters of post-mare age near Posidonius: one demolished part of its rim; another has splashed up the mare filling in Posidonius' center.

A prominent "wrinkle ridge," possibly an anticlinal fold, extends across the surface of the mare.

Lick Observatory photograph.

Figure 6. *Aristoteles and Eudoxus*. Aristoteles, the large crater in the upper-right is a post-mare impact crater. Unlike Copernicus or Tycho, its rays have been darkened until they are almost invisible. Note the ancient crater west (left) of Aristoteles which is almost drowned beneath the mare filling; only the top of its rim is visible. In the upper-left corner is broad, straight Alpine Valley transecting the mountains that rim the northeast wall of Mare Imbrium. Its floor has also been inundated.

Lick Observatory photograph.

Some typical features of primary moon craters are shown in Figures 3, 4, 5, and 6. The crater Copernicus (Figure 3), and the crater Theophilus (Figure 4), are younger than the mare surface on which they lie; Posidonius (Figure 5), on the other hand, is older: its floor has been partially inundated to the level of Mare Serenitatis (Ocean of Serenity). Each of these three craters is about 55 miles in diameter.

Copernicus, Theophilus and Aristoteles (Figure 6) are characterized by steep inner walls whose lower slopes are strewn with many irregular terraces and tilted blocks. Such features probably were formed by caving and slumping of the steep crater walls. The walls of Copernicus tower 3,500 meters (more than 11,000 feet) above the wide and comparatively flat crater floor. A few jagged peaks are clustered near the center of each major crater. These central peaks are irregular in form, not at all like the smooth constructional slopes of earth volcanoes such as Mount Saint Helens, Bachelor, or Maiden Peak in the Cascades. Although the crater rim of Copernicus towers 11,000 feet above the crater floor it rises only about 3,000 feet above the extensive plain which surrounds it. The outer slopes of the crater rim, although diversified by hummocky swales and hills, are gentle compared with the precipitous inner cliffs. Theophilus rim stands well above the surface of Mare Serenitatis, but is not much higher than the rim of Cyrillus which it invades and partially demolishes along about one fourth of its periphery (Figure 4).

The raised rims of Copernicus, Theophilus and Aristoteles are mantled by thick ejecta blankets. In the low sunlight under which the pictures were taken the ejecta blankets show up as a markedly hummocky spattering of randomly oriented hills and depressions. (Figures 3, 4 and 6). At greater distances from the crater they acquire a roughly radial pattern of irregular ridges and swales. At still greater distances each ejecta blanket diminishes rapidly in relief and hence in thickness; they are scarcely discernible 45 miles from the crater rims. The photograph of Copernicus (Figure 3) also shows light-colored feathery streaks, called rays, that radiate outward beyond the ejecta blanket to distances of several hundred miles. Toward Copernicus many of them merge imperceptibly into or are buried beneath the hummocky topography of the ejecta blanket; others arise and splash outward from clusters of small secondary craters and gouge-like depressions.

SECONDARY CRATERS AND RAYS. Telescopic observations of Copernicus and other large primary moon craters reveal great numbers of small craters of more irregular form and shallower depth

than primary craters of equivalent size. They are thickly sprinkled in a broad ring near the outer margin of the ejecta blanket and also appear in smaller clusters that lie at the head of feathery splashes which grade into individual components of the ray system. From telescopic observations and studies of photographs Shoemaker and Hackman (1962, p. 290-291) give this analysis of the origin of the secondary craters and of the rays that surround Copernicus:

"A full explanation of the ray pattern and associated gouge-like craters can be given in terms of the ballistics of material ejected from Copernicus (Shoemaker, 1962). In this explanation the gouges are formed mainly by impact of large individual fragments ejected from Copernicus and the ray elements are splashes of crushed rock derived chiefly from the impact of these fragments. The ray system may thus be conceived as a discontinuous thin layer of ejecta partly from the main central crater and partly from the local gouges.

The radial frequency distribution of gouges shows a sharp mode near 160 kilometers from the center of Copernicus. At greater distances the frequency drops off rapidly, and toward the outer extremity of the ray system the frequency drops gradually to zero. If we come closer to Copernicus from the modal distance, the frequency drops off very rapidly, evidently owing chiefly to the fact that toward the main crater the gouges in the pre-existing lunar surface tend to be covered up or smothered under an increasingly thick deposit of material making up the crater rim. The smothering effect begins about 80 kilometers from the edge of the crater, about where the relief of the sub-radial ridges can first be seen, and from this distance inward there is essentially a continuous blanket of ejecta. The thickness of this blanket ranges from a feather edge at its outer extremity, beyond which the pre-existing lunar surface is exposed between the rays, to a maximum that probably does not exceed about 1,000 meters, the height of the rim."

Strong confirmation of Shoemaker and Hackman's explanation is afforded by the pictures obtained by Ranger 7, which impacted on a mare surface splashed by rays from crater Tycho. Figure 7, one of the photographs taken from Ranger 7 at a height of 34 miles above the moon's surface, shows a typical cluster of small secondary craters—many of them irregular or gouge shaped—scattered across the lower half of the photograph. A splash of light-colored material dusts the surface in a broad ray extending north from the cluster. Three larger cup-shaped primary craters, smooth-sided as if drilled by a lathe, to recall Kuiper's (1959) expressive description of small primary craters—are in the lower

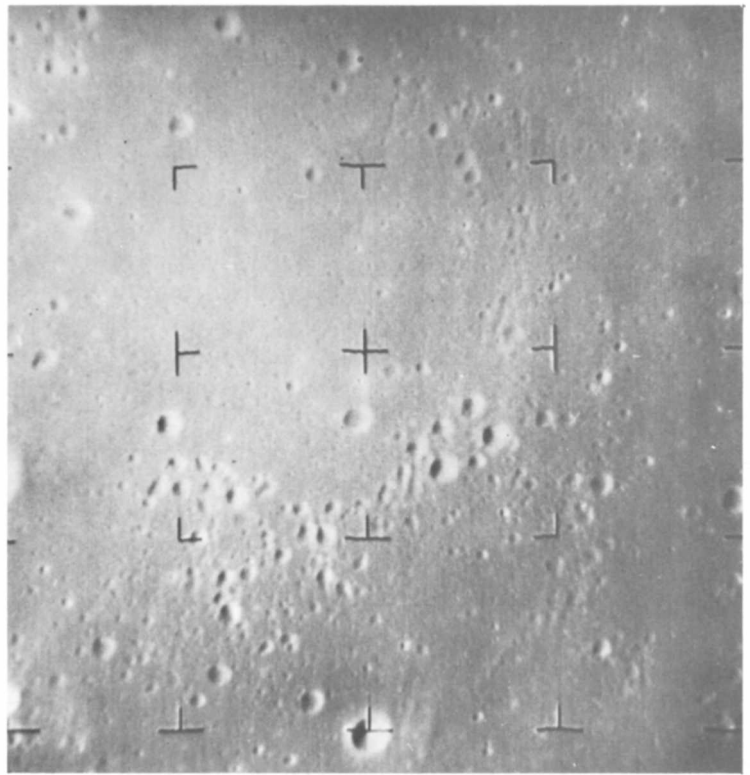


Figure 7. *A Cluster of Secondary Craters*, formed as material ejected from Tycho fell onto the surface of Mare Cognitum. Note that these are shallower than primary craters and that many are gouge-shaped or elongated to the north. The light-colored material in the central and upper-left is a ray splashed from the crater cluster. Several deep, cup-shaped primary craters are scattered over the surface. The area visible is about 16 miles across, and the smallest craters visible are about 20 feet in diameter.

Photograph from Ranger VII spacecraft, 34 miles above the lunar surface. Jet Propulsion Laboratory.

left part of the picture, along the bottom and left edge. Several smaller ones are randomly scattered over the surface. Note that the secondaries are much more irregular in form and shallower in depth than primary craters. Most are elongated and some are gouge-shaped in the direction toward the top of the photograph—away from Tycho, which lies to the south. Tycho was the source of the projectiles that formed the secondaries and the rays. The clustering of secondaries in groups at the head of individual rays must mean that large, but broken and partly disaggregated clumps of rock were shot out as units along ballistic trajectories from Tycho. On falling to the surface of the mare each separate chunk gouged a pit into the spongy upper surface of the mare, but quickly encountered hard resistant material at shallow depth. This harder pavement crushed the far-flung projectiles into a shower of fine rock debris which splashed and skipped forward across the lunar landscape to great distances. I like to think of the action as being comparable to that of a large cluster of loosely-packed snowballs flung onto a pavement covered with a half-inch

of newly fallen snow. Landing at an angle, each impacting snowball digs a furrow through the snow, bursts against the hard pavement below and then splashes forward as a streak of slushy ice.

Bagnold (1942) showed that in African deserts grains of wind-blown sand skip and bound across bare rock surfaces with little loss in energy, but if they splash into accumulations of loose sand their forward motion is checked because their kinetic energy is used up in jarring numerous other small grains into short trajectories. Thus is explained a common feature of many deserts, the gathering and hoarding of a sparse supply of sand into scattered dunes separated by wide floors of barren rock. The same mechanism may operate upon the maria surfaces, thus feeding and emphasizing the feathery bands, loops and small arcuate ridges so characteristic of lunar rays.

In the discussion above the inference has been made that the primary craters on the moon's surface were formed by the infall of meteors, comets, and asteroids from outer space. If this be true, the ejecta blanket, secondary craters, and rays which surround a primary crater are the expectable result of the heaving out of debris along ballistic trajectories by the shock waves that result from hypervelocity impact (Shoemaker, 1962, 1959). This theory is not universally held; even today some students of the moon's morphology believe that all of the moon's craters are of volcanic origin. The volcanic theory was the only one seriously considered in the early stages of the study of moon cratering—which began, of course, in 1610 when Galileo turned his telescope on the moon and discovered its craters. Shoemaker (1962, p. 285) reports that Robert Hooke as early as 1665 had compared lunar craters with those formed by dropping bullets on wet clay, but Hooke rejected an impact origin for the moon's features because "it would be difficult to imagine whence those falling bodies should come."

Since the 17th century, however, much has been learned about meteor craters on earth and also about different kinds of volcanic craters and calderas. This is not the place to review the long and, for some protagonists, bitter controversy over the volcanic versus impact origin of lunar craters. Unfortunately, some students of the phenomena of moon cratering take an "either-or" attitude respecting the origin of lunar features, neglecting the approach that, just as on earth, some craters may be of meteoric and others of volcanic origin. My position is not different from that of most present day students of moon morphology: the large primary

Impact Origin of Lunar Craters

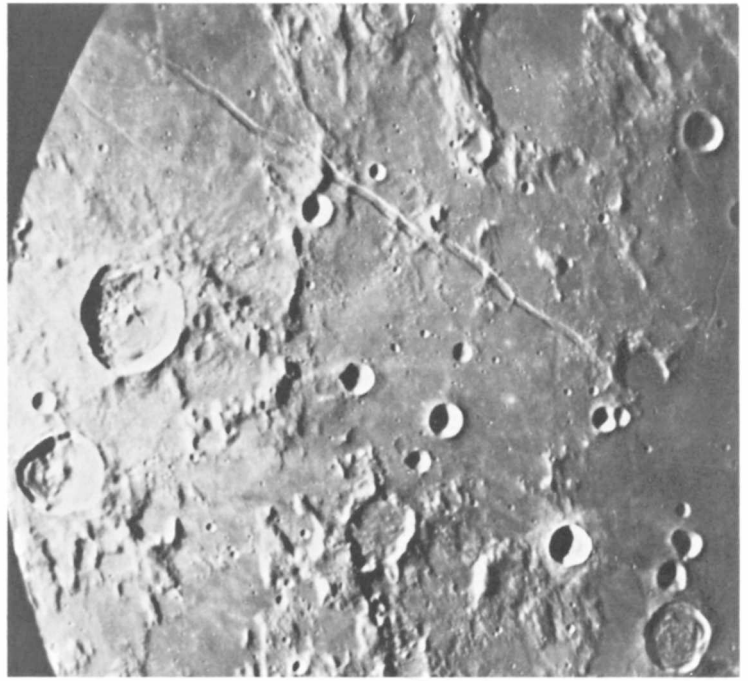


Figure 8. *Ariadæus rille*, a fault trough one to five miles wide and about 125 miles long, cuts across plains, craters, and mountains west of Mare Tranquillitatis.

