The Moon of Earth has been a source of inspiration and curiosity throughout history. For millennia, people have gazed at its changing shape and wondered about its nature and origin. The first real answers have come within our lifetimes: we have witnessed the transformation of the Moon from a remote, passive mirror of the Sun to a planetary body with its own complex history. Twelve humans have walked on the lunar surface to gather samples, take photographs, and make other scientific measurements. An even greater number of robotic explorers have scrutinized the Moon from close range.

Thanks to these and other remarkable achievements, we have begun to unravel the lunar story. Today our knowledge of the Moon is deeper and broader than for any other solar-system object save Earth. By studying the processes and evolution of this nearest planetary body, we achieve not only a deeper understanding of geologic processes in general, but a fuller appreciation of the still more complex histories of the terrestrial planets.

LUNAR BASICS

It makes sense that we should know the Moon so well — after all, it is near enough to Earth that crude surface features can be distinguished with the naked eye. By simply looking up at the Moon (Figure 1), you can discern that its surface consists of two major types of terrain: relatively bright highlands (or terrae in Latin) and darker plains sometimes called the lunar “seas” (or maria).

The Moon orbits the Earth every 27.3 days, which is also the time it takes to rotate once on its axis. In other words, the Moon’s “day” is equal to its “year.” In consequence, we see only one hemisphere of the Moon, called the near side. The unseen
hemisphere (the far side) is sometimes termed the “dark side,” but each hemisphere receives the same amount of sunlight. The Moon revolves around Earth in an orbit inclined about 7° to the ecliptic plane (the plane in which the Earth orbits the Sun), but the lunar spin axis is nearly perpendicular (1.5°) to the ecliptic (Figure 2). This relation has some important consequences: at the lunar poles, the Sun always appears at or close to the horizon. Thus, certain areas near the pole may lie in either permanent sunlight or permanent darkness (Figure 3). The existence of such regions may be of great importance to future lunar habitation, as water ice delivered over time by comets should be stable in the permanently dark areas, where the temperature is only about 50° K.

**Figure 1 (above).** A pair of Lick Observatory photographs have been labeled to show selected lunar features and the location of the nine Apollo (A) and Luna (L) sample-return sites.

**Figure 2 (left).** The near-vertical orientation of the Moon's spin axis to the ecliptic plane creates pockets of permanent sunlight and nighttime at the lunar poles. Note that the plane of the lunar orbit falls in neither the Earth's equatorial plane nor the ecliptic, suggesting that some dynamic process early in the history of the Earth-Moon system may have perturbed these orbital relations.

Seen close up or through a telescope (Figure 4), the terrae resolve into an apparently endless sequence of overlapping craters, ranging in size from small pits at the limit of resolution on even the best photographs to large multiringed basins—one of which exceeds 2,600 km in diameter. All of the basins and nearly all of the craters are the consequence of meteoritic impact (see Chapter 6). Indeed, the great number of impact scars in the lunar highlands serves to remind us that the Moon's early history was exceedingly violent. At least the top few kilometers of the crust have been broken up, crushed, and repeatedly mixed by the force of these collisions.

The dark maria cover about 16 percent of the lunar surface and are concentrated on the hemisphere facing Earth. While the
The Moon's south pole, as seen (at left) in a mosaic of visible-light images by the Clementine spacecraft and (at right) in a radar image from Arecibo Observatory in Puerto Rico. Earth is toward the top in both views. Clementine's view has revealed what appears to be a major depression near the south pole (center), evident by the presence of extensive shadows around the pole. This depression either was formed by impact of an asteroid or comet or is part of the enormous South Pole Aitken basin on the far side. A significant fraction of the dark area near the pole may be permanent shadow and sufficiently cold to trap water of cometary origin in the form of ice. Both views reveal a 20-km-wide crater, named Shackleton, whose floor never sees the Sun.

Geologists can go beyond the scrutiny of the Moon's impacts and volcanic landforms. They can assess the lunar surface in a fourth dimension, time, by determining the relative ages of geologically discrete surface units. According to the geologic law of superposition (Figure 5), younger materials overlie, embay, or intrude older ones. This simple but powerful methodology has allowed us to make geologic maps of the maria, which occur almost everywhere within impact basins, they are geologically distinct. Thus, it is important to distinguish between such features as the Imbrium basin (a large, ancient impact structure) and Mare Imbrium (the dark, smooth volcanic plains that later filled the basin). The maria are significantly younger than the highlands and thus have accumulated fewer craters. This difference in crater density is quite pronounced and easily seen through even a small telescope. Long before Apollo astronauts hopped across the lunar surface, geologists recognized that a substantial amount of time had elapsed between the heavy bombardment of the highlands and the final emplacement of the visible maria.

In the very best telescopic photographs, raised lobes can be seen in some mare regions, which led to the idea that the maria consist of volcanic lava flows. Photographs taken by spacecraft in lunar orbit show confirming evidence for such an origin, including sinuous lava channels (called rilles), domes, cones, and collapse pits. Chemical analyses made in 1967 by automated Surveyor landers — and later the study on Earth of actual lunar samples — showed that the maria are indeed volcanic outflows. They appear darker than the terrae because of their higher iron content; the lunar soil becomes momentarily molten where a meteorite hits it, and the heat produces glasses that are iron-rich and thus dark in color.

