2

EXPLORATION, SAMPLES, AND RECENT CONCEPTS OF THE MOON

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2.1. LUNAR EXPLORATION

Beyond Earth, the Moon is the only body in space that has been systematically sampled. Meteorites have provided chance samples of solar system debris from the asteroids, and may even include fragments of Mars, but the Moon is the only other planet from which samples have been chipped, scooped, raked, spaded, and collected in cores. These samples were collected by the six U.S. Apollo and three U.S.S.R. Luna missions from known locations on the lunar surface. Analyses of rocks and soils from these sites have allowed their use as "ground-truth" points for remotely-sensed physical and geochemical maps of the Moon.

Although exploration of the Moon is incomplete, the effort expended has been extensive (Table 2.1, Fig. 2.1). The first imaging missions (Luna, Zond, and Ranger) were flown from 1959 through 1965. At the same time, systematic Earth-based mapping of the Moon by telescope began (*Kuiper,* 1960) and led to the determination of a lunar stratigraphy (*Wilhelms and McCauley,* 1971). Luna 10 provided the first orbital gamma-ray chemical data in 1966. Lunar Orbiter missions returned high-resolution images of the lunar surface in preparation for the U.S. manned missions. Unmanned soft landings and surface operations (Surveyor and Luna) continued between 1964 and 1976, with the first data on soil physics and chemistry radioed back from the lunar surface in 1966 and the first Soviet robot-collected samples returned by Luna 16 in 1970. The greatest achievements in lunar sampling were the six Apollo manned landings between 1969 and 1972.

Each Apollo landing increased in exploration complexity and returned ever greater amounts of lunar samples. The last three Apollo landings included Lunar Roving Vehicles (LRVs) that expanded the sample collections across traverse distances of about 30 km. From the standpoint of sample mass returned, the 381.7 kg from six Apollo landings far outweigh the 0.3 kg returned by the three Luna robots. This comparison should not be viewed as a denigration of the Luna contribution; Luna 16, 20, and 24 provided important new sample types from areas on the lunar surface that were not visited by Apollo. The number and diversity of the Apollo samples is particularly valuable, however, when consideration is given to the careful human observations that went into their selection and to the extensive range of analyses and measurements possible with larger samples. At our present stage of technological development, robots are still second-rate geologists.

Current interpretations of the global distribution of lunar rock types (Chapter 10) use the gamma-ray and X-ray fluorescence data collected by the orbiting Apollo command modules and spectral data obtained from telescopes on Earth, but the deciphering of these data depends on the "ground truth" now offered by the large suite of samples collected by Apollo astronauts (Chapters 5 through 7). The Apollo astronauts also deployed surface experiments and made personal observations that provided most of the environmental and physical data we now have for the Moon (Chapters 3 and 9).

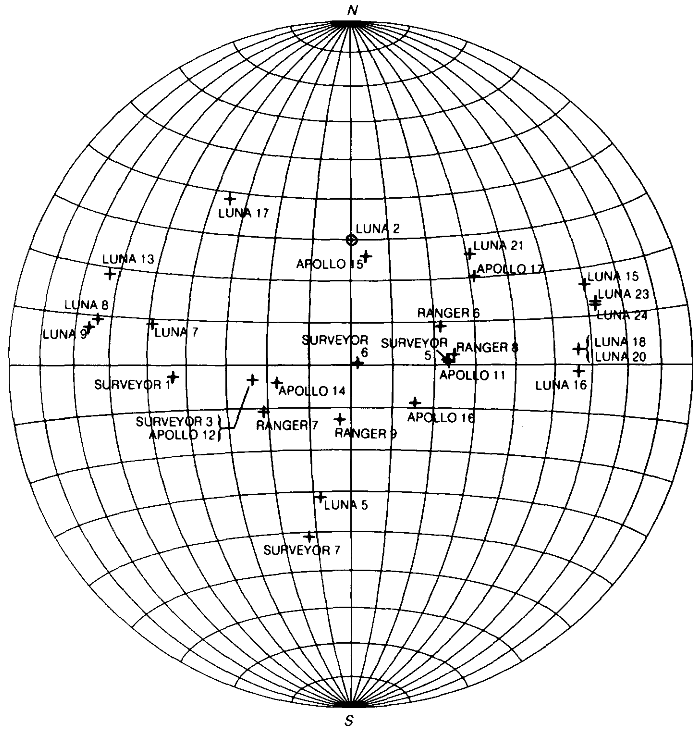


Fig. 2.1. Landing spots of lunar exploration missions, including the impact spots of crashed missions (see Table 2.1). The impact spot of Ranger 4, the only craft to have landed on the farside of the Moon, is shown in Fig. 2.3b. This figure is an equal-area projection drawn to the same scale as the global lunar figures in Chapter 10; it can be copied as a transparency on most copying machines and used as an overlay for the color plates in Chapter 10.

As a direct result of sample studies, we now know that the Moon is not a primitive body that has remained unchanged since the origin of the solar system. We know instead that the Moon had a violent early half-billion years of impact and melting, followed by at least a billion years of volcanic activity. Our knowledge is not comprehensive; the lunar samples are too few and represent only a tiny fraction of the lunar surface. Nevertheless, the study of lunar samples has led to sound hypotheses that address many age-old questions about the Moon. This study goes on still, for the lunar samples continue to reward closer inspection and newer analytical approaches with fresh insight.

2.2. LUNAR SAMPLES

There are three sources of lunar samples for study on Earth. First and most significant are the Apollo samples, *381.7* kg of rock and soil (Table *2.2*) collected at six sites from the central part of the Moon's nearside (facing the Earth). The second source is from three Luna robot landers that collected soil and small rock fragments by drilling 35, 27, and 160 cm into the surface. The Luna missions returned a total of 321 g of lunar material to the U.S.S.R. These first two sources provide samples that can be keyed to known locations on the Moon (Fig. 2.1). The third source of lunar samples consists of lunar meteorites collected on the Antarctic ice cap by both U.S. and Japanese expeditions. Since the first such meteorite was collected in 1979, 10 have been recovered (see Table 2.3), and it is almost certain that more will be found in the future. Chemical studies of these meteorites have provided convincing evidence for a lunar origin; slight differences suggest that they come from other locations than the nine sites sampled by the Apollo and Luna missions. It is thought that the meteorites were blasted off the Moon and sent to Earth by large crater-forming impacts that took place thousands or possibly millions of years ago. Landing on the icecap, the meteorites were preserved to the present.

Data from all three sources are used in this book, but the bulk and complexity of the Apollo sample source requires a more detailed description. A discussion of the Apollo sample types, a description of lunar sample curation, and the history of curation can be found in the Appendix to this chapter. Aspects of the Apollo sample collection and sample identification that are most important for effective use of this book are described below.

2.2.1. The Apollo Collection

Each of the six successful Apollo landings returned a larger number of samples and a greater mass of lunar materials than the previous mission. Table 2.2

TABLE 2.1. History of lunar exploration.

Mission	Launch Date	Accomplishment	Data*
Luna 1	01/02/59	first lunar flyby	
Luna 2	09/12/59	first lunar impact	
Luna 3	10/04/59	first photos of lunar farside	P
Ranger 3	01/26/62	missed the Moon by 36,793 km	
Luna 4	04/02/63	missed the Moon by 8,500 km	
Ranger 4	04/23/62	crashed on the lunar farside	
Ranger 5	10/18/62	missed the Moon by 724 km	
Ranger 6	01/30/64	impact lander; television failed	
Ranger 7	07/28/64	impact lander	P
Ranger 8	02/17/65	impact lander	P
Ranger 9	03/21/65	impact lander	P
Luna 5	05/09/65	crashed on the Moon	
Luna 6	06/08/65	missed the Moon by 161,000 km	
Zond 3	07/18/65	photographed lunar farside	P
Luna 7	10/04/65	crashed on the Moon	
Luna 8	12/03/65	crashed on the Moon	
Luna 9	01/31/66	first lunar soft landing	P
Luna 10	03/31/66	first lunar satellite	SE,CO
Surveyor 1	05/30/66	first soft-landed robot laboratory	P,SM
Lunar Orbiter 1	08/10/66	lunar satellite	P,R,SE,M
Luna 11	08/24/66	lunar satellite	P
Luna 12	10/22/66	lunar satellite	P,M,SE
Lunar Orbiter 2	11/06/66	lunar satellite	P,R,SE,M
Luna 13	12/21/66	soft landing on the Moon	P,C
Lunar Orbiter 3	02/05/67	lunar satellite	P,R,SE,M
Surveyor 3	04/17/67	soft-landed robot laboratory	P,SM
Lunar Orbiter 4	05/04/67	lunar satellite	P,R,SE,M
Explorer 35	07/19/67	lunar satellite	
Lunar Orbiter 5	08/01/67	lunar satellite	P,R,SE,M
Surveyor 5	09/08/67	soft-landed robot laboratory	P,SM,C
Surveyor 6	11/07/67	soft-landed robot laboratory	P,SM,C
Surveyor 7	01/07/68	soft-landed robot laboratory	P,SM,C
Luna 14	04/07/68	lunar satellite	
Zond 5	09/14/68	first lunar flyby and Earth return	
Zond 6	11/10/68	lunar flyby and Earth return	P
Apollo 8 (G)†	12/21/68	first humans to orbit the Moon	P
Apollo 10 (G)†	05/18/69	first docking maneuvers in lunar orbit	P
Luna 15	07/13/69	crashed on the Moon	
Apollo 11 (H)†	07/16/69	first humans on the Moon (07/20/69)	P,S,SM,G, M,SW,D
Zond 7	08/08/69	lunar flyby and Earth return	P
Luna 16	09/12/70	first robot sample return (100 g)	S
Luna 17	11/10/70	first robot rover (322 days, 10.5 km)	P,C,SM,R
Apollo 12 (H)†	11/14/69	second human landing on the Moon	P,S,SM,G,M,SW,D,A
Apollo 13 (H)†	04/11/70	aborted human landing	P
Zond 8	10/20/70	lunar flyby and Earth return	P
Apollo 14 (H)†	01/31/71	third human landing on the Moon	P,S,SM,G,SW,D,A
Apollo 15 (J)†	07/26/71	fourth human landing on the Moon	P,S,C,SM, R,G,CO,SE,SW,D,A
Luna 18	09/02/71	crashed on the Moon	
Luna 19	09/28/71	lunar satellite	P,SE
Luna 20	02/14/72	second robot sample return (30 g)	P,S
Apollo 16 (J)†	04/16/72	fifth human landing on the Moon	P,S,C,SM, R,G,CO,SE,A
Apollo 17 (J)†	12/07/72	sixth human landing on the Moon	P,S,SM,R, G,SE,M
Luna 21	01/08/73	robot lunar rover (139 days, 37 km)	P,C,SM,R
Luna 22	05/29/74	lunar satellite	P
Luna 23	10/28/74	failed robot sampler	
Luna 24	08/09/76	third robot sample return (170 g)	S

TABLE 2.1. (continued).

