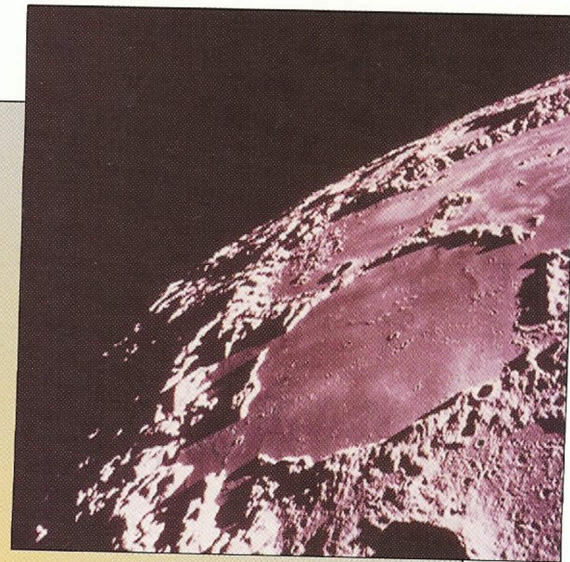
The Moon



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CHAPTER 12

The Moon is a unique satellite in the solar system, the largest relative to its planet. It has a radius of 1738 km, a density of 3.344 g/cm^3 (Earth density = 5.52 g/cm^3), and a mass that is 1/81 that of the Earth. Its orbit is inclined at 5.09° to the plane of the ecliptic. It rotates on its axis once every 27 days. The **moment of inertia** value is 0.3931, consistent with a small increase of density toward the center. The current consensus is that the Moon formed as a consequence of the collision with the Earth of a Mars-sized body about 4.5 billion years ago. The rocky mantle of the impactor spun out to form the Moon, while the core of the impactor fell into the growing Earth. This model explains the high spin of the Earth–Moon system, the strange lunar orbit, the low density of the Moon relative to the Earth, and the bone-dry and refractory composition of our satellite. The model also provides a source of energy to melt the early Moon. The geochemical and petrological evidence is clear that the Moon was molten and floated a crust of feldspar about 4.45 billion years ago. This forms the present white highland crust. The interior crystallized into a sequence of mineral zones by about 4.4 billion years ago. Possibly a small metallic core formed, although the composition of the core is still under debate. Major impacts produced many craters and multiring basins, probably during a spike or "cataclysm" around 3.9–4.0 billion years ago. The oldest basin observed is the South Pole–Aitken Basin and the youngest is the Orientale Basin, which formed 3.85 billion years ago. Beginning about 4.3 billion years ago, and peaking between 3.8 and 3.2 billion years ago, partial melting occurred in the lunar interior, and basaltic lavas flooded the low-lying basins on the surface. This occurred mostly on the nearside, where the crust is thinner. Major activity ceased around 3.0 billion years ago, although minor activity may have continued until 1.0–1.3 billion years ago and the Moon has suffered only a few major impacts (forming, for example, the young rayed craters such as Copernicus and Tycho) since that time.

1. Introduction

The Earth's Moon (Fig. 1) is a unique satellite in the solar system. None of the other terrestrial planets possesses comparable moons: Phobos and Deimos, the tiny satellites of Mars, are probably captured asteroids. Most of the 130 or so satellites of the outer planets are composed of low-density rock-ice mixtures and either formed in accretion disks around their parent planets or were captured. None of them resembles the Moon so that the origin of our unique satellite has been an outstanding problem. It is in plain sight, accessible even to naked-eye observation, yet it has remained until recently one of the most enigmatic objects in the solar system.

The Moon has played a pivotal role in human development. Both the axial tilt and the 24-hour rotation period

FIGURE 1 A composite full-Moon photograph that shows the contrast between the heavily cratered highlands and the smooth, dark basaltic plains of the maria. Mare Imbrium is prominent in the northwest quadrant. The dark, irregular, basalt-flooded area on the west is Oceanus Procellarum. Mare Crisium is the dark circular basalt patch on the eastern edge. (Courtesy of UCO/Lick Observatory, photograph L9.)

of the Earth may be a direct consequence of lunar formation. Indeed, the lunar tidal effects may have been crucial in providing an environment for life to develop. It is also possible that the Moon has stabilized the obliquity of the Earth, preventing large-scale excursions that might have had catastrophic effects on evolution. The other planets are so remote as to be only points of light, or enigmatic images in telescopes.

Without the presence of the Moon, with its distinctive surface features and its regular waxing and waning phases to stimulate the human imagination, it might have taken much longer for us to appreciate the true nature of the solar system. In many other ways, such as the development of calendars and the constant reminder that there are other rocky bodies in the universe, the Moon has had a profound effect on the human race. One of the outstanding human achievements of the latter half of the 20th century has been the exploration of the Moon, including the landing of astronauts on the lunar surface and our understanding both of lunar evolution and origin.

2. Physical Properties

2.1 Orbit and Rotation

The Moon revolves about the Earth in a counterclockwise sense, viewed from a north polar orientation. This is the same sense in which the Earth and the other planets rotate around the Sun. The orbit of the Moon around the Earth is elliptical with a very small eccentricity ($e = 0.0549$) so that it is nearly circular. The orbital speed of the Moon is 1.03 km/s. The Moon rotates on its axis once every 27.32166 days. This is the sidereal month and corresponds to the time taken for the average period of revolution of the Moon about the Earth.

The lunar synodical month or lunation (the time between successive new moons) is 29.5306 days, longer than the sidereal month, as the Earth has also moved in its orbit around the Sun during the interval. The lunar orbit is neither in the equatorial plane of the Earth nor in the plane of the ecliptic (the plane of the Earth's orbit around the Sun), but is closer to, but inclined at 5.09°, to the latter. The axis of rotation of the Moon, however, is nearly vertical to the plane of the ecliptic, being tilted only at 1°32′ from the ecliptic pole. The inclination of the lunar orbit to the equatorial plane of the Earth varies from 18.4° to 28.6°.