Lick Observatory photograph.

craters were almost certainly formed by impact, but the moon also shows clear evidence of volcanic phenomena as well. These conclusions are not based on a desire for fence-straddling prior to the landing of the astronauts but simply on the fact that one process is inadequate to explain all of the varied features observed on the moon's surface—or on the earth's. Evidence will be given later suggesting that the rows of small craters which follow fissures and narrow fault troughs called rilles (Figure 8) on the moon's surface are products of lunar volcanism. Features on the moon that resemble the common shield volcanoes of earth can also be seen through the telescope. Moreover, the fillings of the maria are most likely lava flows or ash flows—in other words, deposits emplaced by the rise and leveling off of lavas or of highly inflated volcanic froths derived from the moon's interior by volcanic activity. Strom (1965) presents convincing evidence that certain lobate scarps on maria surfaces are fronts of frothy lava flows.

But let us return to the impact theory of the moon's primary craters. A well-reasoned account favoring the impact hypothesis was published as early as 1893 by G. K. Gilbert. Many review articles of more recent date summarize and evaluate various theories regarding the origin of lunar craters; among them are Baldwin (1949), Kuiper (1954), Shoemaker (1962), Urey (1962) and Green (1966). Many authors, and E. M. Shoemaker in particular, have marshalled clear evidence showing that meteor

craters on earth—also underground nuclear explosion craters—have very close similarities to the moon's primary craters but differ in notable details from the earth's volcanic cones, craters, and calderas. Detailed analysis will not be repeated here, but the more important points may be listed summarily :

1. Well-formed primary craters on the moon range from at least 235 kilometers in diameter down to small pits of less than a centimeter. Volcanic craters and calderas on earth show no such great range in size. Calderas, the largest of earth's circular volcanic features, are seldom more than 9 miles in diameter.

Figure 9. *Crater Lake Caldera, Oregon.* The lake, six miles long and four wide, occupies the site of a former volcano's crest (Mt. Mazama) which collapsed into the molten rock below the volcano. Sloping away from the top of the cliffs at the right edge of the lake are two large U-shaped glacial valleys, beheaded by the foundering of the mountain's top. A thin sheet of pumice spread over the area by the prevailing winds extends for many miles to the northeast. Continued volcanism after Mazama's collapse built Wizard Island, a typical cinder cone with a small crater at the top. A submerged cinder cone has been discovered beneath the surface of the lake.

Photograph by Delano Photographics (Copyrighted).



2. Calderas are subsidence features. Williams (1948) proves conclusively that the caldera in which Crater Lake (Figure 9) lies was formed by the breakup and foundering of the former top of a large stratovolcano—which has been called Mount Mazama—into the hearth of molten rock that underlay the volcano. The collapse occurred soon after the emission of vast clouds of pumice and ash during a series of explosive eruptions.

Crater Lake, unlike a primary moon crater, is not surrounded by a hummocky ejecta blanket of large and small rocks blasted from the walls of the caldera. True, its gentler slopes are draped by a uniform layer of pumice particles exploded from the former site of Mount Mazama, but the pumice sheet is not pocked by secondary craters and gouges, nor is the pumice itself gathered into splashes, loops and feather-like rays. Collapse and foundering of the former mountain top, rather than blasting out from impact shock, is also proved by the U-shaped glacial valleys left beheaded along the caldera rim (see Figure 9). Before collapse the top of Mount Mazama had been covered by an ice cap which spread from the summit just as the glaciers radiate outward from the top of Mount Rainier today. These glaciers had gouged out large canyons on Mazama's flanks and deposited large morainal ridges in the lower parts of the canyons. But the U-shaped glacial valleys on Crater Lake's rim cannot now be traced upward to their source. Instead the caldera rim slices across them cleanly about in the mid-part of their former course; their upper parts, and the mountain top which fed them, have sunk beneath the level of the present Crater Lake. Striations and gouges left by the ice as it slid and scraped downhill provide clear evidence that large glaciers once filled these U-shaped valleys to the brim. Such glaciers must have headed far upslope; they could not have formed and flowed outward (instead of inward toward the lake) without a large gathering ground for the ice and snow. When Mazama's top collapsed these snowfields and glacier heads were lost, and the hole in which Crater Lake now lies was formed.

3. The distribution of primary craters on the moon appears to be completely haphazard, as would be expected from meteor impacts. Earth volcanoes, on the other hand, are commonly aligned along fractures, folds, or other zones of structural weakness. They generally occur in chains, closely related to mountain uplifts as in the Cascade Mountains of Oregon.

4. The walls of a volcanic caldera or crater are cleanly cut off, and do not show the shock features characteristic of impact craters:

"Except for normal faults, the rocks are rarely deformed in any way that can be related to the opening of the crater. The rocks on the walls of an impact crater, on the other hand, are invariably deformed. . . . The ejecta on the rim of an impact crater . . . except for a minor increment of meteoric material, are composed solely of rock excavated from the space occupied by the original crater. . . . The fragments are generally stacked in inverted order from their original position before ejection. . . . There is no limit to the size of individual fragments—the larger the crater the larger are the biggest pieces thrown out." (Shoemaker, 1962, p. 322).

NEWBERRY CALDERA, OREGON AND RIES IMPACT BASIN, GERMANY. A brief comparison of a large caldera (Newberry, in Oregon) with a considerably larger impact crater (Ries Kettle, in Germany) will bring out some additional features of importance:

Mount Newberry is a large shield volcano, about 30 miles in diameter, which rises above the plateau of central Oregon south-east of Bend. In a late stage of the volcanic activity the summit collapsed, forming a large caldera about 7 miles long and 5 miles wide (Figures 10 and 11). Dimensions are only approximate because subsidence of the top of the volcano did not occur along one continuous and geometrically perfect ring fracture, but along a number of arcuate fissures each of which dies out in a few miles and then is continued by another arcuate fracture offset from the first. Other fractures, straight instead of arcuate, also have contributed to the subsidence. Most of them trend northwest-southeast. Along parts of the rim arcuate breaks are nested one behind the other, so that parts of the caldera wall rise in a series of steps.

Simultaneously with collapse, and following it, renewed volcanic activity contributed to the complexity of the summit caldera. At first only one "crater lake" more than 5 miles across occupied the center of the collapse basin. Eventually it was segmented into two lakes, the present Paulina Lake on the west and East Lake to the east, by eruptive activity which built a complex natural dam of volcanic rocks across the middle of the ancestral lake (Figures 10 and 11). Construction of this dam started with outflow of basaltic lava into the bottom of the crater lake. Over a considerable period of time such eruptions built up a broad underwater analog of a cinder cone (geologists call such cones tuff rings) beneath the waters of the lake. As the fluid lava came into contact with water it was fragmented and chilled, chiefly into small droplets of volcanic glass, most of which are less than a centimeter in diameter. These were flushed outward from the vent in surges of steam and hot water, and accumulated in a broad flat cone of loose glass particles. Wave action in the lake

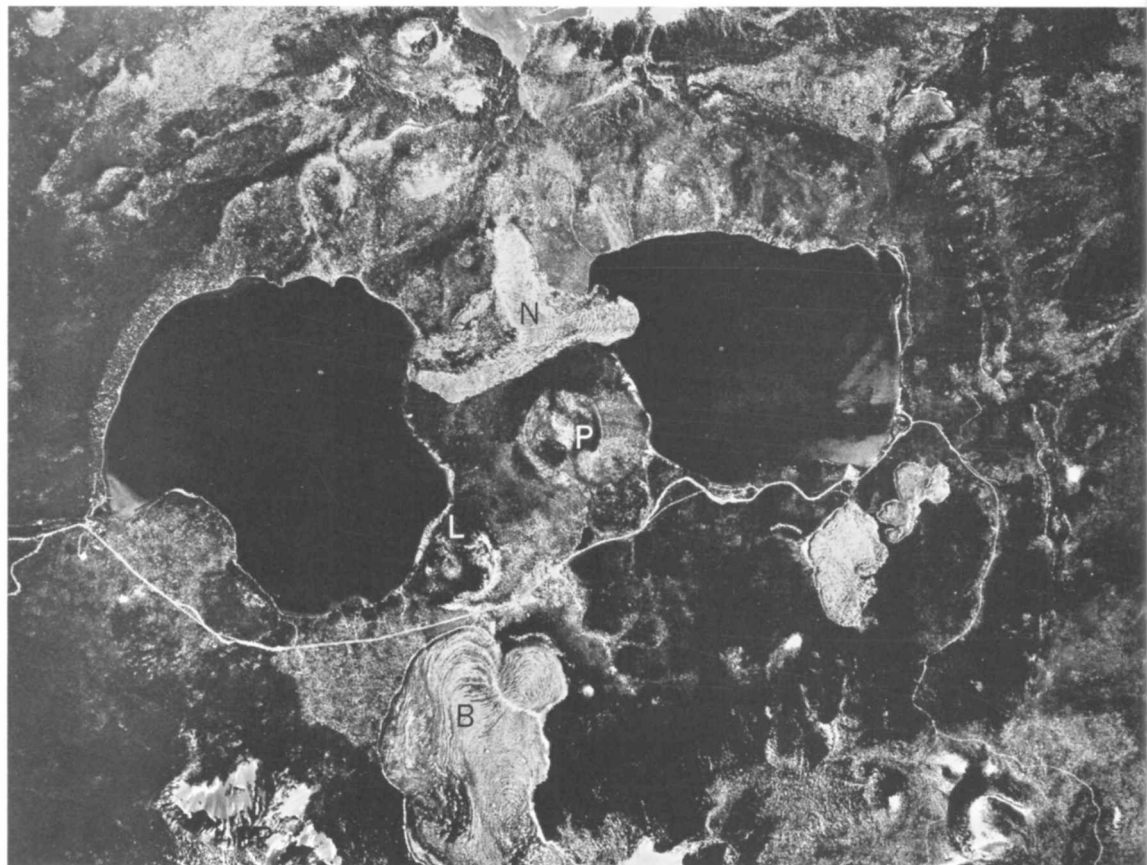


Figure 10



Figure 11

also helped to spread and stratify the material. Slowly this underwater cone grew, filling most of the central part of the lake, and finally emerging above the surface. The central vent, inactive for more than 2,000 years, is now represented by a shallow but broad crater on the southeast shore of Paulina lake. The visible part of the cone is composed of gray to yellowish rock (palagonite, an altered basalt glass). Because it rises only 200 feet above the lake, whereas its younger sister to the northwest (Pumice Cone) towers more than 750 feet above lake level, this crater has been named Little Crater, but if we could measure its total bulk under water it would probably prove to be considerably larger than Pumice Cone.

At roughly the same time Little Crater was building up under water, basaltic eruptions were occurring on other parts of the Newberry volcano, both within the caldera and, particularly, far away from it, well down on the sides of the Newberry shield. Dozens of extensive lava flows of basalt of about this same age poured from many fissures on the flanks of the volcano. Cinder cones grew atop these fissures as well. The broad Newberry shield is decorated by more than 100 cinder cones, most of which were built during the late stages of the volcano's growth (Williams, 1935). Within the caldera additional basaltic eruptions, more explosive in character, were also taking place. Much of their record is lost because the rocks have been buried under later accumulations of pumice and obsidian. Some that are considerably younger than Little Crater, however, have left interesting deposits. High on the east caldera wall above East Lake are two crescentic fissures parallel with the nearby wall of the caldera. Through these fissures frothed basalt lava. As the bubbles from pent-up gases sprouted and grew, the lava fountained upward and on reaching the surface exploded into clots of bubbly scoria. This produced a whole series of small vents with thin rims of

Figure 10. *Mt. Newberry Caldera, Oregon*, a vertical view from the air. The south and east (bottom and right) walls of the caldera are in a deep shadow; the irregular north wall is in sunlight. Paulina Lake is at the left, East Lake to the right. They are separated by two mid-caldera volcanoes, the high Pumice Cone (P) and the lower Little Crater (L) whose main bulk is beneath lake-level. Big Obsidian flow (B) is in the foreground, North Obsidian flow (N) forks into two prongs where blocked by Pumice Cone. Paulina Peak (PP), the highest point on the caldera rim, is at the lower left corner. The area shown is 4.7 by 4 miles. Additional details are seen in Figure 11 and described in the text.

Army Map Service photograph.

Figure 11. *Oblique View into Mt. Newberry Caldera*, looking northeast from above Paulina Peak. Lettered features are the same as in Figure 10. Beyond the caldera the gently sloping flanks of the Newberry shield, interrupted by many cinder cones, slopes off to the horizon.

