FIGURE 1.1.—Lunar nearside photographed 4 days after full Moon from the Pic du Midi Observatory, France, in August 1964. Left (west) half is illuminated at high Sun elevations, which enhance albedo (brightness) variations, and right (east) part at lower Sun elevations, which enhance relief by casting shadows. Terminator (line between dark and illuminated areas) is at long 51° E. Extensive ray systems surround craters Copernicus (upper left center) and Tycho (near bottom). Mare Nectaris, surrounded by concentric rings, is along terminator at lower right.

Note: Before 1961, lunar directions were stated with reference to their position in the sky as viewed from the Earth. Mare Orientale, the “Eastern Sea,” is on the left limb of the Moon as seen in the Northern Hemisphere, that is, near the east horizon of the Earth. In 1961, the “astronomical convention” was adopted in anticipation of manned spaceflight: The direction from which the Sun rises on the Moon was henceforth called east, as it is on the Earth. The definition of north remained the same, but after 1961, more publications began orienting their figures with north at the top rather than at the bottom (as it is seen in astronomical telescopes). The 0° meridian is in the center of the nearside, and the diametrically opposite longitudinal line on the farside is 180°. On most maps, longitudes increase both eastward and westward from the 0° meridian until meeting at the 180° meridian, which is also the terrestrial convention. Some lunar maps use a 360° system of longitudes, increasing eastward from the 0° central meridian. In this volume, the Orientale limb is considered the west, photographs are oriented with north at the top except as noted, nearside longitudes are less than 90°, and farside longitudes are greater than 90°.
1. GENERAL FEATURES

SURFACE

Near full Moon, the naked eye sees a contrast between dark and light surfaces (of low and high albedo, respectively) that has been fancied as a "man in the Moon" or other formations (fig. 1.1). In 1609, Galileo noted that the dark spots are smooth and the brighter areas rugged (Whitaker, 1978). These terrain types are still designated by their 17th-century names maria (singular, mare) and terrae (singular; terra; commonly known as uplands or highlands; table 1.1). The maria constitute about 16 percent, and the terrae 84 percent, of the lunar surface. Maria occupy about 30 percent of the lunar nearside, the hemisphere visible from the Earth; spacecraft exploration, beginning with the Soviet Luna 3 in 1959 (table 1.2; Barabashov and others, 1961; Kopal and Mikhailov, 1962, p. 1–44; Whitaker, 1963), showed that they constitute only about 2 percent of the farside (figs. 1.2–1.4). South of about lat 35° S, however, the proportions are reversed; the southern farside is richer in maria than is the southern nearside (fig. 1.5).

Most of the maria are approximately circular. The circular maria are bordered by annulla or arcuate, commonly mountainous terra rims. The terrain structures in which the circular maria lie are called ringed basins or, simply, basins (see chap. 4; table 1.1; Hartmann and Kuiper, 1962). Most large mountainous rings or arcs that do not encompass maria are also parts of basins (figs. 1.4, 1.5). Concentric rings characterize all well-exposed basins.

The maria are mostly level and smooth at coarse scales but contain local topographic relief. Mare ridges (dorsa) are long intricate wells on the mare surfaces (fig. 1.6). Rilles (rimae) are narrow troughs or grooves much longer than they are wide; they include genetically distinct sinuous, arcuate, and straight varieties. Few ridges but many arcuate and straight rilles cut the terrae as well as the maria. Dark-mantling materials are as dark as or darker than the maria but assume part of the topographic form of the underlying terrain (figs. 1.6, 1.7).

Craters, ranging in size from those visible with binoculars to micrometers observed on returned samples, are ubiquitous on the lunar surface. At coarse scales, they are much more numerous on the terrae than on the maria. Most lunar craters have rims elevated above, and floors depressed below, the surrounding terrain. Craters smaller than about 16 to 21 km in diameter have relatively featureless interiors; larger craters are more complex, possessing central peaks, arcuate wall terraces, and other interior landforms (see chap. 3). Some crater exteriors resemble the adjacent terrain except for a short rim flank; others display coarse concentric structure near the rim crest, grooves on a lower rim flank, and numerous smaller satellitic craters, which are most conspicuous between about one and three crater radii from the rim (fig. 1.6). Bright rays radiate hundreds or thousands of kilometers from some craters (figs. 1.1, 1.6).