The mean Earth–Moon distance is 384,400 km or 60 Earth radii, but the distance varies from 363,000 to 406,000 km. The moon is closest to the Earth at **perigee** and farthest at **apogee**. The Moon is receding from the Earth, due to tidal interaction, at a rate of 3.74 cm/year.

Tidal calculations have often been used to assess the history of the lunar orbit, but attempts to determine whether the Moon was once very much closer to the Earth, for example, near the **Roche limit** (about 18,000 km), which would place significant constraints on lunar origins, produce nonunique solutions. The problem is that the past distribution of land and sea is not known precisely. The continents approached their present dimensions only about 2 billion years ago in the Proterozoic era; oceans with small scattered land masses dominated the first half of Earth history so that the extent of shallow seas, which strongly affect tidal dissipation, is uncertain. Work on tidal sequences in South Australia has shown that, in the late Precambrian (650 million years ago), the year had 13.1 ± 0.5 months and 400 ± 20 days. At that time, the mean lunar distance was 58.4 ± 1.0 Earth radii so that, during the Upper Proterozoic, the Moon was only marginally closer to the Earth.

Over 57% of the surface of the Moon is visible from the Earth, with variations of 6.8° in latitude and 8° in longitude. These variations in the lunar orbit are referred to as librations and are due to the combined effects of wobbles in the rotations of Earth and Moon.

The phases of the Moon as seen from the Earth are conventionally referred to as new moon, first quarter, full moon, and last quarter.

2.2 Eclipses

The presence of the Moon in orbit about the Earth close to the ecliptic plane produces two types of eclipses, so-called lunar and solar, that are visible from the Earth. Lunar eclipses occur at full moon, when the Earth lies between

Moon and Sun and so intercepts the light from the Sun. The Moon usually appears red or copper-colored during such events, as a portion of the red part of the visible solar spectrum is refracted by the Earth's atmosphere and faintly illuminates the Moon. When the Moon is partly shadowed, the border forms an arc of a circle, thus proving that the Earth has a spherical form. Typically there are two lunar eclipses a year, and they can be seen from all parts of the Earth where the Moon is visible.

In contrast, solar eclipses, in which the new moon comes between the Earth and the Sun, are visible only from small regions of the Earth. Between two and five occur each year, but they reoccur at a particular location only once in every 300 or 400 years. The basic cause of the variability in eclipses is that the lunar orbit is inclined at 5.09° to the plane of the orbit of the Earth about the Sun (the plane of the ecliptic). For this reason, a solar eclipse does not occur at every new moon. It is an extraordinary coincidence that, as seen from the Earth, the Moon and the Sun are very close to the same angular size of about 0.5° despite the factor of 389 in their respective distances, so that the two disks overlap nearly perfectly during solar eclipses. The Moon and Sun return to nearly the same positions every 6585.32 days (about 18 years), a period known to Babylonian astronomers as the saros, while other cycles occur up to periods of 23,000 years.

In past ages, eclipses were regarded mostly as ominous portents, and the ability to predict them gave priests, who understood their cyclical nature, considerable political power. There are many examples of the influence of eclipses on history, one notable example being the lunar eclipse of August 27, 413 B.C. This eclipse delayed the departure of the Athenians from Syracuse, resulting in the total destruction of their army and fleet by the Syracusans. Thus, there is a certain irony that the word eclipse is derived from the Greek term for "abandonment."

2.3 Albedo

Albedo is the fraction of incoming sunlight that is reflected from the surface. Values range from 5 to 10% for the maria to nearly 12–18% for the highlands. At full moon, the lunar surface is bright from limb to limb, with only marginal darkening toward the edges. This observation is not consistent with reflection from a smooth sphere, which should darken toward the edge. This led early workers to conclude that the surface was porous on a centimeter scale and had the properties of dust. The pulverized nature of the top surface of the **regolith** provides multiple reflecting surfaces, accounting for the brightness of the lunar disk.

2.4 Lunar Atmosphere

The Moon has an extremely tenuous atmosphere of about 2×10^5 molecules/cm^3 at night and only 10^4 molecules/cm^3 during the day. It has a mass of about 10^4 kg, about 14 orders of magnitude less than that of the terrestrial atmosphere. The main components are hydrogen, helium, neon, and argon. Hydrogen and neon are derived from the solar wind, as is 90% of the helium. The remaining He and ^{40}Ar come from radioactive decay. About 10% of the argon is ^{36}Ar, derived from the solar wind.

2.5 Mass, Density, and Moment of Inertia

The mass of the Moon is 7.35×10^{25} g, which is 1/81 of the mass of the Earth. Although the Galilean satellites of Jupiter and Titan are comparable in mass, the Moon/Earth ratio is the largest satellite-to-parent ratio in the solar system. (The Charon/Pluto ratio is larger, but Pluto, an icy planetesimal, is less than 20% of the mass of the Moon and is the king of the Kuiper Belt, rather than a major planet.) The lunar radius is 1738 ± 0.1 km, which is intermediate between that of the two Galilean satellites of Jupiter, Europa (r = 1561 km) and Io (r = 1818 km). The Moon is much smaller than Ganymede (r = 2634 km), which is the largest satellite in the solar system.

The lunar density is 3.344 ± 0.003 g/cm^3, a fact that has always excited interest on account of the Moon's proximity to the Earth, which has a much higher density of 5.52 g/cm^3. The lunar density is also intermediate between that of Europa (d = 3.014 g/cm^3) and Io, the innermost of the Galilean satellites of Jupiter, with a density of 3.529 g/cm^3. The other 130-odd satellites in the solar system are ice-rock mixtures and so are much less dense.

The lunar moment of inertia is 0.3931 ± 0.0002. This requires a slight density increase toward the center, in addition to the presence of a low-density crust (a homogeneous sphere has a moment of inertia of 0.400; the value for the Earth, with its dense metallic core that constitutes 32.5% of the mass of the Earth, is 0.3315).

