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The Moon after Apollo

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The Apollo missions have gradually increased our knowledge of the Moon's chemistry, age, and mode of formation of its surface features and materials. Apollo 11 and 12 landings proved that mare materials are volcanic rocks that were derived from deep-seated basaltic melts about 3.7 and 3.2 billion years ago, respectively. Later missions provided additional information on lunar mare basalts as well as the older, anorthositic, highland rocks. Data on the chemical make-up of returned samples were extended to larger areas of the Moon by orbiting geochemical experiments. These have also mapped inhomogeneities in lunar surface chemistry, including radioactive anomalies on both the near and far sides.

Lunar samples and photographs indicate that the moon is a well-preserved museum of ancient impact scars. The crust of the Moon, which was formed about 4.6 billion years ago, was subjected to intensive metamorphism by large impacts. Although bombardment continues to the present day, the rate and size of impacting bodies were much greater in the first 0.7 billion years of the Moon's history. The last of the large, circular, multiringed basins occurred about 3.9 billion years ago. These basins, many of which show positive gravity anomalies (mascons), were flooded by volcanic basalts during a period of at least 600 million years. In addition to filling the circular basins, more so on the near side than on the far side, the basalts also covered lowlands and circum-basin troughs.

Profiles of the outer lunar skin were constructed from the mapping camera system, including the laser altimeter, and the radar sounder data. Materials of the crust, according to the lunar seismic data, extend to the depth of about 65 km on the near side, probably more on the far side. The mantle which underlies the crust probably extends to about 1100 km depth. It is also probable that a molten or partially molten zone or core underlies the mantle, where interactions between both may cause the deep-seated moonquakes.

The three basic theories of lunar origin—capture, fission, and binary accretion—are still competing for first place. The last seems to be the most popular of the three at this time; it requires the least number of assumptions in placing the Moon in Earth orbit, and simply accounts for the chemical differences between the two bodies. Although the question of origin has not yet been resolved, we are beginning to see the value of interdisciplinary synthesis of Apollo scientific returns. During the next few years we should begin to reap the fruits of attempts at this synthesis. Then, we may be fortunate enough to take another look at the Moon from the proposed Lunar Polar Orbit (LPO) mission in about 1979.

I. INTRODUCTION

Exploration of the Moon has yielded a plethora of information regarding the chemistry, age, and evolution of the surface materials. A complete and thorough understanding of these data is important for two reasons: first, to decipher the thermal history and origin of Earth's closest neighbor, and, second, to apply that knowledge for better understanding of the scientific data now being collected from other planets. There are indications that the forces of nature that created the material of the Earth were also operative on the Moon and probably the terrestrial planets, Mars, Venus, and Mercury.

To a lesser degree, a study of the Moon is also important in studying the Sun's past. At present, there are numerous new tools