Most terrae appear at first glance to consist of little except large, randomly distributed, overlapping craters. However, regional differences in terrain morphology emerge upon further inspection (Hackman and Mason, 1961). The central and northern nearside is characterized by ridges and grooves radial to the Imbrium Basin, which contains Mare Imbrium (figs. 1.6–1.8). The terrain east of the neighboring circular basin, Serenitatis, has a choppier, less regular pattern of elevations and depressions (fig. 1.7). Several regions contain particularly dense concentrations of craters that are grouped in chains or clusters. Concentric arcs of the Nectaris basin, which encompass the small Mare Nectaris, are conspicuous in the southeast quadrant (fig. 1.1). An even more conspicuous system of concentric rings, radial lineations, and satellite craters surrounds Mare Orientale on the west limb of the Moon (fig. 1.9). Terra plains that are smooth and level like the maria, but lighter in color, occupy more crater floors and other depressions in and near the Imbrium- and Orientale-radial terrains (figs. 1.8, 1.9) than in any other region. These textural patterns in the Imbrum, Nectaris, and Orientale regions, as described in detail in this volume, play major roles in elucidating the geology of the Moon. They are expressions of major stratigraphic units and form the basis for interpreting less distinctive terrae.

The farside seems, at first, to be even less regularly patterned than the nearside. This difference is due mostly to the absence of maria and of the extensive circum-Imbrium radial pattern that characterizes the nearside terrae. Later descriptions show that concentric and radial patterns also characterize the farside (fig. 1.4), although they are generally less extensive, less pronounced, and less well photographed than those of the nearside. The southern farside, which contains most of the farside's maria, also contains the farside's most conspicuous concentric rings and other noncrater morphologies (fig. 1.5). A major purpose of this volume is to show the basic stratigraphic order that underlies the morphologic features of the terrae.
Figure 1.2.—East limb (right edge of lunar disc as seen from the Earth) and adjacent part of
farside, divided by long 90° E. Mare Crisium (C) is on nearside, and Maria Mazarĩna (M) and
Sinthi (S) partly on farside. Maria also fill such craters as Lomonosov (L: 93 km, 27°
N., 98° E.) and Tsiolkovskiy (T: 180 km, 20° S., 129° E.; partly in shadow: compare figs.
1.3, 1.4). Farside terrane in view, which is otherwise mostly terra, includes craters Fakry
(Fa: 179 km, 43° N., 101° E.), Fleming (Fl: 130 km), Hilbert (Hl: 120 km), King (K: 77
km), and Pasteur (P: 235 km). A large subcircular area of light-colored plains lies between
Fleming and Lomonosov. Terminator is at long 13° 1 E.; left-hand (west) edge of photograph
is at nearly the same longitude as terminator in figure 1.1. Apollo 16 frame M-3021,
photographed by Apollo 16 mapping camera on Earthbound flight in April 1972.

Note: This volume includes photographs taken with three types of cameras carried in lunar
orbit by Apollo spacecraft: mapping or metric (M), panoramic (P), and hand-held or
bracket-mounted Hasselblads (H). All missions carried Hasselblads; Apollos 15 through 17
were carried both mapping and panoramic cameras as well (pl. 2; Masursky and others, 1978).

Note: Most crater diameters and positions in this volume are from Anderson and
Whataker (1982). Basin diameters and most crater diameters used in frequency studies are
from my measurements. Latitude is given before longitude throughout the volume. Coordi-
nates differ considerably among various maps, especially on the limbs and farside. One
degree of lunar latitude covers about 30 km.
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FIGURE 1.3.—Part of southern farside centered on mare-filled crater Tsiolkovskiy (T). Overlaps with fig. 1.2; compare Tsiolkovskiy and Hilbert (H; 170 km, 18° S., 108° E.). Other craters: Langemak (L; 102 km; contains small mare patch), Fermi (F; 238 km), Milne (M; 262 km; fig. 1.5), Jenner (J; 72 km; fig. 1.5), Pwyre (P; 141 km), Roche (R; 146 km; superposed crater Pauli contains mare). PI, small ringed basin Planck (325 km, 60° S., 136° E.; figs. 1.4, 1.5). Orbiter 3 frame M–121.