2.6 Angular Momentum

The spin **angular momentum** of the Earth–Moon system is anomalously high compared with that of Mars, Venus, or the Earth alone. Some event or process spun up the system relative to the other terrestrial planets. However, the angular momentum of the Earth–Moon system (3.41×10^{41} g·cm^2/s) is not sufficiently high for classic fission to occur. If all the mass of the Earth–Moon system were concentrated in the Earth, the Earth would rotate with a period of 4 hours. Yet this rapid rotation is not sufficient to induce fission, even in a fully molten Earth.

2.7 Center of Mass/Center of Figure Offset

The mass of the Moon is distributed in a nonsymmetrical manner, with the center of mass (CM) lying 1.8 km closer to the Earth than the geometrical center of figure (CF) (Fig. 2). This is a major factor in locking the Moon into synchronous orbit with the Earth so that the Moon always presents the same face to the Earth, although librations

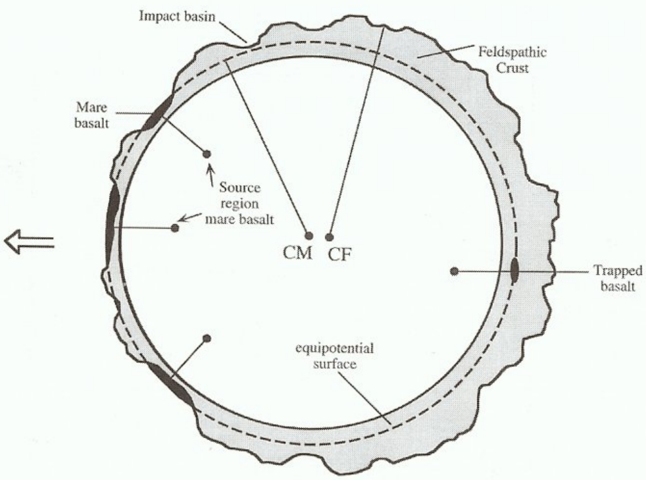

FIGURE 2 A cross section through the Moon in the equatorial plane that shows the displacement toward the Earth of the center of mass relative to the center of the figure, due to the presence of a thicker farside, low-density feldspathic crust. It also illustrates that an equipotential surface is closer to the surface on the nearside. Magmas that originate at *equal depths* below the surface will have greater difficulty in reaching the surface on the farside, a problem exacerbated by the greater farside crustal thickness. However, not all flooding of lunar basins is at the same level. Some magmas originate at different depths, whereas others come from different locations at different times. Others may extrude smaller or greater amounts of lava, leading to differences in the amount of basalt filling a particular basin. These factors contribute to filling of mare basins to differing depths not necessarily related to the equipotential surface.

allow a total of 57% of the surface to be visible at various times.

Various explanations have been advanced to account for the offset of the center of mass from the center of figure. Dense **mare** basalts are more common on the nearside, but their volume is insufficient by about an order of magnitude to account for the effect. It has also been suggested that this offset could arise if the lunar core is displaced from the center of mass. However, such a displacement would generate shear stresses that could not be supported by the hot interior. Another suggestion is that a density asymmetry developed in the mantle during crystallization of the magma ocean, with a greater thickness of low-density Mg-rich **cumulates** being concentrated within the farside mantle. It is unlikely that such density irregularities would survive stress relaxation in the hot interior, unless actively maintained by convection. The conventional explanation for the CM/CF offset is that the farside highland low-density crust is thicker, probably a consequence of asymmetry developed during crystallization of the magma ocean. The crust is massive enough and sufficiently irregular in thickness to account for the CM/CF offset. The scarcity of mare basalts on the farside (Fig. 3) is consistent with a thicker farside crust. Lavas rise owing to the relative low density of the melt and do not

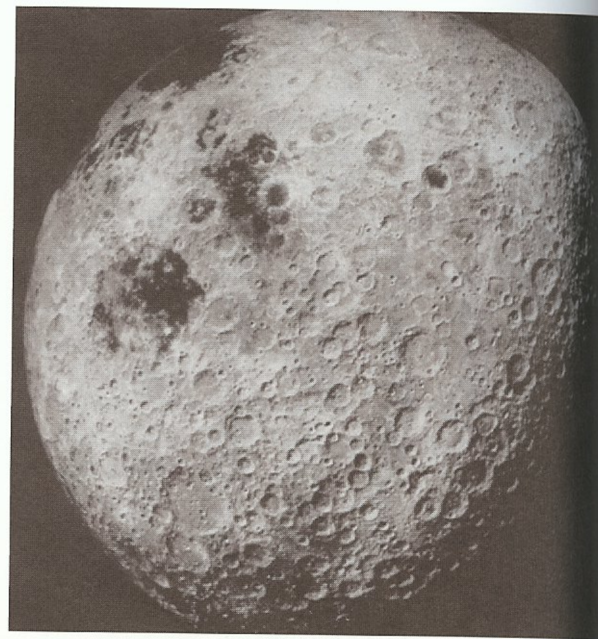

FIGURE 3 The heavily cratered farside highlands. Note the scarcity of mare basalts. Mare Crisium is the dark circular patch of basalt on the northwest horizon. (Courtesy NASA, *Apollo 16* metric frame 3023.)

possess sufficient hydrostatic head to reach the surface on the farside, except in craters in some very deep basins (e.g., Ingenii).

2.8 Remote Spectral Observations

Spectral observations of the Moon from the Earth are limited to the visible and infrared portion of the electromagnetic spectrum between about 3000 and 25,000 Å. These studies identify plagioclase by a weak absorption band at 13,000 Å (1.3 μm) and pyroxene by two strong bands at about 9700–10,000 Å (0.97–1.0 μm), as well as olivine. This technique has enabled mapping of several distinctive mare basalt types on the lunar surface. In addition, mapping of pyroclastic glass deposits has been possible because of their characteristic absorption bands due to Fe^{2+} and Ti^{4+}. These features have also enabled the mapping of the FeO and TiO_2 contents of mare basalts, the amount of anorthosite in the lunar highland crust and the identification of olivine in a few central peaks of craters (e.g., Copernicus).