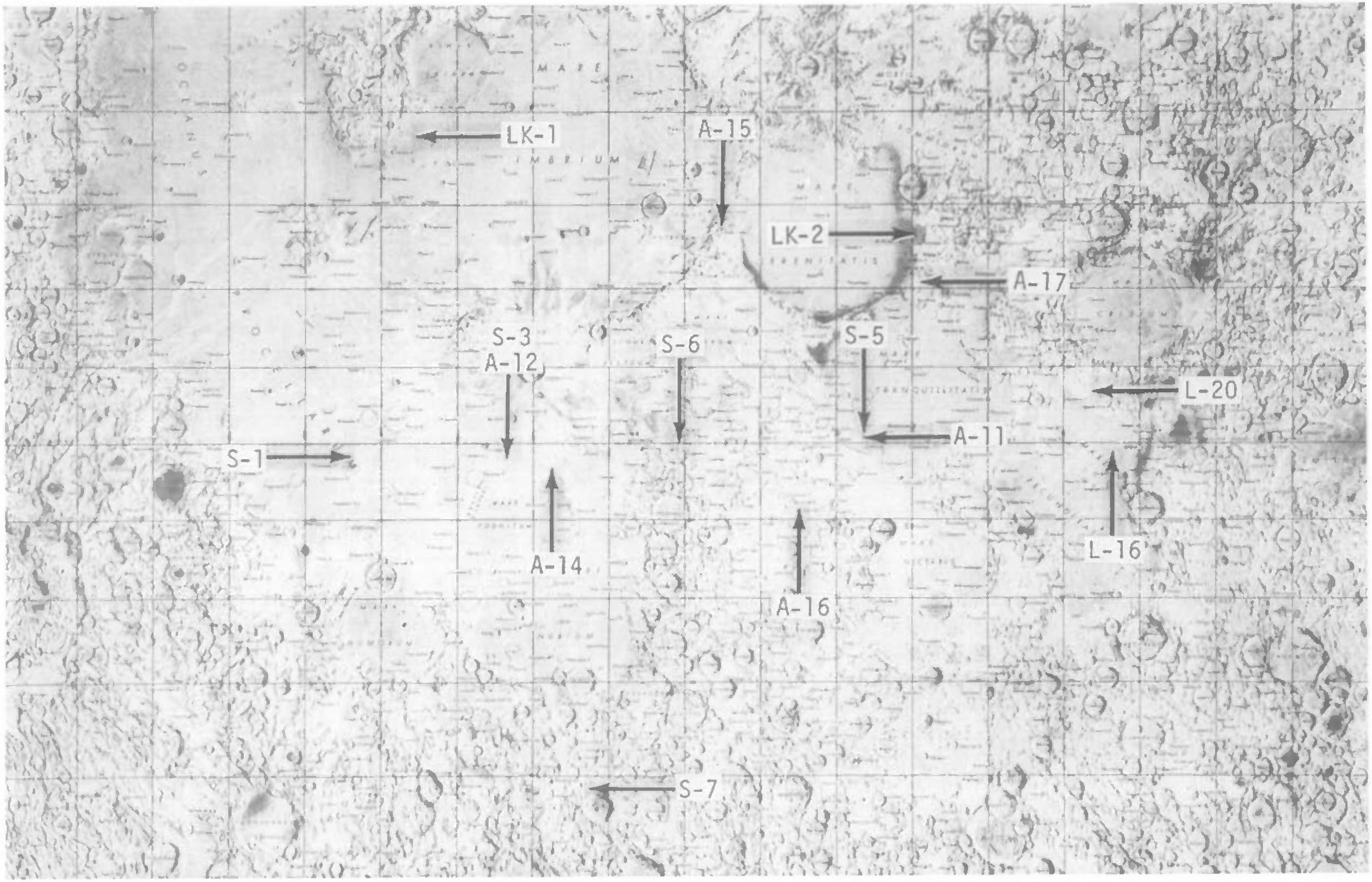


FIG. 1. Location map of all soft-landed spacecraft on the Moon. These include: the five American Surveyor landers (S) and six Apollo lunar modules (A); and the two Soviet sample return Luna Spacecraft (L) and two missions that carried Lunokhod roving vehicles (LK).

to study with increasing degrees of sophistication the processes that are acting on the Sun. Before the return of lunar samples, however, it was not feasible to study the past history of the Sun. The lunar materials have collected and kept a record of the solar particles reaching them from the Sun.

More than fifty spacecraft have flown near or landed on the Moon since 1958. Twelve American astronauts have walked on and sampled its surface, traversing nearly one hundred kilometers. Two unmanned Soviet vehicles have returned samples from two different sites on the Moon, and two others have roamed the lunar surface telemetering their intelligence to the Earth. Five scientific observatories left by the astronauts on the Moon continue today to transmit information about the lunar environment. The two Soviet passive stations and similar laser retroreflectors at three Apollo landing sites are being used to measure the Earth–Moon distance, and also the rate of continental drift on Earth.

About twenty thousand photographs taken from lunar orbit have captured the Moon in great detail, permitting better interpretations of its features. The majority of the hard facts, however, were provided by the soft-landed spacecraft (Fig. 1). Most prominent among these are some 400 kilograms of rock and soil samples that were returned, mostly by the Apollo missions. These samples are being studied by more than a thousand scientists of diverse specialities in nearly twenty countries.

As is customary in scientific research, the findings from lunar studies generated questions that remain unanswered. However, many questions have been satisfactorily answered and several conclusions can be drawn. It is my intention to summarize in this paper the state of the art of lunar science, with emphasis on what I think is important among the results of the six Apollo lunar surface exploration missions.