Photograph by Delano Photographics (Copyrighted).

lava spatter, neatly lined up along the fissures. Similar fountaining of basalt scoria occurred through a northwest-trending fissure that cuts the north wall of the caldera near the northwest corner of East Lake. Basalt surging through this fissure blasted off small chips of rhyolite obsidian exposed on its walls, heating them so hot that most of them melted or at least softened enough to froth into pumice. All transitions occur from bits of obsidian heated only enough to cause slight bubbling of thin sliver edges, to pieces half frothed, and to others so greatly heated that they were converted entirely into pumice.

Rhyolitic volcanic activity did alternate with basaltic, however. The rhyolites of Paulina Peak and those exposed in the bluffs on the north side of East Lake are older than the Little Crater underwater volcano. They are cut by some of the faults that form the caldera rim. Younger than these, and younger than the Little Crater volcano, are a series of tree-covered obsidian domes and flows in the area southeast of East Lake. Somewhat later, but possibly nearly contemporaneous with these, was the building of the high central Pumice Cone by strongly explosive eruptions of frothy shreds of rhyolite pumice and broken bubble walls (glass shards). Growth of this pumice cone completed the dam, dividing the former single crater lake into Paulina and East lakes. Pumice particles and glass shards winnowed out of the eruption clouds by the wind now cover the surrounding country for miles, but the thickest ash fall (up to 20 feet thick) lies to the east—downwind for the prevailing storms of this area.

Because of its wide extent this ash fall is an excellent marker to date the rocks above and below it. It drapes over some cinder cones on the flanks of the Newberry shield, giving them the deceptive appearance of pumice cones of rhyolite ash instead of basalt scoria. Other basalt cinder cones are not dusted over by the ash fall, and hence are younger. Trees killed and charred by this fall of pumice have been dated by radiocarbon methods. They record that the building of Pumice Cone occurred roughly 2,000 years ago. Pumice Cone now appears to be dead, the last stages of its activity were the rise of two small sticky domes of blocky obsidian. One barely pokes through the debris at the bottom of the crater, the other punched upward through the southern rim of the cone in a rounded mass about 400 feet across and 60 feet high.

Younger than Pumice Cone are several flows of lustrous black obsidian. The largest of these, Big Obsidian flow (see Figures 10 and 11), overtopped a circular vent about one-fourth mile north of a curving re-entrant in the south wall of the caldera. From this relatively high ground the sticky lava crept north for nearly



Figure 12. *Astronaut Walter Cunningham Climbs Big Obsidian Flow, testing space-suit design and equipment.*

Photograph by National Aeronautics and Space Administration (NASA).

two miles as a lobate mass festooned with broken and angular blocks disposed into long ridges and swales by combined flow and shear in the semi-solid mass. It pushed up to the south side of Little Crater and finally came to rest with a steep flow front over 60 feet high (Figure 12).

Another large obsidian flow oozed from a hole in the north wall of the caldera and flowed south until it encountered the north slope of Pumice Cone. It then split into two prongs, one of which flowed into East Lake, the other into Paulina Lake (see Figures 10 and 11). Smaller obsidian flows of slightly older age are also visible. On the photographs (Figures 10 and 11) they appear as light-colored lobate patches between the caldera wall and the southeast corner of East Lake.

Mount Newberry volcano is not active now but hot springs pouring into East Lake and others rising at other points on the shield, plus the presence of basalt flows and cinder cones not covered with pumice and hence less than 2,000 years old, make it doubtful whether the volcanic fires at depth have completely died.

Because of the wide variety of its volcanic features Newberry volcano has, since 1964, been used as one of the training grounds where United States astronauts (Figure 12) can get instruction

in volcanic geology, especially on the difference between volcanic calderas and craters produced by meteorite impact. Also the various kinds of unmodified lava surfaces give opportunity to simulate some of the problems regarding bearing strength and vehicle mobility that might be found on the moon. Particularly significant were different kinds of lava surfaces that have been buried under a few inches to a few feet of pumice shreds and ash from Pumice Cone in Newberry, or the pumice from Crater Lake (Mount Mazama). It had been held by some that the highly porous, spongy structure of the moon's surface (as determined by its uniform scattering of light and its thermal insulation characteristics) meant that the surface of the moon is too dusty and fragile to support spaceships. Astronauts who visited central Oregon learned—even before the landings of Luna 9 and Surveyor—what many central Oregonians already knew: plains covered with dust and frothy bits of pumice have plenty of strength to support the heaviest vehicles or buildings but do not furnish good traction for the spinning wheels of automobiles with small tires.

Very different from Newberry Caldera is the impact crater of the Ries basin in Germany. It is 18 miles in diameter, three times the size of Newberry. Other differences arise largely from its greater age. The Ries impact occurred in middle Tertiary time, probably 20 million years or more ago. Therefore erosion and weathering have ravaged the surface and greatly changed the original topography. Also much of its central part was later buried under lake beds deposited on the crater floor. The really striking differences, however, are in the nature of the rocks in the two areas. Some of the hills that rise around the rim of the Ries basin are composed chiefly of ancient rocks of non-volcanic origin—totally unlike the lava flows and ash-fall deposits of a volcanic region such as Newberry shield and caldera. Moreover, these old crystalline rocks have been intensely deformed. They are shattered into breccias, which have themselves been sliced by faults and thrust outward from the crater. South of the rim are breccias composed of sedimentary rocks, chiefly limestone, which rest on undeformed sedimentary rocks below (Shoemaker, 1962, p. 311-314). These sedimentary rocks are of Jurassic age, older than the impact crater, and much older than the lake sediments that cover the crater floor.

The most interesting rock in the Ries basin is a breccia composed chiefly of all varieties of the pre-basin wall rocks. The fragments in this breccia are intensely shattered, shocked and partly melted. Mingled with them are irregular pods of variegated

glass, glass breccias and odd-shaped glass bombs. Although early geologists considered this glass to be of volcanic origin, it has little in common with obsidian flows or pumice deposits. The shock-metamorphosed nature of the wall rock fragments that are invariably enclosed in the glass, the inhomogeneity of the glass itself, and the structural relations of the various kinds of breccias to thrust slices and to both deformed and undeformed rocks in and near the crater wall—all these argue for the production of the glass by partial melting of the rocks under the shock and heat associated with meteorite impact. Such masses of partly melted and highly sintered glass breccias have been found by drilling into the floors of impact craters in Canada. The glass collected in shallow puddles on the deepest parts of the crater floor beneath the filling of breccia.

From melted and sintered sedimentary rocks at Meteor Crater in Arizona, a high-pressure polymorph of silica, coesite, was first identified as a naturally occurring substance (Chao, Shoemaker, and Madsen, 1960). Coesite had previously been made artificially in the laboratory during high-pressure studies of silica. Chao searched for and found coesite in specimens of the glass breccia from the Ries Kettle (Shoemaker and Chao, 1960). This discovery strongly confirms origin by impact for the breccias of the Ries basin. Meteorite impact can supply the pressure and shock demanded for the production of coesite, whereas volcanic activity cannot. Coesite is now regarded as an index mineral for the recognition of meteorite impacts (Pecora, 1960).

Certainly there are almost no similarities in rock structure, mineralogy, and field geology between impact craters such as the Ries Basin or Meteor Crater, and volcanic calderas such as Oregon's Newberry and Mount Mazama (Crater Lake). As more is being learned about shock metamorphism at impact craters, detailed mineralogic work on the shocked and partly melted products appears to be one of the most valuable criteria for recognizing meteorite impact. Many different minerals develop characteristic microscopic features under shock. Moreover, at Meteor Crater, and in and near other impact craters on earth, the soil and rocks contain tiny spherules of iron. These must come from the melted and vaporized parts of the meteorite itself. Thus the distinction between meteor and volcanic craters does not appear to pose an insoluble problem for the first astronaut who lands on the moon.

Maria occupy about one-third of that part of the moon visible from earth. Photographs taken from Russia's probe as it passed the far side of the moon show that maria cover far less area on the hemisphere hidden from earth.

Moon Maria

Large maria, such as Mare Imbrium (Sea of Rains) and Oceanus Procellarum (Ocean of Storms), are plainly visible to the eye at full moon. Because of the lower reflectivity of the mare surfaces, they show up as shadowy patches on the moon's otherwise brightly illuminated disk. Through the telescope (Figures 1, 2 and 6) the maria appear as monotonous dark-colored plains diversified by sparsely scattered craters, isolated island-like mountains, irregular wrinkle ridges, and the narrow fault-troughs which astronomers call rilles (Figure 8). Thus, when observed through the telescope, the maria contrast strongly with the terrae whose bright highlands are revealed as an intricate maze of giant craters so thickly crowded that the younger craters have partially demolished or completely obliterated older ones.

The maria are lower in elevation than the cratered terrae, and all mare surfaces appear to have been built up very close to a common level analogous to sea level on earth. Many craters along the mare "shoreline," or even at some distance inland, appear to have been flooded by the mare filling to the same level as the adjacent mare surface (Figures 2, 5 and 6). Moreover, the mare shorelines indent and partially bury both craters and mountain valleys along their edges, just as the ocean forms an irregular shoreline against the highlands of Scotland or the mountains of British Columbia. This inundation of craters and other topographic features along mare shorelines proves that the filling of the maria is younger than the landmass that makes up the cratered highlands. Yet some craters are younger than the mare which surrounds them, for they deeply indent the mare surface and spread ejecta blankets upon it. Moreover a few of the craters in the terrae are also younger than the maria; for example, the rays that spread outward from Tycho streak across the surfaces of nearly all the maria, reaching distances of more than 1,000 miles from Tycho.

Two closely related questions regarding the maria have aroused much speculation among students of the moon's morphology: What is the origin of the mare basins? What is the nature of the material that fills the mare basins to a common level?

HOW WERE THE MARE BASINS FORMED? Several maria, for example, Mare Imbrium (Sea of Rains), Mare Crisium (Sea of Crises) and Mare Humorum (Sea of Moisture), have nearly circular outlines and are bordered along all or part of their perimeters by ragged mountain ranges that resemble the ejecta blankets which surround major primary craters. Ridges and fault-trough valleys in these peripheral mountains extend radially outward from the edges of the mare basins. Some of the larger straight-

walled valleys—for example, the spectacular Alpine valley (Figure 6) which crosses the raised rim of the northeast side of Mare Imbrium—have flat floors apparently at the same level and co-existent with the adjacent mare surface.

The circular outlines, peripheral mountains, and radial features suggest that at least these maria may be giant impact craters, many times larger than Clavius, Deslandres, and Grimaldi—three of the largest craters of the Terrae. This suggestion is strengthened by the presence of a more or less gradational sequence in size from Mare Imbrium, the largest of the circular maria, through successively smaller circular maria such as Mare Crisium, Mare Nectaris (Sea of Nectar), Sinus Iridium (Bay of Rainbows) and Lacus Mortis (Lake of Death). The Lake of Death covers only 3 to 4 times as much area as Crater Plato, or Crater Archimedes, both of which are old craters that have been partially drowned beneath mare filling coextensive in level with the surface of Mare Imbrium. (See map in pocket, and Figure 2).

Several maria do not have circular outlines, notably the large and irregular Oceanus Procellarum (Ocean of Storms) and the Mare Nubium (Sea of Clouds). The mare filling of these basins, however, may have inundated a cluster of large overlapping impact basins and then have spilled beyond their rims in a shallow flood across low-lying parts of the adjacent terrae.

