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ISBN: 9780123859389

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Academic Press
Volcanism on the Moon

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Chapter Outline

1. Introduction 690
2. Mare Volcanism on the Moon 691
   2.1. Origin of Mare Basalts 691
   2.2. Apollo Mare Basalts 691
3. Styles of Volcanism and Associated Landforms 693
   3.1. Lunar Lava Flows 693
   3.2. Pyroclastics 695
   3.3. Sinuous Rilles 697
4. Nonmare Volcanism 697
5. The Beginning and End of Mare Volcanism 698
   5.1. Early Phase 698
   5.2. Main Phase 699
   5.3. Late Phase 699
See also the Following Articles 700
Further Reading 700

GLOSSARY

albedo Reflectivity of an object. Light and dark are high and low albedo, respectively.
ash Very small fragments of volcanic glass, sprayed out at a vent, cooled quickly, and deposited as a blanket of debris.
basalt A dark, fine-grained rock, rich in iron and magnesium, created by solidification of a lava rich in iron and magnesium.
bombardment The repeated collision of a planet with asteroids over a long time.
cinder cone Hill produced by the buildup of ash or other pyroclastic (q.v.) fragments around a volcanic vent.
collapse pit Small depression associated with subsurface collapse, as over a shallow chamber after lava has been drained from it.
dark mantle deposit Large area of the Moon covered by glassy pyroclastic ash deposits.
fire fountain Spray of lava from a vent, producing a dark mantling deposit.
flow front The terminal end of a lava flow.
impact dark halo crater Crater with dark ejecta, caused by the exhumation of buried lava flows in the lunar highlands.
KREEP Acronym for potassium (K), rare-earth elements (REE), and phosphorus (P); a chemical component in lunar rocks, created as the last phase of the magma ocean (q.v.).
lava Liquid magma extruded onto a planetary surface.
lava tube A channel that is partly or completely rooted over to enclose the lava stream; may form a cave after the flow has cooled.
mafic property describing an enrichment in iron and magnesium at the expense of silicon and aluminum.
magma Liquid rock within the interior of a planet.
magma ocean State of the early Moon in which the entire globe was covered by a layer of liquid rock, hundreds of kilometers thick.
mantle The part of a planet below the crust and above the core. Partial melting of the mantle is the source of magma in most planets.
maria (MAR-ee-ah) Dark areas of the Moon; Latin plural for “seas”; singular is mare (MAR-ay).
pyroclastic Literally “fire-broken”, meaning fragmental rocks produced in explosive volcanic eruptions, includes ash.
regolith Unconsolidated debris overlying bedrock.
rilles Any relatively narrow depression, whose shape can be linear, arcuate, or sinuous. Linear and arcuate rilles have tectonic origins while sinuous rilles are lava channels or tubes.
shield volcano A broad, low-relief volcanic construct made up of flows of relatively fluid lava, usually basalt.
sinuous rille A lava channel or tube in the lunar maria.
terrae (TER-eye) Latin plural for “land”, the cratered highlands of the Moon; singular is terra (TER-ah).
vent Hole in a planet from which volcanic products (lava, ash) may be erupted.
vesicle Hole (frozen bubble) in a sample of lava rock that results from dissolved gas in magma coming out of solution.
viscosity The property of a fluid that causes it to resist flow or movement. Higher viscosity results in slower rates of flow.
xenolith (ZEE-no-lith) Literally “stranger rock”, a fragment of rock from great depths carried to the surface as a clast in a lava flow or pyroclastic deposit.
1. INTRODUCTION

In the years before spaceflight, the Moon was thought to be volcanically active. Astronomers are very fond of volcanoes, so an analogy was made between the craters of the Moon and calderas, the large, circular depressions found at the summit of terrestrial volcanoes. Detailed study of lunar craters and terrestrial analogs eventually provided convincing evidence that the abundant craters of the Moon were formed by the collision of solid bodies over geological time.

The few workers studying the Moon largely ignored the dark maria, the low-lying smooth plains that make up large fractions of the near side seen through a telescope (Figure 39.1). Most early ideas about the maria associated them with ancient sedimentary deposits, either water-laid or mass-wasted material derived from the surrounding highlands. However, in his landmark 1949 book The Face of the Moon, astronomer Ralph Baldwin presented convincing evidence that the maria are made up of floods of basalt, a dark lava, rich in iron that is abundant on the Earth.

In preparation for the Apollo missions, debate on the origin of the maria raged. The return of samples from the Moon settled the issue. The maria indeed are made up of floods of basaltic lava (Figure 39.2), but what is most striking from the returned samples is the age of these lavas. The basalts returned by Apollo range in age from 4300 to 3100 million years, as old as the very oldest rocks on the Earth.

**FIGURE 39.1** Lunar Reconnaissance Orbiter global high-sun image of the Moon showing its two principal terrains: the light, rough highlands (or terra) and dark, smooth lowlands (or maria). Near side on the left, far side on the right. Study has shown that the maria are made up of basaltic lava flows and constitute about 16% of the lunar surface and <1% of the volume of the crust.