Figure 3 (above, left and right). The Moon's south pole, as seen (at left) in a mosaic of visible-light images by the Clementine spacecraft and (at right) in a radar image from Arecibo Observatory in Puerto Rico. Earth is toward the top in both views. Clementine's view has revealed what appears to be a major depression near the south pole (center), evident by the presence of extensive shadows around the pole. This depression either was formed by impact of an asteroid or comet or is part of the enormous South Pole Aitken basin on the far side. A significant fraction of the dark area near the pole may be permanent shadow and sufficiently cold to trap water of cometary origin in the form of ice. Both views reveal a 20-km-wide crater, named Shackleton, whose floor never sees the Sun.

Figure 4. Obtained in 1972 by the crew of Apollo 16, this photograph is predominantly of the lunar far side — the hemisphere never seen before the space age. The large dark circle at upper left is Mare Crisium, which is on the eastern limb of the Moon as seen from Earth; below it are Mare Smythii and Mare Marginis. Innumerable craters scar the ancient, light-colored highlands, which have an albedo (reflectivity) of 11 to 18 percent. The darker, smoother maria (albedo: 7 to 10 percent) are younger regions flooded long ago by volcanic outpourings from the interior. These two basic terrains are distinctly visible even to the naked eye.
entire Moon and to produce a formal stratigraphic sequence for events throughout its history (Table 1). However, stratigraphic analysis cannot by itself determine the absolute ages of surface units. Our understanding of those ages, as well as compositions and rock types, had to await the return of samples from the lunar “field trips” undertaken by the Apollo and Luna missions.

UNDERSTANDING THE LUNAR SAMPLES

From 1969 to 1972, six Apollo expeditions set down on the Moon, allowing a dozen American astronauts to explore the lunar landscape and return with pieces of its surface (Figure 6). The initial landing sites were chosen primarily on the basis of safety. Apollo 11 landed on the smooth plains of Mare Tranquillitatis, Apollo 12 on a mare site near the east edge of the vast Oceanus Procellarum. These first missions confirmed the volcanic nature of the maria and established their antiquity (older than 3 billion years). Later missions visited sites of increasing geologic complexity. Apollo 14 landed in highland terrain near the crater Fra Mauro, an area thought to be covered with debris thrown out by the impact that formed the Imbrium basin. Apollo 15 was the first mission to employ a roving vehicle and the first sent to a site containing both mare and highland units (the Hadley-Apennine region). Apollo 16 landed on a highland site near the rim of the Nectaris basin. The final lunar mission in

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**Table 1** (below). The basic system of lunar stratigraphy has evolved, in a relative sense, from thorough scrutiny of the Moon with telescopes and orbiting spacecraft and, in an absolute sense, from the isotopic dating of lunar rocks and soils.

<table>
<thead>
<tr>
<th>System</th>
<th>Age (10⁹ years)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-Nectarian</td>
<td>began: 4.6</td>
<td>Includes crater and basin deposits and many other units formed before the Nectaris basin.</td>
</tr>
<tr>
<td></td>
<td>ended: 3.92</td>
<td>Impact; includes formation of lunar crust and its most heavily cratered surfaces.</td>
</tr>
<tr>
<td>Nectarian</td>
<td>began: 3.92</td>
<td>Defined by deposits of the Nectaris basin (a large multiring basin on the lunar near side); includes almost four times as many large craters and basins as the Imbrian system; may also contain some volcanic deposits.</td>
</tr>
<tr>
<td></td>
<td>ended: 3.85</td>
<td></td>
</tr>
<tr>
<td>Imbrian</td>
<td>began: 3.85</td>
<td>Defined by deposits of the Imbrium basin; includes the striking Orientale basin on the Moon’s extreme western limb, most visible mare deposits, and numerous large impact craters.</td>
</tr>
<tr>
<td></td>
<td>ended: 3.15</td>
<td></td>
</tr>
<tr>
<td>Eratosthenian</td>
<td>began: 3.15</td>
<td>Includes those craters that are slightly more degraded and have lost visible rays; also includes most of the youngest mare deposits.</td>
</tr>
<tr>
<td></td>
<td>ended: about 1.0</td>
<td></td>
</tr>
<tr>
<td>Copernican</td>
<td>began: about 1.0</td>
<td>Youngest segment in the Moon’s stratigraphic hierarchy; encompasses the freshest lunar craters, most of which have preserved rays.</td>
</tr>
<tr>
<td></td>
<td>(to present)</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5** (above, left and right). At left is a photograph of the Apennine Mountains region and at right its corresponding geologic map. Geologists have used this area to define the lunar stratigraphic system (see Table 1). Debris thrown out during the formation of the crater Copernicus (yellow) lies atop all other units and is therefore the youngest. For example, faint, distant rays of Copernicus’ ejecta overlie the crater Eratosthenes (green). Eratosthenes was created on top of mare basalts (pink), which in turn fill the floor of the crater Archimedes (purple). Note that Archimedes lies both on the smooth deposits of the Apennine Bench Formation (light blue) and on the Imbrium basin (dark blue); however, the Apennine Bench embays mountains rimming the Imbrium basin mountains and is thus younger. Thus the scene’s relative ages increase as follows: Copernicus, Eratosthenes, mare deposits, Archimedes, Apennine Bench Formation, Imbrium basin.
the series, Apollo 17, was sent to a combination mare-highland site on the east edge of the Serenitatis basin.

The Soviet Union has acquired a small but important set of lunar samples of its own, thanks to three automated spacecraft that landed near the eastern limb of the Moon's near side. Luna 16 visited Mare Fecunditatis in 1970, and Luna 24 went to Mare Crisium in 1976. A third site, in the highlands surrounding the Crisium basin, was visited by Luna 20 in 1972.