The case for the impact origin of Mare Imbrium has been succinctly presented by Shoemaker (1964, p. 40-45). He considers Imbrium to be an impact crater, 500 miles in diameter, whose crater walls slumped inward and were largely overtopped by the maria filling—thus extending the total width of the mare surface to about 700 miles. Around the Imbrium Basin is “a great regional deposit that is coarsely hummocky at the crest of the mountain ring and smooth farther from the center of the basin,” and that decreases in thickness with distance from the Imbrium Basin. An infalling object large enough to create the Imbrium Basin must have been several tens of miles in diameter. Baldwin (1965, p. 78-79) calculated that the Imbrium Basin was formed by a low-velocity planetesimal 100 miles in diameter moving about 2 miles per second as it plunged into the moon. Forward motion of the planetesimal was stopped in 20 seconds at a depth of 10 to 15 miles. The huge crater, 400-500 miles in diameter was excavated chiefly by shock waves racing up through the ground at supersonic speeds, and partly by the explosive gas ball generated on impact. Baldwin gives a graphic description of how jets of pulverized rock ejected from the crater may have poured through radial fissures on the rim of the Imbrium basin, eroding them into the broad and ragged valleys that now extend radially

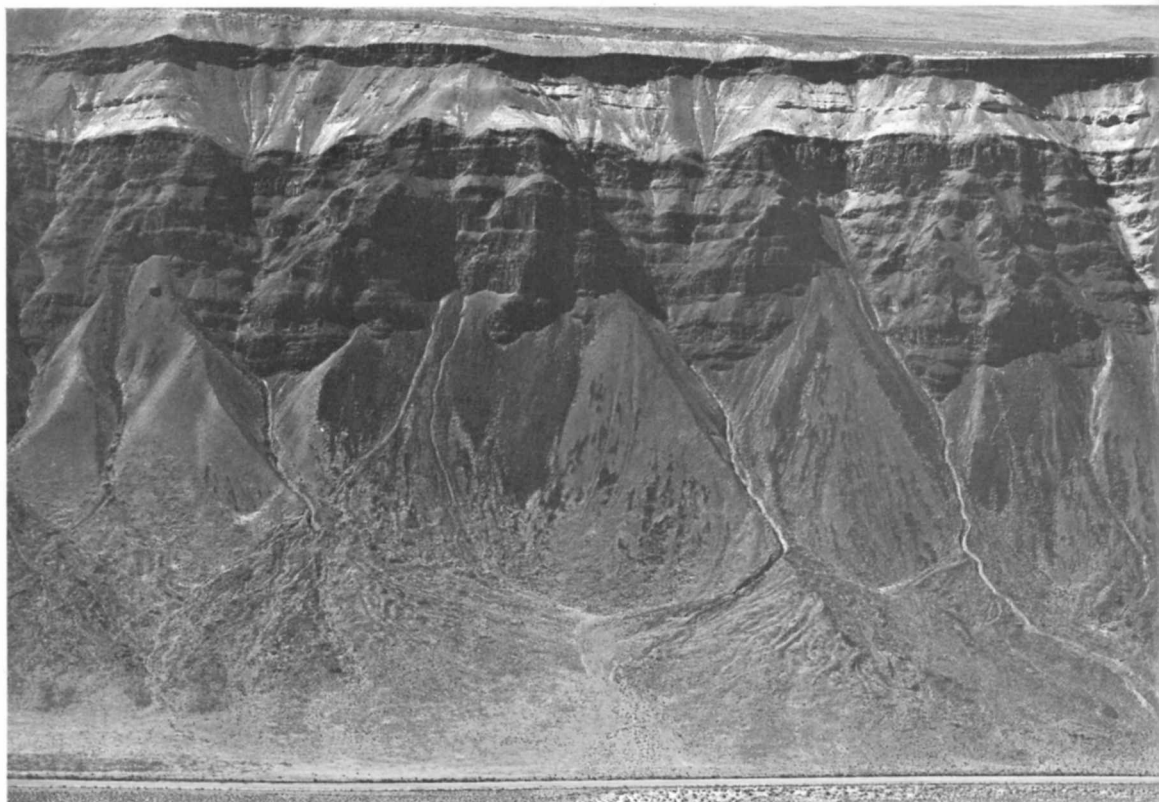


Figure 13. *Flows of Columbia River Basalt*, north face of the Saddle Mountains, south-central Washington. Individual basalt flows are from 30 to more than 150 feet thick. The cliff top rises 1500 feet above the road in the foreground. Light-colored strata near the top of the cliff are water-laid sediments and ash falls, deposited on the basalt plain and then overridden by new flows of basalt.

Photograph from the P.U.D. of Grant County, Washington.

outward through the ejecta blanket heaped on Imbrium's rim. The Imbrium impact was certainly the most dramatic of the many catastrophic events that have left scars on the pock-marked face of the moon.

WHAT FILLS THE MARIA? Embayed shorelines and the filling of isolated craters and fault troughs to the same level as the mare surface, are readily explained if we assume that the maria have been inundated by some kind of fluid such as the common basalt lava on earth, which welled up from the moon's interior through numerous fissures and then spread and ponded in the mare basins and the deeper craters. Such flows of lava would leave a nearly flat surface on solidification.

The great flood basalts known as the Columbia River Basalt (Waters, 1961), which covered most of northeastern Oregon, eastern Washington (Figure 13), and adjacent parts of Idaho during the interval from 20 million to 13 million years ago have solidified to form plains that resemble the maria in topographic

form, and are also roughly comparable to Mare Imbrium in area. The Columbia River basalts rose to the surface from many fissures, and spread into and filled a subsiding basin. The basalts developed an embayed, irregular "shoreline" that conforms to the topography along the rim of the basin, inundating the valleys and other low points to a common level. On the east, where the shoreline of the lava floods banked against a mountainous region, the basaltic flows, each 30 to 260 feet thick, piled up flow on top of flow until they overtopped mountain peaks some of which were over 4,000 feet high. The flows spread still farther eastward, spilled through gaps in the mountains and filled large intermontane valleys, producing great embayments of basalt along the eastern margin of the lava sea. Two of the largest embayments are the Grangeville plateau between the Salmon and Clearwater Rivers in Idaho, and the plain covered by wheatland and timber between Tekoa, Washington and Clarkia, Idaho. Steptoe Butte, an isolated mountain of erosion-resistant quartzite, rises like an island above the basalt floods, just as Mt. Piton (Figure 2) is surrounded, but not overwhelmed, by the filling of Mare Imbrium. After the volcanism had ceased, the Columbia and Snake rivers cut through the great piles of lava and exposed the old buried mountainous topography along their canyon walls.

Minor features of the maria surfaces also suggest that lava flows are present. Strom (1965, p. 29-33) has described and figured lobate ridges and tongues in the central part of Mare Imbrium which have the characteristic forms and steep fronts of basalt flows on earth. Kuiper (1965, p. 70-71) and Strom have also identified dikes (fissure fillings of congealed lava, the kind of features that now occupy the conduits through which the Columbia River basalts rose to the surface) on the Ranger VII photographs of Mare Cognitum.

So close are the analogies between the mare fillings and the great expanses of flood basalts on earth that many scientists accept the theory that the maria are underlain chiefly by basaltic lava. On the photogeologic map of the moon prepared by Mason and Hackman (1962) the maria rocks are described as "Probable lava flows composed of thick sheets of basalt or similar rocks." In general this practice has been followed on most of the lunar geologic maps prepared by the United States Geological Survey and other agencies.

ARE THERE ASH FALLS AND ASH FLOWS ON THE MOON? On earth many lavas are so charged with pent-up gases (chiefly water vapor) that when they rise to the earth's surface they bubble like porridge, froth vigorously like a newly-opened bottle of champagne, or even explode violently as the walls of the bubbles break

and fly apart. Then the liquid rock between the bubbles goes flying outward and quickly cools into tiny slivers of volcanic glass.

If frothing is mild and the lava is of low viscosity, like basalt, many steam cavities sprout within the lava and grow into bubbles from 0.1 to 1 centimeter in diameter. These bubbles rise and accumulate in the upper part of the flow, trapped beneath a thin skin of solidified rock. The bubbly material is carried along with the flowing lava until loss of heat causes the entire flow top to cool and harden into the bubble-filled rock called scoria. If the frothing is slightly more violent, the lava is blown into pasty clots of scoria which fly through the air and accumulate around the volcanic vents, building up cinder cones, like those so common near Bend and Hood River in Oregon. But if the frothing is violently explosive, and the molten rock is a very sticky variety, such as rhyolite or dacite, great seething eruption clouds composed of shreds of pumice and the shattered walls of broken bubbles shoot violently out of the volcano's top. Such eruption clouds may billow upward into the atmosphere for thousands of feet, sending out turbulent surges that rise and fall, accompanied by lightning flashes between different parts of the churning eruption cloud. Eventually, however, gravity overcomes the upward explosive surge and the frothy bits of pumice and broken bubble walls—now hardened into sharp-cornered slivers of hot volcanic glass—come tumbling back to the earth's surface. If the explosion is of short duration and the quantity of ejected material is small, the resultant deposit, on falling to the ground, will drape over the hills and valleys as a thin sheet of volcanic ash—an ash-fall deposit.

If, however, hot pumice and ash keeps blasting out of the volcano throat for a long period of time the accumulation of falling debris on the slopes of the volcano may pile up until it becomes unstable. Then it begins to cascade outward under its own weight, and races downhill as a hot flow of pyroclastic particles encased in a matrix of steam and other gases.¹ Such rapidly moving mixtures

¹ Needless to say, it destroys everything in its path, as the world learned when the 30,000 inhabitants of St. Pierre on the island of Martinique were burned to death in 1903. If the area had been inhabited, an even greater disaster would have occurred in 1912 when an ash flow burst from Novorupta, a vent near the base of Mt. Katmai in Alaska, and buried the floor of a broad valley for more than 20 miles.

of solid and vapor—called ash flows—spread out over the ground in a violent flood of particles buoyed up and made mobile by the constant emission of gas from each hot fragment. Thus an ash flow travels at great speed because each particle is still emitting gas, and these gas hulls surrounding each particle form an almost frictionless medium in which the sharp-edged bubble walls of glass and the distended pieces of hot pumice are carried along much like the droplets of water in clouds or fog are wafted along by the wind.

Ash flows do not drape over high and low areas in the manner of ash falls. Instead they flow like a river, their path conforming to the topography, just like that of a basalt flow. They spread across plains, leaving high areas isolated as islands above their surface, and they embay mountainous topography much like flood basalts. On coming to rest they cool and compact as the interstitial steam and other gases escape upward through porous hot ash and mingle with the air above. Some ash flows are so hot after coming to rest that the glass shards and pumice fragments are still soft enough to weld together into coherent rock (ignimbrite) which superficially resembles lava flows.

Many areas in Oregon are underlain by ignimbrites. They fill a broad valley west of Paulina, are well developed in the hills both north and south of Burns, also along Deschutes River near Tumulo and Warm Springs, and in many other places. Older ignimbrites, whose original glass splinters and pumice have mostly recrystallized into new minerals with the passage of time and the changes caused by burial in the earth's crust, are widespread in central and southeastern Oregon. From hard yellow to brownish ledges of these altered ignimbrites near Antelope, Ashwood, Prineville and Madras come the famous silica-rich "thunder eggs," the state rock of Oregon.

Are there pyroclastic volcanic deposits such as ash falls and ignimbrites on the moon? It appears likely, for there are good reasons to assume that even basaltic lava flows on the moon would bubble more violently than on earth. On the moon basalt lava would weigh only one-sixth as much as the same lava on earth. Pent up gases could froth into bubbles more readily in moon lava, and once the bubbles had formed they would expand rapidly and explode more violently than in similar lava on earth. Indeed it seems probable that basalt lava flows, which seldom show bubbly tops to depths of more than 15 feet on earth, might become completely inflated into froth flows of scoria on the moon. This may account for the fact that the probable lava flows which Strom described from near the center of Mare Imbrium show flow fronts

up to more than 300 feet high whereas basalt flows on earth nearly always have flow fronts less than 50 feet high.

For the same reasons, if the moon does have volcanoes we should expect ashfalls and ash flows to be developed from molten lava even more commonly than on earth. Frothy lava flows, ash flows and ash falls are, then, quite reasonable materials to be expected as a part of the filling of the maria. Much of the surface visible from Luna 9, and one of the loose blocks photographed from the Surveyor spaceship, closely resemble pictures of frothy lava from earth. In the following section I shall review additional evidence that indicates the probable presence of volcanoes on the moon. Real proof of volcanic rocks on the moon, however, must await the return of the first men to visit its surface.

Volcanoes on the Moon

OBSERVATIONS OF POSSIBLE VOLCANIC ERUPTIONS. For centuries astronomers have hoped to see visual evidence of meteor impacts, volcanic activity, or other catastrophic disturbances of the moon's surface. Many "events" have been reported, but because telescopic observation with clear resolution is limited to objects more than a half kilometer in diameter the interpretation of the meaning of these events is often ambiguous. Burley and Middlehurst (1966) have compiled from the literature 159 records of lunar activity of one kind or another which they consider to be reliable and well-dated. The principal kinds of observations noted were temporary bright spots which appeared or faded on the part of the moon in shadow, changes in the brightness of certain craters, and features described as veils, obscurations, and clouds of dust, gas or volcanic ash. There are many possible causes of change in brightness of the lunar surface besides volcanic activity or meteor impact. For example, luminescence of some parts of the surface may be produced by excitation from solar flares (Kopal and Rackman, 1963); also non-uniform cooling of different rocks when shadows pass over the surface of the moon may result in the appearance and fading of bright spots against the black background of the lunar night (Shorthill and Saari, 1965). Kozyrev (1962, 1963), however, has given reasonably convincing evidence of reddish clouds of volcanic origin formed on or near the central peak of the large impact crater Alphonsus. Similar features have been seen in Aristarchus (Greenacre, 1963, 1965).

