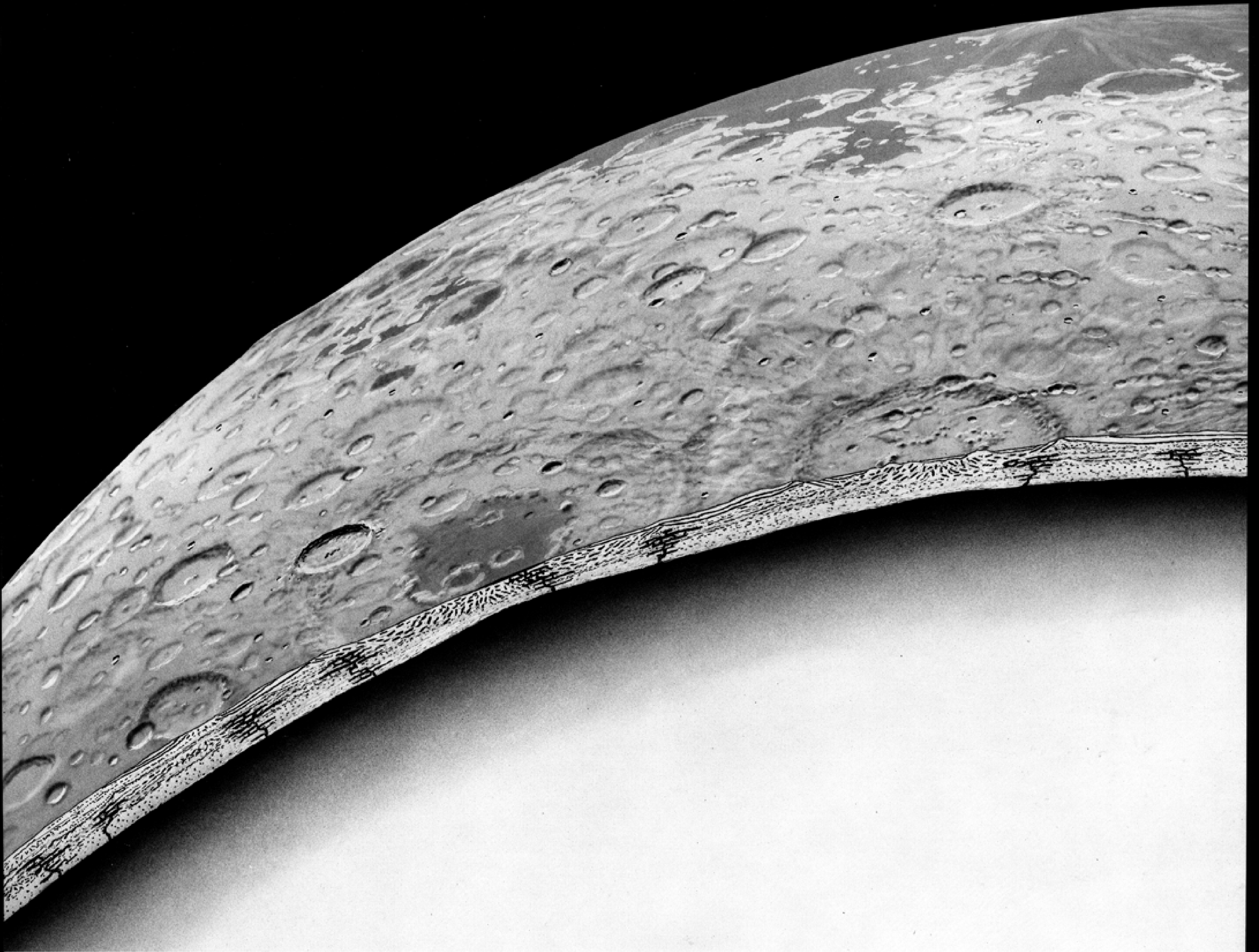

FIGURE 14.1.—Representative area of lunar surface (composite of several regions) and inferred subsurface structure. Mare basalt, gray in plan view and black in cross section, overlies impact melt in basins. Basin and crater ejecta blankets (white in cross section) overlap in several places, in accord with superposed-crater densities and degradational morphologies of surface exposures. Deformation of crustal material beneath basin rings is shown in accord with model in chapter 4; crust is thin, and mantle correspondingly uplifted, beneath basins. Stippling denotes possible unstratified lower crust that may have been reached only by the very largest impacts. True curvature; no vertical exaggeration. Painting by Donald E. Davis, courtesy of the artist.

14. SUMMARY

CONTENTS

GEOLOGIC STYLE OF THE MOON

Two decades of study have shown that two major processes, impact and basaltic volcanism, have shaped the major physical features of the present lunar crust. Impact deposits and basalt presumably also constitute much of the subsurface. Tectonism has modified the original depositional geometry far less than on the Earth.

A typical section of the upper lunar crust consists of laterally continuous, interfingering beds of basin and crater materials that are pierced, deformed, and redistributed by later impacts (fig. 14.1). Deposits of ringed impact basins are the main constituents of this section. Crustal material originally created by extensive plutonism was redistributed far and wide over the surface, partly preserved and partly newly modified, by the great impacts. The upper crust was removed as far as each topographic basin rim. Ejected material, emplaced largely by turbulent surface flow, thickly mantled the surface outside the topographic basin rims for average distances of one basin radius. Beyond this distance, secondary-impact craters, as large as 2 to 4 percent of the basin size, were formed in abundance. Their ejecta incorporated some of the primary basin ejecta that formed them and greater amounts of the circumbasin terrain that they excavated. The primary-ejecta deposits contain much melted and incompletely melted target material, mixed with less highly shocked debris, whereas the secondary deposits contain little or no newly melted material except that from the primary ejecta which formed them. Plains deposits containing the same breccia types as other primary and secondary ejecta are concentrated in the primary/secondary transition zone and among the secondary craters.

