Chapter 5

The Fire Inside

Volcanism and Tectonism in the Maria

To the casual observer, the dark maria of the Moon are very striking. These smooth, low, dark plains occupy about 16 percent of the lunar surface area, but because most are on the near side, they appear to make up a much higher fraction. A variety of ideas about the origin of the maria flourished in the days before the space age. As models for the maria, such concepts as dried-up riverbeds, huge bowls of dust, flows of volcanic ash, or melted material ejected from basins, the largest craters on the Moon, were all proposed. However, in his landmark 1949 book, *The Face of the Moon,* Ralph Baldwin presented convincing evidence that the maria were floods of basalt, a common, dark, iron-rich lava that is abundant on Earth.

Baldwin's supposition did not remain unchallenged, and it took the detailed examination of the Moon in preparation for the Apollo missions, as well as the return of samples of the maria, to settle the issue. The maria indeed are made up of floods of lava, but what is most striking from the returned samples is the age of these lavas. The basalts returned by Apollo range in age from 4.3 to 3.1 billion years old, as old as the very oldest rocks on Earth. (Earth itself is 4.5 billion years old, although rocks of that age have not been found.) The ages of the mare basalt attest to the extreme antiquity of the Moon's surface. The returned lavas also show some interesting chemical characteristics, including a complete absence of any type of mineral that contains water, minerals that nearly always occur in lavas on Earth. These properties, determined during the initial examination of the Apollo samples, gave us a first-order understanding of the basic properties of the Moon.

Lunar Lava Flows

From pictures taken by telescopes on 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; such scarps are very common in the lava flows of basalt found on Earth (Fig. 5.1). These scarps can even be seen in some of the best telescopic pictures of Mare Imbrium. Thus *before* the exploration of the Moon by spacecraft, we had direct evidence for emplacement of the maria by fluid flows. Needless to say, such evidence did not convince the unbelievers; indeed, a few of them remain unconvinced.

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 close-up pictures of the Moon. From these images, we learned that the scale of impact cratering continues downward to the limits of resolution and that the maria are covered by the regolith. Lunar Orbiter spacecraft took detailed pictures showing us a wide variety of landforms most easily attributable to volcanism, including a better view of flow fronts, small domes and cones, snakelike rilles that served as conduits for molten lava (lava channels and tubes), and irregular craters whose shapes are difficult to explain by impact origins. *Surveyors 1, 3, 5,* and *6* all performed soft landings in the maria, giving us a close-up view of the surface and telling us about the nature of the mare surface, including the revelation of some dark rocks covered with small holes, a morphology typical of lava samples.

The samples of the maria returned by the Apollo missions are a form of common lava known as *basalt.* Basalt is a dark lava, made up partly of minerals rich in iron (thus accounting for their dark color) and magnesium. The grain size of basalt is very fine (usually less than 1 mm), a result of the very rapid cooling (Plate 7). Like some Earth basalts, some lunar lavas have small, bubble-like holes *(vesicles),* indicating that the magmas contained gas during eruption. The first basalts returned from the Moon were from the *Apollo 11* landing site in Mare Tranquillitatis. These rocks are remarkable in several respects. The

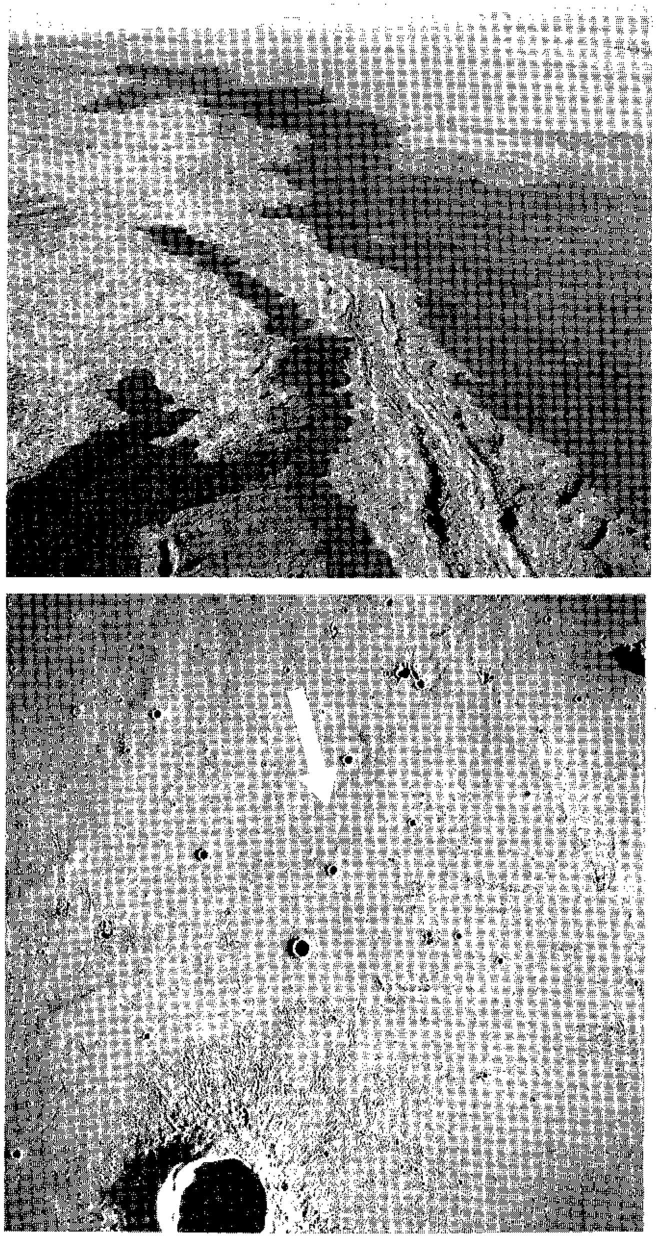

Figure 5.1. Lava flows on Earth and the Moon. Top: a flow of basalt lava in Hawaii, showing a leveed channel within it. Note the lobate margins of the flow. Bottom: flow lobes within Mare Imbrium on the Moon. The flow at top (arrow) displays a leveed channel, similar to the Hawaiian lava flow.

lunar lavas not only are devoid of water or hydrous phase (remember that the hydrogen found in the soil is from the solar wind, see Chapter 4) but also are depleted in all of the volatile elements (those that have very low boiling temperatures), including sodium, zinc, potassium, and phosphorous. Strangely (and surprisingly), the *Apollo 11* basalts have large amounts of titanium, mostly in the form of the mineral ilmenite, an oxide mineral 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 highlands (see Chapter 6), account for the relative darkness (low albedo) of the maria as opposed to the terrae.

Lavas from the Moon were found to contain some minor minerals that are not found in Earth rocks. One of these, another iron-titanium mineral, was given the name armalcolite, in honor of the *Apollo 11* crew (the word comes from the first letters in the names of the crew: *Arm*strong, *Al*drin, and *Col*lins). The compositional properties of the lunar basalts reflect the unique chemical environment in which they formed: a small planet (resulting in low interior pressures) depleted in volatile elements, containing no water, and erupted onto a low-gravity surface in a vacuum. The mare basalts are extremely old by terrestrial standards. Basalts from *Apollo 11* crystallized as a series of lava flows that erupted between 3.8 and 3.65 billion years ago. For comparison, the largest areas of Earth covered by basalt are the floors of the ocean basins. These basalts range in age from zero to about 70 million years old. So the mare lavas on the Moon, some of the youngest lunar rocks, are at least 50–100 times older than comparable rocks from Earth! Basalts *were* being erupted on Earth before 3 billion years ago, but such rocks have been destroyed by terrestrial geological activity.