3. Geophysics

3.1 Gravity

The young ray craters have negative **Bouguer anomalies** because of the mass defect associated with excavation of the crater and the low density of the fallback rubble.

Craters less than 200 km in diameter have negative Bouguer anomalies for the same reason (e.g., Sinus Iridum has a negative Bouguer anomaly of −90 mgal). Volcanic domes such as the Marius hills have positive Bouguer anomalies (+65 mgal), indicating support by a rigid lithosphere. The younger, basalt-filled circular maria on the nearside have large positive Bouguer anomalies, referred to as **mascons** (e.g., Mare Imbrium, +220 mgal). These are due to the uplift of a central plug of denser mantle material during impact followed by the much later addition of dense mare basalt. The gravity signature of young, large, ringed basins, such as Mare Orientale, shows a "bull's-eye" pattern with a central positive Bouguer anomaly (+200 mgal) surrounded by a ring of negative Bouguer anomalies (−100 mgal) with an outer positive Bouguer anomaly collar (+30 to +50 mgal).

The lunar highland crust is strong. High mountains such as the Apennines (7 km high), formed during the Imbrium collision 3.85 billion years ago, are uncompensated and are supported by a strong cool interior. The gravity data are consistent with an initially molten Moon that cooled quickly and became rigid enough to support loads such as the circular mountainous rings around the large, younger, ringed basins as well as the mascons. Even if some farside lunar basins do not show mascons, this may merely be a consequence of the greater thickness of the farside crust. The South Pole–Aitken Basin is particularly significant in this respect. As the oldest (at least 4.1 billion years) and largest impact basin, the fact that it is uncompensated, with major mantle uplift preserved beneath it, this places considerable restrictions on lunar thermal models. It also indicates that melting in the deep interior to produce the mare basalts had no effect on the strength of the crust. The volume of mare basalts is only about 0.1% of the whole Moon so that the amount of melting required to produce them involved only a trivial volume of the Moon.

3.2 Seismology

The lunar seismic signals have a large degree of wave scattering and a very low attenuation so that during moonquakes the Moon "rings like a bell" owing to the absence of water and the very fractured nature of the upper few hundred meters. Observed moonquakes have been mostly less than 3 on the Richter scale; the largest recorded ones have a magnitude between 5 and 5.7. Many are repetitive and reoccur at fixed phases of the lunar tidal cycle. The *Apollo* seismometers recorded the impacts of 11 meteorites with masses of more than one ton. The Moon is seismically inert compared to the Earth, and tidal energy is the main driving force for the weak lunar seismic events.

3.3 Heat Flow and Lunar Temperature Profile

Two measurements of lunar heat flow are available: 2.1 μW/cm^2 at the *Apollo 15* site and 1.6 μW/cm^2 at the *Apollo 17* site. It is interesting that these observed heat flows are close to Earth-based estimates from microwave observations. However these values provide only mild constraints on the bulk lunar abundances of the heat-producing elements K, U, and Th as these are not distributed symmetrically. The lunar interior must have been stiff enough for the past 4.0 billion years to account for the support of the mountain rings and the mascons. The most probable lunar temperature profile is shown in Fig. 4, which indicates temperatures of 800°C at a depth of 300 km. Unlike the Earth, which dissipates most of its heat by volcanism at the midocean ridges, the Moon loses its heat by conduction. Most of its original internal heat has been lost, and **differentiation** has concentrated most of the K, U, and Th near the surface, albeit in a nonuniform manner. The present heat flow could indicate lunar U values as high as 45 ppb or over twice the terrestrial abundances. A more conservative value of 30 ppb U is adopted here, based on petrological and geochemical constraints, as well as accommodating the high heat flow values. This uranium abundance is still 50% higher than the well-established terrestrial value of 20 ppb U. Although there has been considerable controversy over the reality of a higher than terrestrial lunar uranium abundance, it appears to be confirmed by the requirement from the *Clementine* mission data for a higher than terrestrial lunar aluminum abundance. Both Al and U are refractory elements, not easily separated by nebular processes, and their abundances are generally considered to be correlated in the terrestrial planets.

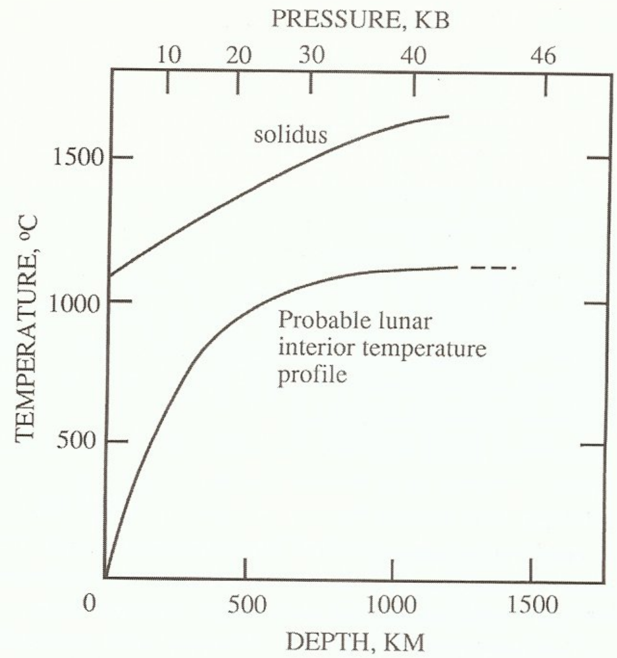

FIGURE 4 The present-day variation of lunar temperature with depth, showing that the temperature is well below that required for partial melting (**solidus** curve.)