Burley and Middlehurst (1966, p. 1010) showed that the greatest number of well-dated lunar "events" occurred when tidal stresses on the moon were greatest (at perigee and apogee of the

moon's orbit). Alternate tidal squeezing and stretching might have a triggering effect on volcanic activity. They conclude: "The nature of a mechanism which might produce a bright spot in the dark portion of the moon is not at present clear, but internal causes seem likely and lunar volcanism is suspected."

SHIELD VOLCANOES, CALDERAS, AND VOLCANIC COMPLEXES ON THE MOON. We have shown that the maria have many characteristics in common with the great flood basalts on earth. Present on the moon, as well, are certain morphologic features that bear a close resemblance to the shield volcanoes and strato-volcanoes which dominate the entire length of the higher parts of the Cascade Range in Oregon. North of the crater Hortensius are a group of dome-like mountains with small craters at their summits (Shoemaker, 1962). Their gentle slopes and cratered tops recall the small shield volcanoes such as Larch Mountain east of Portland, Round Mountain near Madras and the somewhat steeper-sided Mount Bachelor west of Bend. Shield volcanoes are built almost entirely of coalescing and overlapping tongue-like lava flows, some erupted through the central crater, but many breaking forth from radial dikes well down on the flanks of the cone.

Other steep-sided isolated mountains on the moon resemble strato-volcanoes such as Mount St. Helens and Olallie Butte. So far as I know, large and complex shield volcanoes with collapse calderas in their summits, such as Mauna Loa in Hawaii, or Mount Newberry in Oregon have not been definitely recognized on the moon, although Moore (1964) records a possible volcanic complex in the Harbinger Mountains on the moon which contains caldera-like forms and complexly overlapping domes of apparently volcanic origin.

RILLE CRATERS AND CHAIN CRATERS OF THE MAAR-TYPE. Many craters, generally more than a mile in diameter and of uniform size, are lined up along certain rilles on the moon's surface (Figures 14 and 15). Somewhat smaller craters are so closely packed along straight or gently curving lines on some parts of the moon that they partially merge with one another (Figures 15 and 16). These rille craters and chain craters cannot be due to meteor impact, for there is no mechanism that could guide infalling bodies into neat rows with uniform spacing. Instead the evidence is entirely convincing that these craters have been formed by the explosive uprush of pent-up gases escaping from the lunar interior. They have made their way to the surface along great fissures in the moon's crust, and along the faults that define the rilles.

46

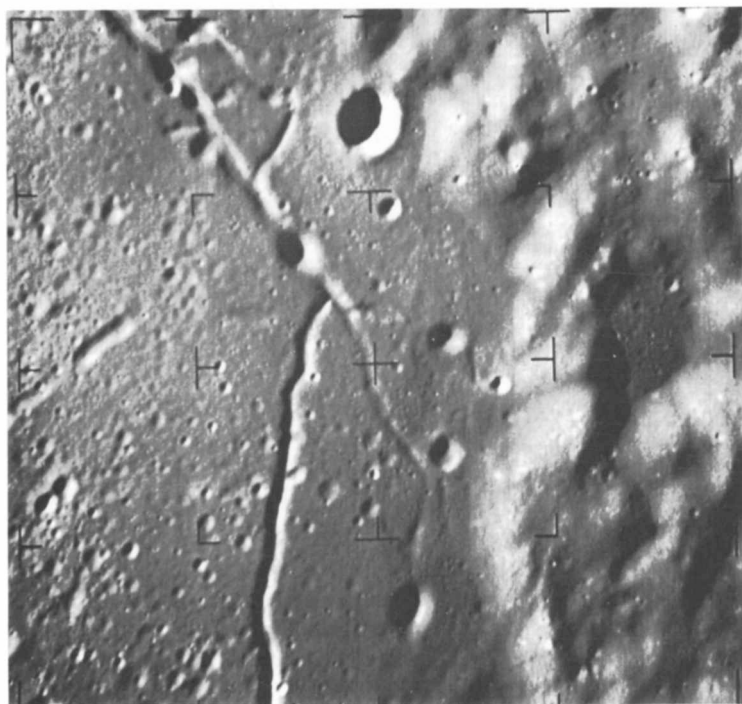


Figure 14

Figure 15

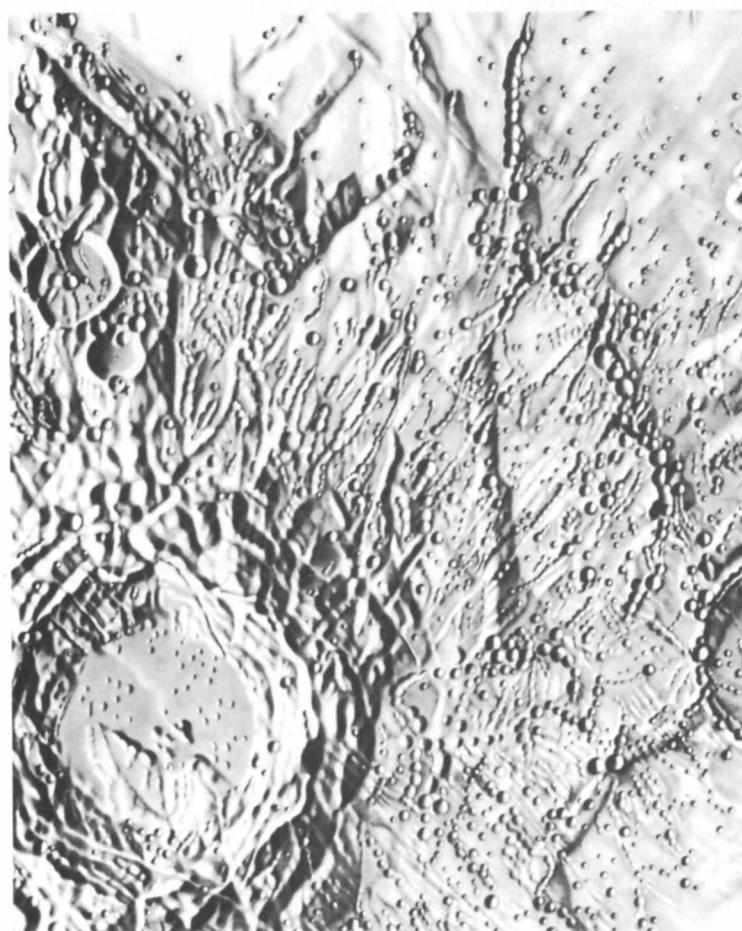




Figure 16

Figure 14. *Rilles on the Floor of Crater Alphonsus.* Several small craters with dark halos of ejecta lie along the northwest-trending rille. The other prominent rille is sharper and craterless. Another small, indistinct rille near the west (left) edge of the photo is made up chiefly of coalescing craters. Alphonsus' east rim and ejecta blanket occupy the right fourth of the photograph. Area shown is 21 miles by 18 miles.

Photograph from Ranger IX spacecraft, 107 miles above the lunar surface. Jet Propulsion Laboratory.

Figure 15. *Map of Crater Copernicus (lower left) and part of its ejecta blanket to the northeast.* Note the abundant rille craters and chain craters. Area shown is 135 miles by 130 miles.

From United States Air Force Lunar Chart (LAC 58).

Figure 16. *Craters and Rilles on the Floor of Alphonsus.* The largest crater is 1.6 miles in diameter. A shallow rille extends northward from it. Another rille, near the right edge, consists of a string of chain craters. Note that most craters have "softened" or "subdued" outlines and inconspicuous rims; a few are sharply cup-shaped and are surrounded by light-colored ejecta. Area shown is 5.8 miles by 5.3 miles.

Photograph from Ranger IX, 12.2 miles above the lunar surface. Jet Propulsion Laboratory.



Figure 17. *Cinder Cones Aligned along a Fissure*, Cascade Mountains, central Oregon. Snowcapped Mount Jefferson volcano rises in the distance.

State of Oregon Department of Geology and Mineral Industries photograph.

Figure 18. *Hole in the Ground*, a maar-type volcanic crater in central Oregon. The crater is 5,000 feet from rim to rim and 425 feet deep.

Photograph by Delano Photographics. (Copyrighted)

Figure 19. *Meteor Crater, Arizona*. This crater, formed by meteorite impact, is 4,000 feet from rim to rim and 600 feet deep, a little smaller but deeper than Oregon's Hole in the Ground. Note the hummocky nature of the ejecta blanket, well brought out by shadows.

Photograph by John S. Shelton.



Figure 18



Figure 19

On earth, chains of volcanic cinder cones are commonly aligned on fissures (Figure 17). These have been built by the fountaining of basalt lava projected in liquid clots out of the vent, and piling up around its margin in solidified bombs and chunks of scoria. In such a cinder cone the crater is small—seldom more than 300 feet across—and the accumulation of rubbly scoria is of sufficient bulk to build up a cone from 100 feet to more than 1,000 feet in height. Pilot Butte and Lava Butte near Bend are well-known examples. Some small craters on the moon resemble these, but most of the chain craters are much larger and deeper and the ejecta piled up around their rims is insignificant in volume. The moon craters appear to have been formed by violent outrush of gases carrying only a little liquid or solid material, but emerging with sufficient violence to pluck, sandblast and core out the walls of the conduit into a large steep-sided crater.

Volcanoes of this same form are also well known on earth, but in contrast to the moon they are not nearly as abundant as the ordinary cinder cones and small shield volcanoes. On earth they are generally referred to as volcanoes of the maar-type, from the name applied to the lake-filled craters of the Eifel volcanic area of Germany. Most maars in the Eifel are of smaller size than the rille craters of the moon. Maars occur in many places on earth, including excellent examples in Oregon. Twin Lakes, located on the east side of Deschutes River between Crane Prairie and Wickiup Reservoirs, lie on a pumice plain east of the Cascade crest in central Oregon. They are two smoothly circular lakes each about one-half mile in diameter. Along the same north-south line that passes through them are additional shallow depressions, now almost filled with lake sediments and ash falls. They closely resemble a line of chain craters on the moon.

Maar craters from many parts of the earth have been interpreted as forming when ascending molten rock comes in contact with water-soaked sediments or with ground water which has poured into the volcanic conduit. Jets of steam produced at the lava-water interface burst explosively to the surface, drilling out any weak spot along the fracture. The steam jets are able to blast deep cone-shaped craters, largely by prying into the many minor rock fractures of the conduit walls and plucking away the loose blocks of rock. Some blocks are blown out of the crater and accumulate as a thin ejecta blanket; larger blocks tumble downward into the frothing magma below. Thus in the breccia that forms the crater filling of most maars one can find blocks that have been brought up from the depths far below the visible crater walls and also blocks that have tumbled downward from ledges near the crater rim.

Probably the most perfect maar in central Oregon is the crater called Hole in the Ground (Figure 18). It was used as a site for the field training of astronauts in 1965 and 1966. It lies at the western edge of the Christmas Lake desert, about 50 miles south of Bend. Hole in the Ground is a circular pit, 5,000 feet in diameter and 425 feet deep. The original pit was much deeper; it has been partly filled by lake deposits, ash falls and debris which has fallen or been washed down the steep inner slopes of the crater. A thin blanket of ejecta, in most places less than 100 feet thick, drapes over the crater rim and thins outward to an indefinite edge in about one mile. Clustered along the rim as part of this ejecta, are great blocks of rock 3 to 10 feet in diameter. Some of these have been rifted from the two basalt flows exposed in the walls of the crater. Other huge blocks are composed of a distinctive highly porphyritic basalt and of rhyolite and a variety of ignimbrite not found in the crater walls; they obviously have been blown up from far below the present floor of the crater. Mixed with this coarse debris in the ejecta blanket is a matrix of various sized volcanic particles ranging downward to fine silt. A crude stratification in the ejecta demonstrates that the ejecta blanket was not formed in one grand explosive event, but is the product of intermittent jets of steam bursting out of the Hole over a period of time.

Hole in the Ground is almost precisely the same size as Meteor Crater in Arizona, but here the similarity ends. Meteor Crater has a distinctly hummocky ejecta blanket composed of shocked and partially melted rock (Figure 19). Although separated into distinct chunks, the broken and shattered rocks in Meteor Crater's ejecta blanket do not show a new stratification; instead they preserve the structures of the rocks from which they were derived but are piled up in an inverted order to the way these rocks occur on the crater walls. Thus rocks from the deepest part of the crater are found at the top of the ejecta blanket and those exposed just below the crater rim are the blocks in the lowest part of the ejecta blanket. By contrast, at Hole in the Ground each layer of the ejecta blanket contains a wide mixture of rock varieties from all levels in the stratigraphic succession. Rocks along the walls of Meteor Crater have been thrust outward, sheared and sharply twisted. They show characteristic impact features such as sandstone blocks partly melted into frothy silica glass, and minute strain fractures pervading each unmelted grain. Some of the finer-grained rocks show impact shatter cones with their apices pointing up in the direction from which the shock waves came. Such features do not appear at Hole in the Ground.