Altogether, these nine missions returned 382 kg of rocks and soil (Table 2), the ground truth that provides most of our detailed knowledge of the Moon. In addition, we have now recognized distinct samples of the Moon that have landed on Earth as meteorites. These serendipitous acquisitions were probably thrown to Earth during impacts on the Moon and provide us with additional, random samples of the lunar surface. Although we do not know their exact source regions, their compositions provide us with additional information on the fine details of lunar chemistry and petrology.

While the most exhilarating discoveries came from studies of lunar material completed years ago, today scientists around the world continue to examine these samples, establishing their geologic contexts and making inferences about the regional events that shaped their histories. What we've learned about the Moon's three major surface materials — maria, terrae, and the soil-like regolith that covers both — is summarized in the following paragraphs.

Regolith. Over the history of the Moon, meteoritic bombardment has thoroughly pulverized the surface rocks into a fine-grained, chaotic mass of material called the regolith (also informally called "lunar soil," though it contains no organic matter). The regolith consists of single mineral grains, rock fragments, and combinations of these that have been cemented...
by impact-melted glass. Because the Moon has no atmosphere, its soil is directly exposed to the high-speed solar wind (see Chapter 4), gases flowing out from the Sun that become implanted directly onto small surface grains. The regolith’s thickness depends on the age of the bedrock that underlies it and thus how long the surface has been exposed to meteoritic bombardment. Regolith in the maria is 2 to 8 meters deep, whereas in highland regions its thickness may exceed 15 meters.

Not surprisingly, the composition of the regolith closely resembles that of the local underlying bedrock. Some exotic components are always present, perhaps having arrived as debris flung from a large distant impact. However, this is the exception rather than the rule. The contacts between mare and highland units appear sharp from lunar orbit, which suggests that relatively little material has been transported laterally. Thus, while mare regoliths may contain numerous terrae fragments, in general these derive not from faraway highland plateaus but are instead material excavated locally from beneath the thin lava flows of the maria.

Impacts energetic enough to form meter-size craters in the regolith sometimes compact and weld the loose soil into a type of rock called breccia. Once fused into a coherent mass, a regolith breccia no longer undergoes the fine-scale mixing and "gardening" taking place in the unconsolidated soil around it. Thus, regolith breccias are "fossilized soils" that retain not only their ancient composition but also the chemical and isotopic properties of the solar wind from the era in which they formed.

Maria. Thanks to our lunar samples, there is no longer any doubt that the maria are volcanic in nature. The mare rocks are basalts (Figure 7), which have a fine-grained crystalline or even glassy structure (indicating that they cooled rapidly) and are rich in the elements iron and magnesium. Basalts are a widespread volcanic rock on Earth, consisting mostly of the common silicate minerals pyroxene and plagioclase, oxide minerals such as ilmenite, and sometimes olivine (an iron-magnesium silicate). The lunar basalts display some interesting departures from this basic formulation. For example, they are completely devoid of water — or indeed any form of hydrated mineral — and contain few volatile elements in general. Basalts from Mare Tranquillitatis and Mare Serenitatis are remarkably abundant in titanium, sometimes containing roughly 10 times more than is typically found in their terrestrial counterparts.

The mare basalts originated hundreds of kilometers deep within the Moon in the total absence of water and the near-absence of free oxygen. There the heat from decaying radioactive isotopes partially melted the mantle, creating magma that ultimately forced its way to the surface. The occurrence of mare outpourings within impact basins is no chance coincidence. The crust beneath these basins must have been fractured to great depth and thinned by excavation by the cataclysmic impacts that formed them. Much later, magmas rose to the surface through these fractures and erupted onto the basin floors.

Figure 7. This mare basalt (top), sample 15016 from the landing site of Apollo 15, crystallized 3.3 billion years ago. The band specimen’s numerous vesicles (bubbles) were formed by gas that had been dissolved in the basaltic magma before it erupted. By shining polarized light through paper-thin slices of a lunar rock (above), geologists can learn much about its crystal structure and composition. Sample 15016 exhibits the minerals plagioclase (lath-shaped black and white crystals), pyroxene (lath-shaped colored crystals), olivine (roundish, brightly colored grains), and ilmenite (opaque).

Figure 8. The western edge of Mare Serenitatis, looking north, as photographed from Apollo 17. The mare’s surface exhibits numerous deep rilles (bottom center) and wrinkle ridges that resulted from strain and deformation within the massive basalt sheet. Mare Imbrium is on the horizon at upper left.
These flecks and spherules of Apollo 17 orange glass are roughly 0.03 mm across. The lunar equivalent to terrestrial ash deposits, they were sprayed onto the Moon’s surface about 3.7 billion years ago in erupting fountains of basaltic magmas. The black particles are pieces of orange glass that have crystallized over time.

Although they may appear otherwise, the maria are typically only a few hundred meters or less in thickness. These volcanic veneers tend to be thinner near the rims that confine them and thicker over the basins’ centers (as much as 2 to 4 km in some places). What the maria may lack in thickness they make up for in sheer mass, which frequently is great enough to deform the crust underneath them (Figure 8). This has stretched the outer edges of the maria (creating fault-like depressions called grabens) and compressed their interiors (creating raised “wrinkle” ridges).

Basalts returned from the mare plains range in age from 3.8 to 3.1 billion years, a substantial interval of time. Small fragments of mare basalt found in highland breccias solidified even earlier — as long ago as 4.3 billion years. We do not have samples of the youngest mare basalts on the Moon, but stratigraphic evidence from high-resolution photographs suggests that some mare flows actually extend (and therefore postdate) young, rayed craters and thus may have erupted as recently as 1 billion years ago.