The chemical composition of the mare basalts has an interesting side effect. In systems of melted rock (magma), the *viscosity* (how "runny" a liquid is) of the liquid depends on the composition and temperature of the magma. The low amounts of aluminum and alkali elements and the high amount of iron in the lunar magmas, coupled with their relatively high temperature at extrusion, result in lavas that have extremely low viscosity. The viscosity of erupted lunar lava is about the same as motor oil at room temperature, much 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 basalt lava flows on Earth, such as the volcanoes of Hawaii.

Mare basalts from the other Apollo missions largely confirm the initial impressions gathered from the study of the first rocks brought back from the Moon, with some surprises and interesting variations. Lavas from the second mission, *Apollo 12*, are lower in titanium than the *Apollo 11* basalts and 600 to 700 million years younger (*Apollo 12* lavas formed about 3.1 billion years ago). Once again, these lavas are low in volatile elements and very rich in iron. The lower titanium and younger ages of the *Apollo 12* basalts confirmed that the maria were not erupted as a single, massive flood of lava across the surface all at one time but rather were formed in an extended process that involved different batches of magma erupting in different places at different times. In short, the samples told us about the complicated volcanic history of a small planet with its own geological evolution.

Mare basalts from the other two mare landing sites extended our picture of mare volcanism, perhaps somewhat misleadingly. *Apollo 15*, which landed just inside the rim of the basin containing Mare Imbrium (Fig. 3.6), returned low-titanium basalts of slightly older age than those from *Apollo 12;* these lavas crystallized about 3.3 billion years ago. *Apollo 17*, landing on the edge of Mare Serenitatis, returned very high titanium basalts, similar to those from *Apollo 11* but of a different age, about 3.7 billion years old. These results suggested to some scientists that the Moon had a fairly simple volcanic history, with early eruptions of high-titanium lavas and late eruptions of low-titanium lavas. The conclusion was also drawn that the Moon "died" volcanically after the *Apollo 12* lavas erupted at 3.1 billion years, a totally unwarranted conclusion that even today persists in lunar folklore.

In addition to the basalt samples returned from the mare

landing sites, little fragments of lava have been found in samples from the highlands as well. These basalts occur in two principal ways: as small rocks in the regolith of highland sites and as fragments of volcanic lava in highland breccias. The former occurrence of mare basalt is likely to result from the deposition of a ray from a crater on the maria, distant from the highland site. Examples are several fragments of high-titanium basalt from the *Apollo 16* regolith. Because secondary craters from the large impact crater Theophilus occur near the site (Fig. 3.8), we infer that these rocks were thrown to the site by the formation of this crater and that they represent a sample of the distant Mare Nectaris. So we can characterize the rocks of distant maria if plausible candidate craters can be identified.

In contrast, mare basalt fragments in highland breccias offer clues to the variety and ages of the earliest phase of lunar volcanism. These breccias from the highlands were assembled before 3.8 billion years ago; therefore, the lava fragments within them must be older than this. Some of the mare basalts are large enough to date by measuring their radioactive isotopes. We find that mare lavas were extruded well before 3.9 billion years ago. The oldest mare basalt yet found is about 4.2 billion years old, only slightly younger than the age of the solidification of the crust. Other fragments date from between 4.1 and 3.9 billion years and display a variety of chemical compositions. Curiously, most of the ancient mare basalt fragments tend to have relatively high contents of aluminum compared with the basalts from the "main phase" of mare eruptions, although a few groups of high-aluminum basalt date from this later era as well.

Basalt is created by partially melting rocks composed mostly of the iron- and magnesium-bearing minerals olivine (a green mineral whose gem version is known as peridot) and pyroxene (a mineral group that includes jade on Earth). From the relatively high density of the mantle, we know that it is largely made up of the minerals olivine and pyroxene. Radioactive, heat-producing elements, such as uranium, made the early mantle very hot—in some places, hot enough to partially melt. These blobs of melt coagulate deep in a planet's interior and slowly migrate upward, where they may force their way to the surface and be extruded onto a planetary surface as a lava flow.

The chemistry of basaltic magmas tells us approximately where they formed within the Moon and what processes have affected them subsequently. Our study of the mare basalts reveals that many regions of the mantle underwent melting episodes at several depths over a very long period of time, a period at least 700 million years long and more likely 1–2 billion years long. These melted pockets found their way to the surface through cracks that they propagated or through the fractures induced by the formation of the giant craters and basins of the highlands. However, only a very tiny percentage of the mantle has been melted to make basalt. Although the maria appear prominent (Fig. 2.1), the lavas are relatively thin compared with the volume of the crust as a whole. It is estimated that the mare basalts probably account for less than 1 percent of the total volume of the crust.

Fire Fountains: Ash Deposits on the Moon

Both the *Apollo 15* and the *Apollo 17* missions returned some unexpected volcanic 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 (Plate 6). These glass samples are homogeneous in their basaltic composition and do not contain the debris of mineral fragments that characterizes the impact-melted agglutinates from the regolith. The surfaces of these glass beads, which have been studied by electron microscope, have small glassy mounds (Fig. 5.2) made up 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 rich in titanium. Once these glasses were recognized from these two sites, where they occur in abundance, small varieties of similar material were recognized at every other landing site. More than twenty varieties of volcanic glass are currently known.

Thus these glasses are of volcanic, not impact, origin, and they represent the products of a spray of low-viscosity lava into space. In Hawaii, eruptions of lava are sometimes accompanied

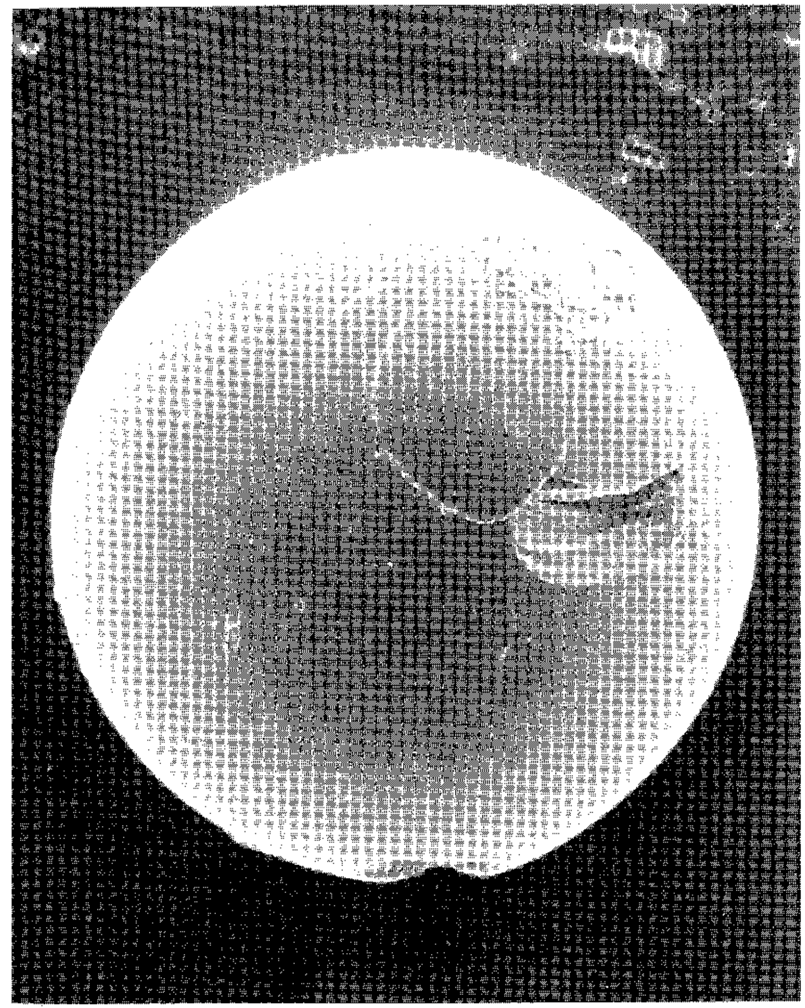

Figure 5.2. SEM image of the surface of a volcanic glass sphere, showing coating by mounds of material. These coatings are made of volatile elements such as sulfur, zinc, and lead and are additional evidence for the origin of these glasses in volcanic fire fountains.