Basin interiors contain rings uplifted by deformation of the basin floor, knobby deposits ejected late in the excavation sequence, and impact-melt rocks. The rings increase in spacing, number, and complexity with increasing basin size. The outermost zones of large basins' interiors are especially complex. The knobby deposits also extend locally beyond the rim.

Smaller primary impacts have disturbed smaller amounts of the crust and redistributed it as lesser strata and fragmental regoliths. These ejecta deposits are proportional to those of basins in average extent; ejecta both of basins and of these smaller craters commonly have asymmetric, lobate or bow-tie map patterns. The secondary craters of basins and craters have similar size-frequency distributions, and the secondary-to-primary size ratio is only slightly smaller for the secondaries of basins. Primary-impact craters larger than 16 to 21 km in diameter have central peaks consisting of severely deformed material derived during crater excavation from beneath the crater center. Unlike the chaotic ejecta of larger craters and basins, ejecta of small simple craters may preserve the bedding of the target, inverted from the original sequence.

Basaltic volcanism probably has altered this basic impact architecture throughout lunar history. Extrusions of Fe-rich, alkali-poor, dry, and reduced basaltic magmas generated in the mantle not only formed the visible maria but also were probably extruded earlier. Relatively silicic basalt, rich in trace elements characteristic of KREEP and originating in the crust, also may have contributed surface extrusions. Basaltic magmas that did not reach the surface must have solidified as extensive dikes and sills in the crust (fig. 14.1). Most lunar basalt has formed planar lava flows, some with lobate frontal scarps; minor eruptions have constructed positive landforms, such as domes and cones.

The position and volume of the extrusions were determined by the crustal and mantle structure established by the basins. The mantle rose beneath each basin and, probably, beneath each large crater to compensate for loss of the crustal overburden. Thus, the crust-mantle interface probably resembles a series of domelike swells, proportional in size to the basins and superposed where basins are superposed. Far more basalt was extruded into basin depressions through the thin crusts that cap the mantle uplifts than through the thick crusts outside the large basins. Except for the Apollo 11 suite from southern Mare Tranquillitatis (fig. 14.2), each suite of basalt samples returned by the Apollo and Luna missions apparently was formed by magmas extruded within a short time from a small, compositionally heterogeneous zone of the mantle.

Pyroclastic glass fountained as liquid droplets from fissures and irregular craters at the mare margins. These pyroclastic deposits are now observed as dark mantles on the nearby terra and mare lavas,

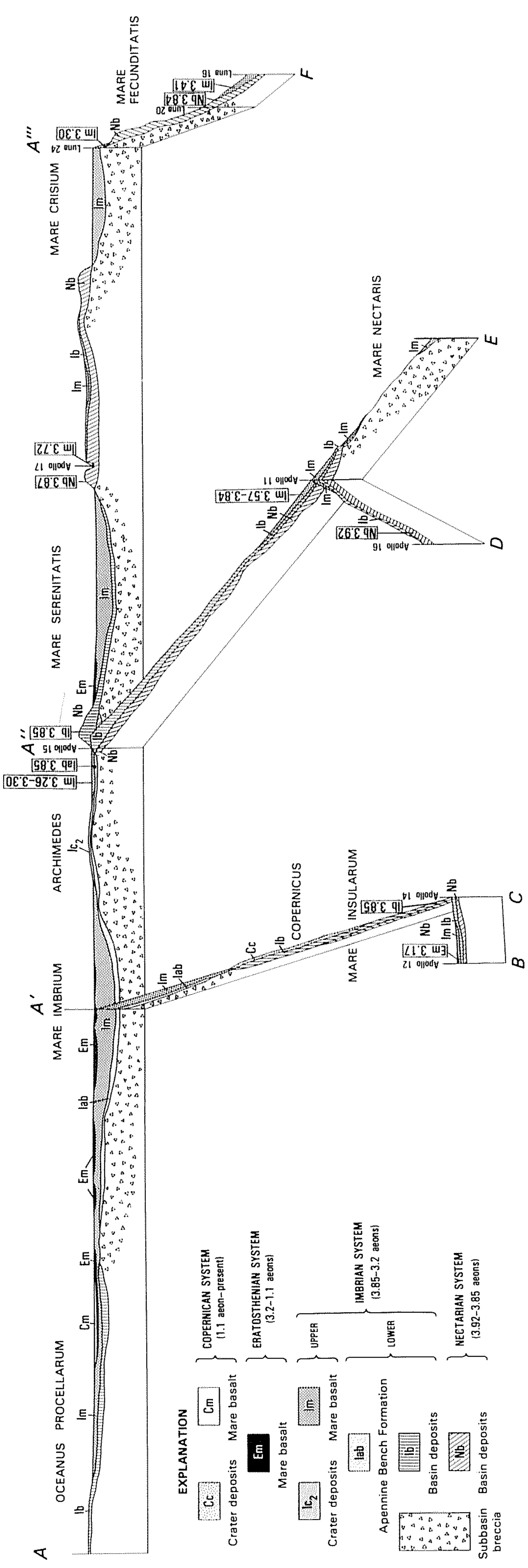

FIGURE 14.2.—Geologic cross section, drawn along lines indicated in figure 8.4 and based on plate 12. Boxes enclose symbols and ages (in aeons) of major sampled and dated geologic units. Brecciated crustal material is shown beneath basins whose deposits are mapped; rest of crust is probably also brecciated. Plains material (Ip, pl. 12) intersected here is Apennine Bench Formation, interpreted as extending over most of floor of Imbrium basin. Other basins probably have similar plains deposits on floors (impact melt and, possibly, volcanic basalt).

and probably also interfinger with the lavas. The total volume of extruded mare basalt and pyroclastic material amounts to only 0.05 to 0.2 percent of the upper 75 km of the Moon.