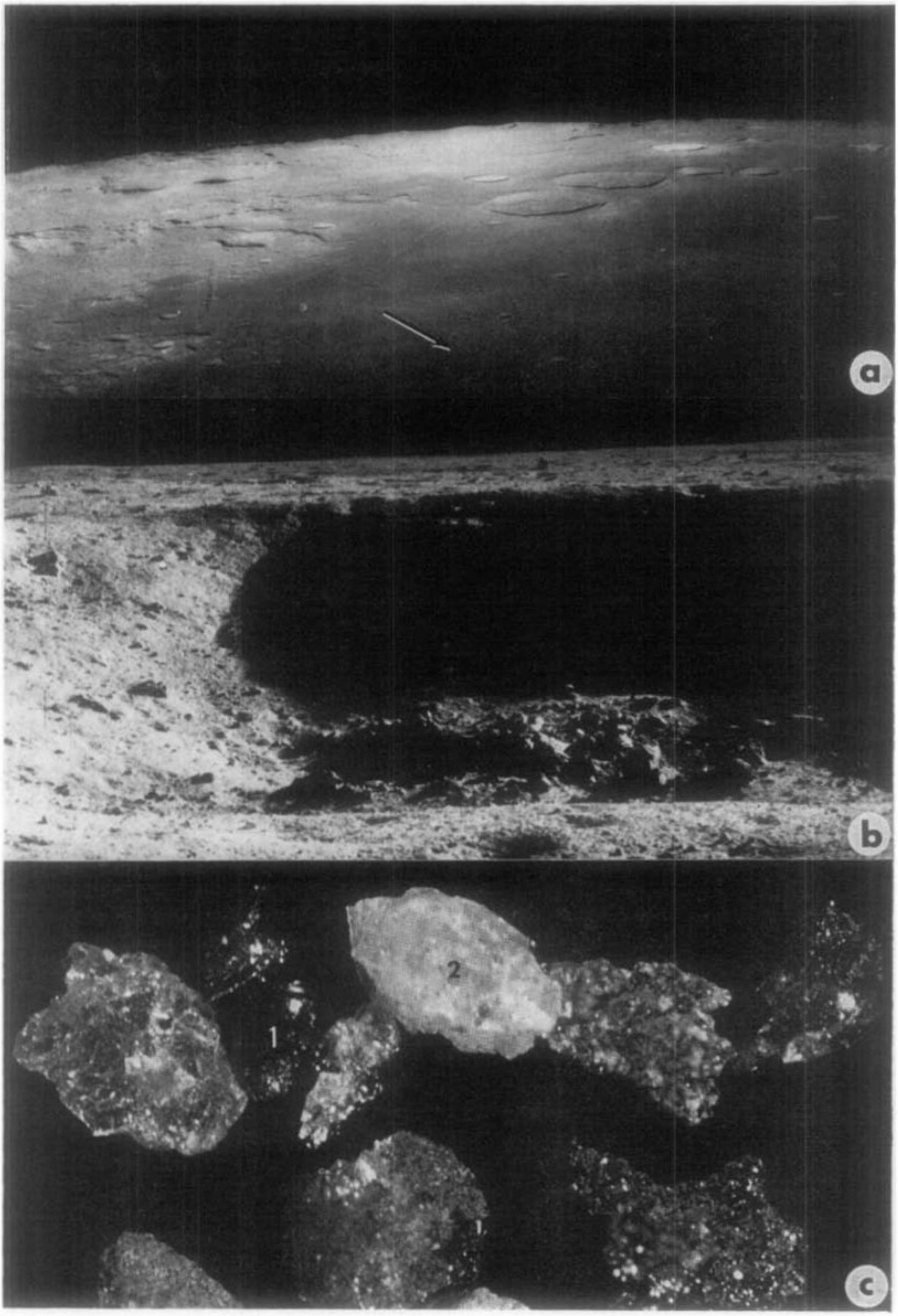
For the past eight years I have been a member of the so-called "lunar science team." Between team members of this "mutual admiration society," intimate verbal contact is the rule rather than the exception. For this reason, it is sometimes hard to acknowledge all contributors to a given result, theory or manner of presentation. However, and at the expense of brevity, it is attempted here to give proper credit to authors for the sake of readers who may wish to consult original papers dealing with the various subjects or areas of discussion. Other summary reports of lunar science include those by Hinners (1971), EL-Baz (1974), Schmitt (1974), Runcorn (1974), and Taylor (1975).