Figure 5.3. A fire fountain of lava in Hawaii. Such eruptions are caused when a volatile-rich basaltic magma is released from a relatively small source vent under high-driving pressure, creating a spray of fine lava droplets. On the Moon such eruptions produced the dark mantle deposits seen in some areas (Fig. 2.16). U.S. Geological Survey photograph.

by very large sprays of magma from the vent. Such spray eruptions are called *fire fountains* (Fig. 5.3) and result in a deposit of ash around the eruptive vent. The ash from Hawaii consists of glass that has a basaltic composition and is frequently coated by a layer of volatile elements. On the basis of similar characteristics, we infer that the lunar glasses represent the products of fire fountains that existed on the Moon over 3 billion years ago. One

difference between the lunar and the Hawaiian ash deposits is that so far no samples of lava corresponding to the lunar ashes in composition and derived from the same magma have been recognized.

The glasses are also evident as regional deposits. During the systematic mapping it was noted that parts of the highlands and maria are blanketed with a very dark material (Fig. 2.16). In the early days of lunar mapping, darkness was often equated with geological youth, and these regional dark deposits were thought to represent the ash deposits of young volcanism. In fact 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 and indiscriminately covers all previous terrain. The principal occurrences of these regional deposits are around the margins of filled mare basins, such as those on the Aristarchus Plateau (Plate 8), Sulpicius Gallus, Rima Bode II (Fig. 2.16), and Taurus-Littrow (the *Apollo 17* landing site). The *Apollo 17* ash is indeed of volcanic origin, but it is old (3.5 billion years), not young.

Several large craters on the Moon have deformed and fractured floors. Along some of these fractures are small (typically a few kilometers in size) irregular craters surrounded by a dark, smooth material (Fig. 5.4). These craters are probably volcanic vents surrounded by ash deposits. They are the lunar equivalent of the *cinder cones* found in terrestrial volcanic fields. To create a cinder cone, magma from depth 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 lands back on the Moon as a small bead thrown on a ballistic path, like a pebble launched from a slingshot. Millions of such beads are made during an eruption, building up a deposit of dark 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 interior. It appears that these glasses

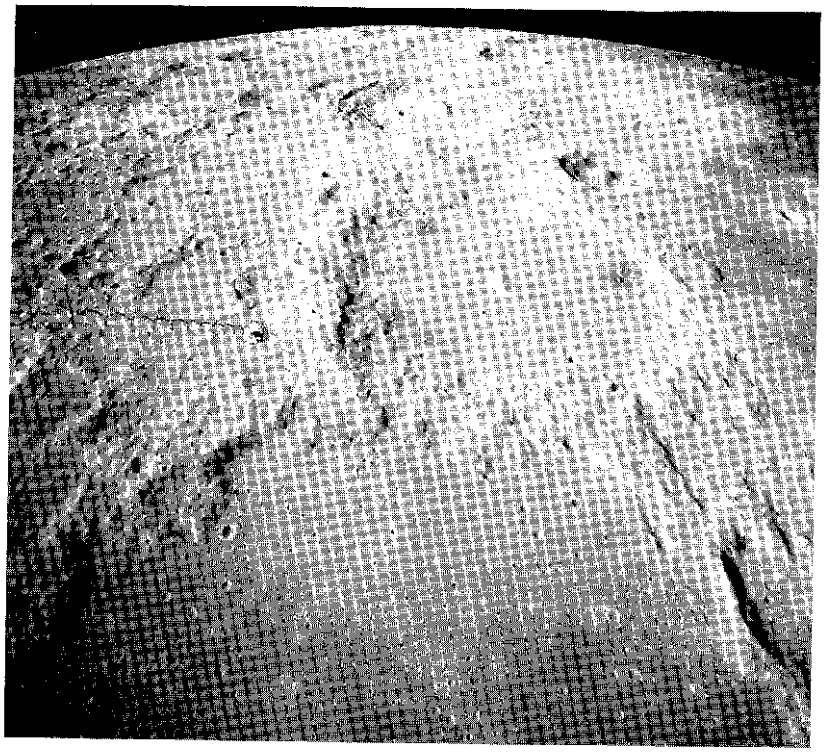

Figure 5.4. The crater Alphonsus (119 km diameter), a fractured-floor crater that has small, dark-halo craters of volcanic origin. These craters may indicate an intrusion of basalt beneath the crater floor.

were generated by the partial melting of an olivine-rich mantle at depths of about 400 km within the Moon. Moreover, unlike all of 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 within the mantle, with little chemical modification from their point of origin. The glasses then erupted into a violent spray at the surface. As such, lunar volcanic glass is our best sample of the deep interior and is an important material for determining the bulk composition of the Moon.

Understanding the mantle is one of the Holy Grails of lunar

science. Although the phase chemistry of the volcanic glass is the best sample of this remote region recognized to date, finding an actual chunk of the material that makes up the mantle would be the best way to comprehend this remote and inaccessible region. The rapid movement of magma through a large section of the Moon during the eruption of the glasses suggests another possibility. Small fragments of the surrounding rock may be ripped from the walls of the conduit through which the magmas rise. Such fragments (called *xenoliths,* meaning "stranger rock," because they are nearly always of a composition very different from the host rock) are found in some lava flows and ash deposits on Earth. It is possible that xenoliths from the mantle might someday be found in the ash deposits of the Moon.

Both the fountain nature of the eruption and the small coatings of volatile materials on the glass surfaces (Fig. 5.2) indicate that pockets of gas and other volatile elements existed deep with the Moon during the main era of mare volcanism over 3 billion years ago. Such an inference is also supported by the vesicles that are found in some samples of mare basalt (Plate 7). The composition of this gas phase is something of a mystery. It certainly is not water vapor (which accounts for almost all of the volatile phase in terrestrial volcanoes) because there is a total absence of water-bearing phases and oxidized material in the mare basalts. The reduced chemistry of lunar lavas makes us think that the gas phase might have been carbon monoxide. A detailed search for trapped bubbles of ancient gas within the glass spheres has not been successful to date, but the quest continues.

Basin Filling and Lava Flooding of the Moon through Time

As mentioned above, 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 at different 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 to understand the many ways that planets lose their heat.

Discrete, single flows of mare basalt appear to be rare. Although many units in the maria have a uniform density of impact craters (denoting continuity of age) and a 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; these scarps may delineate very thin flow lobes (less than a couple of meters thick). The spectacular lava flows within the Imbrium basin (Fig. 5.1) 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 the discharge of a large magma body over a short period of time). For the most part, the maria appear to form a smooth, nondescript surface, and discrete flows are not visible. 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 completely destroyed any original volcanic texture.