Most lunar faulting was caused by the subsidence of mare basalt, which was greatest where basin excavations had thinned and weakened the elastic lithosphere. The lithosphere was probably equivalent to the petrologic terra crust during most of the volcanic and tectonic activity. Arcuate grabens were opened by stretching of the margins of the subsiding basalt sections. Mare surfaces were folded into complex archlike and spinelike ridges where the surface area was shortened; the shortening apparently was greatest where basalt sections of unequal thickness settled differentially. The degree of subsidence is also recorded in the gravity structure of maria; maria and basins that have been fully compensated isostatically are gravitationally neutral, whereas others appear as mascons that represent enduring superisostatic loads of basalt on the lithosphere. Crater floors were uplifted and fractured most extensively where the lithosphere was weakest. Otherwise, internal activity contributed very little to crater development except by generating the mare fillings of many craters and creating small vents for the pyroclastic eruptions.

In summary, geologic history at any given point on the Moon has advanced in a series of catastrophic impacts separated by much longer periods of gradual degradation and intermittent volcanism. Regoliths accumulated on each of the larger deposits in proportion to the duration of exposure and the impact flux at the time. Innumerable small impacts blurred depositional textures unremittingly, but subsurface geometry persisted until disturbed by large impacts. The ejecta from large impacts incorporated and mixed materials from the crater and basin units, the regoliths, the volcanic lavas, and subsurface intrusions. Lunar geology is simple in general style, though commonly very complex in detail.

This account pictures a uniformitarian Moon in which old features once resembled the more recent. Since crustal solidification, the face of the Moon has always displayed craters and ringed basins, and probably has always been spotted by dark maria. Major changes have occurred, however, in the proportions of units. The details of mare distribution constantly shifted as new basins appeared, were flooded, and were covered by later ejecta. Because volcanism continued after the impact rate had decreased sharply, more basalt remained exposed late than early in lunar history (fig. 14.3). The rest of this chapter traces the changing scene from pre-Nectarian to Copernican time and concludes with a summary of unsolved problems.

PRE-NECTARIAN PERIOD

Lunar and pre-Nectarian history began with the formation of the Moon about 4.55 aeons ago. Similar oxygen-isotope ratios of the Earth and the Moon favor accretion in the same general part of the Solar System (Clayton and Mayeda, 1975). The process of accretion has not been agreed upon (Wood, 1979; Cadogan, 1981; Glass, 1982; Taylor, 1982; Hartmann, 1983), despite an intense search for chemical clues in the lunar samples (Dreibus and others, 1977; Kaula, 1977; Anders, 1978; Delano and Ringwood, 1978; Wänke and others, 1978). The accreted material is commonly assumed to have been chemically similar to that of chondritic meteorites, depleted in volatile elements.

The newly accreted material thoroughly differentiated. A feldspathic crust, now averaging about 75 km in thickness, and the upper several hundred kilometers of a denser, ultramafic, much more voluminous mantle are believed to have separated from an extensive early pre-Nectarian magma system. This magma is commonly considered to have formed a global ocean. However, recent modeling of crustal petrogenesis envisions a succession of bodies, which may or may not have been emplaced into the crystallization products of a primordial magma ocean. A chemically distinct core may or may not exist (Levin and Mayeva, 1977; Wiskerchen and Sonett, 1977; Taylor, 1982). A barrage of impacts must have deposited impact-melt pools, heated and mixed the environment of the crustal magmas to considerable depths, and generally influenced the igneous petrogenesis and the sites of magma migration. The differentiation ended at a time commonly estimated at from 4.4 to 4.2 aeons ago; it may have ended at different times in different places.

The cumulative effect of a heavy impact rate during pre-Nectarian time is evident in the highly brecciated, impact-melted, siderophile-rich material that constitutes the Nectarian and Imbrian deposits from which the returned samples were collected. The sample record of individual pre-Nectarian events that affected the solid terra crust, however, is less complete than the photogeologic record.