3.4 Magnetic Field

The lunar rocks contain a stable natural remnant magnetism. Apparently between about 3.6 and 3.9 billion years ago, there was a planetary-wide magnetic field that has now vanished. The field appears to have been much weaker both before and after this period. The paleointensity of the field is uncertain, but perhaps was several tenths of an oersted. The most reasonable interpretation is that the Moon possessed a lunar dipole field of internal origin, all other suggested origins appearing less likely. The favored mechanism is that the field was produced by dynamo action in a liquid Fe core. A core 400 km in diameter could produce a field of about 0.1 oersted at the lunar surface.

Localized strong magnetic anomalies are associated with patterns of swirls, as at Reiner Gamma. These swirls have been suggested to have formed by some focusing effect of the seismic waves that resulted from the large impacts that formed the basins. More work is clearly needed to substantiate this hypothesis and to understand the association of swirls and magnetic fields. Other remnant fields, with field strengths of only about 1/100th of the terrestrial field, were measured at the *Apollo* landing sites.

4. Lunar Surface

The absence of plate tectonics, water, and life, and the essential absence of atmosphere, indicates that the present lunar surface is unaffected by the main agents that affect the surface of the Earth. Ninety-nine percent of the lunar surface is older than 3 billion years and more than 80% is older than 4 billion years. In contrast, 80% of the surface of the Earth is less than 200 million years old. The major agent responsible for modifying the lunar surface is the impact of objects ranging from micrometer-sized grains to bodies tens to hundreds of kilometers in diameter.

Because of the effective absence of a lunar atmosphere, the lunar surface is exposed to ultraviolet radiation with a flux of about 1300 W/m^2. The absence of a magnetic field allows the solar wind (1–100 eV) and solar (0.1–1 MeV) and galactic (0.1–10 GeV) cosmic rays to impinge directly on the surface. The relative fluxes are 3×10^8, 10^6, and 2–4 protons/cm^2/s, respectively. The penetration depths of these particles extend to micrometers, centimeters, and meters, respectively.

The maximum and minimum lunar surface temperatures are about 390 K and 104 K. At the *Apollo 17* site, the maximum temperature was 374 K (111°C), and the minimum was 102 K (−171°C). The temperatures at the *Apollo 15* site were about 10 K lower. The conductivity of the upper 1–2 cm of the surface is very low (1.5×10^{-5} W/cm^2). This increases about fivefold below 2 cm. A cover of about 30 cm of regolith is sufficient to damp out the surface temperature fluctuation of about 280 K to about ±3 K, so that structures on the Moon could be well insulated by a modest depth of burial. This in turn might produce difficulties in losing heat generated in buried structures. Impacts of micrometeoroids of about 1 mg mass could be expected about once a year on a lunar structure.

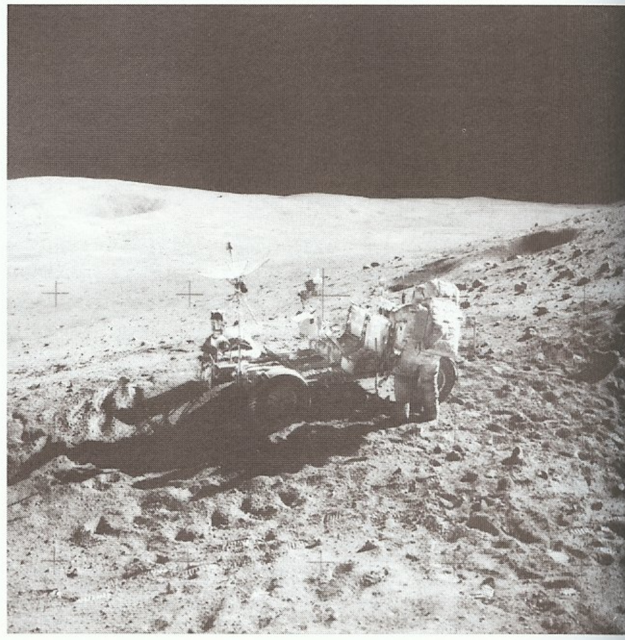

FIGURE 5 *Apollo 16* astronaut John Young and the lunar rover at Station 4 on the slopes of Stone Mountain, illustrating the nature of the lunar surface and the absence of familiar landmarks. Smoky Mountain in the left background, with Ravine crater (1 km in diameter) on its flank, is 9 km distant. (Courtesy of NASA, AS16-110-17960.)

The combination of strong sunlight, low gravity, awkward space suits, and absence of familiar landmarks makes orientation difficult on the lunar surface. All astronauts have commented on the difficulty of judging distance (Fig. 5).

4.1 Regolith

The surface of the Moon is covered with a debris blanket, called the regolith, produced by the impacts of meteorites. It ranges from fine dust to blocks several meters across. The fine-grained fraction is usually referred to as the lunar soil (Fig. 6). This is an unfortunate use of the term "soil," which has organic connotations, but the term is as thoroughly entrenched as the astronomers' use of "metals" for all elements heavier than helium. Although there is much local variation, the average regolith thickness on the maria is 4–5 m, whereas the highland regolith is about 10 m thick.

Seismic velocities were only about 100 m/s at the surface, but increased to 4.7 km/s at a depth of 1.4 km at the

FIGURE 6 The nature of the lunar upper surface is illustrated in this view of small pebbles being collected by a rake near the *Apollo 16* landing site in the Descartes highlands. Lunar sample 60018 was taken from the top of the boulder. (Courtesy of NASA, AS16-116-18690.)

Apollo 17 site. The density is about 1.5 g/ cm^3 at the surface, increasing with compaction to about 1.7 g/cm^3 at a depth of 60 cm. The porosity at the surface is about 50% but is strongly compacted at depth. The regolith is continuously being turned over or **gardened** by meteorite impact. The near-surface structure, revealed by core samples (the deepest was nearly 3 m at the *Apollo 17* site), shows that the regolith is a complex array of overlapping ejecta blankets typically ranging in thickness from a few millimeters up to about 10 cm, derived from the multitude of meteorite impacts at all scales. These have little lateral continuity even on scales of a few meters. Most of the regolith is of local origin: Lateral mixing occurs only on a local scale so that the mare–highland contacts are relatively sharp over a kilometer or so. The rate of growth of the regolith is very slow, averaging about 1.5 mm/million years or 15 Å/year, but it was more rapid between 3.5 and 4 billion years ago.