Eruptions of mare basalt were rare events, even at the height of lunar volcanic activity, between 3.8 and 3.0 billion years ago. Although the maria appear to dominate the Moon, especially on the near side, the visible mare deposits make up much less than 1 percent 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 100 m. In part we know this because of the abundance of highland debris mixed into the mare soils. As mentioned in Chapter 4, this fraction may approach 60 to 70 percent. Because most of this debris is derived from rocks beneath the local bedrock, the implication is that the stack of mare 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 consider the time spans involved in this activity. At the *Apollo 11* site, several different lava flows are represented among the samples. The oldest flows are 3.86 billion years old, but samples of flows of similar composition have a variety of ages, some as young as 3.55 billion years. In addition, lavas in another group, of different composition, are also about 3.5 billion 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 more than 0.3 billion (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 Earth, except for a few months of activity. If this isn't the epitome of inactivity, what would be?

The very long lengths of time between the extrusions of individual lava flows suggest that these ancient flows may have been exposed to space for extended periods. Thus each basalt flow probably had enough time to develop a layer of regolith on its surface. Subsequent flows might have covered this ancient regolith with a layer of lava. Such a burial opens an exciting possibility: If buried regolith could be found, studies of the dust grains in them would give us a snapshot of the radiation and particle output of the Sun and the galaxy, not as it is now but as it was over 3 billion years ago. The regolith is a "time capsule" of extraordinary magnitude! Layers of ancient regolith could be accessed through exposure in crater, rille (Fig. 4.2), or graben walls—anyplace that layers of lava (the *stratigraphy*) might be exposed.

The volume of material erupted during a volcanic episode determines the shape of the resulting landform. Massive eruptions of large volumes of magma produce long, tongue-shaped, lobate flows, not unlike the flow of molasses poured out onto a tabletop. Such eruptions typically are emitted from long, slot-like vents that permit great volumes of lava to reach the surface quickly. Smaller volumes of lava that come out from a narrow, more localized vent (such as a single-pit crater) can produce a variety of other interesting landforms. If the volume of lava erupted cools on timescales similar to the rate of magma supply to the vent, small volcanoes form and may assume a variety of different shapes (Fig. 2.15). Typically, lunar volcanoes form domes of low relief, a few hundred meters high and a few kilometers across. Such landforms resemble the small basaltic shields found in certain volcanic regions of Earth, such as Iceland and the Snake River plain of Idaho.

Other domes appear to be slightly larger and steeper (Fig. 5.5). One of the most spectacular areas in the maria is the Marius Hills,

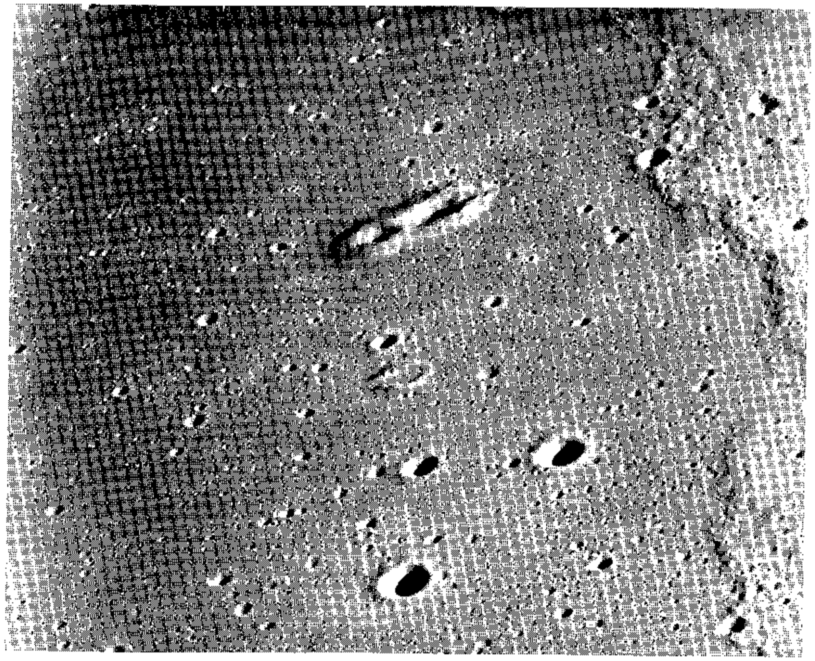

Figure 5.5. Small volcanic cones in Mare Serenitatis. Cones are typically made of cinders and ash, but on the Moon, cinder cones would have a very low profile because of the great distance material is thrown in the low lunar gravity.

the complex area of many small domes in Oceanus Procellarum mentioned in Chapter 2 (Fig. 5.6). The domes of the Marius Hills appear to be slightly steeper than the basalt shields mentioned above. On Earth such differences in shape are caused by differences in the composition of the lava, with steeper domes containing more silica and less iron and magnesium than do 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.

Domes and cones on the Moon are seldom found in isolation but often occur as fields of volcanoes within the maria. The

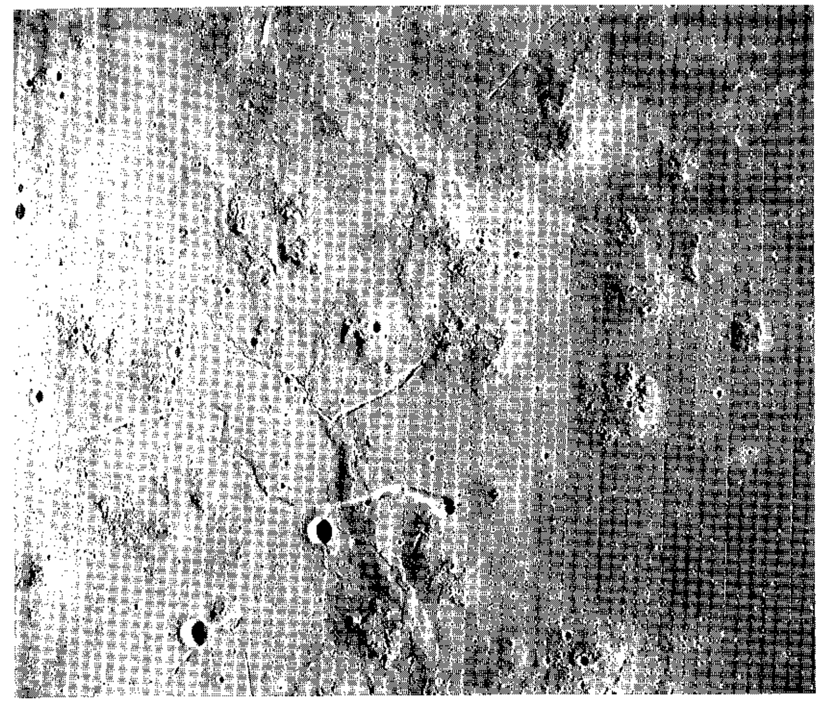

Figure 5.6. The Marius Hills volcanic complex. This area consists of a series of cones, domes, ridges, and sinuous rilles, all situated on a broad, regional upwarp in the maria. It may be the lunar equivalent of the large volcanic shields we see on other terrestrial planets, such as Olympus Mons on Mars.

Marius Hills display many domes and cones, which occur on the summit of a broad topographic swell. The complex is several hundred meters high and has a blister-like profile (Fig. 5.7), suggesting that it may be the lunar equivalent of shield volcanoes found on Earth, Venus, and Mars. The Rümker Hills in northern Oceanus Procellarum form another volcanic complex, similar in appearance to the Marius Hills but smaller. Small basaltic shields, such as those found near Hortensius (Fig. 2.15), occur in several locations near the margins of Maria Imbrium, Nubium, and Serenitatis. 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 (Fig. 5.4).