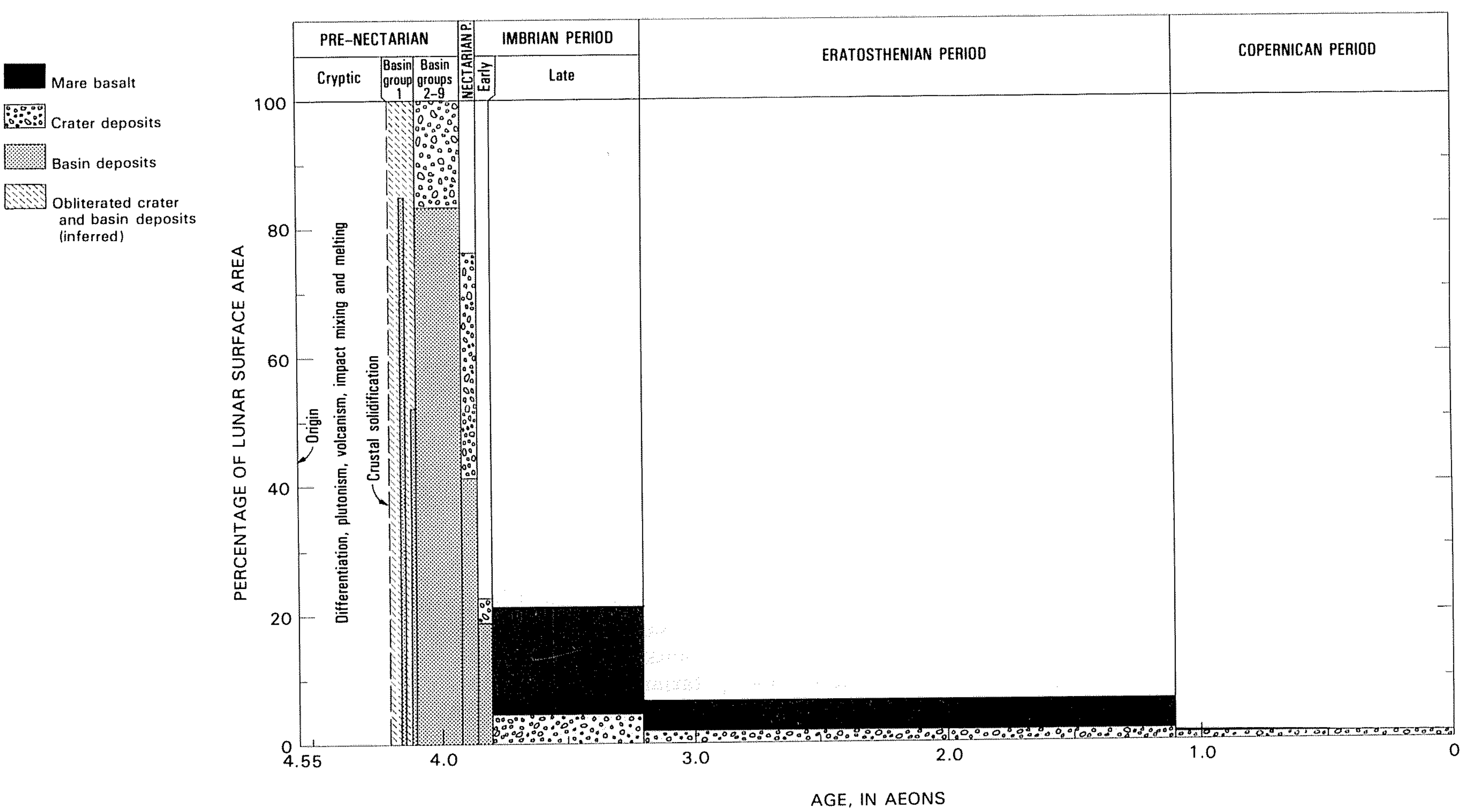

FIGURE 14.3.—Evolution of the lunar surface. Vertical axis, surface area inferred to have been originally covered by each group of deposits. Basin and crater deposits (approximately, the continuous ejecta) are assumed to extend one diameter from the crater or basin center; mare deposits of each age are assumed to extend beneath entire area of younger maria. Procellarum and South Pole-Aitken basins (pre-Nectarian basin group 1) are shown diagrammatically by narrow vertical bars; ages are estimated. Observed and inferred pre-Nectarian crater deposits cover more than 100 percent of the Moon. Early peak in lunar geologic activity is evident.

Mountainous rings of the giant Procellarum and South Pole-Aitken basins apparently constitute the earliest preserved record. Together, these two basins excavated crustal material from 40 percent of the Moon's area, and this material must have covered or impacted most of the Moon. This redistribution of material apparently resulted in terra surfaces more magnesian than average inside the basins and more aluminous outside; furthermore, KREEP-rich material of the deep crust may have been exposed in the deepest parts of Procellarum or of both basins. These newly exposed compositional provinces later became the targets of other basin impacts. The mantle does not seem to have been reached by impacts except, possibly, by the combined excavations of Procellarum and Imbrium. The crustal structure resulting from the giant impacts also set the stage for later mare volcanism and tectonism by determining local thicknesses of the lithosphere and the depths to the mare source regions in the underlying mantle.

Thirty pre-Nectarian basins, including Procellarum and South Pole-Aitken, have been identified or tentatively identified (table 8.2). They are ranked according to crater-density and superposition data into nine age groups. The oldest basins are obscure, whereas the youngest display textures and secondary craters similar to those of Nectarian and Imbrian basins. The spatial distribution of the pre-Nectarian basins seems to be random (pl. 6).

The ages of these basins and of the oldest preserved surface features are only approximately known because few ancient units have been dated absolutely and because extrapolations of frequencies of craters that are saturated to large crater diameters are uncertain. If the impact rate was constant during the pre-Nectarian and Nectarian Periods and if the Nectarian Period lasted 0.07 aeon, about 28 basins (groups 2–9) and 3,400 craters larger than 30 km in diameter formed from about 4.1 aeons to 3.92 aeons ago. This estimate is too young if the Nectarian Period was longer than 0.07 aeon, and too old if the early impact rate declined steeply as is, in fact, commonly assumed. The Procellarum and South Pole-Aitken basins are older than the group-2 basins by an unknown amount; to construct figure 14.3, I assume ages of 4.15 and 4.10 aeons, respectively, for these two giant basins. Many additional craters and basins that are now obscured also formed between the time of crustal solidification and the first group-2 basins.

Although volcanic materials are probably interbedded with the impact deposits, the pre-Nectarian volcanic record is much less evident than the rich impact record. The absence of observed tectonic deformation of pre-Nectarian units suggests that the crust had cooled before the oldest observed basins formed. The lithosphere presumably thickened throughout the pre-Nectarian.

TABLE 14.1.—*Adopted absolute ages of major sampled lunar geologic units*

[Sampling sites: L, Luna; numbers only, Apollo]