A variety of volcanic glasses — distinct from the ubiquitous, impact-generated glass beads in the regolith — were found in the soils at virtually all the Apollo landing sites. They even were scattered about the terrae sites, far from the nearest mare. Some of these volcanic materials are similar in chemical composition, but not identical, to the mare basalts and were apparently formed at roughly the same time.

One such sample, tiny beads of orange glass, came from the Apollo 17 site (Figure 9). They are akin to the small airborne droplets accompanying volcanic “fire fountains” on Earth, like those in Hawaii. The force of eruption throws bits of lava high into the air, which solidify into tiny spherules before hitting the ground. The Moon’s volcanic glass beads have had a similar origin. The orange ones from the Apollo 17 site get their color from a high titanium content (greater than 9 percent) and some of them are coated with amorphous mounds of volatile elements like zinc, lead, sulfur, and chlorine. Their existence suggests that the Moon does have volatile elements deep within its interior.

Terrae. One could easily imagine the lunar highlands to contain outcrops of the original lunar crust — much as we find in Earth’s continents. But what really awaited the astronauts was a landscape so totally pulverized that no traces of the original outer crust survived intact. Instead, most of the rocks collected from the terrae were breccias (Figure 10), usually containing fragments from a wide variety of rock types that have been bro-
ken apart, mixed, and fused together by impact processes. Most of these consist of still-older breccia fragments, attesting to a long and protracted bombardment history.

The highland samples also include several fine-grained crystalline rocks with a wide range of compositions. They are not breccias, but they were created during an impact. During large impacts, the shock and pressure were so overwhelming in part of the crust that the "target" melted completely, creating in effect entirely new rocks from whatever ended up in the molten melee. Of course, the colliding "bullets" become part of this mixture, and these impact-melt rocks contain distinct elemental signatures of meteoritic material.

Virtually all of the highlands' breccias and impact melts among our lunar samples formed between about 4.0 and 3.8 billion years ago. The relative brevity of this interval surprised researchers — why were all the highland rocks so similar in age? Perhaps the rate of meteoritic bombardment on the Moon increased dramatically during that time, resulting in a violent period of cataclysm. Alternatively, the narrow age range may merely mark the conclusion of an intense and continuous bombardment that began much earlier, around 4.5 billion years ago, the estimated time of lunar origin. We cannot distinguish between these two models with the data in hand. To resolve the enigma, we must return to the Moon and sample its surface at carefully selected sites.

A substantial number of small, whitish rock fragments found in the mare soils returned by Apollo 11 and 12 astronauts had a composition totally unlike basalts and virtually unmatched on Earth. They consisted almost entirely of plagioclase feldspar, a silicate mineral rich in calcium and aluminum but depleted in heavier metals like iron. At the time, a few prescient researchers postulated that these rocks came from the lunar highlands. The last four Apollo missions, sent to highland landing sites, confirmed that plagioclase feldspar dominates the lunar crust. More recent global data showed that vast regions of the highland surface are made up of this aluminum-rich, iron-poor component...
The resulting implication was broad and profound: at some point in the distant past much of the Moon's exterior — and perhaps its entire globe — had been molten.

The detailed nature of this waterless "magma ocean" is only dimly perceived at present; for example, the lunar surface may not have been everywhere completely molten. The consequences seem clear, however. In a deep, slowly cooling layer of lunar magma, crystals of low-density plagioclase feldspar would have risen upward after forming, while higher-density minerals would have accumulated at lower levels. This segregation process, termed differentiation, left the young Moon with a crust that was, in effect, a low-density rock "froth" tens of kilometers thick consisting mostly of plagioclase feldspar. At the same time, denser minerals (particularly olivine and pyroxene) became concentrated in the mantle below — the future source region of mare basalts.

It is unclear to what depth the magma ocean extended, but the volatile-element coatings discovered on some mare glasses provide an important clue. If the Moon's exterior really was once molten, the most volatile components in the melt would have vaporized and escaped into space. However, the volatile-coated glasses sprayed onto the lunar surface long after the magma ocean solidified. If the glasses' compositions did not change in their upward migration from the lunar interior, they imply that volatile-rich pockets remained (and perhaps still exist) in the upper mantle. The implication, therefore, is that the magma ocean was at most only a few hundred kilometers deep.

The highland samples returned by the last four Apollo crews provided other surprises. Unlike glasses and basalts, which quench quickly after erupting onto the surface, some of the clasts in the highland breccias contained large, well-formed crystals, indicating that they had cooled and solidified slowly, deep inside the Moon. These igneous rocks sometimes occur as discrete specimens (Figure 12). At least two distinct magmas were involved in their formation. Rocks composed almost completely of plagioclase feldspar, with just a hint of iron-rich silicates, are called ferroan anorthosites. These appear to be widespread in the highlands, and they are extremely ancient, having crystallized very soon after the Moon formed (at least one anorthosite having formed 4.50 to 4.52 billion years ago).

The highlands' other dominant rock type is also abundant in plagioclase feldspar, but it contains substantial amounts of olivine and a variety of pyroxene low in calcium. This second class of rocks is collectively termed the Mg suite, so called because they contain considerable amounts of the element magnesium (Mg). These rocks appear to have undergone the same intense impact processing as the anorthosites, but their crystallization ages vary more widely — from almost the age of the Moon to about 4.3 billion years ago.