**FIGURE 39.2** Hand specimen (top left; markings in centimeters) and thin section (bottom, plane light and xpl; Field of view ~ 2 mm) of Apollo 17 high-titanium mare basalt 70017. Lunar basalts are made up predominantly of augite (Ca-rich pyroxene), olivine, plagioclase, and ilmenite; they are depleted in volatile elements and contain no hydrous minerals.
The lunar lavas have interesting compositions, including a complete absence of hydrous minerals, which often occur in lavas on the Earth. These properties, discovered during the initial examination of the Apollo samples, gave us a first-order understanding of the basic properties of the Moon. We discovered that the Moon has a crust, formed early in its history by global melting (the “magma ocean”). This differentiation produced the plagioclase-rich crust and the mantle source regions for the later mare basalts. Thus, lunar volcanic rocks contain important information about the composition of the deep interior of the Moon.

2. MARE VOLCANISM ON THE MOON

2.1. Origin of Mare Basalts

The samples of the maria returned by the Apollo missions are a form of lava known as “basalt” (Figure 39.2). Just as on Earth, basalt is created by partial melting in the mantle, composed mostly of the iron-rich and magnesium-rich minerals olivine and pyroxene. From its relatively high density inferred from seismic velocity data, we know that the lunar mantle is largely made up of these same minerals. Radioactive, heat-producing elements, such as uranium, made the early mantle hot enough in some places to partially melt. Blobs of silicate melt coagulate deep in a planet’s interior and then slowly migrate upward, where they may force their way to the surface and be extruded onto a planetary surface as a lava flow.

Unlike in the Earth, we see little evidence for the collection of large amounts of magma at shallow depths in the Moon’s crust and for its retention in subsurface “holding chambers”. Most magmas appear to have migrated upward through the mantle and crust and then erupted fairly quickly. The lunar pyroclastic glasses are the most extreme examples of this phenomenon, as they appear to be completely un fractionated, suggesting a rapid ascent from the mantle and violent, immediate eruption. Some mare basalts show evidence for the assimilation of highly differentiated crustal material. Such a process does not imply significant near-surface magma storage, as this material (potassium, rare earths, and phosphorus, termed KREEP) has a low melting point and could be assimilated easily during brief contact with the basaltic magma.

The chemistry of basaltic magmas tells us approximately where they formed within the Moon (at depths of 150–400 km) along with what processes subsequently affected them. Our study of the mare basalts tells us that many different regions of the mantle underwent melting episodes at several depths over a very long period of time, a period lasting at least 700 million years long and more likely over a time span of one to two billion years. These melted pockets found their way to the surface through cracks that they themselves propagated or via fractures induced by the formation of the giant craters and basins of the highlands. However, only a very tiny volume fraction of the mantle was melted to make basalt. Although the maria appear prominent in areal extent, the lavas are relatively thin compared with the volume of the crust as a whole. It is estimated that the mare basalts cover about 16% of the Moon by area (Figure 39.1) but probably account for less than about 1% of the total volume of the crust.

2.2. Apollo Mare Basalts

Like terrestrial basalts, the lunar mare basalts are made mostly of the minerals pyroxene and plagioclase and are rich in iron and magnesium. The grain size of basalt is very fine (usually <1 mm), a result of rapid cooling. Like some terrestrial basalts, some lunar lavas have small, bubble-like holes in them (vesicles), indicating that the magmas contained gas during eruption. As with basalts on Earth, mare basalts are formed by the partial melting of the lunar mantle, made of mostly pyroxene and olivine.

The first basalts returned from the Moon came from the Apollo 11 landing site in Mare Tranquilitatis (Sea of Tranquility). These rocks are remarkable in several respects. Mare basalts are not only devoid of water or any hydrous phase but they are also depleted in all the volatile elements (those that have very low boiling temperatures), including, for example, sodium, zinc, potassium, and phosphorus. Strangely (and surprisingly), the Apollo 11 basalts have large amounts of titanium (Table 39.1), mostly in the form of the mineral ilmenite, an oxide of iron and titanium. The enrichment of the mare basalts in iron and their depletion in aluminum, the exact reverse of the composition of rocks from the lunar highlands, account for the relative darkness (low albedo) of the maria as opposed to the terrae (lunar highlands).

Lavas from the Moon contain some minor minerals that are not found in Earth rocks. One of these, another iron—titanium mineral, was given the name armalcolite, named in honor of the Apollo 11 crew (the word coming from the first letters in the names of the crew, Armstrong, Aldrin, and Collins). The compositional properties of the lunar basalts reflect the unique chemical environment in which they formed: inside a small planet (resulting in low interior pressures), depleted in volatile elements, containing little or no water (but see below), and erupted onto a low-gravity surface in a vacuum.