System or series	Unit or rock type	Sampling site	Age (aeons)	Basis	Reference
Copernican	Small craters	14, 16, 17	≤0.05	Exposure ages	Table 13.2.
	Tycho	17	.109	do	Do.
	Copernicus	12	.81	Ar-Ar ages	Do.
Eratosthenian	Basalt flows	12	3.16	Average of best Rb-Sr and Ar-Ar ages for all flows.	Table 12.4.
Upper Imbrian	Olivine basalt	15	3.26	do	Table 11.3.
	Pigeonite basalt	15	3.30	do	Do.
	Pyroclastic glass	15	3.30	Ar-Ar ages	Do.
	VLT basalt	L24	3.30	Ar-Ar age	Do.
	Feldspathic basalt	L16	3.40	do	Do.
	High-K, high-Ti basalt	11	3.57	Rb-Sr and Sm-Nd ages.	Do. Do.
	Pyroclastic glass	17	3.64	Ar-Ar ages	Do.
	Low-K, high-Ti basalt	11	3.67 3.70	Averages of best Ar-Ar ages for two flows.	Do.
	Thick basalt section	17	3.72	Average of best Rb-Sr and Ar-Ar ages.	Do.
	Low-K, high-Ti basalt	11	3.79	Average of best Ar-Ar ages.	---
Lower Imbrian	Low-K, high-Ti basalt	11	3.84	Average of best Ar-Ar ages.	Table 11.3.
	Apennine Bench Formation (KREEP-rich basalt).	15	3.85	Average of best Rb-Sr, Sm-Nd, and U-Th-Pb ages.	Table 10.1.
	Imbrium-basin ejecta	14, 15	3.85	Young cluster (Apollo 14) and black-and-white breccia (Apollo 15).	Do.
Nectarian	Crisium basin	L20	3.84±0.04	Ar-Ar age	Chapter 9.
	Serenitatis basin	17	3.87	Youngest Ar-Ar ages.	Table 9.2
	Nectaris basin	16	3.92	Average age of feldspathic fragment-laden impact-melt rock from North Ray Crater.	Table 9.1.
Nectarian and pre-Nectarian.	Volcanic-rock clasts	14, 17	3.85-3.98	Individual ages	Table 9.5.
Pre-Nectarian	Plutonic-rock clasts	15, 16, 17	4.17-4.54	Individual ages	Table 8.4.

NECTARIAN PERIOD

The Nectarian System continues the geologic style of the visually detectable part of the pre-Nectarian, but with fewer units (pl. 7). By definition, the Nectarian Period began with the impact that created the Nectaris basin and ended with the Imbrium-basin impact 3.85 aeons ago. Geochronology and photogeology have suggested, but not definitely established, that feldspathic, melt-poor Nectaris-basin material was sampled and dated at the Apollo 16 landing site (fig. 14.2). The age of Nectaris is tentatively estimated at 3.92 aeons on the basis of one interpretation of the ages determined on small samples of this material (table 14.1). If correct, this age implies that the Nectarian Period lasted 0.07 aeon and the pre-Nectarian 0.63 aeon.

From 10 to 12 basins formed during the Nectarian Period; the doubtful ones are Mendel-Rydberg, which may be pre-Nectarian, and Sikorsky-Rittenhouse, which may not actually be a basin. The Nectarian basins are ranked individually by age, but only two distinct age groups are recognized (table 9.4). If 11 basins are Nectarian and the Nectarian Period lasted 0.07 aeon, these basins formed at the rate of 157 per aeon. An extrapolation from the observed number of craters to the whole Moon indicates that 1,330 craters from 30 to 300 km in diameter formed during the Nectarian Period. Their formation rate was 19,000 per aeon, and 121 craters formed for each Nectarian basin. These Nectarian impact rates and crater-to-basin ratio are the basis for my estimates of pre-Nectarian ages and areal coverage (fig. 14.3).

At least one, possibly two, Nectarian basins in addition to Nectaris were sampled (fig. 14.2). Abundant fragment-laden impact melt was collected by Apollo 17 from massifs near the rim of the Serenitatis basin. Isotopically requilibrated clasts have been dated at 3.87 aeons. Although some doubts persist about the provenance of the best dated material, 3.87 aeons is probably the age of Serenitatis (table 14.1). Luna 20 returned small feldspathic fragments of probable Crisium-basin material. Their determined age is a little younger than that of Serenitatis but not so precise.

These young isotopic ages, a concentration of other isotopic ages of terra samples between 3.85 and 3.95 aeons, the relative paucity of older ages, and the apparently old morphologic age of Serenitatis led to the suggestion that a "terminal impact cataclysm" formed most lunar basins. However, the large number of identified and inferred pre-Nectarian and Nectarian basins would create the same effects and would intensely rework the lunar crustal material, as is observed. Although the record does not require a terminal cataclysm, basins may have formed in groups because clusters of projectiles derived by breakup of a single large object temporarily maintained similar orbits after breakup (Wetherill, 1981); these projectiles may have impacted approximately along lunar paleoequators (Runcorn, 1982).

An undetermined amount of volcanism occurred during the Nectarian and pre-Nectarian Periods. If the Nectarian surface was covered by mare basalt at the same average rate as was the Late Imbrian surface (approx 6.4×10^6 km^2 in 0.6 aeon), 0.75×10^6 km^2 of the lunar surface was covered from 3.92 to 3.85 aeons ago. This is enough basalt to cover a circular area about 295 km in diameter—slightly smaller than the smallest basin—in each of the 11 Nectarian basins. Large basins and all basins inside the giant basins would receive more than this average, other basins less. Extrapolation of this rate to the pre-Nectarian depends on the source of heat for the volcanism. If most of it was leftover primordial heat (Hubbard and Minear, 1975), volcanism declined steadily since the crust solidified, and the pre-Nectarian basins would have been filled somewhat more extensively than the Nectarian basins. Failure to detect abundant pre-Nectarian volcanic geologic units and samples would then be explainable by the intensity of the early impact bombardment. If, alternatively, most of the heat came from radioactivity, premare volcanism may have been relatively uncommon (Taylor, 1982, p. 317), and the pre-Nectarian basins would contain relatively little pre-Nectarian basalt. The data are insufficient to choose definitively between these possible early rates of volcanism. Sparse data from mare-basalt clasts found in breccia deposits suggest that more Nectarian than pre-Nectarian basalt was formed (table 9.5). Furthermore, more craters with dark, Mg-rich ejecta, indicating burial of basalt flows by basin debris, are superposed on light-colored planar deposits of Nectarian than of pre-Nectarian age. The buried basalt, however, may be pre-Nectarian.