The anorthosite and Mg-suite rocks could not have crystallized from the same parent magma, so at least two (and probably many more) deep-seated sources contributed to the formation of the early lunar crust. Conceivably, both magmas might have existed simultaneously during the first 300 million years of lunar history. This would contradict our notion of the Moon as a geologically simple world and greatly complicate our picture of the formation and early evolution of its crust.

During early study of the Apollo samples, an unusual chemical component was identified that is enriched in incompatible trace elements — those that do not fit well into the crystal structures of the common lunar minerals plagioclase, pyroxene, and olivine as molten rock solidifies. This element group includes potassium (K), rare-earth elements (REE) like samarium, and phosphorus (P); geochemists refer to this element combination as KREEP. It is a component of many highland soils, breccias, and impact melts, yet the relative abundances of these trace elements remain remarkably constant wherever it is found. Moreover, its estimated age is consistently 4.35 billion years. These characteristics have led to the consensus that KREEP represents the final product of the crystallization of a global magma system that solidified cons ago, so this date reflects the "age" of the lunar crust and mantle as a whole.

Evidence for chemically distinct, widespread volcanic rocks in the highlands — KREEP-rich or otherwise — remains tenuous. Some highland rocks are compositionally similar to mare basalts yet exhibit KREEP's trace-element concentrations. For example, the Apollo 15 astronauts returned with true basalts that probably derive from the nearby Apennine Bench Formation, a large volcanic outflow situated along the Imbrium basin's rim. These
"KREEP basalts" have a well-determined age of 3.85 billion years, so the Imbrium impact must have occurred before this date and probably just before the Apennine Bench Formation extruded onto the surface. Thus, although the extent and importance of highland volcanism remains unknown, it apparently took place early in lunar history and contributed at least some of the KREEP component observed in highland breccias and impact melts.

Apart from actual lunar samples, our knowledge of the distribution of rock types on the Moon derives from a wide variety of remote-sensing data. Some of this information is obtained from telescopic observations of the near side, but most has come from the global survey conducted by the Clementine orbiter in 1994. Clementine carried several imaging cameras sensitive to the visible and near-infrared parts of the spectrum, where absorption bands characteristic of the common lunar rock-forming minerals are found. From Clementine multiwavelength images (Figure 13), we can correlate certain colors with specific geologic units, thus creating the first-ever global maps of the regional rock units that make up the lunar crust.

These remote observations indicate several important facts about the Moon's crust. First, global mapping of iron content confirms that anorthosite is the dominant rock type of the highlands (Figure 11), providing powerful support for the hypothesis of the magma ocean. Another mapping technique using Clementine images has shown that basalts that are highly enriched in titanium, while abundant in the returned sample collection, constitute only a small fraction of the surface lava flows globally. Earth-based spectra indicate that a wide variety of volcanic flows cover the maria, only about a third of which are similar to our sampled basalts. Additionally, these data show that pure anorthosite deposits occur in the inner rings of several basins, including Nectaris, Humorum, and Orientale, and in the central peaks of some craters, including Aristarchus (Figure 13). Both of these latter observations are confirmed by the Clementine data, which also indicate many new rock occurrences that we are just beginning to inventory and catalog. By using the large craters and basins of the Moon as natural "drill holes," we will soon be able to complete a three-dimensional reconstruction of the crust that should offer great insight into the origin and evolution of the Moon.

THE LUNAR INTERIOR

What little we know about the internal structure of the Moon comes from both landed experiments and the tracking of orbital spacecraft. Seismic measurements were made at the Apollo 12, 14, 15, and 16 landing sites. Mild moonquakes shake the lunar interior from time to time and were recorded by the four seismic stations. Some of these seemed to emanate from the upper mantle, while others came from deeper within. Most important, the seismometers were able to record occasional impacts on the Moon — from both natural sources and impacting spacecraft. We derive our knowledge of the interior by measuring how the resulting shock waves of differing frequency and type propagate through and around the lunar globe.

On the basis of these data, we believe that, early in lunar history, an intense meteoritic bombardment shattered and frac-
The laser altimeter on Clementine gave us our first comprehensive look at the topography of the Moon. Surprisingly, the Moon shows nearly the same range of elevation exhibited by the Earth: at least 16 km from the lowest to the highest points. Earth’s wide range is caused by the complex dynamics of plate tectonism, while the Moon’s stems from the preservation of ancient impact basins. Note that while the near side is relatively smooth, the far side shows extreme topographic variation. The large circular feature centered on the southern far side is the South Pole-Aitken basin, 2,600 km in diameter and over 12 km deep.

Gravity mapping obtained from orbiting spacecraft such as Clementine allows us to look at the structure and thickness of the crust globally (Figure 14). On average, the lunar crust is about 70 km thick, but it varies from a few tens of kilometers beneath the mare basins to over 100 km in some highland areas. Under some of the largest basins, the crust was weakened (and indeed partially removed) so much that the mantle has bulged upward. One manifestation of this movement is that basin floors are frequently raised and fractured. Moreover, the intrusion of dense mantle material into the crust changes the local gravity field. An orbiting spacecraft that passes over these mass concentrations, or mascons, experiences slight changes in velocity that can be used to map the mascons’ locations.