Note: Photographs transmitted from unmanned Lunar Orbiter spacecraft in 1966 and 1967 (table 1.2; Levin and others, 1966; Match, 1970) are labeled as follows: "Orbiter" followed by mission number (1–5), M (medium resolution) or H (high resolution), and frame number. Best Lunar Orbiter coverage of each area is outlined on plate 2.
THE GEOLOGIC HISTORY OF THE MOON

FiguRE 1.4.—Equatorial and southern facia. Most of area is heavily cratered, smoother in Gagarin (G; 272 km, 20° S., 140° E.) and north of Herwarth (H; 163 km, 11° S., 162° E.). A distinct linear trough is north of Keeler (K; 169 km). A number of crater and to left (west) of Keeler and Herwarth are parts of Keeler-Herwarth basin (KH). Maria fill Tsiolkovsky (T), Mare Ingenii (MI, in Ingenii basin), Jules Verne (JV; 134 km), part of Poincare basin (Po, compare fig. 1.5), and other depressions. Other craters: Chaplygin (C; 124 km) and Van de Graaff (V, double); other basins: Plouck (PL, compare fig. 1.3) and Mendeleev (M; 320 km, 6° N., 142° E.) Mosaic of Orbiter 1 frame M-115 (left) and Orbiter 2 frame M-35 (right).

FIGURE 1.5.—Southeast limb, showing concentration of maria and various ringed basins (see chap. 4). A: massifs of Australe basin, which enclose Mare Australe, consisting of many small mare patches resting in such craters as Jenner (J; compare fig. 1.3) and Lyst (L; 141 km); Am. Antonini crater or basin (135 km); C: outer ring of Crisium basin; M, Milne (compare fig. 1.3); MS, Mare Smythii in Smythii basin (compare fig. 1.2); PL, Plouck basin (barely discernible; compare fig. 1.3); Po, Poincare basin, containing several mare patches (compare fig. 1.4); S, Schrödinger double-ringed basin (320 km, 76° S., 134° E.). Infinite basins (table 4.2) include Anamundsen-Gamsouldt (AG), Bolmer-Kuptsev (B&K), and Sikorsky-Rittenhouse (SR); Grooves are radial to Schrödinger and to Nectaris basin (N; basin is outside photograph). Crater Flambardt (F; 207 km, 27° S., 80° E.) contains rilles and small mare patches. Orbiter 4 frame M-9.
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Figure 1.6.—Telescopic view of circular Mare Imbrium (MI) and Imbrium basin. MF, Mare Frigoris; PP, Palus Putredinis; arrow, Apollo 15 landing site. Imbrium-basin rim is composed of Montes Alpes (MAI), Montes Apenninus (MAp), Montes Caucasus (MC), and terra occupied by Imbrium crater bounding mare feature Sinus Iridum (SI). Lunar stratigraphic scheme of Shoemaker and Hackman (1962) is based on relations among Imbrium basin, planar material of Apennine Bench (AB), Archimedes (left of A), mare material, Eratosthenes (E), and Copernicus (C); 95 km; compare fig. 1.1; satellite craters are visible east of crater (see chap. 2, 7). "Wrinkle ridges" (dorsa) are above A; rilles are below PP. Crater pairs (see chap. 3) include Aristillus and Autolycus (right of A), Caroline Herschel and Heis (CH), Feuillée and Beer (FB), and Helicon and Leverrier (HL). Other features: Cassini (Ca), Euler (Eu), Langberg (L), Manlius (M), Plato (Pl), Pythagoras (Py), and Timarchus (T); many irregular craters north of Mare Frigoris; d, dark-mantled terra surface. Mount Wilson Observatory photograph, catalog No. 257.
1. GENERAL FEATURES