EARLY IMBRIAN EPOCH

During the Early Imbrian, two large impacts left effects on the terra that still dominate its appearance (pl. 8). The creation of Imbrium, the Moon's third largest known basin (after Procellarum and South Pole-Aitken), uplifted rings that are the largest lunar mountains after those of South Pole-Aitken, and launched ejecta over most of the nearside and part of the farside. Thick primary ejecta was deposited within several hundred kilometers of the basin, and some probably reached more than 1,000 km from the rim. Extensive light-colored plains consisting of primary and secondary ejecta were deposited beyond the primary ejecta. Secondary craters formed over vast outlying areas, possibly even at the antipode of the impact point. The KREEP-rich breccias recovered from the Fra Mauro Formation at the Apollo 14 landing site and lesser amounts of breccia from Montes Apenninus at the Apollo 15 landing site yield an average age of about 3.85 aeons. The same age was obtained for fragments of KREEP-rich volcanic basalt or impact melt probably derived from a planar deposit near the Apollo 15 landing site (Apennine Bench Formation), which is contemporaneous with or slightly younger than the basin (tables 10.1, 14.1). The Imbrian Period, therefore, began 3.85 aeons ago. The Imbrium basin was the site for the most voluminous preserved extrusions of lunar mare basalt.

The other large Early Imbrian basin, Orientale, formed about 50 million years later on the west limb of the Moon and ended the era of enormous impacts. In accord with the younger relative age of the Orientale basin and its distance from later maria, its effects on the terra are even more striking than those of Imbrium. The Orientale ridged ejecta, impact melt, ejecta plains, secondary craters, and ring structure serve as models for the interpretation of older basin materials. A similar role at the small end of the size series of impact basins is played by the third Lower Imbrian basin, Schrödinger.

The Early Imbrian Epoch was too brief, and the effects of Orientale and of later mare extrusions too severe, for smaller impacts or volcanism to have left a conspicuous record. The oldest high-K, high-Ti flow excavated from the subsurface at the Apollo 11 landing site may be Early Imbrian (fig. 14.2; table 14.1). Orientale formed on a thick terra crust not previously thinned by a giant basin, and so, unlike Imbrium, it was not the site of abundant later basalt extrusions. Volcanism of terra composition may have formed some terralike plains and domical landforms during the Early Imbrian Epoch.

LATE IMBRIAN EPOCH

The record of the rest of lunar geologic history differs greatly from that of the 0.75 aeon already summarized. The cessation of giant impacts enabled the mare-basalt flows, which were continuously extruded, finally to remain preserved on the lunar surface. Previously, they had been catastrophically excavated and redistributed along with terra materials of the target or, if not disrupted, at least were blanketed by impact ejecta so as to loose their distinctive surface albedo. More visible mare units are Late Imbrian than any other age. Basalt of this age constitutes parts of all the larger maria (pl. 9).

Late Imbrian craters are also numerous and are surrounded by moderately well preserved ejecta blankets (pl. 9). Late Imbrian basalt is the Moon's most abundantly sampled and most reliably dated material (fig. 14.2; tables 11.3, 14.1). Three age groups are mapped here (pl. 9).

Units of the oldest group, which formed within about 0.05 aeon, occupy elevated terrain in the outer Procellarum-basin shelf and terrain outside Procellarum, localities where they were protected from later volcanism. Their subsurface extent is probably much greater. Samples 3.79 aeons old were obtained from a buried unit at the Apollo 11 landing site. Units of the intermediate-age group, which span the interval from about 3.75 to 3.50 aeons ago, lie at the surface in all maria and are especially abundant outside Procellarum. They probably formed in all basins but remained uncovered where a thick lithosphere blocked ascent of magmas and prevented sufficient basin subsidence to allow subsequent basalt extrusion. This and the older group of mare units commonly are faulted inside Procellarum but rarely outside, a further indication of relative subsidence. Apollos 11 and 17 collected Ti-rich basalt samples of this group 3.57 to 3.70 aeons old and 3.72 aeons old, respectively. The sampled flows were extruded intermittently and sparsely in the shallow pre-Nectarian Tranquillitatis basin but much more rapidly in the Taurus-Littrow Valley marginal to the Nectarian Serenitatis basin. Pyroclastic dark-mantling materials fountained from the marginal zones of Serenitatis and other basins while the intermediate-age and, probably, the older groups of basalt units were forming; samples of such pyroclastic material collected by Apollo 17 are 3.64 aeons old.

Addition of the third and youngest group of mare basalt units further depressed the older units and the underlying basin, further fracturing the older mare and the adjacent basin material. These young basalt units appear in all maria, most abundantly in those whose total basalt section is thick because of a thin lithosphere. Units of this young group cover as much area as those of the other two groups combined, but are probably not proportionally voluminous because the older units underlie many or all of their exposures. If the rate of volcanism declined continuously during the Late Imbrian Epoch, the young group of basalt units is only one-seventh as voluminous as the intermediate-age group. Al-rich mare-basalt extrusions outside Procellarum are represented by fragments collected by Luna 16 from Mare Fecunditatis (3.40 aeons old) and very-low-Ti fragments collected by Luna 24 from Mare Crisium (3.30 aeons old). Abundant Ti-poor basalt samples from an older, relatively silicic flow and a younger, thinner, relatively mafic flow were collected by Apollo 15 from a marginal mare of Imbrium (Palus Putredinis) and were dated at 3.26 to 3.30 aeons. Pyroclastic material also formed at that time. In the convention adopted in this volume, the Apollo 15 and Luna 24 units formed late in the Late Imbrian Epoch.

The Late Imbrian Epoch lasted about 0.6 aeon, from about 3.8 aeons (Orientale impact) to 3.2 aeons ago (about midway between the older Apollo 15 and younger Apollo 12 absolute ages). Imbrian mare-basalt units probably covered the entire area now covered by maria (including the mare area covered by younger craters), that is, about 17 percent of the lunar surface, or 6.5×10^6 km^2.