Mare basalts from other Apollo missions largely confirm the initial impressions gathered from these studies, but contained some surprises and interesting variations. Lavas from Apollo 12 are lower in titanium (Table 39.1) than the Apollo 11 basalts and are 600–700 million years younger (erupted about 3100 million years ago). Once again, these lavas are low in volatile elements and rich in
iron. The lower titanium and younger ages of the Apollo 12 basalts confirm that the maria were not erupted as a single, massive flood of lava across the surface all at one time but rather, the formation of the maria was an extended process that involved different batches of magma erupted in different places at different times. In short, the samples told us that the Moon had a complicated volcanic history and a protracted geological evolution.

Mare basalts from the other two mare landing sites extended our picture of mare volcanism. Apollo 15, which landed just inside the rim of the basin containing Mare Imbrium, returned low-titanium basalts (Table 39.1) slightly older than those from Apollo 12; these lavas crystallized about 3300 million years ago. Apollo 17, landing on the edge of Mare Serenitatis, returned very high-titanium basalts (Figure 39.2; Table 39.1), similar to those from Apollo 11, but slightly younger, about 3700 million years old. These results led some to conclude that the Moon had a fairly simple volcanic history, with early eruptions of high-titanium lavas and late eruptions of low-titanium lava. The conclusion was also drawn that the Moon “died” volcanically after the Apollo 12 lavas were erupted at 3100 million years, a totally unwarranted conclusion that even today is widely believed and recounted.

In contrast, mare basalt fragments found as clasts “within” highland breccias offer clues to the variety and ages of the earliest phases of lunar volcanism. These breccias from the highlands were assembled before 3800 million years ago; therefore, the lava fragments within them must be older than this. Some of these mare basalts large enough to date were erupted well before 3900 million years ago. The oldest mare basalt yet found is about 4200 million years old, only slightly younger than the age of the solidification of the crust. Other fragments display a variety of chemical compositions and date from between 4100 and 3900 million years old. Curiously, most of the ancient mare basalt fragments tend to have relatively high contents of aluminum compared to the basalts from the main phase of mare eruptions, although a few groups of high-alumina basalt date from this later era as well.

| TABLE 39.1 Chemical Composition of Typical Mare Basalts and Pyroclastic Glasses (After Taylor, 1982) |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                | Apollo 11 High-Ti   | Apollo 12 Low-Ti | Apollo 15 Low-Ti | Apollo 17 High-Ti | Luna 16 KREEP Basalt | Apollo 15 Green Glass | Apollo 15 Orange and Black Glass |
| SiO₂                          | 39.8               | 43.6             | 44.1             | 37.8             | 43.8               | 50.8               | 45.2               | 38.6               |
| TiO₂                          | 10.5               | 2.60             | 2.28             | 13.0             | 4.90               | 2.23               | 0.38               | 8.81               |
| Al₂O₃                         | 10.4               | 7.87             | 8.38             | 8.85             | 13.7               | 14.8               | 7.5                | 6.32               |
| FeO                           | 19.8               | 21.7             | 22.7             | 19.7             | 19.4               | 10.6               | 20.0               | 22.0               |
| MnO                           | 0.30               | 0.28             | 0.32             | 0.27             | 0.20               | 0.16               | 0.26               | –                 |
| MgO                           | 6.69               | 14.9             | 11.3             | 8.44             | 7.05               | 8.17               | 17.5               | 14.4               |
| CaO                           | 11.1               | 8.26             | 9.27             | 10.7             | 10.4               | 9.71               | 8.5                | 7.68               |
| Na₂O                          | 0.40               | 0.23             | 0.27             | 0.36             | 0.33               | 0.73               | 0.13               | 0.36               |
| K₂O                           | 0.06               | 0.05             | 0.04             | 0.05             | 0.015              | 0.67               | 0.03               | 0.09               |
| Cr₂O₃                         | 0.25               | 0.96             | 0.85             | 0.41             | 0.28               | 0.35               | 0.53               | 0.75               |
| P₂O₅                          | –                  | –                | –                | –                | –                  | 0.70               | –                  | –                 |
| Th (ppm)                      | 1.8                | 0.75             | 0.50             | 0.34             | 0.9                | 10.3               | 0.08               | –                 |
| Mg/(Mg + Fe)                  | 0.38               | 0.55             | 0.47             | 0.43             | 0.39               | 0.38               | 0.59               | 0.54               |
3. STYLES OF VOLCANISM AND ASSOCIATED LANDFORMS

3.1. Lunar Lava Flows

From pictures taken by telescopes on the Earth, the maria appear smooth and dark. The impression is that these plains fill in the holes and depressions of the Moon, suggesting a fluid emplacement. At close-up scales, small, lobe-shaped scarps can be seen (Figure 39.3); such scarps or lava fronts are very common in the basalt lava flows found on the Earth. These scarps can be seen in some of the best telescopic pictures of Mare Imbrium. Thus, we had direct evidence for emplacement of the maria by fluid flow “before” the exploration of the Moon by spacecraft.