Hole in the Ground is another maar whose development doubtless started when molten rock rose toward the surface along a fissure and encountered copious supplies of groundwater. At the time of its development a Pleistocene lake occupied the entire Christmas Lake basin; the ancient shorelines of this Lake are well developed only a mile or two east and southeast of the crater. Highly permeable basalt flows occur on the walls of Hole in the Ground and a thick succession of basalt flows and other volcanic rocks underlies the crater at depth. These rocks are capable of pouring large amounts of water into the fissure through which the molten basalt was rising. To the east from Hole in the Ground are three additional places where molten rock broke through to the surface along the trend of the same fissure. The most easterly is Fort Rock, a large tuff ring of palagonite (a rock composed of drastically chilled droplets and fragments of basalt glass which have later altered and hydrated into the yellowish-brown rock that geologists call palagonite). The tuff ring grew on the lake bottom as an underwater volcano, much as Surtsey is now growing on the ocean floor off the coast of Iceland.

We have compared the maar-like chain craters of the moon with the kind of earth maars where molten rock has come up through lakes or underground aquifers and generated huge outpourings of steam. In some maar-like craters on earth ground water can hardly have played a major role, because the rocks in which the maar is formed have highly impermeable walls incapable of transmitting large amounts of water. Such maars, as Shoemaker (1962) has pointed out, are generally developed from mafic alkalic magmas of highly explosive character which contain large amounts of primary water and other volatiles dissolved in the liquid rock itself. Such violently explosive magmas should tend to blast out large maar-like craters instead of building normal lava shields or cinder cones. We have already seen that the lowered gravity on the moon would tend to make lava frothier and more explosive than on earth. This may be the basic factor that accounts for the predominance of maar-like volcanoes on the moon.

On first thought it does not seem likely that water played any part in the formation of maars on the barren parched surface of the moon. Yet this possibility is not completely incredible, as will be shown in the next section.

Permafrost on the Moon

On the earth 72 percent of the surface is covered by water, and another 3 percent lies buried beneath frozen water in the form of glacial ice. Evaporation from the ocean and other water bodies, aided by transpiration from plants, adds water vapor to the atmosphere. The winds redistribute most of it back to the earth's surface as rain and snow. Thus on earth there is a continuous recycling of water and all parts of the planet are bathed in its life-giving bounty from time to time. Even mountains in the driest deserts show abundant gullies carved by running water and the flat lands at their base are being slowly added to by deposits from the ephemeral flash floods that occasionally roar out of the gullies and washes—perhaps once or twice a year or perhaps only once in a century.

In areas with moderate rainfall (15 to 40 inches) flowing streams are permanent. Here wells drilled to shallow depth yield water to the pump. Below a certain level, called the water table, the pores, cracks and all other openings in the rocks are filled with water. This ground water seeps downward and outward toward adjacent streams and lakes but is constantly renewed by later rains. Even in the desert where replenishment comes rarely, deep wells will generally yield water which has seeped downward as far as there are openings and then stagnated in the lowest parts of the desert basin. Such water, however, may be unfit for drinking because of the high concentration of soluble salts leached from the rocks and further concentrated by the continual evaporation of the groundwater pulled up by capillarity into soils heated by the desert sun. In more humid areas these salts are continuously flushed out of the underground storage basins by recurrent rains and are ultimately brought to the oceans by rivers which receive a part of their water from underground percolation. By these processes the water is constantly circulated, at least in small amounts, to every part of the planet.

In polar regions there is a slight modification of the water cycle. Over much of the polar areas the average annual temperature is below the freezing point of water, even though the long days of summer may be warm and pleasant. Soil and rock are poor conductors of heat. The water contained in the cracks and rock pores underground remains continuously frozen in the polar regions, forming a "permafrost layer" of tightly frozen ground. During the warm summer months melting will progress downward from a few centimeters to a meter or more, but the meltwater produced cannot penetrate the frozen ground below. It stands on the surface in shallow ponds and quagmires until evaporated or refrozen. Thus the arctic tundra is almost always saturated with water. Even Barrow, Alaska, where the average rainfall is only

5 inches per year—less than that of the Mohave desert in California—lies in a swamp during the summer months.

How did the earth first acquire its water and ice? Some astronomers have held that it condensed from a primitive atmosphere during the early stages of the earth's formation. Rubey, (1951, 1955), however, has amassed a great body of evidence indicating that both the hydrosphere and the atmosphere of the earth had their origin in the volatile substances slowly released by volcanic activity over the last four billion years—the approximate time since the origin of the earth. Melted rock formed in the earth's interior and rising to the surface in volcanoes contains, in most instances, a little less than 1 percent by weight of water and small amounts of other volatiles, notably oxides of carbon, and sulphur compounds. As the molten rock melt—geologists call it magma—cools and crystallizes, either on the surface as lava flows, or beneath the surface of the ground in subterranean chambers, the water vapor, carbon dioxide and other volatiles separate from the melt and make their way upward to the surface through pores and cracks in the rock. Water vapor is the most abundant of the gases released by active volcanoes, and the earth's surface temperature variation is such that it can exist stably in three forms: vapor, liquid and solid.

It is interesting to speculate a bit about the implications of Rubey's hypothesis as applied to the moon. We have raised the strong probability that the moon's maria are underlain mainly by volcanic rocks. Moreover, the maar-like chain craters and rille craters so abundantly developed on the moon's surface are clear evidence of a de-gassing of the moon's interior. Because of the moon's lower gravity we reason that its magmas will be more frothy and explosive than comparable magmas that come to earth's surface. It also follows that on the moon frothing and explosive activity will begin at greater depth within the dikes and other conduits than on earth.

Astronomers have long known that the moon is too small to hold an atmosphere or hydrosphere—in the moon's low gravity, water vapor, nitrogen, carbon dioxide and other gaseous products would diffuse rapidly into outer space. Thus the vapors that escape from broken bubbles of lava during an explosive eruption on the moon's surface would quickly diffuse outward and be lost. Steam and ice crystals, however, would surely develop above a lava flow erupted into the cold of the lunar night, but the eruption cloud would quickly dissipate with the settling of the volcanic glass, ice crystals, and other condensates back to the moon's surface, plus the rapid diffusion into space of those vapors which survived the lunar cold.

What would happen to water vapor and carbon dioxide released some distance underground on the moon? They might be freed either by frothing of magma in dikes or other underground bodies at shallow levels, or, more significantly, they may have been released in quantity during the slow crystallization of magma in huge underground chambers covered by a mile or more of moon rock. On earth crystallization of molten rock at depth results in the release of fluids with temperatures above the critical point of water. These work their way upward toward the surface, cooling off slowly, altering their wall rocks, and gradually becoming diluted with the ground water and soil atmosphere as they approach the surface. Here they finally emerge as fumaroles, geysers and hot springs, or even as dry gas springs composed largely of carbon dioxide. Would de-gassing of underground magmas on the moon follow a similar pattern? It seems unlikely because of the marked cold to be expected in moon rocks only a few centimeters below the surface.

We noted earlier that the temperature of a meter or two below the surface is about -25° Centigrade and, because of the great insulating capacity of the spongy materials above, there is little or no fluctuation of this temperature between the lunar day when the temperature rises to over 100° Centigrade at the equator and the lunar night when it plunges to about -150° Centigrade. Under such conditions volcanic water released underground and free to diffuse into the pores or other openings of permeable moon rocks would never reach the surface. Instead it would freeze into ice while still underground and this process would in time effectively seal all openings in the rocks with ice. In short, volcanic processes would establish a permafrost layer with its upper surface in spongy rock beneath the moon's surface.

There would seem to be no lack of volcanic water to develop such a permafrost layer. If the moon's maria are indeed composed of volcanic rocks, the amount of water released from these magmas would be many times greater than could be stored in the permafrost layer. Therefore most of the primordial water must have reached the surface and evaporated. Nearly all of this vapor would, of course, be lost in space, but some of it may still be present as ice in permanently shadowed mountain clefts of the polar regions where direct rays from the sun never reach. Here, where temperatures are always 100 degrees or more below the freezing point, ice would be as stable as many other kinds of rock—just as it also would be underground.

Dry ice (carbon dioxide ice) might also be a component of the underground permafrost layer, particularly in the polar areas where temperatures are certainly low enough to cause precipitation of carbon dioxide frost during the lunar night if carbon dioxide vapor is available. Leighton and Murray (1966) reach the conclusion that the polar caps on Mars, which grow and then wane with the season, are probably solid carbon dioxide. Their theoretical model indicates that CO_2 must condense in large amounts relative to H_2O from the Martian atmosphere. They also remark that "water-ice permafrost probably exists under large regions [of Mars] at polar and temperate latitudes" (p. 144).

The probability of a permafrost layer on the moon, maintained over geologic time by water (and possibly carbon dioxide) given off during volcanic activity, has many interesting implications. Any attempt to establish and maintain a lunar base will have as its first major problem the obtaining of an adequate water supply. If permafrost exists at shallow depths, lava tubes, caves and other large openings in the volcanic terrain of the maria will be filled with ice, just as are many well-insulated lava tubes on earth in climates as mild as those of Oregon and Washington. Even in the hot climate of central Oregon, ice occurs in lava tubes that are well insulated from the summer heat by a covering of pumice 1 to 4 feet thick. Arnold Ice Cave supplied ice for the city of Bend for many years prior to the development of modern ice-making machinery.

Moreover ice in large quantity may be found on the moon in other underground passageways. The most abundant tectonic features on the moon appear to be great tensional fractures: for example the radial fissures extending out from Mare Imbrium and from nearly all the larger impact craters, faults such as the Straight Wall, and the many rilles, some more than 200 miles long. Any available fluids from volcanism would rise along these fractures, and we would expect their upper parts to be filled and sealed with ice and other volcanic sublimates.

Moreover, these cracks and fissures—by analogy with what we know from earth—would also be the channelways through which new molten rock from the moon's interior would seek egress to the surface. Let us picture the rise of basalt magma along a fissure or rille already filled with ice. If the rise of magma was slow, the ice would melt ahead and water in close contact with the magma would be converted to steam. The inevitable result would be that when the steam pressure equalled the weight of the overlying load of ice and rock a strong steam explosion would occur and the

immediately underlying magma would froth into violent eruption. Perhaps this explains the great abundance of volcanoes of the maar-type lined up in closely spaced order along certain rilles and major fissures. Are these moon volcanoes, like so many maars on earth, the product of phreatic eruptions induced by hot molten rock coming in contact with supplies of underground water?

The moment rocks are exposed to the action of the atmosphere and water at the earth's surface a complex series of changes sets in which ultimately reduces hard rocks to loose soil, loam, clay and sand. These changes are in part due to chemical reactions, many of them slow-acting and very complex in nature, and some of them aided or made possible by biologic activity of bacteria, molds, earthworms and other soil-inhabiting organisms. The result is that most of the common rock-forming minerals, over a long period of time, are dissolved away or else rotted to hydrous clays, complex silicates, oxides and hydroxides of aluminum and iron, plus a wide variety of other substances. Such weathering is called chemical weathering.

Along with the chemical weathering goes mechanical weathering, the result of processes which break and shatter rock in place with little or no change in chemical composition. One of the most potent agents of mechanical weathering is the force of crystallizing ice. Water seeps into the cracks and pores in rocks and soils, expands on freezing and bursts the bonds between the mineral grains. Porous soils may be heaved up a few inches to accommodate the ice crystals growing within them. Roots—from the largest trees to the smallest lichen—also penetrate into cracks in rock (or under sidewalks and street paving) breaking and heaving up the slabs they have loosened. Rocks spall and shatter when differentially heated in a forest fire, or under the shock and heat of a lightning stroke. The swelling of newly-produced clays or other minerals formed by chemical weathering may also exert enough force to break unaltered parts of the rock. Through all these mechanical processes, working together with chemical weathering, rock is changed into soil and other loose materials. Over most of the earth's surface these products of weathering hide the solid bedrock below.

On the earth, streams of water, slow-moving glaciers, waves pounding against the ocean shore, and wind blowing over the lands, all pick up and transport away some of these products of weathering. Ultimately they are deposited again, generally in the sea or a lake, on a river floodplain or in a desert basin. The process of removal and transportation of this debris is called erosion; the

Space Weathering on the Moon

58 dropping and piling up of the transported debris is deposition, or in geologic terms sedimentation.