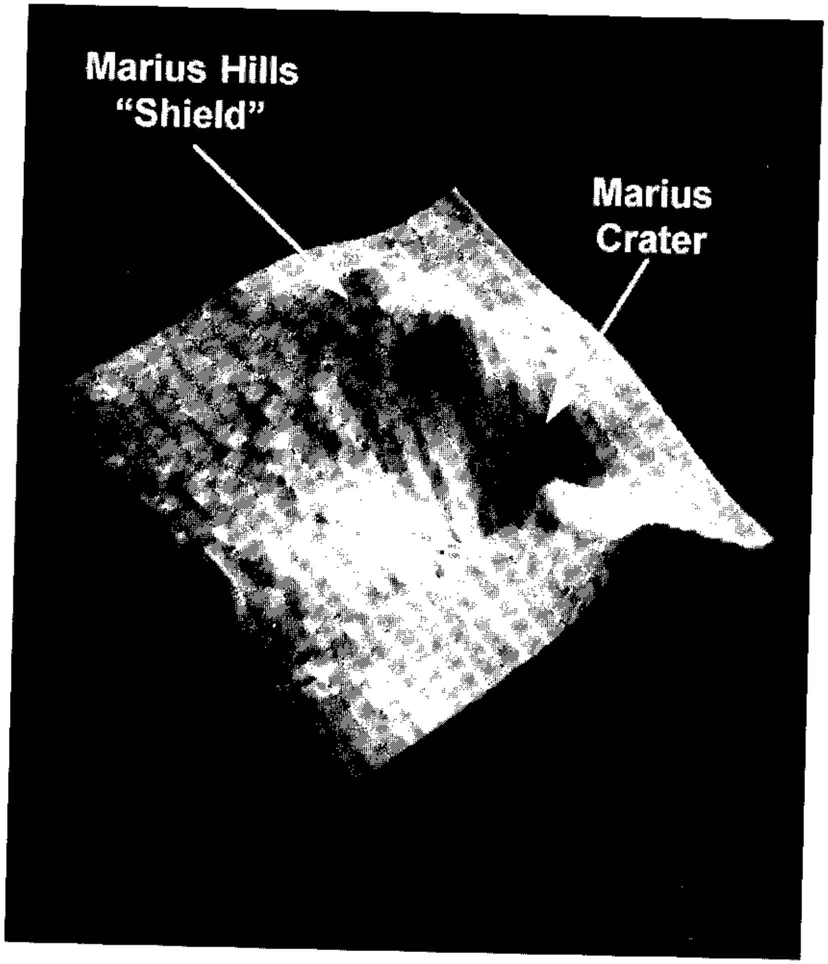

Figure 5.7. Three-dimensional, perspective topographic rendition of the Marius Hills based on Clementine laser altimetry. The shape of volcanic field suggests that this area is a lunar shield volcano.

These features are surrounded by ash deposits (as shown by remote-sensing data) and are often associated with the volcanic modification of large craters that originally formed by impact.

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 (Fig. 3.6). Sinuous rilles are narrow, winding valleys that occur primarily within the maria.

Some originate in highland terrain, but all trend downslope and empty into mare material. Many rilles begin in irregular craters (Fig. 3.6), some of which are surrounded by dark mantle material. Before the Apollo missions, many ideas were advanced for the origin of these features, including their origin as water-cut stream channels. However, the absence of any water on the Moon, the basaltic nature of the maria, and the irregular shapes of these features all have led to the consensus that rilles are lava channels, some of which were partly roofed over to form lava tubes (Fig. 5.8).

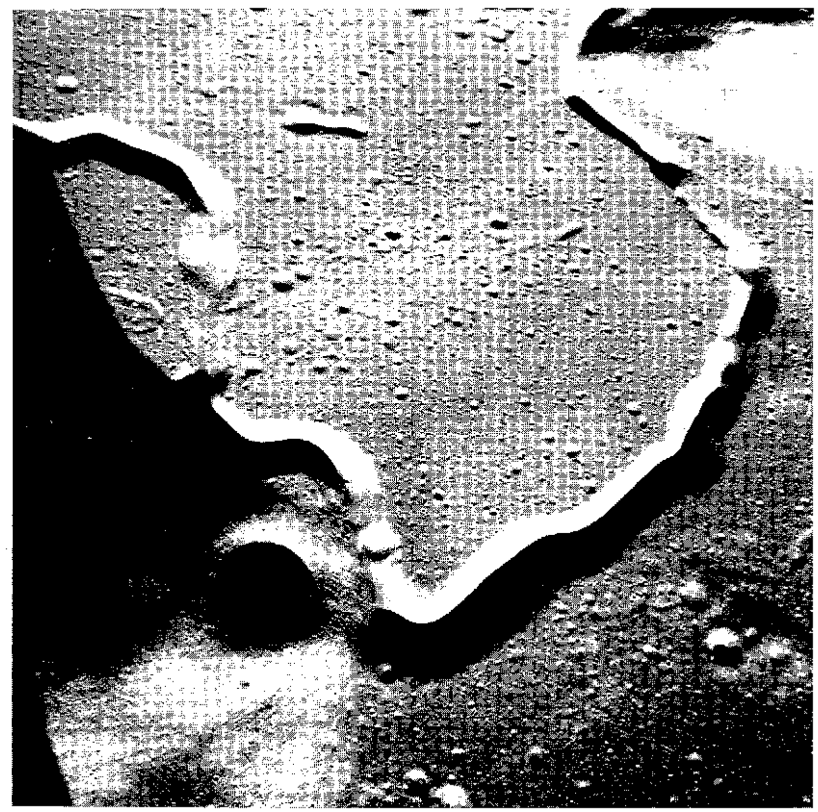

Figure 5.8. Hadley Rille, a lava channel-tube in Mare Imbrium, site of the *Apollo 15* landing. Evidence from Hadley Rille confirmed that sinuous rilles on the Moon are features created by flowing lava.

The *Apollo 15* mission was sent to Hadley Rille, just inside the rim of the Imbrium basin (Fig. 3.6). Hadley is one of the largest sinuous rilles on the Moon, being over 100 km in length, 1 to 3 km wide, and up to 1 km deep. The rille begins in an elongate, irregular crater in the Apennine Mountains, winds its way through the maria, snaking back and forth through the maria, and finally becomes shallow and appears to merge into a complex set of fractures north of the *Apollo 15* site (Fig. 3.6). The rille was examined at its rim near the landing site, where the rille is 1.5 km wide and 300 m deep (Fig. 5.8). 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 (Fig. 4.2). Layers of mare lava are exposed in the walls of Hadley Rille, with all layers confined to the upper 60 m of the rille. Color data from the Clementine mission confirm that the walls of sinuous rilles on the Moon expose mare basalt (Plate 8).

Although all scientists agree that sinuous rilles are lava channels and tubes, the exact mode of formation remains somewhat contentious. On Earth, lava channels are created when a flow that is 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, in which 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 that has emerged in the last few years holds that lava channels are primarily *erosional* features. The claim is that the eruption of 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 in the highlands of rille source craters that are connected to sinuous rilles by channel segments in terra material indicates that some erosion has occurred. This 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 filling in of preexisting depressions, as clearly shown by Hadley Rille, where the lava channel merges into preexisting valleys north of the *Apollo 15* landing site (Fig. 3.6).

Mare Tectonism: Deforming the Surface of the Moon

Tectonism is the process whereby planetary surfaces are broken up, deformed, warped, and stretched. On Earth, a very dynamic and active planet, tectonism is complex and continual. Lunar tectonism is very simple, and there are only two principal classes of tectonic feature. Their mode of formation is well understood, and their distribution patterns are understandable in terms of the filling of the basins by lava. Moreover, the tectonism appears to have been confined mostly to a very narrow interval of time about 3 billion years ago, and subsequent activity has been minor, with some conspicuous exceptions.