We obtained our first detailed look at the maria from the robotic precursor missions sent to scout the Moon for Apollo. The Ranger 7 spacecraft was the first to return detailed, close-up pictures of the Moon. We learned from these images that the scale of impact cratering continues downward to the limits of resolution and that the maria are covered by the regolith, an unconsolidated blanket of debris that overlies the mare lava bedrock. Lunar Orbiter obtained detailed pictures of a wide variety of landforms attributable to volcanism, including a better view of the flow fronts, small domes and cones, snakelike rilles that served as conduits for molten lava (lava channels and rilles), and irregular craters, whose shapes are difficult to explain by impact origins.

![Figure 39.3](image-url) **Figure 39.3** Flow fronts in Mare Imbrium (arrow). Wrinkle ridges (bottom left) are compressional tectonic features created by loading of the crust by the stack of flood lavas of Mare Imbrium. Flows here are part of a complex that is 800 km long, 20–40 km wide, and 20–60 m thick.

The Surveyor 1, 3, 5, and 6 spacecraft all performed soft landings in the maria. These missions gave us a close-up view of the surface and revealed dark rocks covered with small holes, a morphology typical of lava. The chemical composition of the mare basalts is typical of lava. The chemical composition of the mare basalts is typical of terrestrial lava. The viscosity of the lava is dependent on the composition and temperature of the magma. The low amounts of aluminum and alkali elements and high amount of iron in the lunar magmas, coupled with their relatively high temperature upon extrusion, result in lavas that have an extremely low viscosity. The viscosity of erupted lunar lava was about the same as motor oil at room temperature (about 10 P), a factor of 10 more fluid than terrestrial lava. Such runny, fluid flows spread out great distances, and this property, in addition to the low lunar gravity, accounts for the great lengths (up to hundreds of kilometers) that lava flows can reach on the Moon. Such a fluid character to the lava also explains the tendency of mare lavas to form low, broad structures rather than steep-sided volcanoes and to be erupted in lava channels, as are many basaltic lava flows on Earth, such as on the volcanoes of Hawaii.

Discrete, single flows of mare basalt appear to be rare. Although many units in the maria have a uniform density of impact craters (denoting similar age) and single color, they appear to be made up of many thin, small lava flows. High-resolution photographs sometimes reveal scarps or moats occurring around impact craters that may delineate very thin flow lobes (less than a couple of meters thick). The spectacular lava flows within the Imbrium basin (Figure 39.3) are often used in textbooks to illustrate the volcanic nature of the maria, but these flows are unique on the Moon and their appearance probably indicates a specialized set of eruption circumstances (e.g., the rapid inflation of the crust and discharge of a large magma body over a short period of time). For the most part, the maria appear to be a smooth, nondescript surface and discrete flows are not obvious. It is likely that the maria consist of a complex series of relatively thin lava flows, in which subsequent regolith production and impact erosion have destroyed any original volcanic texture.

Smaller volumes of lava that erupt from a narrow, more localized vent (such as a single-crater) can produce a variety of other interesting landforms. If the volume of lava cools on timescales similar to the rate of magma supply to the vent, small volcanoes form and may assume a variety of different shapes (Figure 39.4). Typically, lunar volcanoes form domes of low relief, a few hundred meters high and a few kilometers across. Such landforms resemble small basaltic shields found in certain volcanic regions of the Earth, such as Iceland and the Snake River plain of Idaho.

Other domes appear to be slightly larger and steeper. One of the most spectacular areas in the maria are the Marius Hills, a complex area of many small domes in Oceanus Procellarum (Figure 39.5). The domes of the...
Marius Hills have steeper sides than do the basalt shields mentioned above. On Earth, such differences in shape are caused by differences in the composition of lava, steeper domes containing more silica and less iron and magnesium than the low, broad shield volcanoes. The causes for steep domes on the Moon are less well understood but appear to be related to styles and rates of extrusion, rather than to lava composition. Eruptions of shorter duration, possibly mixed with minor interludes of ash eruption, would build up a construct with steeper slopes than would the quiet effusion of the very fluid, low-viscosity lavas.

**FIGURE 39.4** Small volcanic features of the lunar maria. Top left: vent area of the late Imbrium flows (Figure 39.3), showing dark mantling and spatter constructs. Bottom left: small shield volcanoes near Hortensius. These features are likely to be small basaltic constructs, erupted from a single vent. Top right: spatter cones aligned along a fissure vent near Hortensius. Bottom right: cones, rilles, and linear vents near the Hortensius volcanic complex.