The processes of weathering, erosion and deposition are continually at work altering the face of the earth. To their action we owe the deep soils of our corn belt, the spectacular ragged mountains and deep fiords of Alaska, the changing panorama of cliffs, sand, rocks, and waves along the Oregon Coast, the dark canyons of the Snake and Imnaha river in northeastern Oregon—eroded to a mile in depth through the Columbia River flood basalts.

No such features are found on the moon. The absence of oceans and atmosphere prohibits weathering, erosion and deposition of the kinds that are familiar to us. Yet there are processes on the moon that break down the rocks on the surface to a kind of “moon soil” very different from that on earth. Also there is one form of erosion—downslope movements under the action of gravity—that affects steep scarps and cliffs on the moon, reducing them in height by landslides and flows of loose material exactly like the landslides, avalanches and rockslides on earth. Deposition too is a real process on the moon. We have already considered how meteor impacts form deposits which we call ejecta blankets and rays. Moon volcanoes also form ash falls, ash flows and lava flows—deposits which may be the principal components of the maria. Such deposits are, of course, very different from the shales, sandstones, conglomerates and limestones formed by the action of erosional agents and of rock-building organisms on earth.

So different are the processes that form “soils” on the moon that perhaps the term “space weathering” is wholly inappropriate. However, I have chosen to group here, under this term, those processes which tend to break down the rocks of the moon’s surface, both physically and chemically.

RADIATION WEATHERING. The lunar surface has received enormous doses of cosmic radiation over the long lapse of geologic time. From experiments on earth we know that these radiations cannot fail to produce profound effects in the minerals thus bombarded. Damage to crystals by cosmic rays is chiefly a result of spallation reactions. Spallation and “sputtering” effects in solid crystals include fission tracks and many minor space lattice defects, but the main sources of atomic disarrangements are from the recoil nuclei and from disintegration of heavy ions. These produce areas of intense structural damage within crystals, and in the course of geologic time must have important effects in shattering minerals and producing a layer of finely pulverized dust on the moon’s surface. Gamma radiation, and bombardment by light particles such as protons and alpha particles from solar flares also produces defects in crystals, among them the so-called

metamict structures where radiation damage is so severe that the characteristic optical and X-ray characters by which minerals are identified are lost.

Such radiation damage is believed by many scientists to be responsible for the fading with time in the brightness of the rays that radiate from impact craters. Only the youngest moon craters show strongly illuminated rays and we note a progressive darkening if we examine successively older and older ray-craters under the telescope. Darkening of crystals subjected to high-energy radiation in the laboratory has been demonstrated, as has the development of luminescence and other color effects in certain minerals. There may be other factors, however, that aid in causing the rays to darken with time. One is the mixing and dilution of the ray material with the underlying darker maria material as a result of meteor and micrometeor impacts.

METEOR IMPACT AS A CAUSE OF SPACE WEATHERING. Shoemaker (1962) has made detailed analyses from all available data of the rate of cratering on the moon, from craters one meter in diameter to the largest. He concludes that the maria have been cratered repeatedly at any one place by small impacts since the time the maria were formed, although large craters 50 miles across are only sparsely represented. So much cratering by small meteors has occurred that small craters which once covered all parts of the maria have been lost by the superposition of other craters upon them. In each cratering event material is churned and broken at the crater site, ejected by the shock waves, and distributed over a wide area. Shoemaker calculates that about half of the fragments ejected from a small crater will land within a kilometer of the site of impact, but other pieces will be thrown to great distances and some may even be ejected at the velocity of escape and leave the moon completely. He estimates that the micrometeor influx to the moon's surface is so great that a complete turnover of the uppermost millimeter of the moon occurs at least every hundred years.

Impact from small meteors and micrometeors is, therefore, probably the greatest single agent in "space weathering" of the moon's surface. As we already know, meteor impacts shatter and destroy rock. If not melted or vaporized completely, the minerals are severely shocked, broken and damaged in other ways. Meteor impact also completely disrupts the structural arrangement that the rocks had prior to impact, piling them up in broken and shattered condition as an ejecta blanket with a reversed stratigraphy to that in the walls of the crater. Repeated meteor impact has mixed debris from all parts of the moon into an indiscriminate rubble; it serves as both a giant plow and a mixing mill for the

materials of the moon's crust. A striking feature of the photographs from the Ranger, Surveyor and Russia's Luna probes is that even on steep slopes the underlying rocks appear to be masked or completely buried under a thin layer of loose rubble. Although other processes have helped to pulverize this material, meteor impact is undoubtedly the dominant process that has given the upper layer of the moon its fragmental fine structure.

The flying debris ejected from impact craters causes both erosion and deposition on the moon's surface. Some erosion is caused by a limited amount of material being ejected with the velocity of escape. Every particle that does fall back will tend to knock material downhill from its original point of impact, to start secondary slides and the rolling of loose particles down steep slopes. Over great periods of time these downslope movements must have important effects in reducing the high rims of major craters and their central peaks. They will also have the effect of rounding off sharp corners, blunting the outcrops of rock ledges, and filling the floors of depressions. Thus is explained the abundant "softened" and "subdued" craters—both primaries and secondaries—which are so abundant in the Ranger photographs (Figures 7 and 16).

INSOLATION. Still another process which undoubtedly shatters rock at the surface of the moon and causes some net movement of the particles downslope is the differential expansion and contraction of rocks with the heat of the lunar day and the cold of the lunar night. Rock is a poor conductor of heat; when the sun shines full upon it the outer surface heats up rapidly and expands but the interior remains cool. Hence the outer layer tends to pull away and spall off from the interior. This kind of weathering is called insolation. It is of little, if any, importance on earth because the temperature between day and night on earth is not sufficient to spall the rock, although possibly the slight expansions and contractions might weaken bonds between minerals in some rocks if repeated enough times. On the moon, however, the great range in temperature—approximately 250° C. at the equator—between the lunar day and lunar night must lead to scaling and spalling of many rocks. On the earth, forest fires often cause great spalling of rock ledges. Our great-grandfathers were surprised that columns and blocks of granite—the most enduring building stone—were completely ruined by spalling during the Chicago fire of 1871.

WEATHERING AND CEMENTATION OF ROCKS BY CRYSTALLIZATION OF MINERALS IN PORES AND CRACKS. Another factor of importance in the mechanical breakdown of rocks is the crystalliza-

tion of new minerals in pores and other openings. We have already described this process as responsible for frost action—the marked shattering of rocks and loosening of soils in the polar regions, and in the temperate zones in winter, by the force of crystallization of ice. It often escapes our attention, however, that swelling during growth of many other minerals produces the same effects. Telephone poles lining the highway across the Bonneville salt flats west of Salt Lake City are shattered to matchsticks for a foot or two above the surface of the salt flat within a few years after they have been set in the salt. The pole acts as a wick, and pulls up by capillarity the brine produced after each rain. There the water evaporates and the growing salt crystals split open the cell structure and grain of the wood. Blocks of rock along the edge of the Bonneville salt flats and in Death Valley are similarly shattered. Hard sun-baked clays on the floor of Death Valley are broken and heaved up, much like frost-heaved soil in the Arctic, by the rise and evaporation of salty ground water below them after a heavy rain. Even the swelling of feldspar crystals as they rot to clay by chemical weathering may break bonds between other minerals in a feldspar-rich granite, reducing this hard rock to a pulverulent grus of loose particles.

Similar kinds of reactions must take place on the moon, assisting in the breakdown of the rocks and minerals on its surface. Yet on the moon the net effect of these processes may be more in the direction of sealing and cementing rocks than in adding to their pore space by disrupting them. Certainly this must be true at depths of only a few centimeters below the surface. We have already noted how ice in the permafrost layer heals all breaks and openings in loose material, making it both hard and impermeable. Watery solutions from volcanic activity entering the zone of porous rock just below the moon's surface could not fail to spread in this zone and precipitate not only their ice but also their sulphur, iron chlorides, and other dissolved salts while the fluids cooled and their more volatile components evaporated into space. On earth newly-erupted lava flows are often encrusted with soluble substances precipitated from an evaporating gas-phase, but these are quickly removed in solution by the first hard rain. In the near vacuum of the moon such materials would accumulate, and we should expect the rocks at shallow depths to be heavily encrusted with such sublimates and precipitates. If it were not for the constant overturn of the surface layer by small meteors and micrometeors these processes long ago would have encrusted the surface fragmental debris, cementing it into hard rock.

In short, the face of the moon is a dirty face, encrusted with the grime and sweat wrung out of its interior through millions of

centuries. It has never been cleansed by the rains which wash our lands and carry the soluble salts away to the sea.

Life on the Moon

Can forms of life similar to those we know on our planet have evolved on the moon as well? The lack of air and water, the tremendous changes in temperature, and the pitiless rain of cosmic rays and lethal radiations from the sun would seem to make the very idea of life on the moon unthinkable. Yet life on our own planet has made many remarkable adaptations to inhospitable surroundings. The shores of Antarctica, the firn and ice at the summit of Mount Hood, the barren sands and hard-baked clay of the Alvord desert east of Steens Mountain—all these support living things in abundance. True, any environment we can think of on the moon's surface seems much more inhospitable than these, but what of conditions in the twilight zone from a few centimeters under the ground surface to the top of the permafrost layer—if permafrost really does exist on the moon? Near the top of this zone the heat of the sun will penetrate, but not with the searing intensity that it has on the surface. Here, too, is partial to complete protection from the dangerous radiation and from the constant bombardment of micrometeors and particles in the solar wind. Deeper in the zone, at or near the permafrost boundary, water would be available. The spongy upper crust of fragmented and shattered rock should also contain substantial amounts—and in soluble form—of the many rare trace elements essential to life. These would have been concentrated there largely as sublimates and precipitates from volcanic exhalations which spread, cooled and crystallized in this spongy surface deposit during the last stages of their rise toward the surface.

Abelson (1966) has recently reviewed the chemical events that might have transpired to produce life on a primitive earth whose atmosphere and hydrosphere were formed by outgassing of the interior as suggested by Rubey (1951, 1955). He concludes that volatiles distilled from the interior reacted with an alkaline crust to form a primitive ocean having a pH of 8-9 and an atmosphere consisting chiefly of CO, CO₂, N₂, and H₂. Solar radiation reacting with such a mixture yields HCN. Ultraviolet radiation of HCN solutions yields amino acids and other proto-biologic building blocks, and polymerization of HCN in weakly alkaline solutions also yields a number of substances of biologic interest.

The requisite conditions for these primitive-earth reactions might have been possible over millions of years in the zone between the moon's surface and the top of its permafrost layer.

Particularly favorable times and conditions would have occurred when volcanism was pouring new volatiles into the zone, thus providing a steady warming mechanism for part of it, as well as constant replenishment of lost vapors.

Whether or not the spark of life actually was kindled and still survives within this zone will be known before long. One thing, however, appears to be certain: if man is to stay upon the moon and to build stations for research and exploration, the zone between the permafrost layer and the surface appears to be the only favorable site for his home. If a permafrost layer is really present this zone can supply the water and, in cooperation with solar engines maintained on the surface, can provide the "air conditioning," the protection from lethal rays, and the useful chemicals necessary for men to live and work in the hostile environment of our sister world.

References

- Abelson, P. A. (1966). CHEMICAL EVENTS ON THE PRIMITIVE EARTH. National Academy of Sciences, Proceedings, v. 55, p. 1365-1372.
- Bagnold, R. A. (1942). THE PHYSICS OF BLOWN SAND AND DESERT DUNES. Wm. Morrow and Company, New York, 265 p.
- Baldwin, R. B. (1949). THE FACE OF THE MOON. University of Chicago Press, Chicago, 139 p.
- Baldwin, R. B. (1965). A FUNDAMENTAL SURVEY OF THE MOON. McGraw-Hill Book Co., New York, 149 p.
- Burley, J. M. and Middlehurst, B. M. (1966). APPARENT LUNAR ACTIVITY: HISTORICAL REVIEW. National Academy of Sciences, Proceedings, v. 55, p. 1007-1011.
- Chao, E. T. C., Shoemaker, E. M. (1960). FIRST NATURAL OCCURENCE OF COESITE. Science, v. 132, p. 220-222.
- Gilbert, G. K. (1893). THE MOON'S FACE: A STUDY OF THE ORIGIN OF ITS FEATURES. Philosophical Society of Washington Bulletin, v. 12, p. 241-292.
- Green, J. (1966). LUNAR EXPLORATION AND SURVIVAL. Douglas Paper No. 4038, Douglas Aircraft Company, Advanced Research Laboratory, Huntington Beach, 131 p.
- Greenacre, J. A. (1963). A RECENT OBSERVATION OF LUNAR PHENOMENA. Sky and Telescope, v. 26, p. 306-317.
- Greenacre, J. A. (1965). THE 1963 ARISTARCHUS EVENTS. New York Academy of Science Annals, v. 123, p. 811-816.
- Kopal, Z. (1962). TOPOGRAPHY OF THE MOON in "Physics and Astronomy of the Moon," Z. Kopal, ed., Academic Press, New York and London, p. 231-282.