Apollo Lunar Missions	Crew
8	F. Borman, J. Lovell Jr., W. Anders
10	T. Stafford, J. Young, E. Cernan
11	N. Armstrong, E. Aldrin Jr., M. Collins
12	C. Conrad Jr., R Gordon Jr., A. Bean
13	J. Lovell Jr., J. Swigert Jr., F. Haise
14	A. Shepard Jr., S. Roosa, E. Mitchell
15	D. Scott, J. Irwin, A. Worden
16	J. Young, T. Mattingly II, C. Duke Jr.
17	E. Cernan, R. Evans, H. Schmitt

* Data types are abbreviated as follows: A = atmosphere and ion studies; C = surface chemistry; CO = chemical mapping from orbit; D = dust analysis; G = surface-based geophysics; M = meteoroid studies; P = photography; R = radiation environment studies; S = samples returned to Earth; SE = selenodesy measurements; SM = soil mechanics studies; SW = solar wind studies. More detailed descriptions of individual experiments are given in Chapters 3, 9, and 10.

†The Apollo manned missions fall into three major categories with the following letter designations: G (lunar orbit without lunar landing); H (lunar landing with limited mobility); and J (lunar landing with Lunar Roving Vehicle). The H missions (30 metric tons) were three times as heavy as the Apollo 8 and Apollo 10 G missions (10 metric tons); the J missions (50-60 metric tons) were twice as heavy as the H missions.

Detailed information on U.S. missions can be found in *Mantell and Miller* (1977); comparable information on U.S.S.R. missions is in *Johnson* (1979).

summarizes sample data for each Apollo mission and for the total program. The number of samples and total weight entries at the top of each column document the total size of the collection.

The status of the Apollo samples as of 1989 is reported in Table 2.2. By 1989, almost two decades after the first samples were obtained, the Apollo collection was probably the most intensively studied suite of rocks on Earth. The original 2196 samples had been split into more than 78,000 subsamples, but 87% of the sample mass remained "pristine." These samples, protected from chemical alteration inside nitrogen-filled cabinets, are available for future study. A sample is considered pristine if it has been stored continuously in dry nitrogen since its preliminary examination at the Lunar Receiving Laboratory (LRL). Many of the pristine samples have been studied and sampled extensively in the nitrogen-filled cabinets of the Lunar Sample Laboratories at NASA Johnson Space Center (JSC). The lower proportion of pristine samples (71-84%) in the collections returned by Apollo 11 through 14 is due, in part, to the quantity of samples allocated for tests related to biological quarantine early in the Apollo program.

The Apollo astronauts collected a variety of rock and fine-grained regolith samples at each site. Detailed descriptions of the various sampling techniques and resulting sample types are given in the Appendix to this chapter. Table 2.2 also summarizes the relative abundances of igneous rocks, rocks produced by impact processes, fine-grained regolith collected from the surface, and cores at the six Apollo sites. The relative abundances of mare rocks (basalt, dolerite) are also reported.

Cores provide the only samples suitable for detailed studies of variations in regolith properties with depth. Apollo cores were collected with 31.8-to 72-cm-long drive tubes (for a detailed description of Apollo sampling tools, see *Allton,* 1989). At some locations the astronauts collected cores with a single drive tube; at other locations they sampled deeper layers by connecting two drive tubes. At Apollo sites 15 through 17 a battery-powered drill was used that could drive up to eight connected 40-cm-long core tube sections. The bottom of Table 2.2 lists the types of cores collected at each Apollo site.

2.2.2. Lunar Sample Identification

A system of sample identification had to be developed before records of samples could be maintained. The basic format of identification numbers for the Apollo samples was adopted before the first samples were returned, but refinements of the system appeared from time to time through the program.

Following each Apollo mission, the Lunar Sample Preliminary Examination Team (LSPET) assigned a unique five-digit generic sample number to each of the following types of returned samples: (1) each coherent fragment larger than 1 cm in diameter; (2) each sieved fraction of a single fine-grained soil sample; (3) each unsieved portion of a single fine-

TABLE 2.2. Apollo sample summary.

	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17	Apollo Total
Original Collection							
Number of samples	58	69	227	370	731	741	2196
Total weight (kg)	21.6	34.3	42.3	77.3	95.7	110.5	381.7
Sample Status as of 1989 (% of total weight)							
In Curator's Custody							
Pristine samples at JSC *	63.5	70.3	65.8	69.7	78.6	75.8	72.9
Pristine samples at BAFB †	6.9	13.7	16.0	15.7	12.5	14.8	14.0
Returned samples at JSC	16.8	7.8	10.5	7.4	4.4	4.4	6.9
Allocated Samples							
For analysis	3.7	2.3	2.1	1.9	1.8	1.3	1.9
For educational display	1.3	2.7	3.0	4.1	1.2	2.5	2.5
Consumed	7.8	3.2	2.7	1.3	1.5	1.2	1.8
Lithology (% of total weight)							
Rocks (>10 mm)	44.9	80.6	67.3	74.7	72.3	65.9	69.5
Anorthosite				(0.4)	(10.5)	(0.5)	(2.8)
Basalt	(19.9)	(52.2)	(9.1)	(37.9)		(29.1)	(22.9)
Dolerite (coarse basalt)		(26.3)					(2.4)
Other igneous rocks	(2.1)	(0.2)				(4.0)	(1.3)
Breccia	(22.9)	(1.9)	(58.2)	(34.1)	(36.8)	(32.3)	(33.4)
Impact melt				(2.3)	(25.0)		(6.7)
Fines (<10 mm)	54.6	16.8	30.6	17.0	19.3	26.7	24.0
Unsieved	(54.6)	(16.8)	(0.8)	(5.1)	(8.5)	(11.3)	(11.1)
<1 mm			(27.3)	(10.7)	(9.2)	(13.9)	(11.5)
1–2 mm			(1.0)	(0.4)	(0.7)	(0.6)	(0.5)
2–4 mm			(0.8)	(0.4)	(0.5)	(0.5)	(0.4)
4–10 mm			(0.8)	(0.4)	(0.5)	(0.4)	(0.4)
Cores	0.4	1.2	0.9	6.0	7.4	6.6	5.2
Other		1.4	1.0	2.4	1.2	0.9	1.2
Cores Collected							
2-cm Drive Tube							
Single	2	2	2				6
Double		1	1				2
4-cm Drive Tube							
Single				1	1	2	4
Double				2	4	3	9
2-cm Drill Core							
Number				1	1	1	3
Maximum depth (cm)				237	221	292	

* JSC = Johnson Space Center, Houston, Texas.
BAFB = Brooks Air Force Base, San Antonio, Texas.
Numbers in parentheses represent subtotal percentages within a group.

TABLE 2.3. Lunar meteorites.

Discovery	Location/Number	Weight (g)
Anorthositic Breccias		
1982	Allan Hills 81005	31.4
1984	Yamato 791 197	52.4
1985	Yamato 82192	36.7
1986	Yamato 82193	27.0
1987	Yamato 86032	648.4
1987	Yamato 793274	8.7
1989	MacAlpine Hills 88104	61.2
1989	MacAlpine Hills 88105	662.5
Basaltic Compositions		
198	Elephant Moraine 87521 (breccia)	30.7
199	Asuka 31 (unbrecciated cumulate)	- 500

grained soil sample; (4) each section of a drive tube or drill stem containing a lunar soil core; (5) each special sample.

The numbering system became more organized as succeeding missions explored larger areas and returned more samples. A description of the system used for each mission may be found in the Sample Information Catalogs issued by the Lunar Sample Curator (JSC, Houston, Texas). A brief summary is given in the adjacent sidebar.

2.3. NEW VIEWS OF THE MOON FROM EXPLORATION

Until lunar samples were returned by the Apollo missions, our understanding of the Moon, especially of its composition and history, was severely limited. Since meteorites had been the only extraterrestrial materials available for laboratory analysis, there had been speculation that the Moon might be like some meteorites: an ancient body condensed from the solar nebula (*Urey,* 1965, 1966) and unaffected by the terrestrial processes of segregation into crust, mantle, and core. The Apollo samples proved that the Moon was not a primitive body, unchanged since its origin. The samples provided ample evidence for over a billion years of planetary evolution, catastrophic meteorite bombardment, and intense igneous activity that have altered the Moon since its origin about 4.6 b.y. ago. The major problem in understanding the Moon's early history then became the need to see through this early history of chemical segregation, bombardment, and volcanism to the Moon's primordial origins.

The most visible evidence of lunar chemical segregation is the existence of two very different terrains on the Moon: the highlands and the maria.

LUNAR SAMPLE NUMBERING

A two-part number identifies each sample in the Apollo collection. The first part is a five-digit "generic" number; the second part is a one- to four-digit "specific" number. The specific number is placed to the right of the generic and separated from it by a comma (e.g., 15362,28).

The first one or two digits of the five-digit generic number always identify the Apollo mission, as follows:

10 — Apollo 11	14 — Apollo 14	6 — Apollo 16
12 — Apollo 12	15 — Apollo 15	7 — Apollo 17

The Luna samples have similarly been given five-digit numbers, of which the first two correspond to the mission:

16—Luna 16	20— Luna 20	24— Luna 24

Lunar meteorite names and numbers are listed in Table 2.3.

For samples collected during Apollo missions 11 through 14, the LSPET assigned the last three digits of the generic numbers without regard to sample type or location within the landing site. For samples collected during Apollo missions 16 and 17, the second digit of the generic number generally identifies the location where the sample was collected. For samples collected during Apollo missions 15 through 17, the fifth digit of the generic number generally identifies the sample as unsieved fines, a sieved fraction of fines, or a rock as follows:

——— y0	Unsieved <10-mm fines	——— y4	4–10-mm sieved fraction
——— y1	<1-mm sieved fraction	——— y5	a >10-mm rock from the same sample bag
——— y2	1–2-mm sieved fraction	——— y6 to ——— y9	for additional rocks from the same sample bag
——— y3	2–4-mm sieved fraction		

When more than five rocks were in a bag, the LSPET assigned numbers 5 through 9 in successive decades (y + 1, y + 2, y + 3, etc.) until each rock received a unique generic number. Gaps are common in lists of sample numbers for these later missions because a sample bag rarely contained exactly five rocks and a sample of fines large enough to provide four sieved fractions plus an unsieved reserve.