**FIGURE 39.5** Marius Hills volcanic complex. Image on the left is the topographic map from stereoimages and laser altimetry showing blister-like shape. Image on the top right is from the Kaguya lunar orbiter, showing numerous small domes and cones occurring on up warped, shield-like surface. Bottom right shows the flanks of the complex in Oceanus Procellarum. This feature has been proposed to be a lunar shield volcano.
Domes and cones on the Moon seldom are found in isolation, more often occurring as fields of volcanoes within the maria. The Marius Hills display many domes and cones, all of which occur on the summit of a broad topographic swell (Figure 39.5). The complex is several hundred meters high and has a blister-like profile, suggesting that it may be the lunar equivalent of a shield volcano, as are found on the Earth, Venus, and Mars. The Rümker Hills in northern Procellarum is another volcanic complex, similar in appearance to the Marius Hills, but smaller. Small basaltic shields, such as those found near Hortensius (Figure 39.4), occur in several locations near the margins of Maria Imbrium, Nubium, and Serenitatis. The new precision global topographic data reveal that these volcanic fields are all associated with shield-like blisters, possibly reflecting a phase of basaltic shield building. The last type of central-vent volcano on the Moon is the cinder cone, typified by irregular dark halo craters found along fractures in some crater floors, such as those of the crater Alphonsus. These craters are surrounded by low albedo ash deposits (as shown by remote-sensing data) and are often associated with the volcanic modification of large craters that originally formed by impact.

3.2. Pyroclastics

Both the Apollo 15 and 17 missions returned some unexpected and surprising material. Small glass beads were found in abundance at both sites: clear emerald green glass at the Apollo 15 site and black and orange glass from the Apollo 17 site (Figure 39.6). These glass beads are homogeneous, with a basaltic composition (Table 39.1), and do not contain mineral debris that characterizes impact-melted glasses from the regolith. The surfaces of these glass beads have small amorphous mounds of a variety of volatile elements, including lead, zinc, and halogens such as chlorine. The Apollo 15 green glasses are very rich in magnesium and extremely low in titanium (an unusual composition for a lunar magma), whereas the orange and black Apollo 17 glass is very rich in titanium (Table 39.1). Once these glasses were recognized from these two sites where they occur in abundance, small spheres of similar material were recognized from every landing site. More than 20 varieties of this type of glass are known.

These glasses are of volcanic, not impact, origin and they represent the end products of low-viscosity lava sprayed into space. During basaltic eruptions on Earth, lava effusion is sometimes accompanied by sprays of magma from the vent. Such eruptions are called fire fountains and result in a deposit of ash around the eruptive vent. The ash from Hawaiian eruptions consists of glass that has basaltic composition and is frequently coated by a layer of volatile elements. On the basis of similar characteristics, the lunar glasses represent products of fire fountains that existed on the Moon over three billion years ago. One difference between the lunar and terrestrial ash deposits is that so far no samples of mare basalt lava with compositions corresponding to the lunar ash (presumably derived from the same magma) have been recognized.

Until recently, all lunar volcanic products were thought to be completely free of water. New studies of Apollo 15 green glass revealed a startling relation: the interiors of some of these glasses contain trapped water, dissolved in the glass, indicating that water did exist in the deep interior of the Moon at the time of eruption. Amounts of trapped and dissolved water in the glasses indicate that the lunar mantle may contain up to 700 ppm water, almost as high as some terrestrial mantle values. This water must have been incorporated into the deep lunar interior during accretion and some trapped water may yet remain there.
In addition to pyroclastics in the samples, volcanic glasses are also evident as regional deposits. It was noted during geological mapping that parts of the highlands and maria are blanketed with very dark material (Figure 39.7). Darkness was often equated with geological youth, and these regional dark deposits were thought to represent ash deposits from young volcanic activity. Such a concept was responsible in part for the selection of the Apollo 17 landing site near the margin of one of these regional deposits. It was predicted that this material was volcanic ash because it typically occurs in the vicinity of irregular craters of volcanic origin, indiscriminately covering existing terrain. The principal occurrences of these regional deposits are around the margins of filled mare basins, such as those on the Aristarchus plateau (Figure 39.8), Sulpicius Gallus, Rima Bode (Figure 39.7), and Taurus-Littrow (the Apollo 17 landing site). The Apollo 17 ash is indeed of volcanic origin, but it is old (3700 million years), not young.

The floors of several large craters on the Moon are deformed and fractured. Along some of these fractures, small (typically a few kilometers in size), irregular craters are surrounded by dark, smooth material. These craters are probable volcanic vents, surrounded by ash deposits. They are the lunar equivalent of “cinder cones” found in terrestrial volcanic fields. To create a cinder cone, magma charged with volatiles is squirted out through a very narrow conduit. The release of the low- viscosity lava under high pressure through a small vent causes the lava to spray into a “mist” of liquid rock droplets. The spray of droplets quickly cools in flight and each droplet, thrown on ballistic paths, lands back on the Moon as a small bead of glass. Millions of beads made during an eruption build up a deposit of ash that surrounds the vent.

Phase chemistry allows us to determine which minerals can coexist at certain temperatures and pressures. Studies of the phase chemistry of volcanic glasses have given us a great deal of insight into the very deep lunar interior. It appears that these glasses were generated by the partial melting of an olivine-rich mantle at depths of about 400 km. Moreover, unlike all the mare basalts, the glasses appear to be largely unmodified from their chemical composition at their point of origin. Such a relation indicates that the magmas from which the glasses formed must have ascended very rapidly up through the Moon from deep in the mantle, with little chemical modification from their point of origin. The glasses then erupted into an explosive spray of molten rock at the surface. As such, lunar pyroclastic glass is our best sample of the deep interior and is an important material for determining the bulk composition of the Moon.