- Kopal, Z. and Rackman, T. W. (1963). EXCITATION OF LUNAR LUMINESCENCE BY SOLAR FLARES. *Nature*, v. 201, p. 230-241.
- Kozyrev, N. A. (1962). SPECTROGRAPHIC PROOFS FOR EXISTENCE OF VOLCANIC PROCESSES ON THE MOON in "The Moon," Z. Kopal and Z. K. Mikhailov, eds., Academic Press, London and New York, p. 263-271.
- Kozyrev, N. A. (1963). VOLCANIC PHENOMENA ON THE MOON. *Nature*, v. 198, p. 979-980.
- Kuiper, G. P. (1954). ON THE ORIGIN OF THE LUNAR SURFACE FEATURES. *National Academy of Sciences, Proceedings*, v. 40, p. 1096-1112.
- Kuiper, G. P. (1959). THE EXPLORATION OF THE MOON. *Vistas in Aeronautics*, v. II, Pergamon Press, New York, p. 273-313.
- Kuiper, G. P. (1965). III. INTERPRETATION OF RANGER VII RECORDS in "Ranger VII Experimenters' Analyses and Interpretations," *National Aeronautics and Space Administration Technical Report 32-700*, Pasadena, p. 9-73.
- Leighton, R. B. and Murray, B. C. (1966). BEHAVIOR OF CARBON DIOXIDE AND OTHER VOLATILES ON MARS. *Science*, v. 153, p. 136-144.
- Mason, A. C. and Hackman, R. J. (1962). PHOTOGEOLOGIC STUDY OF THE MOON in "The Moon," Z. Kopal and Z. K. Mikhailov, eds., Academic Press, London and New York, p. 301-315.
- Moore, H. J. (1964). A POSSIBLE VOLCANIC COMPLEX NEAR THE HARBINGER MOUNTAINS OF THE MOON. *U. S. Geological Survey, Astrogeology Studies, Annual Progress Report*, July 1, 1963 to July 1, 1964, Part A, p. 42-51.
- Pecora, W. T. (1960). COESITE CRATERS AND SPACE GEOLOGY. *Geotimes*, v. 5, No. 2, p. 16-19.
- Ronca, L. B. (1965). AN INTRODUCTION TO THE GEOLOGY OF THE MOON. *United States Air Force Office of Aerospace Research, Special Report No. 23*, ARCRL-65-357, 31 p.
- Rubey, W. W. (1951). GEOLOGIC HISTORY OF SEA WATER. *Geological Society of America Bulletin*, v. 62, p. 1111-1147.
- Rubey, W. W. (1955). DEVELOPMENT OF THE HYDROSPHERE AND ATMOSPHERE, WITH SPECIAL REFERENCE TO THE COMPOSITION OF THE EARTH ATMOSPHERE in "Crust of the Earth," A. Poldervaart, ed., *Geological Society of America, Special Paper 62*, p. 631-650.
- Shoemaker, E. M. (1959). IMPACT MECHANICS AT METEOR CRATER ARIZONA. *U. S. Geological Survey, Open File Report*, July 1959, 55 p. Published also as Chapter 11 in Vol. IV, "The Moon, Meteorites and Comets," of "The Solar System," B. M. Middlehurst and G. P. Kuiper, eds., *University of Chicago Press*, 1963.

- Shoemaker, E. M. (1962). INTERPRETATION OF LUNAR CRATERS in "Physics and Astronomy of the Moon," Z. Kopal, ed., Academic Press, New York and London, p. 283-359.
- Shoemaker, E. M. (1964). THE GEOLOGY OF THE MOON. Scientific American, v. 211, No. 6, p. 38-47.
- Shoemaker, E. M. and Chao, E. T. C. (1960). ORIGIN OF THE RIES BASIN, BAVARIA, GERMANY. Geological Society of America Bulletin, v. 71, p. 2111-2112.
- Shoemaker, E. M. and Hackman, R. J. (1962). STRATIGRAPHIC BASIS FOR A LUNAR TIME SCALE in "The Moon," Z. Kopal and Z. K. Mikhailov, eds., Academic Press, London and New York, p. 289-300.
- Shorthill, R. W. and Saari, J. M. (1965). NON-UNIFORM COOLING OF THE ECLIPSED MOON. Science, v. 150, p. 210-212.
- Strom, R. G. (1965), in "Interpretation of Ranger VII Records," by G. P. Kuiper, National Aeronautics and Space Administration Technical Report 32-700, Pasadena, p. 9-73.
- Urey, H. C. (1962). ORIGIN AND HISTORY OF THE MOON in "Physics and Astronomy of the Moon," Z. Kopal, ed., Academic Press, New York and London, p. 481-523.
- Waters, A. C. (1961). STRATIGRAPHIC AND LITHOLOGIC VARIATIONS IN THE COLUMBIA RIVER BASALT. American Journal of Science, v. 259, p. 583-611.
- Williams, Howel (1935). NEWBERRY VOLCANO OF CENTRAL OREGON. Geological Society of America Bulletin, v. 48, p. 253-304.
- Williams, Howel (1948). THE ANCIENT VOLCANOES OF OREGON. Oregon State System of Higher Education, Condon Lecture Publication, Eugene, 64 p.
- Wright, F. E., Wright, F. H., and Wright, H. (1963). THE LUNAR SURFACE in "The Moon, Meteorites, and Comets," Vol. IV of "The Solar System," B. M. Middlehurst and G. P. Kuiper, eds., University of Chicago Press, p. 1-56.

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ABOUT THE MAP

This map has been prepared by the Space Sciences Laboratory to be used by S&ID's scientists and engineers engaged in lunar research. It is hoped that the map will be an aid to other scientists and engineers as well, and also to amateur astronomers and students.

The map is unique in that it identifies the maximum number of surface features consistent with top-quality photographic detail. To obtain this quality, we are indebted to Dr. A. E. Whitford of Lick Observatory, who provided original plates from the Moore-Chappell series. This series was compiled over a period of ten years and is generally considered to be the best ever made. From the set, we selected two brilliantly clear plates which were matched for librations.

There are two ways of mounting lunar photographs on a page: north up, as observers in the northern hemisphere see the moon with the naked eye, and south up, as the moon is observed with a telescope, which inverts the image. Although astronomers have adopted the convention of putting the lunar north pole at the bottom of the page, we decided to break with that tradition. As space vehicle trajectories are being planned to take man to the moon, it is more convenient to visualize the lunar terrain in its true relationship to the launch pad.

While the nation's lunar exploration program involves a number of scientific disciplines, astronomy and geology are perhaps the two which have contributed most to an understanding of the nature of the lunar surface. In preparing our map, we were fortunate in having the assistance of an outstanding member of each science—Dr. Dinsmore Alter, Director Emeritus of Griffith Observatory, whose observations of the lunar crater Alphonsus laid the groundwork for Dr. Kozyrev's recent discovery of a gaseous emission from the crater's central mountainous ridge; and Dr. Jack Green of S&ID's Space Sciences Laboratory, whose studies of terrestrial formations have led to a more comprehensive knowledge of possibly analogous lunar features.

Since the invention of the telescope, more than 700 lunar features have been named—far too many to identify on the map without destroying the pictorial excellence of the photographs. Dr. Alter and Dr. Green have therefore selected 309 which are geographically prominent, or which, as in the case of Linne, are pertinent to the question of the nature of lunar formations. It should be noted, however, that many features on the moon have not yet been officially named. For example, no designation has been given to the long irregular ridges on the floors of Maria Serenitatis, Tranquillitatis and Imbrium; the rille on the east side of the floor of Alphonsus; a similar rille west of the Straight Wall; the rectangular formation just west of the Ptolemaeus-Alphonsus boundary, and the oval rays east of Copernicus.

The designations of the named lunar features are those adopted by the International Astronomical Union and published in **Named Lunar Formations** (M. A. Blagg and K. Müller, London, 1935). Some of these were subsequently revised in the **Photographic Lunar Atlas** (G. P. Kuiper, ed., University of Chicago Press, 1960) and the resolution adopted by IAU commission 16 during the XI General Assembly in 1961. A few exceptions, indicated by quotation marks, are also identified as they are commonly referenced in astronomical literature.



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Supplement to
**Moon Craters
and
Oregon Volcanoes**

by
Aaron C. Waters

CONDON LECTURES

Oregon State System of
Higher Education
Eugene, Oregon, 1966

through
the eyepiece

the

MOON

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DISTANCE FROM EARTH (Surface to surface—nearest point)	
Maximum (miles)	246,900
Minimum (miles)	220,700
Mean (miles)	233,800
(kilometers)	376,300
MASS	
In U.S. short tons	8.107×10^4
In kilograms	7.355×10^{22}
In terms of Earth's mass	0.01230
In terms of sun's mass	3.697×10^{-8}
DENSITY, MEAN	
In terms of water	3.34
In terms of Earth's mean	0.6043

MAGNITUDE	
Mean of full moon	12.5
DIAMETER	
Miles	2160
Kilometers	3476
In terms of Earth's mean diameter	0.27227
Mean geocentric, angular	31.07"
TEMPERATURES	
Sun at zenith	214°F (101°C)
Night	approx. -250°F (-157°C)
ALBEDO (average)	0.07

VELOCITY OF ESCAPE AT SURFACE	
In terms of Earth's	0.213
Miles per second	1.68
Kilometers per second	2.38
SURFACE GRAVITATION	
In terms of Earth's	0.165
In feet per second per second acceleration	5.31
In cm per second per second acceleration	162
LIBRATIONS, MAXIMUM	
Geocentric in longitude	7°54'
Geocentric in latitude	6°50'

SELECTED LUNAR DATA

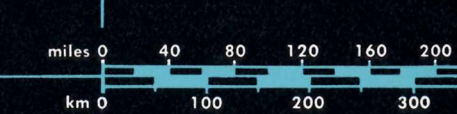
AVERAGE LENGTH OF MONTHS	
Synodic	29.530588 days
Sideral	27.321583 days
Dracentic (nodical)	27.212220 days
Anomalistic	27.554550 days
Tropical	27.321582 days
REGRESSION OF NODES	
Period of	18.5995 years
Annual change	137°35'
ADVANCE OF LINE OF APSIDES	
Mean period of	8.8503 years
Annual change	40°57'

ORBIT (With respect to Earth)	
Semi major axis (miles)	238,855
(kilometers)	384,400
Apogee (miles)	251,968
Perigee (miles)	225,742
Parallax, mean	57'02".54
Inclination of orbit plane to ecliptic, mean	5°08'43"
Maximum	28°35'
Minimum	18°19'
Inclination of moon's equator to ecliptic	1°32'
Eccentricity, mean	0.0549
Velocity in orbit, mean	5806
Angular (degrees/hour)	3969
Linear (miles/second)	3638
(kilometers/second)	5806

VISIBLE SURFACE	
Always visible	41.0%
Sometimes visible	18.0%
LARGEST VISIBLE CRATER	
Bailly (not visible at this libration)	183
Diameter (miles)	225.742
(kilometers)	363.8
LARGEST CRATER VISIBLE IN ALL LIBRATIONS	
Clavius	146
Diameter (miles)	185 x 24
(kilometers)	235

HIGHEST VISIBLE ELEVATION	
From the floor of Newton to a peak on its wall, stated as (feet)	29,000
(meters)	8,839
LARGEST VISIBLE VALLEY	
Rheita Valley (miles)	115 x 15
(kilometers)	185 x 24

The greater part of these data are quoted from "Introduction to the Moon" by Dr. Bernard Allen.



For approximate measurements of features of the moon, each segment of the grid line (2 inches) can be assumed to represent approximately 220 miles (354 kilometers). It should be noted, however, that features near the edges of the photographs are distorted due to foreshortening.

☐ Published by the Oregon State System of Higher Education.
Designed by JoAn Rice, University of Oregon Publications Office.
Typography and printing by University of Oregon Press.