Tectonic features can result either from compression (squeezing the crust) or from extension (stretching the crust). Compression produces a common landform in the maria, the *wrinkle ridge* (Figs. 2.12, 2.13). Although wrinkle ridges can be very complex in detail, they are simple in general and are the result of the surface being squeezed laterally. Think of wrinkle ridges as similar to the folds that appear in a tablecloth when the edges are pushed together toward the center of a table. Extension results from stretching the crust, and the resulting landform is a fracture or fissure. If relative movement occurs along the plane of the fracture, it is called a *fault*. Faults are very common tectonic features on all of the solid planets and are often found in the maria of the Moon. Two faults running parallel to each other with a block dropped downward between them is called a *graben*, the most common extensional tectonic feature on the Moon (Fig. 5.9). Think of faults and graben as similar to cracks that develop in a painted surface

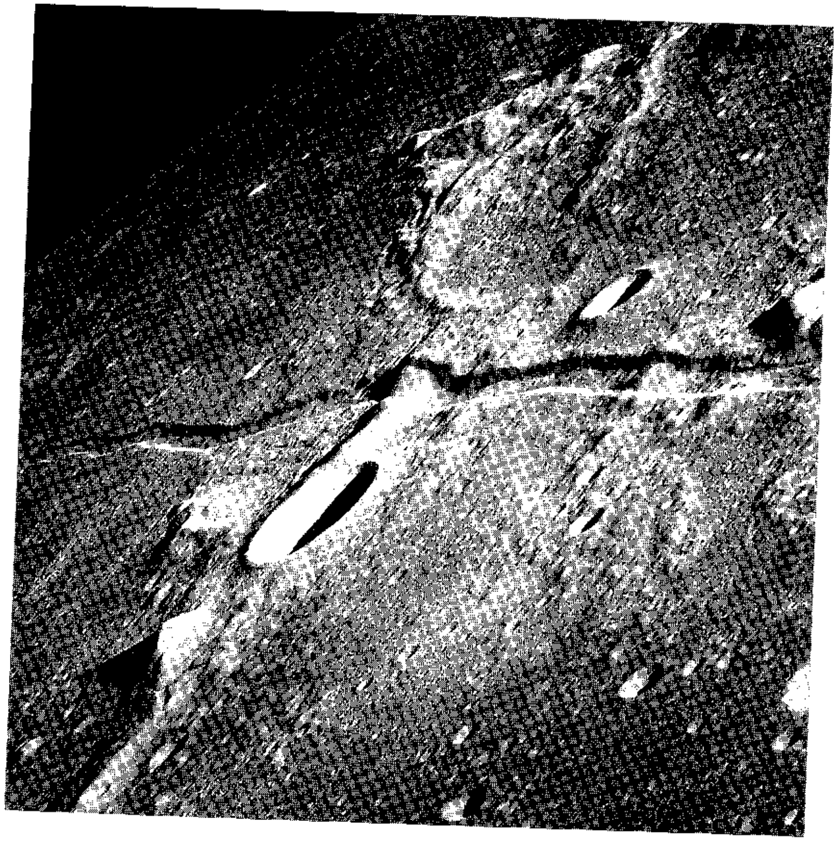

Figure 5.9. A graben, a tectonic feature caused by two parallel, normal faults, with a down-dropped block between them. Most graben on the Moon are found around the edges of the mascon mare basins.

that is bent or bowed outward, where the paint surface breaks because of the strain.

The pattern of deformation of the crust is quite simple in concept. The circular mare basins fill with lava over an extended period of time, up to several hundred million years. As the massive weight of the lava accumulates, it loads the crust, which must accommodate this added weight. The center of the basin sags inward, creating a regional stress field in which the interior of the basin is under compression, forming wrinkle ridges, while

the edges of the basin experience tension, creating faults and grabens. This relation is beautifully illustrated by the patterns of deformation around the Humorum and Serenitatis basins, where we find arcuate grabens along the basin edge and circular wrinkle ridges inside the basin (Fig. 5.10). In a nutshell, this is the tectonic story of the Moon. Nearly all the grabens and wrinkle ridges correspond to this pattern of deformation, following the regional trends created by the impact basins.

The History of Volcanism on the Moon

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 from the *Apollo 14* highland breccias. These fragments represent pieces of a lava flow extruded onto the surface 4.2 billion years ago, a time so remote that we can only guess at what conditions were like on Earth. Volcanic eruptions probably were more or less continuous throughout the period of the heavy bombardment between 4.3 and 3.8 billion years ago. Traces of this epoch of volcanism on the Moon 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 (Plate 9). This iron could represent unsampled highland rocks, but it could also signify flows of iron-rich mare basalt that have been ground up into the regolith of the highlands by the intense impact bombardment of early lunar history.

During the final phases of the heavy bombardment, 3.9 to 3.8 billion years ago, several large, well-preserved basins formed. These basins still have recognizable ejecta blankets, and the smooth, far edges of their debris layers appear to fill craters and other depressions in several areas. Such light plains have all the compositional properties of highland rocks, and Apollo results tell us that the light plains of the highlands are an impact formation, associated with the large multiring basins. However, some