FIGURE 1.7—Telescopic view centered on Mare Serenitatis (MS), overlapping area of figure 1.6. Lineations in Montes Harenus (H) on southern part of Serenitatis rim are radial to Montes Apenninus; nonincise hummocky terrain adjoins Montes Caucasus and Montes Alpes. Terrain east of Mare Serenitatis consists of irregular craters and masulls. Other features: Ar, Aristoteles (87 km, 30° N., 17° E.); At, Atlas (87 km); E, Endoxus; H, Hercules; JC, Julius Caesar; M, Manilius; MH, Mare Humboldtiani; MT, Mare Tranquillitatis; P, Posidonius; R, Ritter (29 km, 2° N., 19° E.); RH, Rima Hyginus; densely cratered northern terrain including W. Bond (W; 158 km, 65° N., 4° E.); d, dark-mantling material. Arrows, Apollo 15 and 17 landing sites. Mount Wilson Observatory photograph, catalog No. 262.
1. GENERAL FEATURES

1.9. - Southwest limb (lower left as seen from northern hemisphere of the Earth). Arrows indicate long 90° W; upper arrow on equator and lower on south pole. Conspicuous linear features are radial to Mare Orientale and ringed Orientale basin (centered at 20° S., 95° W.). Light-colored plains form part of terrain outside Orientale radial, for example, in Schiller-Zuclius basin (SZ), in central part of crater Schackard (S; 227 km, 44° S., 35° W.), and in and near crater Wargentin (W; 84 km). Other basins: Bailly (B; 300 km, 66° S., 69° W.), Grimault (G; partly mare-filled), Mendel-Rydelley (MR, barely visible), and South Pole-Aitken (SA, mountainous masses); OP, part of Oceanus Procellarum in Procellarum basin. Footprint-shaped crater is Schiller (180 km). Orbiter 4 frame M-180.

Figure 1.8. - South-central nearside, including parts of "Fra Mauro peninsula" (FM) and Mare Nubium (MN), mare-filled crater Pitalus (P), fresh crater Tycho (T; 85 km, 43° S., 11° W.; compare fig. 1.1), moderately fresh crater Werner (W), and north-south-trending "backbone" of terra, including "chain" of large craters Procellae (P; 153 km, 9° S., 2° W.), Alphonsus (Alp), Arzachel (Ar), Purbach (Pu), Regiomontanus (R), and Walter (Wa, 140 km, 35° S., 1° E). Smooth terra plains lighter than maria fill many craters, including those in "chain" and Alboxenius (Alb), Deslandres (D), Hipparchus (H), Orientus (O), Playfair G (PG), and Stoffers (S). Rupes Recta (RR, "Straight Wall") and grooves ("sculpture") in upper right quadrant are radial to Imbrium basin. Apollo 14 landing site is just beyond north edge of photograph, above letters FM. Mount Wilson Observatory photograph.
The uppermost layers of both the maria and the terrae consist of fragmental material called regolith (Showmaker and others, 1967a, 1968). Regoliths are generally thinner than about 5 or 6 m on the maria and thicker than that on the terrae (Showmaker and Morris, 1970; Cooper and others, 1974). They dominate the lunar scene at closeup scales (fig. 1.11) but are not evident in the telescopic and Lunar Orbiter photographs shown here, except as they affect albedo (figs. 1.1–1.9). The term "soil" is commonly used either as a synonym for regolith or in reference to its fine surficial material. Because this volume emphasizes regional relations, it does not discuss the regolith in detail.

The underlying bedrock of the maria is basaltic and has a density of 3.3 to 3.4 g/cm³. Mare basalt typically extends hundreds of meters below the surface and locally reaches depths of about 5 km (see chap. 5). In contrast, the lunar bedrock is feldspathic (plagioclase-rich) material with a lower density estimated at 2.90 to 3.05 g/cm³ (Basaltic Volcanism Study Project, 1981, p. 671). Seismic data indicate that this lunar terrain material forms a crust 45 to 60 km thick in the west-central nearside (fig. 1.11; Toksöz and others, 1974; Koyama and Nakamura, 1979) and 75 km thick in part of the southeastern nearside (beneath the Apollo 16 landing site; Nakamura, 1981). Extrapolations of these measurements to other regions are based on elevation data, estimates of the crustal density, and models of isostatic compensation, all of which are subject to further refinement (Solomon, 1978; Thurber and Solomon, 1978). Where measured, average elevations are highest relative to the Moon's center of mass, one the farside than on the nearside (Kaula and others, 1974; Bills and Ferrari, 1977); the crust may be as thick as 120 km under some elevated terrains on the farside (fig. 1.12; Bills and Ferrari, 1977). Most estimates of the mean crustal thickness fall within the range 74 ± 12 km (Kaula and others, 1974; Bills and Ferrari, 1977; Kaula, 1977; Haines and Metzger, 1980; Basaltic Volcanism Study Project, 1981, p. 180-182). A mean thickness of 62 km corresponds to about 10 percent of the Moon's volume, of 74 km to about 12 percent, and of 86 km to about 14 percent (radius, 1,738 km).