The specific part of the sample number, located to the right of the comma, provides a unique identification for each subdivision of a sample. Usually, the LSPET assigned specific number "0" to the whole sample. Each subsample (chip, aliquant, thin section, etc.) retains the generic number of its source and receives the next higher unused specific number for that sample.

This sample numbering scheme can be confusing to those who are not involved in lunar sample studies. Lunar researchers are often guilty of reciting lunar sample numbers as if they were the names of old friends, expecting their listeners to draw a physical or chemical image of the "famous" sample mentioned. However, the Apollo sample numbering scheme also serves a very useful purpose in helping to track down data. In this book the Apollo generic sample numbers are used extensively, not to confuse but to provide easier access to more information about the sample being discussed. The indexes of this book and of many other references list generic sample numbers; a search based on generic sample number is a powerful method for obtaining a broad range of data on a particular lunar sample.

Physically, the highlands are rough and intensely cratered while the maria are relatively smooth. Although these bright (highlands) and dark (mare) areas of the Moon have been obvious since prehistoric times when they were given mythical anthropomorphic shapes, it required actual sampling of these two terrains to provide the fundamental clues about lunar origin and evolution.

From low orbit the Apollo astronauts were impressed by the sharp contrasts between juxtaposed mare and highland regions (Fig. 2.2). At an orbital altitude of only 60 km, the passage over highland mountain ranges rising abruptly 3 km above the flat maria was spectacular.

Studies of the Apollo and Luna samples have provided direct evidence of the major differences between these terrains. Chemically, the lunar highlands are enriched in Ca and Al while the maria are richer in Fe and Ti. In rock type, the highlands consist mostly of old impact-shocked plutonic (deep-seated) rocks while the maria consist of basaltic lavas. Mineralogically, the highlands are dominantly feldspar while the maria have more abundant pyroxene.

The first probe to orbit behind the Moon, Luna 3, showed a surprising absence of mare terrain on the lunar farside. Although mare basalts cover about 16% of the lunar nearside, less than 1% of the farside

Fig. 2.2. A view from orbit of the sharp terrain differences between mare and highland regions on the Moon. This is an oblique view of the rim of Mare Crisium. Mount Fuji, 3776 m high, has been drawn in for scale.

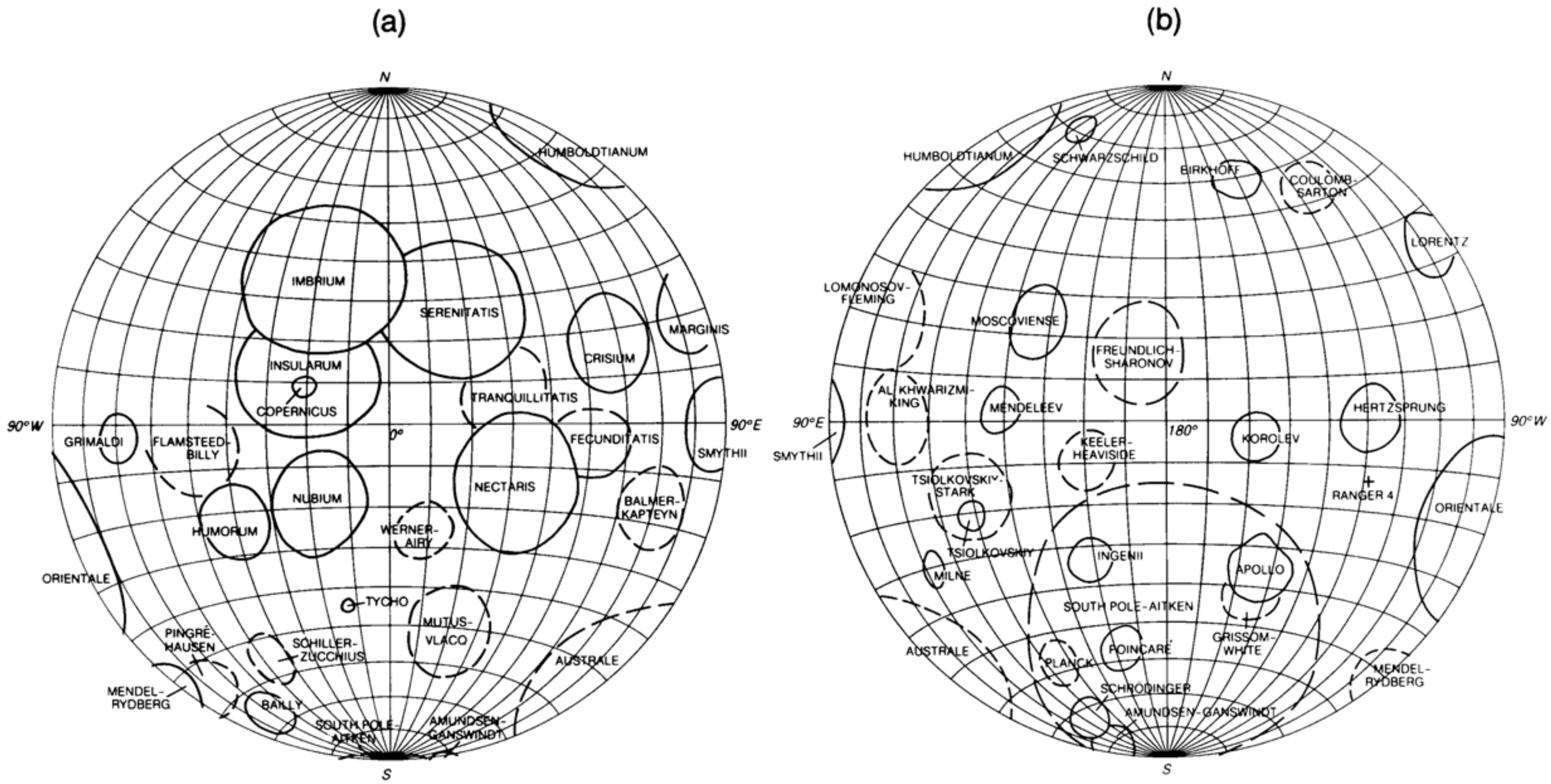


Fig. 2.3. Major impact basins on the **(a)** nearside and **(b)** farside of the Moon. These are equal-area projections drawn to the same scale as the global lunar figures in Chapter 10; they can be reproduced as transparencies on most copying machines and used as overlays for the color plates in Chapter 10.

has mare basalt cover. The cause of this imbalance in the distribution of lunar maria is still unknown; suggestions range from a thickened farside crust, through which basalt could not rise, to the absence of deep mantle melting beneath the farside. A gap in our lunar sample collection is the absence of any samples—mare or highland—obviously from the lunar farside. (Some lunar meteorites may be from the farside.)

The deposits from mare basalt eruptions have done much to soften some of the relief on the nearside of the Moon. However, the topography of all parts of the Moon remains dominated by major impact basins. Figure 2.3 shows the sizes, locations, and names of many of the most prominent lunar impact basins. These basins are useful geographic reference features for discussing locations on the Moon, and the names listed in Fig. 2.3 are used throughout this book (see Chapter 4 for detailed discussion of basin-forming impacts).

2.4. NEW CONCEPTS OF THE MOON FOLLOWING EXPLORATION

Although this book is focused on the data from the Moon instead of interpretations, it would be incomplete without a discussion of recent models of lunar origin and evolution based on these data.

2.4.1. Origin of the Moon

The origin of the Moon, like the origin of the Earth, has been cause for speculation since prehistoric times. Modern speculation began when George Darwin (1879) hypothesized that the Moon formed from the Earth by fission of a single larger body. Two other modern hypotheses that are considered "classical" are formation along with the Earth as a sister planet (*Schmidt,* 1959) and gravitational capture of a body formed elsewhere in the solar system (*Gerstenkorn,* 1955).

Many people anticipated that the Apollo program would be more than sufficient to provide the final answer on the origin of the Moon. This probably would have been the case if the Moon were a primitive undifferentiated, homogeneous body (*Urey,* 1966). The differentiation of the Moon into concentric zones of differing chemical composition and its active geologic past, however, have obscured its origins. We have sufficient data on celestial mechanics (gravitational effects) to know that the dynamical constraints (shape, gravity, moment of inertia) alone are not sufficient to pin down the Moon's origin; the data available for lunar geophysical analyses and particularly for lunar geochemistry are too few to be conclusive. However, as often happens in science, the post-Apollo work, especially on lunar samples, has combined the earlier, simpler hypotheses and added a new twist. It has been proposed (*Hartmann and Davis,* 1975; *Cameron and Ward,* 1976) that a large object, possibly Mars-size, impacted Earth to expel large amounts of material (fission hypothesis), condense much of that vaporized material in orbit (sister planet hypothesis), and incorporate much of the exotic collider (capture hypothesis). This new combined hypothesis goes a long way toward reconciling the strong points and solving the dilemmas in dynamics, chemistry, and geophysics that are coupled with adherence to any of the individual classical hypotheses. *Hartmann et al.* (1986) summarize the development of these hypotheses in their book, *Origin of the Moon.* Figure 2.4, from a computer model by *Kipp and Melosh* (1986), illustrates this new view of the first 12.5 minutes of the impact process that may have led to the origin of the Moon.

To truly understand the origin of the Moon, more data are needed. From future geophysical surveys, we need to learn more about the Moon's heat flow, its mantle thickness and seismic velocity structure, and whether it has a metallic core. From future geochemical studies, we need to determine the lunar inventory of heat-producing radioactive elements, the abundances of refractory and volatile elements, and the abundances of siderophile elements (those that tend to be miscible with iron). The magnesium-to-iron ratio must also be known for comparison with the Earth. These seem at first glance to be simple measurements, but they are measurements that can now only be obtained from a few of the varied parts of the differentiated Moon. The reassembly of these parts can be done with confidence only after the history of lunar differentiation is known, by the determination of volumes and ages of rock types at the surface, and by the use of geophysics and geochemistry to infer their sources at depth. Future lunar global data from orbit and from the lunar surface will be required to create and test a convincing theory of the Moon's origin.