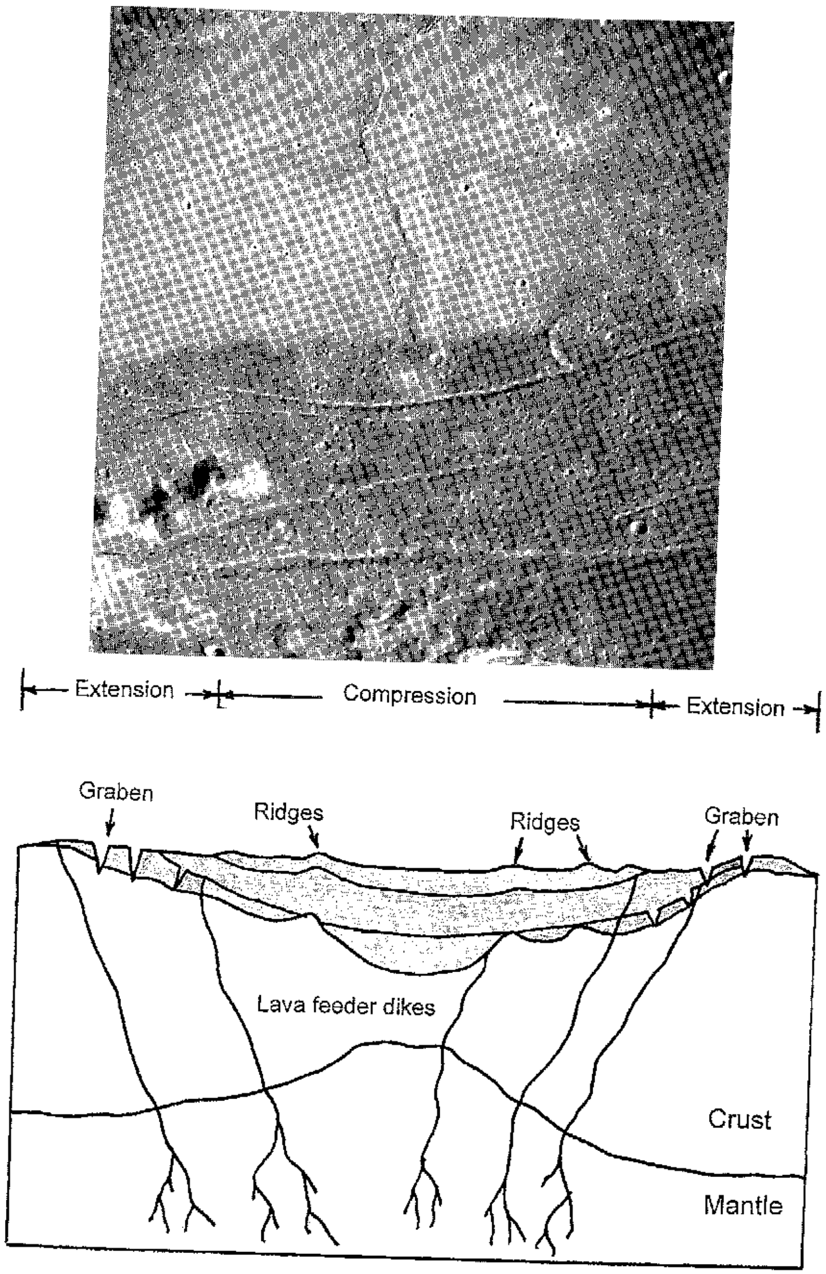

Figure 5.10. The basic tectonic scheme of the Moon. Top: the interior of Mare Serenitatis shows compressional wrinkle ridges while the edge shows extensional graben. In the cross-section drawing (bottom), the loading of the crust by the thick stack of dense lava results in such a stress pattern. After Heiken, Vaniman, and French, *Lunar Sourcebook*, Fig. 4.29.

of these plains display small (1–3 km diameter) impact craters whose ejecta are relatively dark (Fig. 5.11). Be careful not to confuse these dark-halo impact craters with the dark-halo cinder cones found along crater floor fractures (Fig. 5.4). Dark-halo impact craters are found in the light plains of the highlands and cluster in regional groups, such as in the Schiller-Schickard impact basin (Fig. 5.11). Spectral observations of these craters indicate that their low albedo is caused by mare basalt lava making up the crater ejecta—yet this is an area of impact-made plains. How can this be?

The dark-halo impact craters are excavating *buried* deposits of mare basalt (Fig. 5.11). Because the plains that bury the lava flows are themselves 3.8 billion years old, the basalt flows that they cover must be older than this. Thus a map that shows the light plains of the Moon and that displays dark-halo impact craters is a map of ancient maria—basaltic lavas that were emplaced before 3.8 billion years ago. This remote-sensing evidence for the regional extent of ancient maria complements the sample evidence of tiny fragments of lava in highland breccias and indicates that the early Moon was a planet of active volcanism. The extent of the ancient maria is compatible with a broadly declining rate of lava extrusion with time.

The "main phase" of mare volcanism began when the very high rates of cratering typical of early lunar history declined to the point where the lava flows were no longer destroyed and ground up into powder soon after they were extruded. This decline of the impact flux was very rapid between 3.9 and 3.8 billion years ago, leveling off after 3.8 billion years. From that time onward, the extruded lava flows were bombarded by impact, but the cratering did not destroy the flows. These flows make up the visible maria. The earliest lavas from this period are the high-titanium basalts of Maria Tranquillitatis and Serenitatis, basalts returned by the *Apollo 11* and *17* missions. These flows erupted between 3.8 and 3.6 billion years ago. The complete extent of early high-titanium lavas cannot be determined because they are everywhere partly covered by younger flows. We suspect that they are quite extensive over the near side.

A long period of eruption of lower-titanium basalt followed, from 3.6 billion years to an undetermined time, certainly as late as 3.1 billion years ago but perhaps much later. Some of the lavas

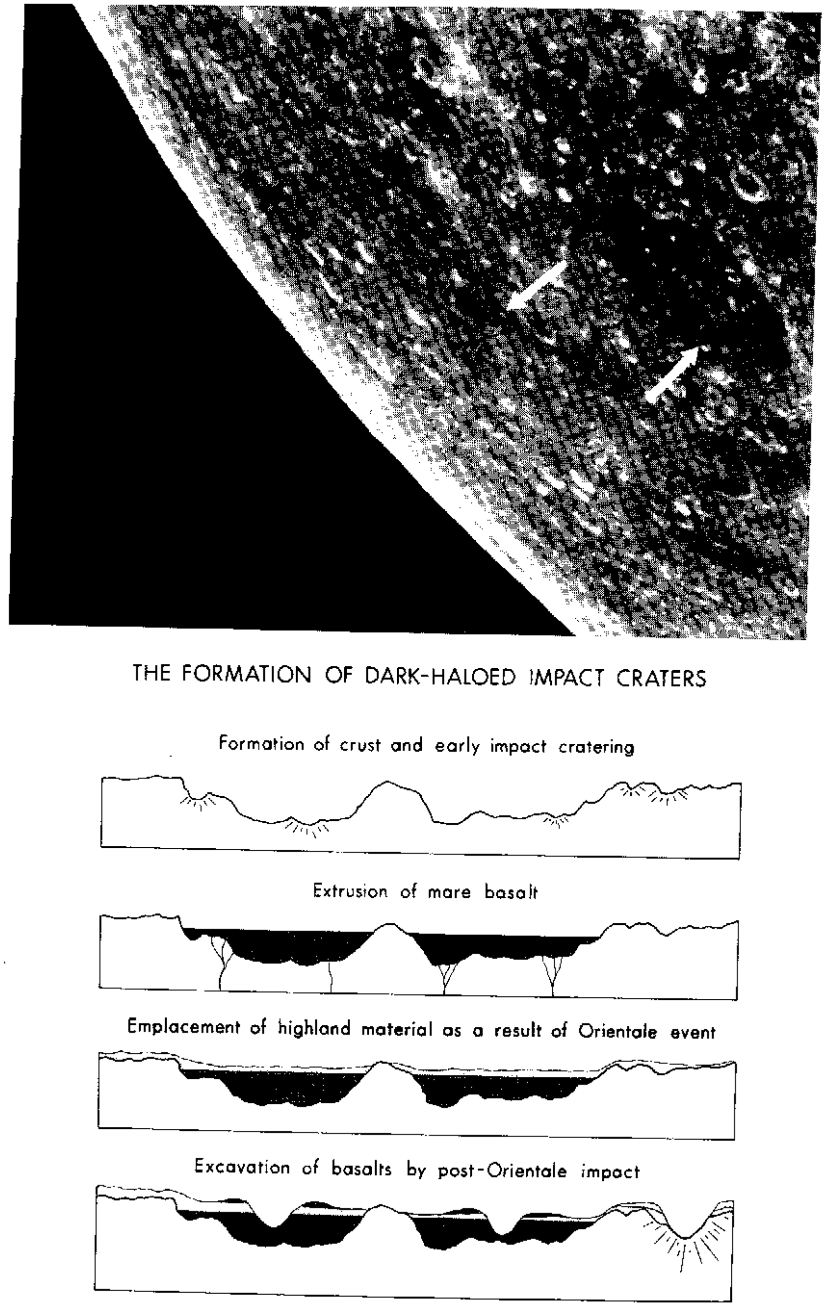

Figure 5.11. Dark-halo craters of impact origin (arrows) indicate ancient mare volcanism. Such craters have excavated basalt from beneath the light-toned, highland plains of the Orientale basin. These lava flows therefore predate the basin, which is 3.8 billion years old. Below: a schematic shows the inferred sequence of events.

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 3.6 to 3.4 billion years and have moderate to extremely low titanium contents. Eruptions of low-titanium lavas in Mare Imbrium at 3.3 billion years ago *(Apollo 15)* and in Oceanus Procellarum at 3.1 billion years *(Apollo 12)* followed. The lavas from the *Apollo 12* site are the youngest mare basalts in the sample collection.