The lunar crust varies from region to region, but does it contain stratified layers as well? The sparse seismic results do not require the presence of different rock types in the lower crust. However, we know that mafic (iron- and magnesium-rich) rocks exist in abundance on the rims of the large impact basins Imbrium and Serenitatis — precisely where material blasted out from great depths in the crust should have come to rest. These basaltic rocks have some peculiar properties. They were formed 3.9 to 3.8 billion years ago (the age of the last basin-forming impacts) but cannot be made by melting any combination of the known highland rock types. They also contain rock and mineral clasts of relatively deep-seated origin and have no soil or regolith-breccia fragments within them. If these rocks were thrown out as molten ejecta during the cataclysmic blasts that formed the basins, they provide direct evidence for a lower crust that is more mafic than the average upper crust.

The mantle constitutes about 90 percent of the volume of the Moon and is thought to consist of an olivine-pyroxene mixture that varies both regionally and with depth in complex ways that are not fully understood. Source regions for the mare basalts apparently were situated 200 to 400 km below the surface, so our mare samples provide tracers of the upper-mantle compositions. For example, at least some zones in the mantle must contain large concentrations of ilmenite (an iron-titanium oxide), because they spawned the titanium-rich basalts found in Marc Tranquillitatis and Marc Serenitatis. However, Clementine’s finding that these basalts have minor areal extent makes this compositional anomaly much less acute.

Until the Clementine mission, we had no global map of the topography of the Moon. The spacecraft carried a laser altimeter that repeatedly measured the distance to the surface, and
over time these data were combined into a global map of lunar topography (Figure 15). This new global map has given us several great insights into the nature and structure of the Moon. First, the dynamic range of topography is much greater than we had previously thought, over 16 km, comparable to that of the Earth! Second, the near side appears relatively smooth, with typical relief of only 5 to 6 km, whereas the far side exhibits the full 16-km range of relief. This difference is caused by widespread infilling of the near-side basins by mare basalts and the relative paucity of maria on the far side (Figure 4). Moreover, the wide range of relief on the far side is caused mostly by the presence of the huge South Pole-Aitken basin (Figure 15), the largest excavation on the Moon, which is surprisingly deep — over 12 km, on average.

![Figure 16](image)

*Figure 16. A schematic cross section of the lunar interior, which may or may not include a small metallic-iron core. The Moon's center of mass (CM) is offset by 2 km from its center of figure (CF), so an equipotential surface (which experiences an equal gravitational force at all points) lies closer to the lunar surface on the hemisphere facing Earth. Therefore, magmas originating at equipotential depths will have greater difficulty reaching the surface on the far side, accounting for the paucity of mare deposits there.*

The Moon’s center of mass is offset from its geometric center by about 2 km in the direction of the Earth, probably because the crust is generally thicker on the far side (Figure 14). This may not seem like much of an offset, but it may explain why so few maria exist on the far side of the Moon. Imagine a subsurface boundary akin to a global water table, attracted toward the center of mass with equal gravitational force at every point (Figure 16). Because of the 2-km offset, this equipotential surface lies farther from the top of the crust on the far side. It is possible, therefore, that basalt magmas rising from the interior reached the surface easily on the near side, but encountered difficulty on the far side.

The Moon currently has no global magnetic field. Yet many of our lunar samples cooled in the presence of a surprisingly strong magnetic environment that was most intense 3.6 to 3.8 billion years ago (an estimate considered crude because of our sparse sampling of the crust). The “paleomagnetism” found in certain lunar samples has led some researchers to postulate that the Moon once possessed a significant global magnetic field produced by dynamo motion within a metallic-iron core.

However, the size — and even the existence — of this metallic core remains unresolved. First, the low uncompressed bulk density of the Moon (3.3 g/cm³) means that it is depleted in iron relative to other terrestrial planets and particularly with respect to the Earth (4.5 g/cm³). Second, the best estimate of the lunar moment of inertia implies that the Moon’s interior has a nearly uniform density throughout and that an iron-rich core can be no larger than about 400 km in radius. Third, the Moon’s weak interaction with the Sun’s magnetosphere argues that a highly conducting lunar core can be no greater than 350 to 450 km in radius. Such a core would constitute some 2 to 4 percent of the total lunar mass.

**HYPOTHESES OF LUNAR ORIGIN**

In their surveys of the solar system, astronomers have discovered dozens of satellites around other planets. Yet, of the four inner planets, only the Earth and Mars have moons (and the latter’s are probably captured asteroids). Our Moon is large as satellites go, particularly when compared to the modest size of Earth itself. The creation of the Moon was thus an unusual event in terms of general planetary evolution, and our knowledge of the solar system — however detailed — would be profoundly incomplete without determining how our enigmatic satellite came to exist.

Traditionally, scientists have investigated three models of lunar origin. In the simplest hypothesis, termed *co-accretion*, the Earth and Moon formed together from gas and dust in the primordial solar nebula and have existed as a pair from the outset. A second concept, called the *capture* scenario, envisions the Moon as a maverick world that strayed too near the Earth and became trapped in orbit — either intact or as fragments torn apart by our planet’s strong gravity. According to the third model, termed *fission*, the Earth initially had no satellite but somehow began to spin so fast that a large fraction of its mass tore away to create the Moon.

We had hoped that our astronauts would return with results that would allow us to choose decisively from among these three models. Instead, the Apollo samples have persuaded us that none of these models are completely satisfactory. First, the
The birth of the Moon? During the 1970s, two teams of scientists independently proposed that an object perhaps the size of Mars could have collided with Earth and thrown enough matter into orbit to create the Moon.