2.4.2. Diversity of Lunar Rock Types

One of the fundamental discoveries of the Apollo program was that the Moon is made up of a variety of igneous rock types that differ widely in both their chemistry and mineral composition. The first-order differences are between the dark basalts of the maria and the lighter-colored feldspar-rich rocks of the highlands, as described in section 2.3. There is also a great diversity among the highland rocks themselves. Three major types have been identified:

Ferroan anorthosites, which are rich in Ca and Al and composed largely of the mineral *plagioclase feldspar* ($CaAl_2Si_2O_8$-$NaAlSi_3O_8$), are one of the most

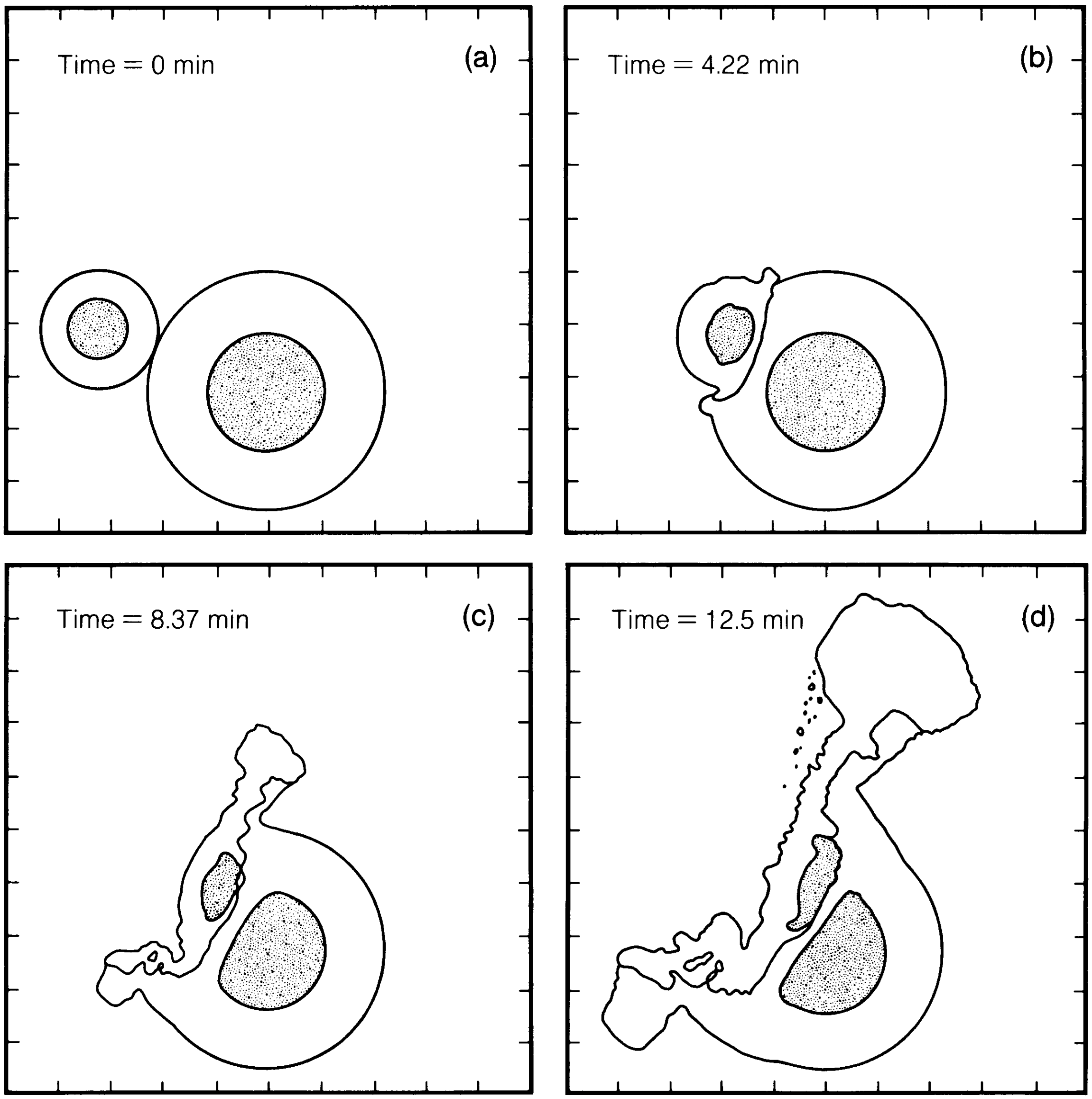


Fig. 2.4. A computer simulation showing 12.5 minutes in the duration of a hypothetical collision between a Mars-sized planet and the proto-Earth. The dotted circles at the center of each planet represent their metallic cores, which are surrounded by silicate mantles. In this illustrated hypothesis the "jetted" silicate material being ejected in the last frame will provide a large part of the Moon, while the metallic parts of both bodies will coalesce in the Earth; the result would be a Moon with little or no metallic core, which fits our present knowledge of our natural satellite (after *Kipp and Melosh,* 1986).

ancient of highland rock types. Ferroan anorthosites are relatively common among samples from the Apollo 16 landing site and among the anorthositic lunar meteorites (Table 2.3).

Magnesium-rich (*Mg-rich*) *rocks* are clearly distinct from the ferroan anorthosites. They may contain nearly as much plagioclase as the ferroan anorthosites, but they also contain Mg-rich grains of minerals such as olivine $[(Mg,Fe)_2SiO_4]$ and pyroxene $[(Ca,Mg,Fe)SiO_3]$. Different rock names within this group—such as *norite* (plagioclase plus low-Ca pyroxene), *troctolite* (plagioclase plus olivine), and *dunite* (abundant olivine)—reflect differences in the proportions of plagioclase, olivine, and pyroxene that make up these rocks.

KREEP rocks are crystalline highland rocks that contain a chemical component enriched in such elements as potassium (K), the lanthanides or "rare-earth elements" (REE), and phosphorus (P). The KREEP component is also generally accompanied by relatively high concentrations of the radioactive elements U and Th. The appearance of KREEP in lunar rocks indicates extensive chemical separation within the Moon, and the enrichment of the heat-producing elements U and Th makes KREEP-bearing rocks important in understanding the Moon's thermal history.

Detailed descriptions of these three categories of highland igneous rocks are given in section *6.3,* but the descriptions given above are sufficient for this chapter. The chemical and mineralogical diversity among highland and maria igneous rocks has been a major problem in understanding the origin and early history of the Moon. Extensive analytical studies, laboratory experiments, and theoretical modeling have attempted, ever since the first samples were returned to Earth, to explain how the different rocks formed, how they are related to each other, and how one type may have been derived from (or may have given rise to) others. This active debate continues at the present time.

2.4.3. Differentiation of the Moon and Origin of the Lunar Crust

The major differences between the lunar maria and highlands indicate large-scale chemical segregation (differentiation) of the original materials that accreted to form the Moon. There is general agreement on this point, but the details of differentiation are still mysterious. Early recognition of the fact that the highlands are composed mostly of Ca-rich plagioclase ($CaAl_2Si_2O_8$), a relatively light mineral, led to the suggestion that this mineral represents crystal flotation at the top of a very deep (400 km?) "magma ocean" (*Wood et al.,* 1970). This startling concept—a planet drowned in a molten silicate sea with temperatures greater than 1400°C—has survived in several modifications since its introduction. The evolution of this concept from *1969* to 1985 *is* illustrated in Fig. *2.5;* the discussion that follows is a summary of the major data that have led to these variations in the magma-ocean hypothesis.

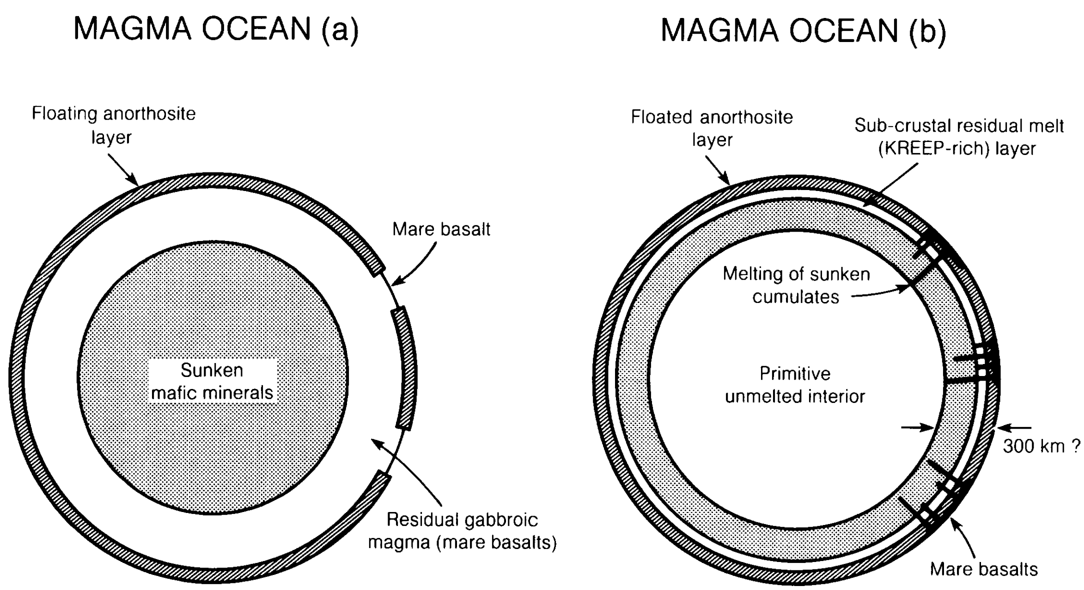


Fig. 2.5. Evolution of the "magma ocean" concept. **(a)** An early model (after *Wood et al.,* 1970) that supposed the entire Moon was initially molten and the mare basalts seen from Earth were parts of the chilled magma ocean exposed through holes in the crust. **(b)** A synthesis of several studies done between 1970-1974 that limited the magma ocean to the outer ~300 km and allowed the mare basalts to form later by remelting (black lines ascending through the sunken cumulates; *LAPST,* 1985).