Little is known about lunar intracrustal structure, except that seismic velocities appear to increase at about 20 to 25 km below the surface of southern Oceanus Procellarum (Toksöz and others, 1974). This discontinuity may indicate a change in physical state (open cracks above; solid, denser material below) or in chemical composition (Todd and others, 1973; Herzberg and Baker, 1980). At least the upper few kilometers of the terrae crust consists of breccia, a rock type composed of angular fragments (clasts) set in a finer-grained matrix.

Beneath the terrae crust and constituting all or most of the region containing the lunar volume is the lunar lithosphere. Its density is close to that of mare basalt and to the mean lunar density, 3.34 g/cm³. Seismic data suggest that the mantle is fairly uniform at least to 1,100±100-km depth, although small seismic-velocity changes have been modeled (Goins and others, 1979). Seismic shear waves are attenuated below 1,100±100 km. This central part of the Moon may or may not include melted zones and (or) a chemically distinct (metallic or sulfide-rich) core (Wilkerson and Sonett, 1977; Goins and others, 1979; Taylor, 1982).

In the past, the mechanically deformable elastic lithosphere seems to have coincided with the lunar crust, which may be considered the petrologic or chemical lithosphere (see chap. 6, 8). Today, the elastic lithosphere must include much of the mantle as well.

The basic facts and assumptions about the lunar subsurface are needed as background for later discussions of lunar tectonism and petrogenesis and for perspective on the overall constitution of the Moon. This volume, however, mostly discusses the three-dimensional form of the materials in the upper few kilometers or tens of kilometers beneath the terrae and mare surfaces.
1. GENERAL FEATURES

A. Lunar Module and astronaut at Apollo 11 landing site. Regolith consists of loose, footprint-compacted material and a few rocks. Apollo 11 frame H-3931.

B. Wall of Rima Hadley (Hodley Rille) at Apollo 15 landing site, showing the only inplace outcrops of lunar strata visited by astronauts, overlain by thin regolith and loose boulders. Montes Apenninus, in distance, appear smooth because of cover of loose debris (compare rugged appearance of mountains in fig. 1.6). Apollo 15 frame H-12115.

**Figure 1.10**.—Astronaut views of lunar surface.

A. Astronaut views of lunar surface. Lunar Module and astronaut at Apollo 11 landing site. Regolith consists of loose, footprint-compacted material and a few rocks. Apollo 11 frame H-3931.

B. Wall of Rima Hadley (Hodley Rille) at Apollo 15 landing site, showing the only inplace outcrops of lunar strata visited by astronauts, overlain by thin regolith and loose boulders. Montes Apenninus, in distance, appear smooth because of cover of loose debris (compare rugged appearance of mountains in fig. 1.6). Apollo 15 frame H-12115.

**Figure 1.11**.—Two interpretations of major features of lunar crust and mantle.

A. Schematic equatorial slice through entire Moon. All known endogenic moonquakes are on nearside. Crust believed to be thicker on farside than on nearside. Longitudes of Apollo seismometers are shown. From Gomme and others (1979, fig. 66).

B. Similar, crustal structure but different mantle structure hypothesized by Latham and others (1978). $V_p$, compressional-wave velocity; $V_s$, shear-wave velocity; $\sigma$, Poisson's ratio; $Q_s$, quality factor for shear waves.
Figure 1.12.—Approximate crustal thicknesses (in kilometers) on nearside (A) and farside (B). From Bills and Ferrari (1977, fig. 3).