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 continuous filling of the basins from 3.8 billion 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 can discover the age of the last eruption, we will know when the Moon "shut down" thermally, at least to the point where no lava could get out of its interior.

In many books, one reads that volcanism on the Moon stopped about 3 billion years ago. Such a statement is totally without foundation. Many areas of the maria have been identified as having a lower density of impact craters than the sampled flows of the *Apollo 12* site (aged 3.1 billion years). The very young lava flows with well-developed scarps in Mare Imbrium (Fig. 5.1) appear to have high contents of titanium and thorium (a radioactive element) and crater densities of a factor about two to three lower than the lavas of the *Apollo 12* site. Thus these Imbrium flows may be 1.5 to 2 billion years old; we cannot estimate their absolute age any more precisely than this.

Other relatively young flows are found around the Moon, 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 landing on the Moon back 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 possibly as low as 1 billion years old. Interestingly, television images returned by

Surveyor 1 show that this site has the thinnest regolith of all mare sites visited, a depth estimated to be between 1 to 1.5 m thick. For comparison, the regolith at the *Apollo 12* site (which is underlaid by the youngest *sampled* mare basalts) is about 4 m thick. As already mentioned, regolith thickness reflects the age of the bedrock upon which it forms. Thus we have an independent way to estimate the relative age of the Flamsteed P basalts from the Surveyor data. These images are consistent with an age for these lavas of about 1 billion years old.

Consider for a moment a great "what if?" in the history of lunar exploration. The dogma that volcanism died on the Moon at 3 billion years was a direct consequence of the study of samples returned by the *Apollo 12* mission, and as we have seen, these lavas are about 3.1 billion years old. The *Apollo 12* site was picked near a Surveyor landing craft to demonstrate the new concept of a pinpoint landing, a capability that was essential if Apollo was to visit the hazardous areas of the highlands. Mission planners for *Apollo 12* picked the *Surveyor 3* spacecraft as the target site to test pinpoint landing. What if, instead, they had chosen the *Surveyor 1* site, near Flamsteed P? The samples from *Apollo 12* would have been found to be only 1 billion years old. Instead of a Moon that had geologically "died" over 3 billion years ago, we would have marveled that such a small planet could be volcanically active for almost *4 billion* years. What a startlingly different picture of lunar evolution would have emerged! As it is, we do not know (and will not until we return to the Moon) how long the Moon was erupting lava and when its thermal engine shut down.

The very last gasps of volcanism on the Moon may have occurred about 800 million years ago. Ejecta from the crater Lichtenberg (about 20 km diameter) is covered by a lava flow, which is therefore younger than the crater (Fig. 5.12). 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 to 1,000 million years. Thus Lichtenberg, along with its overlying lava flow, is probably *younger* than 1 billion years. This mare unit is the youngest lava flow currently recognized on the Moon.

The sum of the evidence suggests that 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 Orientale basin (Fig. 5.11). As 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 filling of the near-side basins continued for several hundred million years, gradually loading the crust and deforming the filled basins by interior compression and exte-

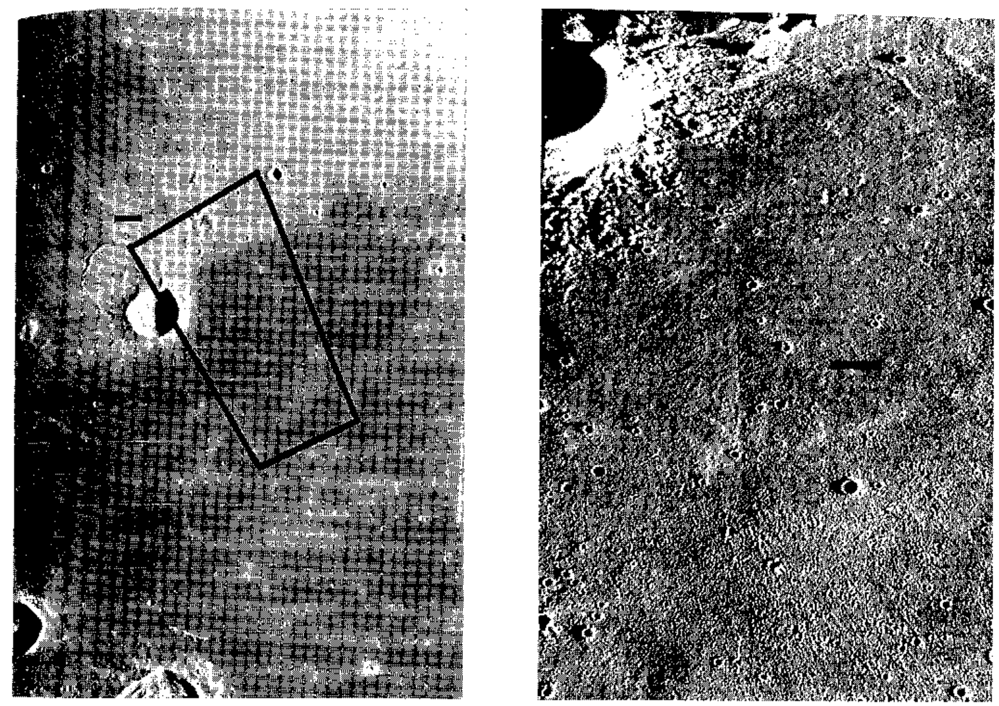

Figure 5.12. The rayed crater Lichtenberg (20 km diameter), partly covered by lava. These lavas must postdate the crater. Because Lichtenberg still shows rays, it must be young in absolute terms, probably younger than 1 billion years. These mare lavas are thus among the youngest basalts recognized on the Moon.

rior extension (Fig. 5.10). Some impact craters underwent volcanic modification, including interior flooding and the formation of cinder cones on their floors (Fig. 5.4). Large-scale regional deposits of ash were erupted along the margins of some maria (Fig. 2.16). 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 (Fig. 5.12). Some of these young eruptions may have occurred since 1 billion years ago, a time that seems remotely old but, in fact, is "only yesterday" in the ancient and silent world of the Moon.

Chapter 6

The Terrae
Formation and Evolution of the Crust

The *terrae* (or highlands) of the Moon are the oldest exposed parts of the original crust (Fig. 6.1). This overwhelming landscape of craters upon craters attests to the lunar history of impact bombardment—the crushing, grinding, melting, and mixing that the crust has experienced. Spectacular, multiring basins (the largest impact craters of the Moon) cover large areas of the highland crust, excavating to great depths and mixing crustal materials on scales of tens of kilometers. Strange landforms that were once puzzling can now be explained as products of this basin formation. To understand this story, we must first read through the overprint of impact. Smooth plains cover vast tracts, some of which are ancient maria that are buried by the debris blankets of the large basins. By looking at the highlands, we look back to the earliest phases of lunar history—to the formation of its crust, probably by large-scale, planetwide melting.

Breccias: Crushed, Fused, and Broken Bits of the Crust

As mentioned previously, a breccia is an aggregate rock made up of bits of preexisting rocks. We have already looked at breccias in relation to the regolith, and their presence attests to the impact bombardment that created the unit in which they are found. In a similar manner, the breccias of the highlands are mute testimony to the epoch of the nearly inconceivable violence that led to the formation of the cratered highlands. Virtually all of the samples returned from the highlands are breccias (Fig. 6.2). Six of the seven meteorites that come from the Moon are breccias. Indeed, because the entire outer layer of the Moon