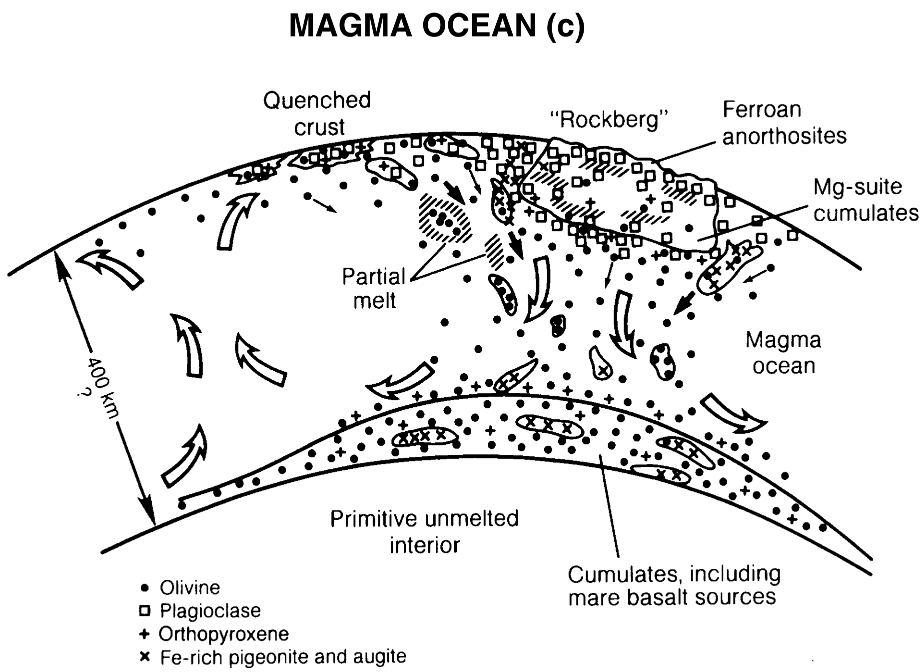


Fig. 2.5. (*continued*) **(c)** This figure incorporates details required to account for the differences between ferroan anorthosites and the Mg-suite rocks by forming "rockbergs" on the magma ocean above down-flowing regions within the magma ocean (*Longhi and Ashwal, 1985*). See Chapter 5 for descriptions of the minerals shown.

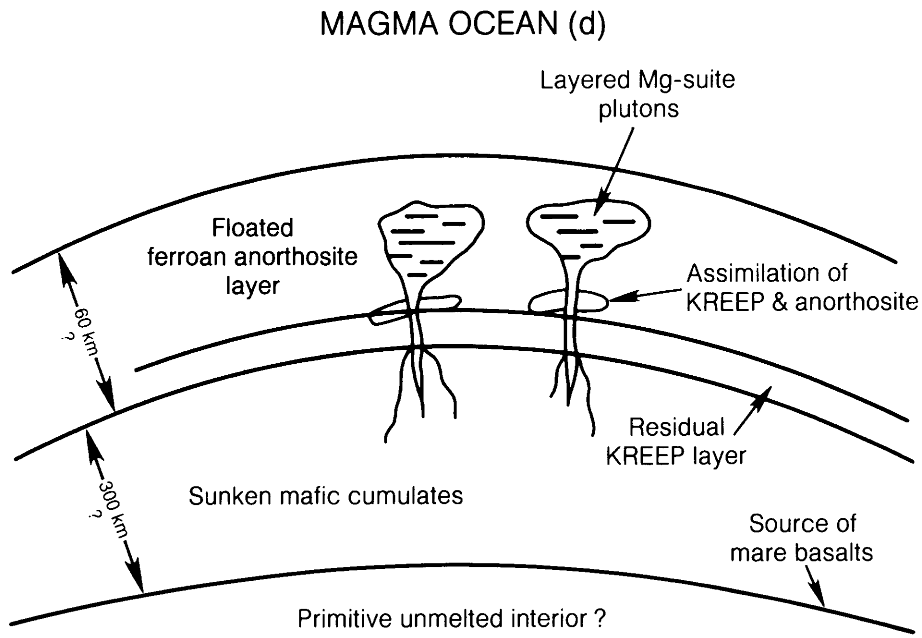


Fig. 2.5. (*continued*) **(d)** A more recent model that allows for the ferroan anorthosites to form by flotation on the magma ocean but accommodates a younger age for the Mg-suite rocks by formation through partial melting in the interior with assimilation of older KREEP and anorthosite compositions (synthesis of several studies by *LAPST,* 1985).

The basic argument for a "magma ocean" has been the need for a mechanism to float a plagioclase-rich crust, while denser minerals such as olivine and pyroxene sank. The idea soon developed that these sinking dense minerals accumulated into deep layers that subsequently became the source areas for at least some mare basalts. The main data constraints on the magma-ocean hypothesis follow; for details, see *Warren* (1985).

A global, plagioclase-rich crust. Although we lack global coverage, available data from Apollo samples, remote measurements from lunar orbit, and gravity data indicate that the lunar highlands' surface material averages about 75% plagioclase. Seismic data and the composition of ejecta from large impact basins indicate that this enrichment in plagioclase extends to depth as well. This high abundance of one mineral indicates that some global process concentrated it; flotation in a huge magma system is most likely.

Uniformity of incompatible trace-element ratios. "Incompatible" trace elements are those not required to make the common minerals that crystallize in igneous rocks. Instead, these elements end up concentrated in the last liquid dregs of the magma ocean. This may be the ultimate origin of KREEP (see the section below on formation of the anorthositic crust). Lunar rocks rich in incompatible trace elements may have quite variable total abundances of these elements, but the ratios of these elements to each other are remarkably constant. This suggests that the enrichments in trace elements derive from a single global source, such as a residuum from a magma ocean.

Possibly extensive melting. Assuming the existence of a magma ocean, estimates of its depth vary from about 100 km to virtually the center of the Moon, a depth of 1738 km. As summarized by *Warren* (1985), calculations on the depth of melting are based mostly on mass-balance arguments about the abundances of plagioclase and incompatible elements in the crust, estimates of the stresses causing thrust faults in the crust, and estimates of the depths of mare basalt source regions that formed as a consequence of magma ocean crystallization. On balance, the evidence favors a possible magma shell deeper than about *250* km but probably no more than 1000 km deep.

The nature of the hypothetical magma ocean is also uncertain. It is not known whether it would have been a melt of whole-Moon composition or a partial melt. The tendency of partial melts to separate from their source regions and for a solid-melt system to convect suggests that total melting is unlikely,

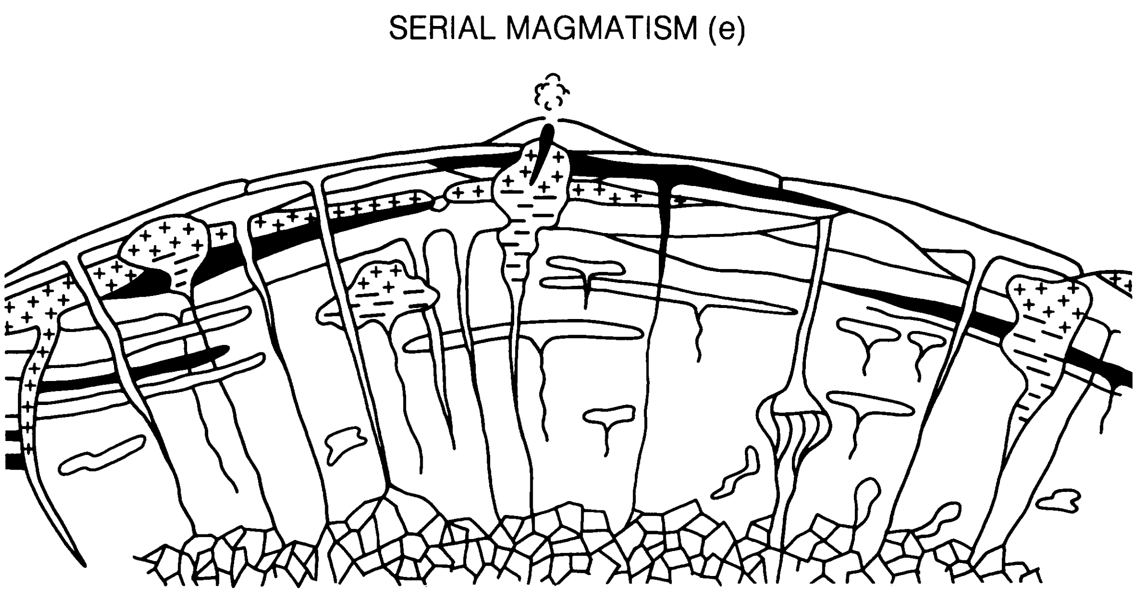


Fig. 2.5. (*continued*) **(e)** A model by *Walker* (1983) that allows for production of the entire range of lunar crustal rock types without any magma ocean. This model generates the Eu anomalies in Fig. 2.6, which led to the magma ocean concept, by an open-system series of melting events with fractionation and admixture of residual liquids. This panel shows the complex series of aluminous basalt flows, sills (black horizontal layers), and intrusions allowed by the model. The evolving and sometimes conflicting hypotheses illustrated in these five panels are evidence of the vital debate that continues over the data from a handful of lunar samples.

although this assumes that the Moon was originally solid. It is possible that the magma ocean was derived from partial melting of the lunar interior and was continuously fed by a "magmifer" (a term analogous to "aquifer" and used to describe the quasisolid mantle, beneath a magma ocean, with extractable partial melt; see *Shirley,* 1983). Some models for the Moon's origin, such as fission from Earth, however, depict the Moon beginning as a molten body, so a totally molten magma ocean cannot be ruled out.

Complementary europium anomalies. The average highlands crust has a positive europium (Eu) anomaly relative to other REE, indicating an Eu enrichment in plagioclase (Fig. 2.6). This chemical signature is an important and fundamental part of the lunar database, worth considering in some detail. Europium is in the middle of the lanthanide elements (atomic numbers 57 to 71) in the periodic table; these lanthanides (or REE) play an important role in understanding rock and mineral origins (see Chapters 5, 6, and 8). The Eu anomaly considered here is seen when the REE abundances in a sample are ratioed to a fixed standard, commonly their abundance in very primitive meteorites (chondrites) that have not undergone any form of planetary segregation, although a model REE composition for the bulk Moon has also been used (Fig. 2.6). In contrast to the average highlands crust, mare basalts have negative Eu anomalies that were apparently inherited from their deep source regions in the lunar mantle. Plagioclase must therefore have been separated from the magmas from which these mare basalt source regions formed, implying that the source regions now contain the dense olivines and pyroxenes that sank (or at least did not float) as plagioclase floated in the magma ocean.

Geochemical distinctiveness of ferroan anorthosites. As shown in section 6.3, some of the most ancient of lunar samples are ferroan anorthosites. *Warren* (1986) finds evidence that an already solid crust of ferroan anorthosites was there to be assimilated by somewhat younger Mg-rich highland magmas that rose through the crust. In this view, the ferroan anorthosites formed earlier and from a different magma than the bulk of the highlands crust. Ferroan anorthosites have large positive Eu anomalies, consistent with an origin coupled to plagioclase flotation. This is also consistent with the magma ocean hypothesis.