Five components make up the lunar soil: mineral fragments, crystalline rock fragments, breccia fragments, impact glasses, and **agglutinates.** The latter are aggregates of smaller soil particles welded together by glasses. They may compose 25–30% of a typical soil and tend to an equilibrium size of about 60 μm. Their abundance in a soil is a measure of its maturity, or length of exposure to meteoritic bombardment. Most lunar soils have reached a steady state in particle size and thickness. Agglutinates contain metallic Fe droplets (typically 30–100 Å) referred to as "nanophase" iron, produced by reduction with implanted solar wind hydrogen, which acts as the reducing agent, during melting of soil by meteorite impact.

A *megaregolith* of uncertain thickness covers the heavily cratered lunar highlands. This term refers to the debris sheets from the craters and particularly those from the large impact basins that have saturated the highland crust. The aggregate volume of ejecta from the presently observable lunar craters amounts to a layer about 2.5 km thick. The postulated earlier bombardment may well have produced megaregolith thicknesses in excess of 10 km. Related to this question is the degree of fracturing and brecciation of the deeper crust due to the large basin collisions. Some estimates equate this fracturing with the leveling off in seismic velocities (V_p) to a constant 7 km/s at 20–25 km. In contrast to the highlands, bedrock is present at relatively shallow depths (tens of meters) in the lightly cratered maria.

4.2 Tectonics

The dominant features of the lunar surface are the old heavily cratered highlands and the younger basaltic maria, mostly filling the large impact basins (see Figs. 1 and 3). There is a general scarcity of tectonic features on the Moon, in great contrast to the dynamically active Earth. There are no large-scale tectonic features, and the lunar surface acts as a single thick plate that has been subjected to only small internal stresses. Attention has often been drawn to a supposed "lunar grid" developed by internal tectonic stresses. However, the lineaments that constitute the "grid" are formed by the overlap of ejecta blankets from the many multiringed basins and have no tectonic significance. Most of the lunar tectonic features are related to stresses associated with subsidence of the mare basins, following flooding with lava.

Wrinkle ridges (or mare ridges) are low-relief, linear to arcuate, broad ridges that commonly form near the edges of the circular maria. They are the result of compressional bending stresses, related to subsidence of the basaltic maria from cooling.

Rilles, which are extensional features similar to terrestrial grabens, are often hundreds of kilometers long and up to 5 km wide. Unlike the wrinkle ridges, they cut only the older maria as well as the highlands and indicate that some extensional stress existed in the outer regions of the Moon prior to about 3.6 billion years ago. They should probably be termed grabens so as to avoid confusion with the sinuous rilles, such as Hadley Rille, that are formed by flowing lava, presumably through thermal erosion. The set of three rilles, each about 2 km wide, that are concentric to Mare Humorum at about 250 km from the basin center are particularly instructive examples, showing a clear extensional relation to subsidence of the impact basin (Fig. 7).

4.3 Lunar Stratigraphy

The succession of events on the lunar surface has been determined by establishing a stratigraphic sequence based on