Both the fountain nature of the eruption and the small coatings of volatile materials on the glass surfaces indicate that during the main era of mare volcanism over three billion years ago, pockets of gas and other volatile elements existed deep within the Moon. Such an inference is also supported by the presence of the vesicles (holes) that are found in some samples of mare basalt. The principal composition of this gas phase is something of a mystery. Despite the recent discovery of small amounts of water within the glass beads, the reduced chemistry of lunar lavas suggests that the gas phase might have been composed predominantly of carbon monoxide. In any event, we now...
know that a multicomponent complex of a variety of volatile elements was present in the mare source regions.

3.3. Sinuous Rilles

One common landform of the maria deserves special mention, if only because the Apollo 15 mission (July 1971) was sent specifically to investigate one of them. **Sinuous rilles** are narrow, winding valleys that occur primarily within the maria; in size, they are typically a few hundred meters to a kilometer wide, several hundred meters deep and can be tens of kilometers to over hundred kilometers long. Some originate in highlands terrain (Figure 39.8), but all trend downslope and empty into mare material. Many rilles begin in irregular craters, some of which are surrounded by dark mantling material. Several ideas were advanced for the origin of these features before the Apollo missions, including water-cut stream channels. However, the absence of water on the Moon, the basaltic nature of the maria, and the irregular shapes of their source craters led to the consensus that these features are lava channels, some of which were partly roofed over to form **lava tubes**.

The Apollo 15 mission was sent to Hadley Rille, just inside the rim of the Imbrium basin (Figure 39.9). Hadley is one of the largest sinuous rilles on the Moon, being >140 km in length, 1–3 km wide, and several hundred meters deep. The rille begins in an elongate, irregular crater in the Apennine Mountains and winds its way through the maria, snaking back and forth through the mare, finally becoming shallow and appearing to merge into a complex set of fractures north of the Apollo 15 site. The rille was examined at its rim near the landing site, where the rille is 1.5 km wide and 300 m deep. Samples of basalt collected on the rille edge are probably the only samples in the Apollo collections that were taken from bedrock. A ledge of bedrock seen in the orbital photographs probably consists of this mare basalt unit. Layers of mare lava are exposed in Hadley Rille; at the Apollo 15 landing site, layering is confined to the upper 60 m of the rille wall. Color data from the Clementine mission confirm that the walls of sinuous rilles all over the Moon expose outcrops of mare basalt.

Although all workers agree that sinuous rilles are lava channels and tubes, their exact mode of formation remains contentious. On Earth, lava channels are created when a flow extruded at moderate rates cools from the margins inward; this cooling tends to confine the molten, active part of the flow along a central axis. This axis becomes the channel and, in some cases, is bridged over to form a lava tube. In this mechanism, lava channels are primarily “constructional” features, where the overflow of lava builds up levees and raises the topographic level of the flow axis. Lava can accumulate laterally on the walls of the channel, narrowing the channel width; in fact, such narrowing away from the vent is a common feature both of lava channels on Earth and of sinuous rilles on the Moon. Another concept holds that lava channels are primarily “erosional” features. The claim is that the eruption of a very high-temperature, fluid lava would flow turbulently and would soften, melt, and then remove underlying material, forming a lava channel by erosion. In such a model, the sinuous depression in the maria consists of material removed by the flow of liquid lava and incorporated into the mare deposits.

The occurrence of rille source craters in the highlands that are connected to sinuous rilles by channel segments in terra material indicates that some erosion must have occurred. The eroded segment may have been enlarged by collapse, a process common in lava channels. In general, however, geological evidence indicates that sinuous rilles and terrestrial lava tubes and channels are formed dominantly by construction. The large size of sinuous rilles, argued by some as evidence for erosion, can also be a result of the infilling of preexisting depressions, as clearly shown in the case of Hadley Rille, where the lava channel merges into preexisting valleys north of the Apollo 15 landing site (Figure 39.9).

4. NONMARE VOLCANISM

During the pre-Apollo geological mapping of the Moon, many highland landforms, including smooth light plains, wormy textured materials, and steep domes, were
interpreted to be of volcanic origin. The Apollo 16 mission in 1972 was specifically sent to the Descartes highlands to sample these highland (supposedly differentiated) volcanic rocks. However, the rocks from this mission are all impact breccias and the idea of highland volcanism (specifically, the eruption of evolved rocks of higher silica and/or lower iron than the mare basalts) was viewed as discredited by these mission results.