II. The Apollo Missions

A. Mare Tranquillitatis

It was a giant leap for Neil Armstrong to take the first step on the Moon. The Apollo 11 mission was also a giant leap for science because it provided the first returned samples from another body in the solar system. Before Apollo, no matter how sophisticated the instruments were of remote sensing, whether from Earth or from lunar orbit, no undisputable conclusions could be drawn as to the nature of the lunar surface materials. The exact chemistry of a rock, the mineral species that form its fabric, as well as the absolute age of that rock are among the fundamental parameters necessary for a full understanding of its origins and its history. These parameters are nearly impossible to define without having the rock samples to study in the laboratory.

The Apollo 11 landing site is in a relatively smooth and level part of Mare Tranquillitatis (Fig. 2a). This part of Tranquillitatis is characterized by a low albedo (reflecting only about 9% of incident sunlight; Pohn and Wildey, 1970) and a high density of craters (Grolier, 1970; Trask, 1970) ranging in diameter from less than one meter to several tens and hundreds of meters. Materials of the regolith, the uppermost fragmental surface layer, range in size from very fine particles to blocks more than a meter across. The landing was made about 6 km west-southwest of the center of the landing ellipse. The astronauts avoided a blocky-rimmed crater named West, which is about 180 meters in diameter and 30 meters deep. Its hummocky ejecta extends about 250 meters out from the rim


a
b
1
2
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crest. Ejected blocks, radially arranged around that crater were photographed by the astronauts, and samples of its finer ray materials were probably returned by Apollo 11.

Samples from this site consist of (a) coarse-to-fine grained ophitic basalts of igneous origin, (b) microbreccias, which are believed to be a mechanical mixture of soil and small rock fragments compacted into a coherent rock and (c) fine-grained soil (LSPET, 1969). The soil is a diverse mixture of crystalline fragments and glassy fragments (Fig. 2c). It contains a small number of crystalline fragments which are totally different from any of the sampled igneous rocks. These fragments were interpreted to have been derived from the nearby highlands by Wood *et al.* (1970). This interpretation was found to hold true on later Apollo flights. The soil was also found to contain small fragments of iron meteorites (LSPET, 1969).

Evidence of shock effects duc to meteoroid impacts are well preserved in soil samples and the fabric of returned rocks. The shock features in rock fragments are equivalent to those produced in the lab at 40 kilobars (Quade *et al.*, 1970), or higher, and in the fine dust to those approaching the megabar region (von Engelhart *et al.*, 1970). Evidence that the regolith is the product of meteoroid impacts include the following.

1. Observation of glass coatings on blocks (Fig. 2b) as well as rock and soil samples (McKay *et al.*, 1970); some of the coatings contain extra amounts of elements attributed to the impacting meteorites (Anders *et al.*, 1971, and Laul *et al.*, 1971).
2. Presence of minute impact pits, also known as "zap craters," on surfaces of rocks and soil samples (e.g. Hörz *et al.*, 1971).
3. Occurrence of fragments, mostly angular, of basaltic rocks and glass or glass-coated rocks (Fig. 2c).
4. Aggregation of fragments and particles back into a coherent rock, breccia (LSPET, 1969).
5. Deformation of the structure of individual minerals (plagioclase and pyroxene) and the production of fractures, planar structures, and multiple twinning (Short, 1970).
6. Further deformation causing complete disruption of the mineral lattice, shock-induced thermal melting, and recrystallization of the materials (von Engelhardt *et al.*, 1970).
7. Smallness of the median particle size, in the soil, which may represent the average mineral grain size in the crystalline rocks (Duke *et al.*, 1970). Sizes below a few microns dominate (Gold *et al.*, 1971).
8. Presence of small particles of meteoritic debris (composed mostly of iron–nickel) in the soil or aggregated with lunar particles (Chao *et al.*, 1970).

Studies of trace elements in the Apollo 11 basalts have shown that the samples are remarkably similar in a wide range of chemical characteristics. These characteristics distinguish the Apollo 11 rocks from basaltic meteorites and terrestrial basalts. As reported by Gast and Hubbard (1970) they show (1) a high concentration of titanium, zirconium, and rare earth elements, (2) a two- to fourfold depletion of europium relative to samarium and gadolinium, and (3) a low abundance of sodium relative to the other major elements. Gast and Hubbard (1970) conclude that these basalts must have formed by the eruption of lavas from beneath the surface of the Moon, after segregation of molten rock and its fractionation to produce this particular composition.