Antiquity of highland igneous rocks. Age data clearly indicate that the Moon underwent extensive chemical fractionation prior to 4.4 b.y. ago. Ferroan anorthosites and many (but not all) Mg-suite rocks have crystallization ages and model ages older than 4.4 b.y., and model ages for other highland igneous rocks and mare basalts indicate that their source regions had formed by 4.4 b.y. ago. A magma ocean would be a very efficient mechanism for concentrating these igneous source regions so early in lunar history.

Serial magmatism: Alternatives to the magma ocean. Some investigators have suggested that there never was a magma ocean, favoring instead

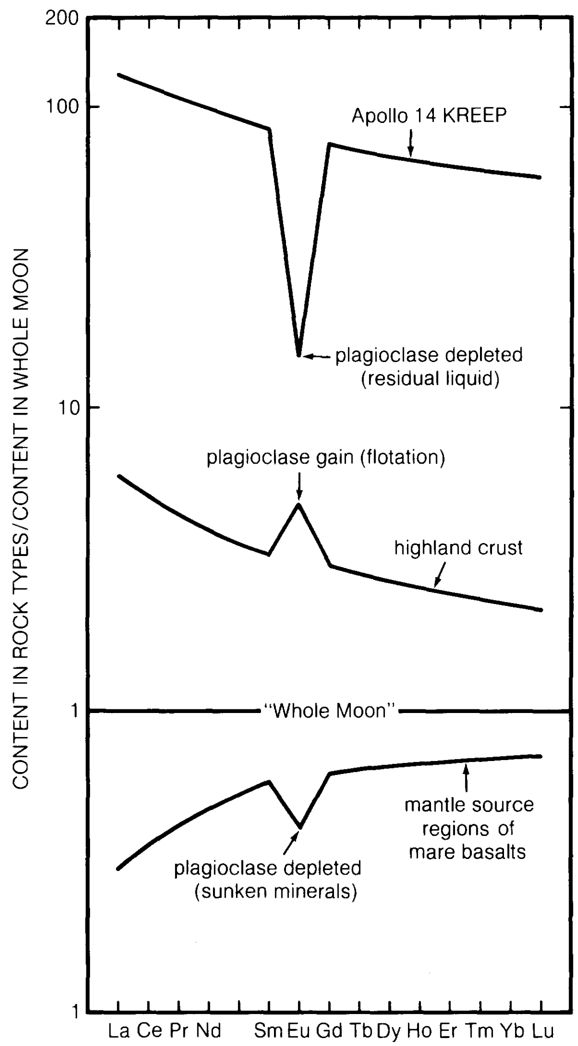


Fig. 2.6. Rare-earth element (REE) concentrations and Eu anomalies in the plagioclase-rich lunar crust, in the source regions for lunar mare basalts, and in KREEP basalts from the Apollo 14 site. The Eu anomalies are due to excursions from smooth trends in the ratio of lanthanide element abundances of a rock compared to a model whole-Moon composition. The Eu anomalies are caused by accumulation or removal of Eu-enriched plagioclase (after *S. R. Taylor,* 1982).

the formation of anorthosites and other feldspathic cumulates in numerous magmas that intruded the primeval crust. This idea has been dubbed "serial magmatism." *Longhi and Ashwal* (1985) have developed the most elaborate model for the formation of ferroan anorthosites by this mechanism. They depict anorthosites rising as solid but plastic masses from layers deep in the lunar crust. This would account for the enrichment of plagioclase in the crust, but it requires that the crust be extremely hot (partially molten) for 50 to 100 m.y.

Serial magmatism is now almost universally evoked to explain the formation of Mg-suite magmas. Opinion is split about whether ferroan anorthosites came from a magma ocean or were produced by serial magmatism, although most investigators favor the magma ocean idea. A test to distinguish between the magma ocean and serial magmatism hypotheses for the formation of ferroan anorthosites is to determine accurately the abundance of plagioclase in the crust. Serial magmatism implies that the average crustal composition is roughly noritic or basaltic, containing 15-20 wt.% Al_2O_3, corresponding to a plagioclase abundance of less than 55%. The magma ocean hypothesis requires a crust richer in plagioclase. This test awaits the completion of the Lunar Observer mission, which will produce global geochemical, mineralogical, and geophysical data (Chapter 11).

2.4.4. The Present View of Lunar Magmatic Evolution

Our sampling of the Moon is limited. We lack global photogeologic, geochemical, and geophysical coverage, and many details of lunar history are controversial. Nevertheless, a broad outline of lunar igneous evolution can be constructed; for details and numerous references, see *Warren* (1985).

Formation of the anorthositic crust. As the Moon formed, its outer portions consisted of a layer of molten silicate magma in which plagioclase floated and accumulated into the first stable lunar crust. At the same time, the heavier olivine, pyroxene, and eventually ilmenite ($FeTiO_3$) sank to form the source areas for mare basalts. As the ocean crystallized, it evolved to produce a residual liquid rich in trace elements; this residuum is the first of the KREEP constituents formed on the Moon and has been dubbed "urKREEP" by *Warren and Wasson* (1979a). Meteoritic bombardment continuously reduced mountains of anorthosite to rubble, leaving only remnants for geologists to study 4.5 b.y. later.

Formation of Mg-rich rocks. Although some authors have developed complicated, quantitative models to explain how both anorthosites and the Mg-suite rocks could come from a magma ocean (e.g., *Longhi and Boudreau,* 1979), it seems almost certain that most Mg-suite magmas are the products of melting events that postdate the magma-ocean epoch. Nevertheless, some of them might have formed even before the magma ocean had totally solidified. Chemical data and petrologic modeling indicate that Mg-suite magmas assimilated urKREEP and ferroan anorthosites. Different amounts of assimilation produced the diversity seen within the Mg-suite. The sources of the magmas are not known; they could represent partial melts of previously undifferentiated lunar material at depth in the Moon or they may be partial melts of Mg-rich mineral cumulates deep in the magma ocean. They might even be products of melting at the interface between the primitive interior and the bottom of the magma ocean. The melting could have been started by convective overturn of the magma ocean cumulate pile, which would originally have had the less dense Mg-rich rocks on the bottom and progressively denser Fe-rich rocks above.

Formation of KREEP basalts and the subsequent fate of urKREEP. The residual material remaining after 99% of the magma ocean had crystallized would have been rich in FeO and trace elements and enriched somewhat in silica. This material oozed its way into the lower crust, altering the original rock compositions. Some might have undergone liquid immiscibility, producing granitic and FeO-rich complementary melts. Low-K Fra Mauro (LKFM) basalt, which exists as impact melt sheets associated with large basins (Chapter 6), could contain a component that is the product of this process. Partial melting of lower crustal rock contaminated with urKREEP probably gave rise to KREEP basalts. The zone of KREEP-rich material in the lower crust seems to have acted as a source of trace elements for rising magmas to assimilate. Both Mg-suite and mare basalt magmas seem to have been affected by it. At this point in the Moon's history, it may have appeared as shown in Fig. 2.7a. This conjectural reconstruction of the Moon at about 3.9 b.y. ago dramatically shows that up until that time the process of cratering predominated over igneous processes in determining lunar geomorphology.

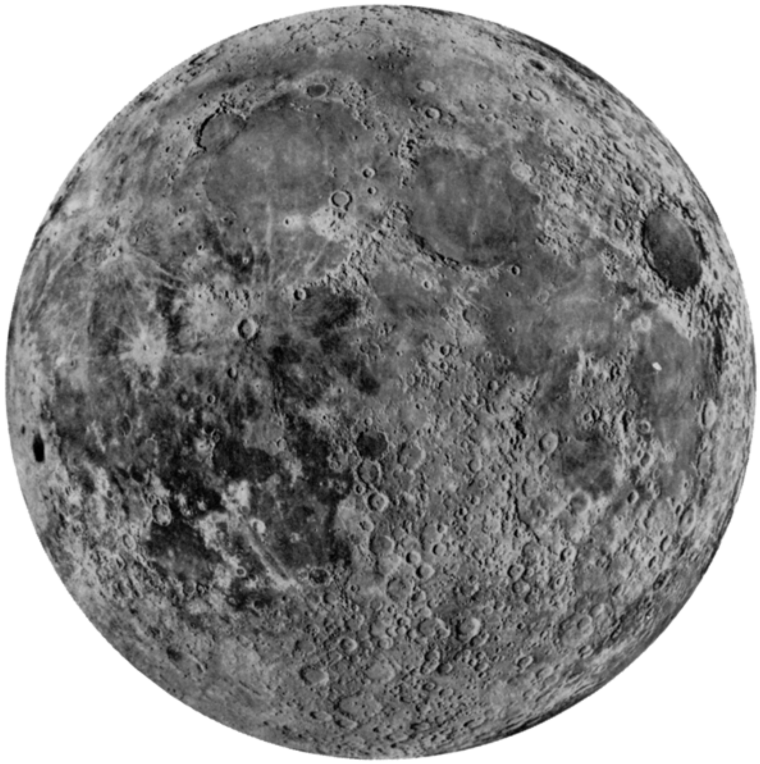
Formation of mare basalts. The chemical diversity of mare basalts demonstrates that their genesis is very complicated. Their Eu anomalies indicate that they formed by partial melting of cumulates that developed from the magma ocean after plagioclase had crystallized (Fig. 2.6). Experiments at elevated temperatures and pressures on melts thought to represent primary magmas indicate that they formed at depths ranging from 100 to

(a)

Fig. 2.7. Historical evolution of the nearside (Earth-facing) face of the Moon; modified from *Wilhelms and Davis* (1971). **(a)** Features as they probably appeared immediately following most of the major basin-forming impact events, but just prior to the formation of the Imbrium basin about 3.8-3.9 b.y. ago (see Fig. 2.3a and section 4.4). Figure is by Don Davis.

(b)

Fig. 2.7. (*continued*) **(b)** Features as they appeared immediately after the most extensive mare lava floods (about 3 b.y. ago). Figure is by Don Davis.



(c)

Fig. 2.7. *(continued)* **(c)** The present appearance of the Moon. Figure is by Don Davis.

500 km from source rocks rich in olivine and orthopyroxene (pyroxene without Ca), sometimes accompanied by clinopyroxene (pyroxene with Ca). The abundances of the source rock minerals and the percentage of partial melting varied. Most of the magmas so produced began to crystallize and therefore fractionated (lost crystals) before reaching the surface. Also, most mare basaltic magmas assimilated small amounts of KREEP or (in a few cases such as the "very-high-K" basalts; see section 6.1) granite prior to eruption.