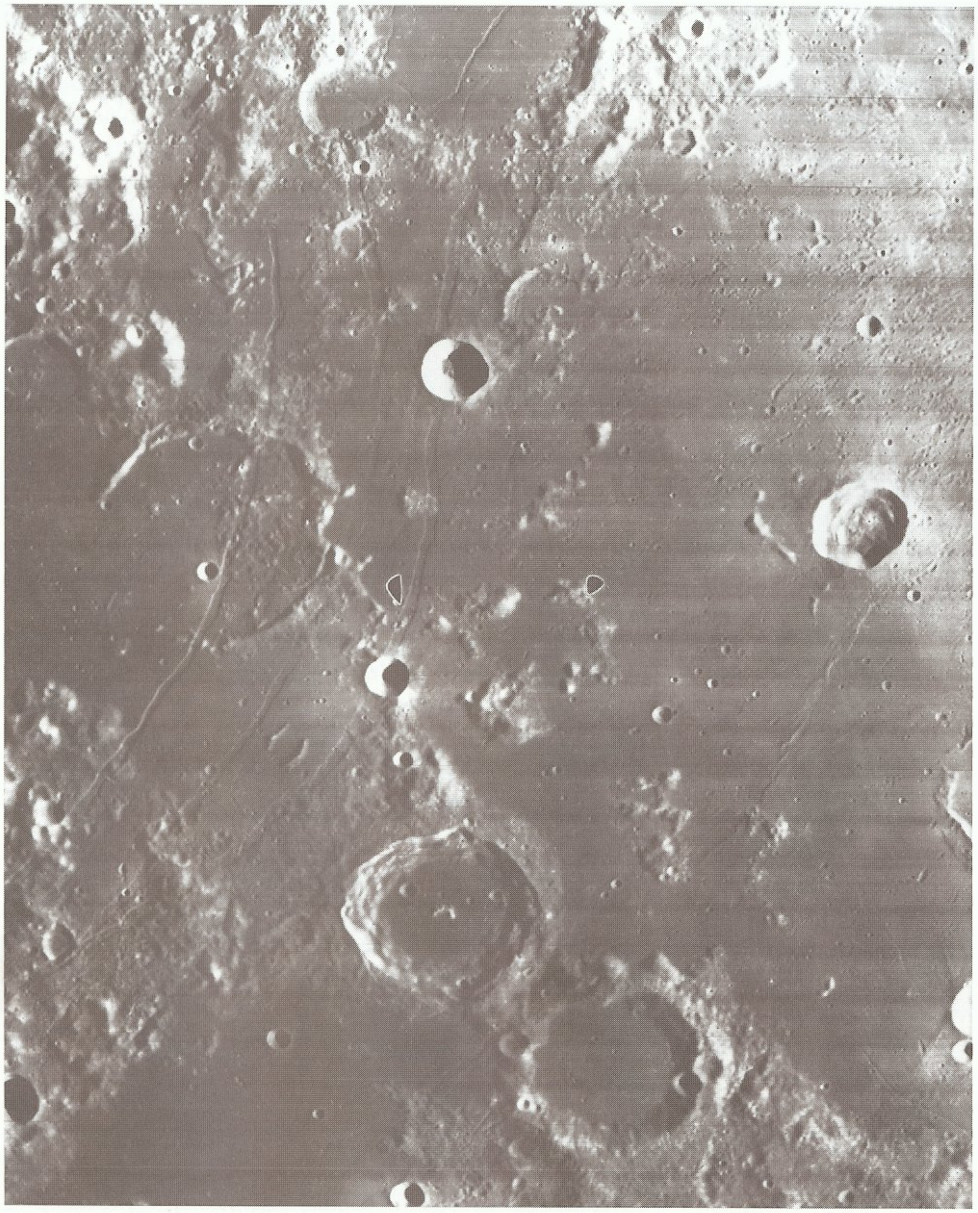

FIGURE 7 Three sets of curved rills or grabens, each about 2 km wide, concentric to Mare Humorum, the center of which is about 250 km distant. The ruined crater intersected by the rilles is Hippalus, 58 km in diameter. The crater at the bottom right, flooded with mare basalt, is Campanus 48 km in diameter. (Courtesy of NASA, Orbiter IV-132-H.)

the normal geological principle of superposition, a fundamental contribution due to Gene Shoemaker. Geological maps based on this concept have been made for the entire Moon, notably by Don Wilhelms. Relative ages have been established by crater counting, and isotopic dating of returned samples has enabled absolute ages to be assigned to the various units. The formal stratigraphic sequence is given in Table 1.

5. Lunar Structure

5.1 Lunar Crust

Reevaluation of the *Apollo* seismic data indicate that the lunar highland crust is 45 km thick (rather than 60 km) at the *Apollo* landing sites and the average crustal thickness lies between 54 and 62 km in thickness. The farside crust averages about 15 km thicker than that of the nearside. The crust thus constitutes about 9% of lunar volume. The maximum relief on the lunar surface is over 16 km. The deepest basin (South Pole–Aitken) has 12-km relief.

The mare basalts cover 17% of the lunar surface, mostly on the nearside (see Fig. 1). Although prominent visually, they are usually less than 1 or 2 km thick, except near the centers of the basins. These basalts constitute only about 1% of the volume of the crust and make up less than 0.1% of the volume of the Moon.

Seismic velocities increase steadily down to 20 km. At that depth, there is a change in velocities within the crust that probably represents the depth to which extensive

TABLE 1 **Lunar Stratigraphy**

System	Age (billion years)	Remarks
Copernican	1.0 to present	The youngest system, which includes fresh ray craters (e.g., Tycho), begins with the formation of Copernicus.
Eratosthenian	1.0–3.1	Youngest mare lavas and craters without visible rays (e.g., Eratosthenes).
Imbrium	3.1–3.85	Extends from the formation of the Imbrium Basin to the youngest dated mare lavas. Includes Imbrium Basin deposits, Orientale and Schrödinger multiring basins, most visible basaltic maria, and many large impact craters, including those filled with mare lavas (e.g., Plato, Archimedes).
Nectarian	3.85–3.92	Extends from the formation of the Nectaris Basin to that of the Imbrium Basin. Contains 12 large, multiring basins and some buried maria.
Pre-Nectarian	Pre-3.92	Basins and craters formed before the Nectaris Basin. Includes 30 identified multiring basins.

fracturing, due to massive impacts, has occurred. At an earlier stage, this velocity change was thought to represent the base of the mare basalts, but these are now known to be much thinner. The main section of the crust from 20 to 60 km has rather uniform velocities of 6.8 km/s, corresponding to the velocities expected from the average anorthositic composition of the lunar samples.

5.2 Lunar Mantle

The structure of the mantle (Fig. 8) has been difficult to evaluate on account of the complexity of interpreting the lunar seismograms. The average **P-wave velocity** is 7.7 km/s and the average S-wave velocity is 4.45 km/s down to about 1100 km. Most models postulate a pyroxene-rich

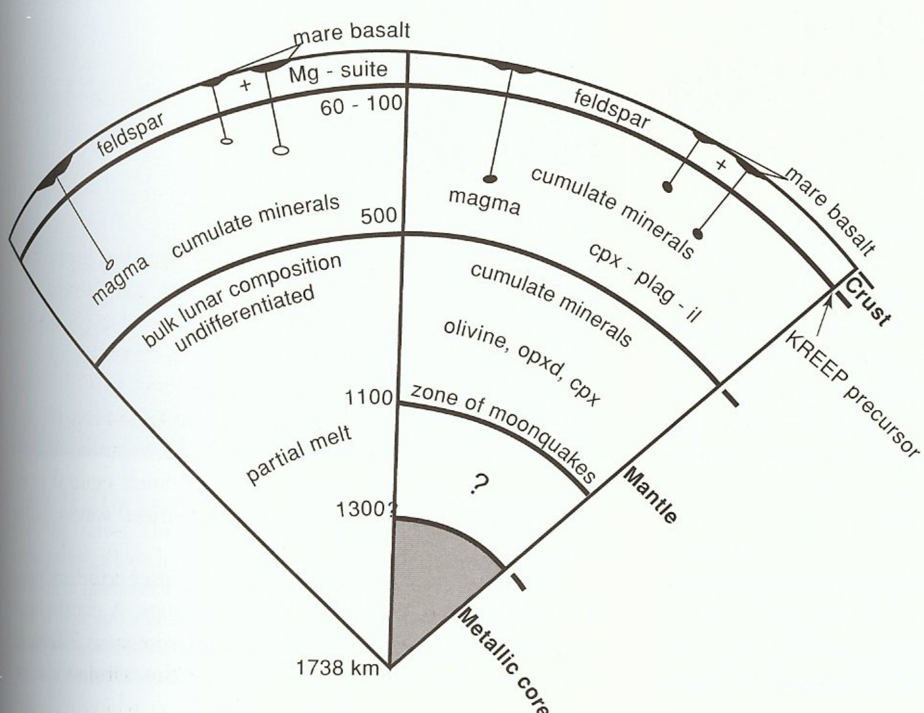

FIGURE 8 Two alternatives for the internal structure of the Moon. On the left, only half of the Moon melted and differentiated and the deep interior has primitive lunar composition. Some partial melting has occurred due to the presence of K, U, and Th. This model is consistent with the lunar free oscillation periods (Amir Khan, Univ. Copenhagen, personal communication). On the right, the Moon was totally melted and differentiated, forming a small metallic core. (Adapted from Taylor, 2001.)