During the same epoch, the continuous deposits of craters larger than 30 km in diameter covered about 1.7×10^6 km^2 of the whole lunar surface, or about 25 percent of the mare area. Late Imbrian craters of this size formed at the rate of 280 per aeon, only about 1.5 percent of the Nectarian rate. If crater age assignments to the Lower Imbrian Series are correct (pl. 8), the Early Imbrian cratering rate (approx 3,000 per aeon) is transitional between the Nectarian and Late Imbrian rates, closer to the latter. Thus, the crater-size impacts declined simultaneously with the basin-size impacts.

ERATOSTHENIAN PERIOD

Volcanism continued during the Eratosthenian Period, generating extensive flows in Oceanus Procellarum and Mare Imbrium and less extensive flows in other maria. These lavas are predominantly Ti-rich except in northern Mare Imbrium and Mare Frigoris. At least the Ti-rich types were derived from sources rich in radioactive elements and were extruded through thin lithospheres. Graben formation had ceased by the Eratosthenian Period except in uplifted crater floors, but thick sections of basalt and the underlying basin floors continued to sink sufficiently to crumple the mare surfaces into ridges. The only absolutely dated Eratosthenian basalt samples are those of four compositional types collected from at least three flows at the Apollo 12 landing site. These rocks, which are 3.16 aeons old, are atypical of the mare units surrounding this site, most of which are Imbrian in age.

Interfingering of crater and mare materials is more obvious in the Eratosthenian System than in any other time-stratigraphic unit. Most Eratosthenian craters are rayless; some superposed on low-Fe, low-Ti mare materials and terrae are rayed. Exploration has confirmed an early hypothesis that a time-dependent exogenic process fades rays—probably the manufacture by small impacts of Fe- and Ti-rich agglutinitic glasses at the expense of crystalline materials.

Ages younger than those of the Apollo 12 basalt samples and older than Copernicus must be interpolated by data on small superposed craters calibrated with models of the cratering rate. Available terrestrial and lunar data are consistent with a constant impact rate since the start of the Eratosthenian Period until the present, if mare and crater substrates of the same age display different crater frequencies. This constant rate would create 41 of the 132 observed Eratosthenian and Copernican craters larger than 30 km in diameter per aeon, a rate that is substantially lower than even the Late Imbrian rate and that signals a final leveling out of the early bombardment which shaped so much of the Moon's face. The Eratosthenian Period thus lasted about 2.1 aeons. The only impacting bodies available to create craters since the beginning of the Eratosthenian Period were similar to those still present in Earth-Moon space today (Shoemaker and others, 1979; Shoemaker, 1981).

COPERNICAN PERIOD

By the time the Coperican Period began, volcanism had yielded the stage almost entirely back to impact. Copernican mare units are known in only a few spots in the intermediate trough of the Procellarum basin that were also the favored sites of Eratosthenian volcanism. Later, further global cooling, depletion of radioactive-heat sources by extrusion of magma, and consequent lithospheric thickening and strengthening halted surface volcanism. The only possible melted zones today are below the zone of deep moonquakes, about $1,000 \pm 100$ km deep, in the zone where seismic shear waves are attenuated (Goins and others, 1979). Whatever core dynamo may have generated an early magnetic field (Runcorn, 1980) has been extinct for aeons.

The beginning of the Copernican Period has been accurately dated on neither the relative nor the absolute time scale. Absolute ages thought to date Copernican units include a questionable age of 0.8 aeon for Copernicus, a probably accurate age of 0.1 aeon for Tycho, and accurate ages of 2 to 50 million years for small craters dated by Apollo 14 and 16 samples (tables 13.2, 14.1). An estimate for the duration of the Copernican Period, assuming a constant impact rate and a nonequivalence of the crater frequencies on basalt and crater substrates, is 1.1 aeon. If this calculation is correct, limited volcanism lasted until at least 1 aeon ago—a late date by lunar, though not by terrestrial, standards.

Today, the Moon's surface is changing very slowly. Regoliths have formed during the past aeon at the sluggish rate of less than 1 mm per million years (Shoemaker, 1970; Quaide and Oberbeck, 1975). Downslope movement of debris is continuing to degrade slopes, but at a rate too slow to obliterate even such fine-scale features as the secondary-impact craters of Tycho (fig. 3.6), which formed during the Earth's Mesozoic Era. Freshly exposed crystalline material is being very gradually converted to darker glasses. No Copernican units except a few small craters are being added to the Moon. The meteorite impacts recorded by the Apollo seismometers prove that impacts still do occur; one large enough to probe the deep interior of the Moon struck the farside in July 1972 (Nakamura and others, 1973). One to three craters at least 10 km in diameter may form every 10 million years (Shoemaker, 1981). Volcanism and almost all tectonism have ceased.

REMAINING PROBLEMS

This account has shown that much has been learned about the Moon during the past two decades. The origin of the maria and of most craters is settled. Key deposits exposed at the surface have been dated on both the relative and absolute time scales, and the antiquity of the Moon's face has been established. The composition of the Moon and many of its geologic units has been learned to a good first approximation.

It should also be clear that some key questions remain unanswered. Lunar remotely based studies and direct exploration, though in a lull, have not completed their job. The Moon's mode and place of origin are still unknown. Its subsurface structure is very poorly known even in relatively well explored areas. Because Imbrium is the only basin that is well dated on both the relative and absolute time scales, the premare impact rate is too poorly calibrated before 3.85 aeons ago to establish such important points as the time of crustal solidification and the origin and lifetime of large Solar-System projectiles. The dates of volcanism before 3.8 and after 3.2 aeons ago are uncertain. The ages of most of the rayed craters are uncertain within broad limits. The relation among composition, source depth, and extrusion site of the mare basalt flows is hypothetical. The compositions of the farside maria are unknown. Terra compositions are known only very crudely from a few spot samples extrapolated from orbital measurements made at low resolutions of a small percentage of the surface. The origin of central peaks and shallow floors of complex craters is uncertain. The origin of basin rings and even of the position of the boundary of basin excavation—central questions in studies of impact mechanics, lunar petrology, and stratigraphy—is frustratingly elusive.