Mare volcanism is known to have been active by about 3.9 b.y. ago, while the Moon was still being heavily bombarded; Fig. 2.7a shows small amounts of lava—some impact melts, some mare basalts—in the bottoms of large impact craters. However, at about 3.9 b.y. ago the rate and scale of cratering decreased. There followed a period of perhaps 1 b.y. in which many of the larger craters on the lunar nearside were inundated by mare basalts (Fig. 2.7b). From ~3 b.y. ago to the present it appears that igneous activity on the Moon was very sparse, and the terrain-forming processes were controlled by sporadic meteorite impacts that have led to the Moon we see today (Fig. 2.7c). Chapter 4 provides greater detail on these surface processes.

APPENDIX: APOLLO SAMPLE TYPES AND LUNAR SAMPLE CURATION

A2.1. Apollo Sample Types

The Apollo astronauts collected several types of samples that can be distinguished on the basis of collection techniques and/or types of equipment used. As a result, the type and amount of data about the lunar surface environment and the type of information contained within the sample can differ from sample to sample. Descriptions of the major types of samples in the Apollo collection follow. The type of sample can generally be determined from the lunar sample catalog or other documents available at the Planetary Materials Laboratory (PML; NASA Johnson Space Center, Houston, TX 77058 USA).

Contingency sample. At the first four Apollo landing sites, the first astronaut to step onto the lunar surface sampled the loose, fine-grained regolith and rocks by scooping at several places with the contingency sampler; this was a combined scoop and bag on the end of a rod that allowed it to be quickly swept through the uppermost few centimeters of the lunar surface. He then removed the bag from the sampler and stored it in a pocket of his suit. This ensured the return of some lunar material from the site if surface exploration had to be aborted on short notice. The crews of Apollo 16 and Apollo 17 did not collect a contingency sample.

Rocks were present but generally small (<6.5 cm) in the contingency sample. The rocks and fines of the sample represent a small area of the lunar surface near the lunar module (LM). Although the astronauts tried to scoop up a variety of rocks, they spent little time deciding where to collect the contingency sample. The fine-grained component is a mixture of material from several points within the area sampled.

Bulk sample. The bulk sample was collected only at the Apollo 11 site. It consists of 38.3 kg of regolith scooped from several points near the LM and combined as a single sample. Astronaut Armstrong scooped small rocks and fine-grained regolith from the surface at 22 or 23 locations a few meters northwest and west of the LM. He returned to the LM nine times to pour the contents of the scoop into one of the two Apollo Lunar Sample Return Containers (ALSRC) that remained on the Modularized Equipment Storage Assembly (MESA) of the LM. Some of the activity was within the field of the TV camera; some was outside the range of any imagery.

Documented sample. The astronauts documented the settings of many rock and fine-grained regolith samples with down-sun and cross-sun photographs of the undisturbed area before collecting the sample and a down-sun photograph of the area after the sample was removed. When the gnomon (a vertical scale on a small tripod) was within the area photographed, its image and shadow could be used to determine precisely the vertical vector and the down-sun direction. The gnomon also served as a scale, a color chart, and a reflectivity reference for the sample and surface features near the sample.

The "before" photographs documented the relationship of a sample and its surroundings before astronaut activity disturbed the surface. The "after" photograph showed the effects of collection activity on the surface characteristics and supported the identification of the collected sample. The Lunar Sample Preliminary Examination Team (LSPET) successfully determined depth of burial and lunar surface orientation for many documented rock samples by comparing the rock shape and shadow patterns recorded in the "before" photographs with the shape and shadows observed. under artificial illumination in the laboratory. These rock orientations were needed to evaluate directions of micrometeoroid impacts and radiation effects on the surface samples.

The procedure for fully documenting a lunar sample required participation by both astronauts and consumed several minutes of the limited time available for exploring the lunar surface. Note that the Apollo 11 samples discussed as "documented" samples in the catalog are "selected" samples according to the definitions presented here. At the Apollo 11 site, the astronauts did not have adequate time to provide photographic documentation or voice descriptions of the lunar surface setting.

Selected sample. Astronaut teams collected many samples of rock and fine-grained regolith without the full set of photographs required to document the sample in its lunar setting. They placed each "selected" sample in a numbered bag and generally discussed the sample and its lunar setting while collecting and bagging the sample.

Without the documentation photographs, members of the LSPET could not determine the lunar surface orientation or depth of burial for the sample. Also, the reflectivity of the sample before handling and packaging could not be measured without these photographs.

On the positive side, the astronauts could work independently while collecting the selected samples, and many selected samples could be collected within the time required to fully document one sample. Collection of lunar material in the "selected sample" mode provided a larger number and a wider variety of lunar samples than would have been possible if all samples had been fully documented.

Rake sample. The Apollo 11 bulk sample of fine-grained regolith included a few marble-sized and larger rocks of varied lithology. The rocks were large enough to support extensive tests and yet small enough to permit the return of a significant population if the finer fraction could be left on the Moon.

A new lunar tool, the lunar sampling rake, was therefore developed for the later Apollo missions to support collection of the rocks distributed through the upper few centimeters of the fine-grained regolith. When the astronaut pulled it through the regolith, the rake retained rocks larger than a centimeter across but the finer material remained on the surface. Commonly, the astronaut added one or more scoops of the fine-grained regolith to a rake sample before closing the sample bag. The crews of Apollo 15 and later missions collected rake samples.

Rake samples include rocks that represent the population distributed across a few square meters of the lunar surface. Fines in the rake sample bag are a mixture of samples of fine-grained regolith collected from one or more spots in the raked area plus fines attached to the rocks when they were collected.

Cores. Cores are only 5.2% by mass of the total collection, but they are extremely valuable. They are the only source of reliable information about the near-surface texture and stratigraphy of the lunar regolith. At some localities the astronauts dug shallow trenches, photographed the layering observed, and scooped samples from the bottom and walls of the trench. However, a returned core is the only type of Apollo sample that permits the detailed study of variations in the physical and chemical properties of the lunar regolith with depth. The samples provide information on the Moon's cratering history, a record of solar activity and cosmic-ray flux, and structure of the lunar regolith.

The Apollo astronauts collected 21 cores from the 6 landing sites by pushing or hammering drive tubes into the regolith. They used a battery-powered drill to sample deeper layers of the regolith at one point in each of the last three Apollo sites.

Drive tubes used during the first three missions were 2 cm in diameter. Each tube could hold a core 31.6 cm long, but the lengths of six cores collected with single drive tubes during these missions ranged from 10.5 to 19.3 cm. Lengths of the two cores collected with double drive tubes (units made of two drive tubes threaded together) were 37.7 and 41.1 cm.

Improved drive tubes used during the last three missions were 4 cm in diameter and capable of holding a core 34.3 cm long. Of the 22 core segments collected with the large-diameter drive tubes, 14 had been dissected as of spring 1988. These included six cores (lengths ranging from 46.7 to 66.3 cm) collected with double drive tubes and two cores (31.4 and 29.3 cm) collected with single drive tubes.

The Apollo 15 and 16 astronauts used six drill-stem segments each to sample the upper 237 and 221 cm, respectively, of the regolith. The Apollo 17 crew, using eight drill-stem segments, sampled to a depth of 292 cm. Cores collected with the battery-powered drill are about 2 cm in diameter.

A2.2. Lunar Sample Curation

Three major objectives of lunar sample curation are to (1) protect the samples physically, (2) preserve chemical integrity, and (3) maintain accurate records. These objectives could be met by counting the samples accurately, surrounding them with an inert atmosphere, and sealing them in a secure vault. But the main value of the collection lies in the use of lunar materials to determine the nature of the Moon and to test new hypotheses about its origin and history.

Therefore, curation of the Apollo collection (and of U.S.S.R. Luna samples in U.S. possession) also requires the allocation of samples to support current scientific studies while meeting the major objectives that are designed to conserve this resource for future studies. This balance is accomplished through a combination of special facilities, controlled access to sample processing and storage areas, and strictly enforced procedures. Similar protective curation is maintained for the lunar meteorites from Antarctica, but these have already been long exposed on the Earth's surface, and they are therefore maintained in a separate facility with less stringent environmental controls. The lunar meteorites are curated by the Johnson Space Center (JSC) and the Smithsonian Institution. The Meteorite Working Group at JSC handles all sample requests.

Physical security. One major objective of Apollo and Luna sample curation is to protect samples in the collection from unauthorized removal or loss due to natural hazards such as hurricanes and tornados. Two vaults in the Lunar Sample Building (Johnson Space Center Building 31-A), which was completed in 1979, provide good physical protection for stored samples. The vaults meet the Bank Protection Act requirements for class 9R bank vaults and they are designed to withstand tornadic winds even though the rest of the building may be demolished. Flooding should not endanger lunar samples stored in the vaults because the elevation of the vault floor is above the highest tide predicted for a maximum hurricane at the Johnson Space Center.

In 1976, before the Lunar Sample Building was constructed, the Curator moved about 14% of the Apollo collection to a remote storage facility at Brooks Air Force Base (BAFB) in San Antonio, Texas, as a precautionary measure in case of damage or loss of the main collection at Houston. These samples are still retained there in remote storage. To ensure selection of a representative subset of the samples, all the larger rocks and many smaller rocks were sawed to provide major subsamples for storage at the remote facility.

Samples for allocation to approved investigators are prepared in the Planetary Materials Laboratory (PML) adjacent to the storage vaults on the second floor of the Lunar Sample Building. The vaults, laboratories, and adjacent corridors are a NASA Limited Area. NASA regulations restrict access to such areas; operational procedures further restrict access to the vaults and the corridor outside the vault during working hours. At other times, unauthorized entry or movement within the Limited Area will activate alarms that alert Johnson Space Center security.

Two individuals witness each movement of samples within the PML. They transfer samples from the vault to the laboratory processing cabinets only when the samples are required for study or for allocation. Excepting three samples on display near the visitor area, samples are returned to the vault promptly when processing or study is completed. When a hurricane warning is issued, all samples in the laboratory are moved to the vault.

Protection from contamination. Contamination control is a major concern of lunar curation. The abundant oxygen and water vapor in the Earth's atmosphere could react with samples from the dry, near-vacuum environment of the lunar surface; contaminants introduced as the samples are stored or processed could bias the results of critical analyses (for example, Pb solder or Rb in wallboard). The small size of typical samples allocated for analysis accentuates the effects of contamination.