Moon’s bulk composition appears to be similar, but not identical, to the composition of the Earth’s upper mantle. Both are dominated by the iron- and magnesium-rich silicates pyroxene and olivine. One important distinction is that, unlike Earth, the Moon generally lacks volatile elements. Another involves the relative dearth in lunar material of what are termed siderophile (“metal-loving”) elements such as cobalt and nickel, which tend to occur in mineral assemblages containing metallic iron. Thus origin by co-accretion would appear doubtful.

A second key constraint comes from oxygen’s three natural isotopes: $^{16}$O, $^{17}$O, and $^{18}$O. Ratios of the abundances of these isotopes found in lunar and terrestrial materials exhibit a single trend, indicating that the Moon and Earth originated in the same part of the solar system (see Chapter 26). By contrast, these same ratios are different in major meteorite groups derived from the asteroids or Mars. So the Earth and Moon must share some common genetic link.

Beyond this geochemical evidence, the mystery of lunar origin has several physical clues. For example, given the dynamics of close encounters, it would have been all but impossible for our young planet to have captured a body of lunar size. Moreover, the Earth-Moon system possesses a great deal of angular momentum, but far less than that needed for fission. Also, the Moon’s orbit does not lie within the plane either of the Earth’s equator or the ecliptic plane (Figure 2). Finally, the Moon is gradually receding from the Earth at roughly 3 cm per year — a curious effect caused by the gravitational coupling of the Moon and our oceans. Tidal bulges raised in the ocean do not lie directly along the Earth-Moon line but actually precede it (Figure 17) because Earth’s rotation drags them along for some distance before they can adjust to the Moon’s changing location in the sky. This misalignment slows the Earth’s rotation slightly (0.00001 second per century). The Moon in turn is pulled forward in its orbit, speeds up, and inches farther away (3 cm per year). The two worlds must surely have been closer in the distant past. However, we may never know just how close because the orbital recession going on now cannot be extrapolated back to the time of lunar origin.
Recently, a fourth idea for the Moon’s birth — the giant-impact hypothesis — has gained popularity and even something of a consensus among planetary scientists. In 1975 two research teams (William Hartmann and Donald Davis, and Alastair Cameron and William Ward) independently proposed that a giant object hit the infant Earth some 4.5 billion years ago (Figure 18). The off-center blow ejected a mixture of terrestrial and impactor material into orbit around Earth that soon coalesced to form the Moon. Since most of this material would have been a white-hot vapor, this scenario can explain both the Moon’s dearth of volatiles and its enrichment in refractory elements (those that remain solid at high temperature). To create a proper Moon, the impactor’s iron and siderophiles must have already been concentrated in its core before the collision; that core then became incorporated into the mantle of the Earth. Theorists’ calculations show that at least half to nearly all of the lunar mass was derived from the outer layers of the colliding body (Figure 19). Remarkably, they also suggest that the ejected matter collapsed into a disk almost immediately and coalesced into nearly final form within just a few years.

The giant-impact hypothesis neatly explains (or allows for) the orientation and evolution of the Moon’s orbit, as well as the Earth’s relatively fast spin rate. Moreover, it makes the uniqueness of the Earth-Moon system seem more plausible. That is, impacts of such cataclysmic magnitude might have occurred only rarely, rather than being a requirement for planetary formation. Part of the reason for this model’s current popularity is doubtless because we know too little to rule it out: key factors such as the impactor’s composition, the collision geometry, and the Moon’s initial orbit are all undetermined.

The advent of the giant-impact hypothesis has not solved the problem of lunar origin. For example, the close genetic relation of Earth and Moon (inferred from the oxygen-isotope ratios) is not an obvious consequence of a giant impact, especially if most of the lunar mass derived from the projectile. Also, the colliding object must have been at least the size of Mars to throw a Moon’s worth of mass into orbit. Consequently, research into the effects of such cataclysmic impacts in early planetary history continues at a brisk pace. But this model for lunar origin appears to explain the most salient features of the Moon with the minimum amount of special pleading.

**THE ONCE AND FUTURE MOON**

Much has happened to the Moon since its formation, and three decades of intensive study by spacecraft now enable us to devise an outline of lunar history (Figures 20, 21). However, the following scenario should be regarded only as a progress report. Many chapters in this history are still obscure, and some of the speculations here could easily be disproved by further research or exploration.

Assuming that a giant impact did create the Moon, the assembly period was quite brief by planetary standards. In fact, chunks of debris cascaded together so rapidly that the growing sphere became very hot and melted almost completely to a depth of at least a few hundred kilometers. As this magma ocean gradually cooled and crystallized, meteorites continued to bombard the Moon at a very high rate, fragmenting and mixing the upper...
most portions of the primordial crust. The Moon's molten outer shell solidified by about 4.3 billion years ago, when the last residues of the original magma system crystallized as the KREEP source region. This was not the end of the Moon's magmatic life, however. Deep within the lunar mantle, radioactive heat created zones of magma that were forced upward and onto the surface as eruptions of volcanic lavas (the maria).

Meanwhile, violent collisions continued to overturn and mix the upper crustal materials thoroughly, destroying most of the original geologic formations within the primordial crust and

Figure 21. Geologic maps of the evolution of the lunar near side at four key dates: (a) Just before the mammoth impact that formed the Imbrium basin, about 3.85 billion years ago. Brown represents pre-Nectarian and Nectarian deposits; pink is ancient mare basalts (now obliterated). (b) Just after the Orientale basin impact (beyond the limb at left), about 3.8 billion years ago. Deposits from the Imbrium basin (blue) dominate much of the lunar near side; purple signifies post-Imbrium deposits. (c) At the end of the Imbrian Period, about 3.2 billion years ago; widespread mare basalts (red and pink) have largely covered the Imbrium basin deposits. (d) At present; greens and yellows represent craters and the ejecta that surround them. The face of the Moon has remained largely unchanged for 3 billion years.
surface outflows of volcanic rock. Some of the larger impacts created multiring basins that penetrated below the broken, intermixed debris layer and threw deep-seated, pristine samples of the Moon’s interior onto the surface for our collection and inspection several eons later.