Some of these questions can probably be answered by continued experimental and field study on the Earth. The origin of complex craters and basin rings might yield to further study of terrestrial craters, laboratory and large-scale explosive experiments, and physical theory. Other questions, such as the distribution of mare-basalt compositions, can be partly answered by continued geologic mapping, crater-frequency counts, telescopic spectral studies, and petrologic theory. Still other questions may be answerable by continued examination of the 80 percent of lunar samples that have not yet been thoroughly analyzed.

Answers to most of the remaining geologic questions, however, require resumption of lunar spaceflights. A global orbiter could gather important data concerning: (1) mare compositions; (2) terra compositions (an even more serious gap from the point of view of the petrologist, the geochemist, and the cosmogonist attempting to learn the origin of the Moon and the Solar System); (3) the Moon's gravitational field; (4) the topography of basins, especially Orientale; (5) the puzzling problem of lunar magnetism; and (6) the stratigraphy of poorly photographed regions (particularly the polar regions above lat 40°, a zone along long 100°–120° W., and the east limb on both the nearside and farside hemispheres). Knowledge of the Moon's third dimension could be greatly improved by this remote exploration. Mars is better photographed than the Moon.

Other problems will require additional samples from the Moon itself. Table 14.2 lists my recommendations for the landing sites of unmanned sample-returning spacecraft that could answer some of the key geologic questions. Objectives fall into five main categories: (1) absolute ages needed to calibrate the stratigraphic column, (2) compositions and textures to decide such genetic problems as the hypothetical terra volcanism, (3) crustal compositions at points of known stratigraphic context that can be extrapolated to larger areas, (4) mantle compositions inferrable from samples of currently unsampled color and age units of mare basalt, and (5) compositions and ages of premare volcanic basalt. Data from most of the selected targets can be extrapolated by means of currently available or future orbital sensing. Petrologists and geochemists might have a different list. The highest priority is given here to dating the Nectaris basin, whose relative age is well known and which, therefore, would provide the needed calibration for the premare cratering rate. Manned missions could achieve multiple goals at single landing sites but are not likely to be resumed within the foreseeable future.

Whether these programs should be undertaken is, of course, a matter of priorities. Very few spaceflights are undertaken by any nation or consortium of nations for purely scientific purposes. Moreover, some scientists give the Moon a low priority despite the easy accessibility of this primitive, cool, internally inactive, silicate planet unmodified by air or water that has preserved an unsurpassed record of the early Solar System. These recommendations are offered here in the belief that the Moon contains additional clues to our understanding of the Solar System, including our own home planet.

TABLE 14.2.—*Potential landing sites for future unmanned lunar sampling missions*

[Each probe is considered capable of returning a single sample of regolith randomly selected from within the designated area. Contributions from Paul D. Spudis]

Priority	Stratigraphic unit	Landing area	Figure	Objective
1	Nectaris basin	(a) Ejecta, near lat 35° S., long 42° E (b) Plains (impact melt?), near lat 22° S., long 41° E	9.1 9.2A	(a) Absolute age. (b) Composition.
2	Copernican mare	Southeast of Lichtenberg, near lat 31° N., long 67° W	13.7	(a) Absolute age. (b) Composition of source.
3	Terra plains (see also priority 11)	(a) Albategnius (b) Ptolemaeus	1.8, 10.36 1.8, 7.7	Nonmare volcanism or buried mare basalt flows(?).
4	Terra domes	(a) Gruithuisen gamma or delta (b) Hansteen alpha	10.45A 10.45B	Nonmare volcanism(?).
5	Farside mare	(a) Floor of Tsiolkovskiy (b) Mare Ingenii	1.3, 3.27A 1.4	Composition of source.
6	Maunder Formation	South of Mare Orientale	4.4B	(a) Age of Orientale basin. (b) Composition of thick crust.
7	Copernicus	Impact melt on floor	3.35	(a) Absolute age. (b) Deep crustal composition(?).
8	King	Impact melt on floor	3.32	(a) Farside crustal composition. (b) Absolute age.
9	Ancient crust	Near lat 30° N., long 160° E	8.1	(a) Composition. (b) Absolute age.
10	South Pole-Aitken massifs	South of Korolev, lat 21.5° S., long 160° W	9.21A	(a) Farside crustal composition. (b) Absolute age.
11	Pre-Late Imbrian mare(?) basalt	(a) Center of Schickard (b) North of Balmer	7.6 1.5, 9.5	(a) Absolute age. (b) Composition.
12	Early Late Imbrian mare	Mare Marginis, in Ibn Yunus	4.7	(a) Absolute age. (b) Composition (KREEP-rich?).
13	Eratosthenian mare	(a) Southwestern Mare Imbrium (a) Surveyor 1 region, near lat 2.5° S., long 43.5° W	5.1 12.6	(a) Absolute age. (b) Calibration of color spectra.
14	Central Mare Serenitatis	Between Bessel and Dawes	11.13	(a) Calibration of color spectra (standard spectrum). (b) Absolute age (near Imbrian-Eratosthenian boundary).
15	Orientale lobate ejecta	Near lat 53° S., long 79° W	4.4D	Impact melt or other ejecta.
16	Alpes Formation	Southeast of Vallis Alpes, near lat 45° N., long 5° E	10.12	(a) Impact-melt/debris content. (b) Composition of deep ejecta.
17	Apennine Bench Formation	Near lat 27° N., long 8° W	6.10	(a) Impact melt or KREEP-rich volcanic materials(?). (b) Absolute age. (c) Calibration of gamma-ray data.
18	Fissured crater-floor deposits	Floor of Murchison, lat 1° W., long 5° N	10.28	Ejected impact melt (Imbrium?).