A regional exposure of light plains near the Apollo 15 landing site is the Apennine Bench Formation (Figure 39.9). These plains predate the basalts of Mare Imbrium, but postdate the impact that created the basin. As determined by a variety of remote-sensing techniques, these deposits have composition identical to small fragments of relatively high-alumina basalts of volcanic origin found at the nearby Apollo 15 landing site. These KREEP basalts (Table 39.1) are relatively enriched in potassium (K), the rare-earth elements (REEs), and phosphorus (P). In major-element composition, they are fairly aluminous and iron-poor, compared to most mare basalts. Their origin is still debated, but one idea is that they are partial-melting products of an aluminous source (likely present in the lower crust). If this concept is correct, the Apennine Bench Formation is a major surface manifestation of premare, “highland” (i.e., not mantle-derived) volcanism.

Several isolated domes and mountain-like constructs of very red color occur in the highlands; these features have been suggested to represent a different style of highland volcanism. The blister-shaped Gruithuisen domes are very red and occur along the main rim of the Imbrium basin (Figure 39.10). Spectral data suggest that these features are very low in iron and new spectra in the thermal infrared from the Lunar Reconnaissance Orbiter (LRO) Diviner instrument indicate relatively high silica content. These observations suggest that the domes are piles of extruded silica-rich lavas, similar to terrestrial rhyolite. No such samples have been found in the Apollo collections, but the weight of the new remote-sensing data indicate that the range of volcanic rock types on the Moon may be as great as those found on Earth.

5. THE BEGINNING AND END OF MARE VOLCANISM

The maria were not erupted all at once as a massive flood of lava. The Moon underwent a long and protracted volcanic evolution, characterized by different degrees of interior melting and different types of eruptions of different compositions and places over a long period of time. The production of magma through time is an important basis for reconstructing lunar thermal evolution. Such information allows us to compare the Moon with the other terrestrial planets and to understand the many ways that planets lose their heat.

5.1. Early Phase

The earliest extrusions of lava on the Moon may have been the outpouring of liquid rock onto the still-cooling, crusted-over surface of the early Moon. Indeed, the line between volcanism and crustal formation was probably indistinguishable in early lunar history. The oldest unequivocal volcanism on the Moon is represented by tiny chips of mare basalt found as clasts in the Apollo 14 highland breccias. These fragments represent pieces of a lava flow extruded onto the surface 4200 million years ago, a time so remote that we can only guess at what conditions were like on the Earth. Volcanic eruptions probably were more or less continuous, though sporadic, throughout the period of heavy impact bombardment between 3400 and 3800 million years ago. Traces of this volcanism can be found in the tiny fragments of lava in the highland breccias but may also be evident as a chemical signature in cratered terrains. Some regions of the highlands appear to contain relatively large amounts of iron. This iron could represent unknown highland rocks but it is possible that flows of iron-rich mare basalt have been ground up into regolith of the highlands by the intense impact bombardment of early lunar history.

During the final phases of the heavy bombardment (3900—3800 million years ago), several large, well-preserved basins formed. These basins still have recognizable ejecta blankets and the smooth, far edges of their
debris layers fill craters and other depressions in many areas. Such deposits have all the compositional properties of highland rocks. The Apollo results tell us that the light plains of the highlands are impact ejecta associated with the large multiring basins. However, some of these plains display small (1- to 3-km diameter) impact craters whose ejecta are relatively dark. Dark halo impact craters are found in some of these light plains and cluster in regional groups, such as those in the Schiller–Schickard impact basin. Spectral observations indicate that their low albedo is caused by mare basalts making up the crater ejecta—yet this is an area of impact-generated plains deposits.

These dark halo impact craters are excavating “buried” deposits of mare basalt. Because the plains that bury the lava flows are themselves 3800 million years old, the basalt flows that they cover must be older than this. Thus, light plains on the Moon that display dark halo impact craters are ancient maria—basaltic lavas that were emplaced before 3800 million years ago. This remote-sensing evidence for ancient maria of regional extent complements the sample evidence of tiny fragments of lava in highlands breccias and indicates that the early Moon was a planet of active volcanism as well as subject to intense impact bombardment.

5.2. Main Phase

This stage of mare volcanism began when very high rates of cratering declined to the point where the extruded lava flows were preserved and not destroyed by being ground up into the megaregolith. The impact flux declined very rapidly between 3900 and 3800 million years ago, leveling off after 3800 million years. From that time onward, the extruded lavas were bombarded by impact, but the cratering was not intense enough to destroy the flow surfaces. These lavas make up the visible maria. The earliest lavas from this period, represented by the samples of the Apollo 11 and 17 missions, are the high-titanium basalts of Maria Tranquilitatis and Serenitatis. These flows erupted between 3800 and 3600 million years ago. The complete extent of the early high-titanium lavas cannot be determined because they are partly covered by younger flows; they may be extensive over much of the near side.

A long period of eruption of low-titanium basalt followed, from 3600 million years to an undetermined time, certainly as late as 3100 million years ago, but perhaps much later. Some of the lavas from this time were of the high-aluminum variety, particularly in the eastern maria Crisium and Fecunditatis, as sampled by the Soviet Luna 16 and 24 sample return missions. These basalts date from 3600 to 3400 million years and have moderate to extremely low titanium content. Eruption of low-titanium lavas in Mare Imbrium at 3300 million years ago (Apollo 15) and Oceanus Procellarum at 3100 million years (Apollo 12) followed. The lavas from the Apollo 12 site are the youngest mare basalts in the sample collection.