The Imbrium and Orientale basins represent the last major impacts on the Moon. The Imbrium impact took place an estimated 3.85 billion years ago, and the Orientale impact probably occurred within a few tens of millions of years thereafter. At about this time the cratering rate was declining very rapidly, and more volcanic flows were being preserved from destruction. Mare volcanism may well have been more extensive before the Imbrium basin was formed, but just how much more is not known.

After about 3.0 billion years ago, the cratering rate apparently became relatively constant. The flooding of impact basins by molten basalts also began to fall off rapidly about then. Conceivably, some very small amounts of basalt surfaced onto the maria until the crater Copernicus appeared (roughly 1 billion years ago). But the dominant geologic activity on the Moon ever since has been the ongoing peppering of the surface by meteorites, punctuated by the occasional formation of a large crater. For all practical purposes, the Moon is now geologically dead.

Despite its violent beginnings, the Moon became quiescent long ago and now affords us the opportunity to examine a “fossil” from the early solar system, a planetary body frozen in time. Its most active geologic period, from 4.5 to about 3 billion years ago, perfectly complements the observable geologic record of the Earth, for which rocks older than 3 billion years have been almost completely destroyed (see Chapter 9). Thus, the Moon holds secrets of planetary processes that we could barely imagine before the Space Age, and we see in its battered surface many of the processes ubiquitous throughout the solar system.

Although we have explored the Moon extensively with spacecraft, much of it remains mysterious. Clementine has gone a long way toward satisfying our need for global remote-sensing reconnaissance of the surface. More recently the Lunar Prospector spacecraft arrived on the scene to map the global abundance of uranium and thorium (which track KREEP) and measure the lunar magnetic field. Another of its instruments detected gas emitted from the lunar interior, refining our estimate of the Moon’s bulk composition. Finally, we have obtained a high-fidelity map of the near-side gravity field—our best method for probing the lunar interior, in the absence of a global surface network.

Whereas Clementine data gave us hope that patches of water ice may lie hidden in the permanent darkness near the Moon’s south pole, Lunar Prospector has all but proven the existence of water ice near the south pole and also discovered what appears to be additional ice near the north pole (Figure 22). The spacecraft’s neutron spectrometer detects neutrons ejected when cosmic rays collide with atoms in the Moon’s crust. Many of the initial “fast” neutrons created by these collisions escape into space. Others bounce off other atoms before flying away, and some are slowed (“cooled”) significantly when they strike something similar in mass, such as the nucleus of a hydrogen atom. During its passes over the poles, Lunar Prospector detected increases in these slower neutrons and decreases in the number of medium-speed neutrons that bounce off atoms other than hydrogen. This coincidence indicates that the regolith contains substantial hydrogen, which must exist predominantly in molecules of ice. (Some hydrogen is implanted by the solar wind.) Conservatively, at least 10 million tons of ice is mixed with the uppermost regolith in the shadowed polar regions.

Orbiters can only do so much, however, and lunar scientists hope someday to place a new generation of instruments directly on the lunar surface. For example, a global network of geophysical stations would help elucidate the Moon’s mantle and core structure, variations in its crustal thickness, and its enigmatic paleomagnetism. Measuring the heat flowing from the interior would constrain the Moon’s enrichment in radioactive uranium and thorium and, by association, other refractory elements. Of course, we would welcome the return of additional lunar samples to answer nagging unknowns, such as the age of the youngest lunar lava flows on the Moon. Such a flow could be identified from orbital remote-sensing data, whereupon a small probe is dispatched to collect a single “grab sample” of regolith. Isotopic dating of rock chips within such a sample would yield an absolute age for the lava flow and thus add a key datum to lunar thermal and geologic history.

Right now, there are no plans for future human missions to the Moon, but if launch costs can ever be lowered significantly, we may eventually return there. The establishment of a permanent presence on the Moon opens up scientific vistas that are difficult to foresee clearly. Each Apollo mission provided a surprise, and undoubtedly far more rock types and geologic processes await discovery. From a permanent outpost or base on the Moon, we could begin a detailed exploration of our complex and fascinating satellite that could last for centuries uncovering not only its secrets, but the early history of our home planet as well.

From: NASA/Johnson 1: Thomas Hunt, Kalmbach Publishing 2: Don Anderson (Galetech) 3: Guy Masters (Scrips Inst. of Oceanography) 4: Don Anderson 5: Dixon Rohr (Lamont-Doherty Earth Observatory) 6: Adam Dziewonski (Harvard Univ.) 7: NASA 8: Walter Smith (NOAA) and David Sandwell (Scrips Inst. of Oceanography) 9: Scientific American 10: Don Davis 11: Stephen Grand (Univ. Texas), Bob van der Hilst (MIT) 12: Lisa G. Agabian (Plates Project, Univ. Texas) 13: Frank Lemoine and James Fawley (NASA/Goddard) Table 1 and 2: Don Anderson

CHAPTER 10: The Moon

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CHAPTER 11: Mars

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CHAPTER 12: Interiors of the Terrestrial Planets

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CHAPTER 13: Atmospheres of the Terrestrial Planets

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