Pristine lunar samples are stored, studied, and prepared for allocation inside cabinets filled with flowing, high-purity nitrogen gas that carries less than 5.7 ppm H_2O, 20 ppm O_2, and 2 ppm Ar. This relatively inert atmosphere protects the samples from reactions with oxygen and water vapor and from contamination by other components of the Earth's atmosphere. For storage or transfer outside a processing cabinet, a lunar sample is sealed in three teflon bags or in a rigid container plus two bags. All are filled with nitrogen. Since the packaging is permeable to gases over a long period, the packaged samples are stored in nitrogen. In the pristine sample vault, the samples are stored in glove cabinets supplied with flowing nitrogen. At the BAFB remote facility, the samples are sealed in a nitrogen-filled, thick-walled stainless steel cabinet. Periodically, personnel from Johnson Space Center visit the remote facility, analyze the gas in the cabinet to check the integrity of the system, and flush the old gas from the cabinet with fresh nitrogen.

Overall cleanliness of the lunar sample vaults and laboratories is important because dust could enter the processing or storage cabinets when they must be opened for cleaning or glove replacement. Both facility construction and operating procedures prevent such contamination. Careful selection of building materials used inside the processing and storage areas reduces the number of particles contributed by the structure, and the use of materials with the lowest levels of critical elements (e.g., Pb, Au, Hg, and the rare-earth elements) reduces the impact of contamination if it should occur.

Operating procedures are designed to reduce the numbers and types of particles introduced into the laboratory. Access to the laboratories is controlled. Workers and visitors preparing to enter must remove all gold jewelry and put on nylon coveralls, caps or snoods, gloves, and booties to reduce contamination from material on their shoes and the lint and dust carried by their clothes. An air shower between the change room and the laboratory-vault area replaces air from the change room with filtered air before the individual enters the cleaner area.

A high-efficiency filtration system removes dust and other particles from the conditioned air fed to the vaults and laboratories of the Lunar Sample Building. Air in these work areas meets or exceeds Class 1000 Clean Room specifications. Positive air pressure blocks the entry of unfiltered air and directs air movement from all rooms within the laboratory-vault complex toward the exterior. Pressure is highest in the Pristine Sample Vault and lowest, but still positive, in the change room at the entrance.

The floor plan and operational procedures restrict access to the vaults; most of the traffic is downstream (in the air flow) from areas where packaged samples must be handled briefly outside the protective nitrogen atmosphere of the cabinets.

As a lunar sample is subdivided by prying, chipping, or sawing, any contact with other materials can result in contamination. The effects of this potential contamination are minimized by (1) restricting the materials allowed to contact the sample and (2) selecting materials that are relatively abundant in the lunar samples, where possible. Only aluminum, teflon, and stainless steel are allowed to touch the lunar samples during processing in the JSC Lunar Sample Laboratory.

Actually, a rock is its own best container. Therefore, for extremely critical analyses, a sample larger than the mass required for a proposed test will be allocated. The investigator can remove an exterior layer, using techniques and tools that will not affect the results of the test and thereby have an absolutely pristine sample for the analysis.

Operational procedures reduce the probability of cross contamination between Apollo sites or between samples from the same site. Samples from only one Apollo site can be transferred into in a nitrogen cabinet. Before a sample from a different site can be moved in, all samples, equipment, and supplies must be removed and the cabinet cleaned according to established procedures. Different samples from the same Apollo site can be transferred into a processing cabinet, but only splits from one sample can be open at the same time.

Lunar sample records. The Lunar Sample Curator maintains extensive records, both paper and electronic, for each lunar sample. These include photographs that document the surface features of rocks as they were before any laboratory operations other than a thorough dusting, the initial description prepared by one or more members of the LSPET, and the original copies of laboratory records that document all processing of the sample in facilities operated by the Lunar Sample Curator.

Sample location, mass, and some of the other information in the datapack are included in the Lunar Sample Data Base (LSDB) that is currently maintained on the Solar System Exploration Division computer at JSC. This database provides ready access to an accurate inventory of the Apollo collection and of Luna samples that have been received from the U.S.S.R. Planetary Materials Laboratory personnel update this interactive database each time a sample is moved. Updates to the interactive file are checked daily using a backup file that is accessible only to the system operator. The electronic lunar sample inventory permits a real-time check on the status of any split of a lunar sample in the collection. The ease of access to the basic inventory data has led to the development of several auxiliary files with expanded descriptions and operational details.

A2.3. Curation History

The opportunity to study lunar samples excited the global scientific community. NASA carefully reviewed the proposed studies and evaluated the qualifications of the individuals and their laboratories. Many organizations expended great effort to demonstrate the capability to obtain reproducible results with small samples. More than two years prior to the first lunar landing, 110 scientists in the United States, England, Germany, Canada, Japan, Finland, and Switzerland had been selected as principal investigators by the NASA Office of Space Science and Applications.

To support this massive program of study and analysis, NASA and representatives of the scientific community developed plans for the curation and study of lunar samples during several years prior to the first lunar landing. Isolation of persons (astronauts and others exposed to lunar samples) and materials that had either direct or indirect contact with the lunar surface became a central element in the plans because existing scientific evidence could not demonstrate conclusively that the Moon was lifeless. Precautions against potentially pathogenic life forms therefore had to be taken.

Sterilization of lunar samples would destroy their value for many scientific experiments (for example, determination of the presence of gases in lunar samples). Therefore, the astronauts, samples, and other equipment were placed in a quarantine facility while the lunar examples were being examined for potential biological activity. The Lunar Receiving Laboratory (LRL) was designed to satisfy the interrelated requirements of contamination control, quarantine, and time-dependent experimentation. Construction of the LRL at the NASA Manned Spacecraft Center (MSC; now JSC) in Houston, Texas, was completed prior to the first lunar landing.

Facilities for biological tests associated with the quarantine and other time-dependent scientific tests were provided within the sample isolation area. A comprehensive scientific examination of the lunar samples was conducted during the quarantine period within sterile gloveboxes to provide the world with initial descriptions of the samples, to curate those samples, and to provide an advisory committee with information needed to allocate the samples to investigators.

The Apollo astronauts packed some samples from each mission in aluminum boxes designed to seal and maintain the vacuum of the lunar surface environment during the trip to Earth and the LRL. For various reasons, some boxes did not maintain that low pressure. After the first mission, the crews also packed other samples in a variety of closed but unsealed bags. Samples in the leaking boxes and unsealed bags experienced limited exposure to the atmosphere of the LM and command module (CM) as the containers underwent two or more decompression/compression cycles during the several days between their removal from the lunar surface and splashdown in the Pacific Ocean. Within a few hours of landing, the sample boxes and other sample containers were sealed in plastic bags on the recovery ship prior to the flight to Houston.

The original plan for sample quarantine and examination at the LRL was to examine the samples and perform the initial processing tasks in a vacuum environment (10^{-6} torr). A large vacuum chamber with ports for observation and photography and glove ports for sample manipulation had been installed in the LRL. After a few samples from the Apollo 11 selected sample box had been processed, a leak developed rapidly in one of the gloves. Unprotected samples were shifted quickly to another section of the cabinet before the section with the leaking glove was isolated for repair. The entire vacuum system had to be sterilized with dry heat in order to replace the glove without violating the biological containment.

Following that accident, the unopened Apollo 11 bulk sample box was transferred from the vacuum lock to a nitrogen cabinet in the Biological Preparation Laboratory. Rocks and fines in the bulk sample were examined, described, photographed, and chipped in nitrogen cabinets. The two cores and the contingency sample were also processed in those cabinets. Most of the core samples and material from the bulk and contingency samples remained in the nitrogen cabinets until the end of the Apollo 11 sample quarantine.

The Apollo 12 documented sample box leaked during the return to Houston. When tested at the LRL, the internal pressure was a significant fraction of atmospheric pressure and the ratios of nitrogen, oxygen, and argon approximated those in Earth's atmosphere. Internal pressure of the selected sample box was 40 to 60 μm when probed; that box was opened in the vacuum system. The LSPET processed rocks and fines from the documented sample box, the contingency sample, the tote-bag samples (four large rocks returned in an unsealed bag), and cores in nitrogen-filled cabinets.

No samples were returned from the Apollo 13 mission. Because of an accident during the trip to the Moon, the crew was not able to land on the lunar surface.

The LRL biological barriers remained intact during the preliminary examination of samples returned by the Apollo 14 crew. All samples were examined and processed in nitrogen-filled glove cabinets. Because of the importance of biological protection in handling the Apollo 11, 12, and 14 samples, nitrogen pressure in the glove cabinets was held slightly below atmospheric pressure to maintain the biological barrier. When a leak occurred, nitrogen that had contacted lunar materials would not escape. Instead, the terrestrial atmosphere would enter the cabinet. To protect the lunar samples from contamination, they were removed from sealed containers only while being studied or subdivided.

By 1971, detailed scientific studies of the Apollo 11, 12, and 14 samples had clearly established that lunar rocks and soils contained no life forms (living or fossil), no toxic materials, and no water. As a result, the biological protection requirements were dropped and no quarantine was imposed for the lunar samples returned by Apollo 15 and later missions. The cabinets of the lunar sample processing lines were therefore operated with a positive nitrogen pressure throughout the preliminary examination period to protect the lunar samples from terrestrial contamination should a leak occur.

Lunar Receiving Laboratory facilities were used for the preliminary examination, initial processing, and time-critical physical and chemical tests of lunar samples from all the Apollo missions. The growing collection of lunar samples was also stored in the LRL until 1971. Part of the operation moved to JSC's Building 31 when a new vault for storing lunar samples and a laboratory for processing lunar samples returned by investigators became operational. All laboratories for processing lunar samples were concentrated on the second floor of Building 31 in 1973. Lunar samples were stored in vaults distributed around JSC (in Buildings 1, 16, 31, and 45) until late 1979.

The Curator moved representative samples totaling about 14% of the collection to a remote storage facility at BAFB in February 1976. After evaluating several proposed sites for the active collection, NASA decided to keep the collection in Houston. At this time the Lunar Sample Building (Building 31-A) was constructed at JSC.

The Curator consolidated lunar samples stored at JSC in the vaults of Building 31-A during August and September 1979. Pristine sample processing began in the second-floor laboratories of the new building after the samples were moved. All lunar sample activity at JSC was consolidated in 1982 when the returned sample processing laboratories moved from Building 31 to the first floor of the Lunar Sample Building.