Eruptions of mare basalt were rare events, even at the height of lunar volcanic activity, between 3800 and 3000 million years ago. Although the maria appear to dominate the Moon (Figure 39.2), especially on the near side, the visible mare deposits actually make up less than about 1% of the volume of the crust. The total accumulated thickness of lava in most mare deposits varies widely but is typically less than a few kilometers and large areas of basalt may be thinner than a few tens of meters. In part, we know this because of the abundance of highlands debris mixed into the mare soils; this fraction may approach 60–70%. Because most of this debris is derived from rocks beneath the local bedrock, the implication is that the stack of basaltic lava flows is thin.

There is a tendency to think of the maria as a hotbed of geological activity on the Moon, at least in the past. Certainly there has been activity in the maria, but very long time spans separate periods of activity. At the Apollo 11 site, several different lava flows are represented among the samples. The oldest flows are 3860 million years old, but samples of flows of a similar composition have a variety of ages, some as young as 3550 million years. In addition, another group of lavas, of a different composition, are also about 3500 million years old. Thus, at this one site, we have evidence for at least four (and perhaps more) separate lava flows, emplaced over a period of >300 million years. This geologically “active” area of the Moon has been completely quiet for a period of time longer than vertebrate life has existed on the Earth.

5.3. Late Phase

The only other source of information on the age of mare lavas is the relative age data provided by geological mapping. This mapping shows that many different kinds of flows spilled out onto the maria between the dated and sampled eruptions, providing for a more or less continuous infilling of the basins from 3800 million years ago onward. A key piece of information for lunar volcanic history is one we do not have—what is the age of the “youngest” mare basalt eruption on the Moon? This question has an important bearing on the thermal history of the Moon. If we know the age of the last eruption, we know when the Moon “shut down” thermally, at least to the point where magma could no longer get out of its interior.

Many areas of the maria have been identified that have a lower density of impact craters than the sampled flows of the Apollo 12 site (aged 3100 million years). The very young lava flows with well-developed scarps in Mare Imbrium have crater densities a factor of two to three lower than the lavas of the Apollo 12 site. Thus, these Imbrium flows may be 1500–2000 million years
old; we cannot estimate their absolute age any more precisely than this. Other relatively young flows are found from Oceanus Procellarum in the west to Mare Smythii in the east. One notable example is the Surveyor 1 landing site (the site of the very first American soft landing on the Moon in 1966) within the lava-filled crater Flamsteed P in Oceanus Procellarum. Crater density suggests that these lavas are some of the youngest flows on the Moon, having an age of about one billion years old. Interestingly, television images returned by Surveyor 1 show that this site has the thinnest regolith of any mare site ever visited, estimated to be between 1 and 1.5 m thick. For comparison, the regolith at the Apollo 12 site (which is underlain by the youngest "sampled" mare basalts) is about 4 m thick. As regolith thickness reflects the age of the bedrock upon which it forms, we have an independent way to estimate the relative age of the Flamsteed basalts from the Surveyor data. These estimated regolith thicknesses are consistent with an age of about 1000 million years for these lavas.

The very last gasps of volcanism on the Moon may have occurred as recently as 800 million years ago. Ejecta from the crater Lichtenberg (20 km in diameter) is covered by a lava flow, which is therefore younger than the crater. Lichtenberg has rays and is a member of the youngest class of craters on the Moon. Estimates of the absolute age of Lichtenberg are uncertain, but craters of this size tend to have their ray systems completely destroyed on timescales of 500–2000 million years. Thus, Lichtenberg and its overlying lava flow are probably “younger” than 2000 million years. This mare unit is the youngest lava flow currently recognized on the Moon.

The Moon has been volcanically active for most of its history. Massive extrusions of lava probably began in dim antiquity, during the era when the Moon’s crust was being ground to a pulp by very high rates of bombardment. Extrusion of basalt continued throughout the era of basin formation, including the eruption of the massive amounts of lava that now underlie the highland plains deposited by the impact that made the Orientale basin. As the basins ceased to form, large expanses of mare deposits began to be preserved, forming the complex series of overlapping lava flows and ash deposits that make up the visible maria. Slow, prolonged infilling of the near-side basins continued for several hundred million years, gradually loading the crust and deforming the filled basins by interior compression and exterior extension. Some impact craters underwent volcanic modification, including interior flooding and the formation of cinder cones on their floors. Large-scale regional deposits of ash were erupted along the margins of some maria. Younger lava deposits tend to be less voluminous than the older deposits, indicating that the intensity of volcanic activity has declined with time. The youngest lava flows are confined to Procellarum and Smythii. Some of these young eruptions may have occurred since one billion years ago, a time that seems remotely old, but, in fact, is “only yesterday” in the ancient and silent world of the Moon.

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