upper mantle that is distinct from an olivine-rich lower mantle beneath about a depth of 500–600 km. Seismic data are ambiguous regarding the nature of the lunar mantle below 500 km. They may be interpreted as representing Mg-rich olivines or indicate the presence of garnet. If the latter is present, this has profound implications for the bulk Moon Al content. However this distinction cannot be made on the basis of the Apollo seismic data.

The main foci for moonquakes lie deep within the lower mantle at about 800–1000 km. The outer 800 km has a very low seismic attenuation, indicative of a volatile-free rigid lithosphere. Solid-state convection is thus extremely unlikely in the outermost 800 km.

Below about 800 km, P- and S-waves become attenuated ($V_S = 2.5$ km/s). P-waves are transmitted through the center of the Moon, but S-waves are missing, possibly suggesting the presence of a melt phase. It is unclear, however, whether the S-waves were not transmitted or were so highly attenuated that they were not recorded.

5.3 Lunar Core

The evidence for a metallic core is suggestive but inconclusive. Electromagnetic sounding data place an upper limit of a 400- to 500-km radius for a highly conducting core. The moment of inertia value of 0.3931 ± 0.0002 is low enough to require a small density increase in the deep interior, in addition to the low-density crust. Although a metallic core with radius about 400 km (4% of lunar volume) is consistent with the available data, denser silicate phases might be present. The resolution of these problems requires improved seismic data.

6. Impact Processes

6.1 Craters and Multiring Basins

One of the most diagnostic features of the lunar surface, that is in great contrast to the surface of the Earth, is the ubiquitous presence of impact craters at all scales, from micrometer-sized "zap pits" to multiring basins. The largest confirmed example is the South Pole–Aitken Basin (180°E, 56°S), 2500 km in diameter and 12 km deep. The presence of the larger Procellarum Basin (3200 km diameter, centered at 23°N, 15°W) covering much of the nearside is questionable. Although the correct explanation for the origin of the lunar craters had already been reached by G. K. Gilbert in 1893 and R. B. Baldwin in 1949, this topic was the subject of ongoing controversy until about 1960, and the question still surfaces occasionally in popular articles. Since meteorites and other impacting bodies could be expected to strike the Moon at all angles, the circularity of the lunar

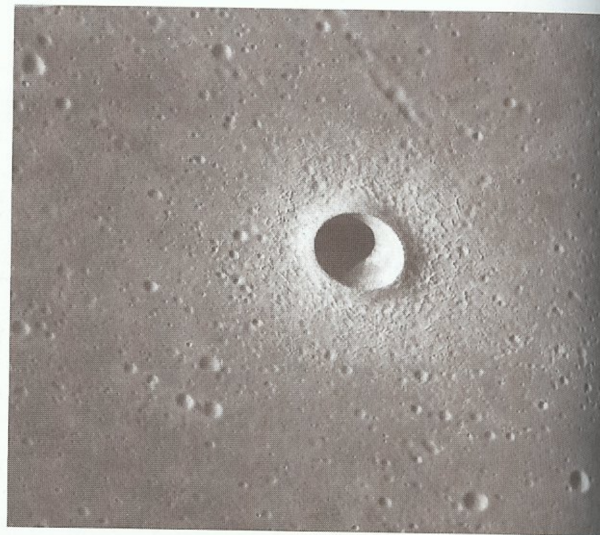

FIGURE 9 An oblique view of crater Linné in northern Mare Serenitatis. The rim crest diameter is 2450 m. Note the ejecta blocks on the rim, dunelike features on the flanks, and secondary craters at 1–3 crater radii from the rim crest. Linné was famous in the 19th century as a "disappearing" lunar crater because it was not seen by several observers. This was a consequence of observations at the limits of Earth-based telescopic resolution. (Courtesy of NASA, *Apollo 15* pan photo 9353.)

craters was long used as an argument against impact and in favor of a volcanic origin. It was eventually realized that bodies impacting the Moon at velocities of several km/sec explode on impact and the explosion mostly forms a circular crater regardless of the angle of impact, except for very oblique impacts. The morphology of the craters resembles that of terrestrial explosion craters and is quite distinct from the landforms of terrestrial volcanic centers.

The smallest craters are simple bowl-shaped depressions, surrounded by an overturned rim and an ejecta blanket (e.g., Linné, 2450-m diameter, Fig. 9). With increasing size, more complex forms develop. At diameters greater than about 15–20 km, slump terraces appear on the crater walls. Central peaks formed by rebound appear at crater diameters greater than about 25–30 km (e.g., Copernicus, 93-km diameter, Fig. 10). Central-peak basins, in which a fragmentary ring of peaks surrounds a central peak (e.g., Compton, 162 km diameter), develop in the size range 140–180 km. Larger craters develop internal concentric peak rings in place of the central peak (e.g., Schrödinger, 320 km diameter, Figs. 11 and 12). Such central peaks and peak rings may develop from fluidized waves during impact.

The ultimate form resulting from impact is the multiring basin, which may have six or more rings. A classic lunar example is Orientale (Fig. 13). This structure is 920 km in diameter (about the size of France), with several concentric