FIG. 2. Apollo 11: (a) Oblique view looking west of the landing site (arrow) in southwestern Mare Tranquillitatis. There are numerous craters, several hundred meters across, in the site area, like the one shown in Fig. 2b. Note the proximity of highland masses to the mare surface in which the LM landed (Apollo 11 frame 6092); (b) A cluster of blocks in the center of the floor of a crater 200m in diameter. Presence of the blocks suggests exposure of bedrock that underlies the regolith (uppermost fragmental layer) by the impact that created the crater (Apollo 11 frame 5954); (c) Fragments of Apollo 11 soil composed mainly of basaltic rock, but including a dark-colored glass fragment (1), the product of impact metamorphism and a light-colored anorthositic fragment (2), probably derived from the nearby highlands (Photograph courtesy of Carl Zeiss Company).

Ages of rock fragments from the Apollo 11 basalts were investigated by various radiometric age-dating techniques. The rubidium–strontium analyses on total rocks and minerals appear to produce the most consistent internal isochrons. Albee *et al.* (1970a) reported precise internal isochrons of rubidium 87–strontium 87 in five rocks giving the same age of 3.65 ± 0.05 billions years. They considered this to be the crystallization time of the Mare Tranquillitatis basalts sampled on Apollo 11. Argon 40–argon 39 age-dating techniques of seven crystalline rocks also indicated a similar age of 3.7 billion years (Turner, 1970).

Age-dating of the fine dust from Apollo 11 produced other significant results. Concentrations of uranium, thorium, and lead in the soil samples are very low: from less than one to a few ppm. However, the extremely radiogenic lead allows radiometric dating of the fine soil. Based on the ratios of lead 207:lead 206, lead 206: uranium 238, lead 207:uranium 235, and lead 206:thorium 232, Tatsumoto and Rosholt (1970) obtained a concordant age of 4.66 billion years. Silver (1970) also reported that uranium–thorium–lead isotope relations in dust samples yield apparent model ages of about 4.6 billion years. He emphasized that the discrepency between rock ages and dust ages poses a problem of rock genesis on the Moon.

In summary, the Apollo 11 rock and soil samples provided significant new information from which the following are emphasized.

1. The majority of Mare Tranquillitatis samples are volcanic rocks of basaltic composition. This is a confirmation of pre-Apollo photogeologic interpretations, as well as interpretations of data transmitted by the Surveyor missions.
2. The rocks are remarkably similar in composition except for the concentrations of a few minor and trace elements. By terrestrial standards, they are rich in iron and titanium, and poor in sodium, carbon and water. They also do not contain any evidence that life once existed on the Moon.
3. The volcanic rocks are derivatives of differentiation in a melt at depth (rather than being impact-produced, near-surface melts). There is also ample chemical evidence that the original magmas had low oxidation levels.
4. Samples of fine dust and soil are in most part derived from the basaltic rocks. The soil is chemically similar to the rock samples except for minor components which are probably derived from the nearby (anorthositic) highlands.
5. Rocks, rock fragments, and fine dust are most likely the product of repeated impacts on solid bed rock surfaces. There is ample evidence of modifications of the original rock structures by shock metamorphism, including the formation of glass and breccias.
6. The lunar volcanic rocks at the Apollo 11 site are extremely old; they crystallized from melts 3.7 billion years ago. (This particular fact contradicts some earlier suggestions that the Moon has been volcanically active in the recent past.) The model age of the soil, 4.6 billion years, probably represents the age of the Moon.

B. *Oceanus Procellarum*

Since the Apollo 11 mission landed too far west of the planned landing point, one of the main objectives of the Apollo 12 mission was to develop and exercise the capability of pinpoint landing. The general area of the Surveyor III landing site was selected as the target of this mission.

The site is located in the extreme southeastern part of Oceanus Procellarum (Fig. 1) and it is covered by a broad ray which is believed to have originated by ejection of material from the crater Copernicus some 370 km to the north (Fig. 3a). The mare material in this site is characterized by a relatively smooth surface and a smaller number of craters per unit area than the Apollo 11 site (Trask, 1970; Pohn, 1971).

The Apollo 12 site is characterized by a distinctive cluster of 50–400 m craters that was named the "Snowman" (Fig. 3b). The lunar module landed on the northwest rim of the 200 meter Surveyor crater, within which Surveyor III had landed two years earlier. The regolith at the site is made up of microscopic particles to blocks several meters across. In addition to samples of

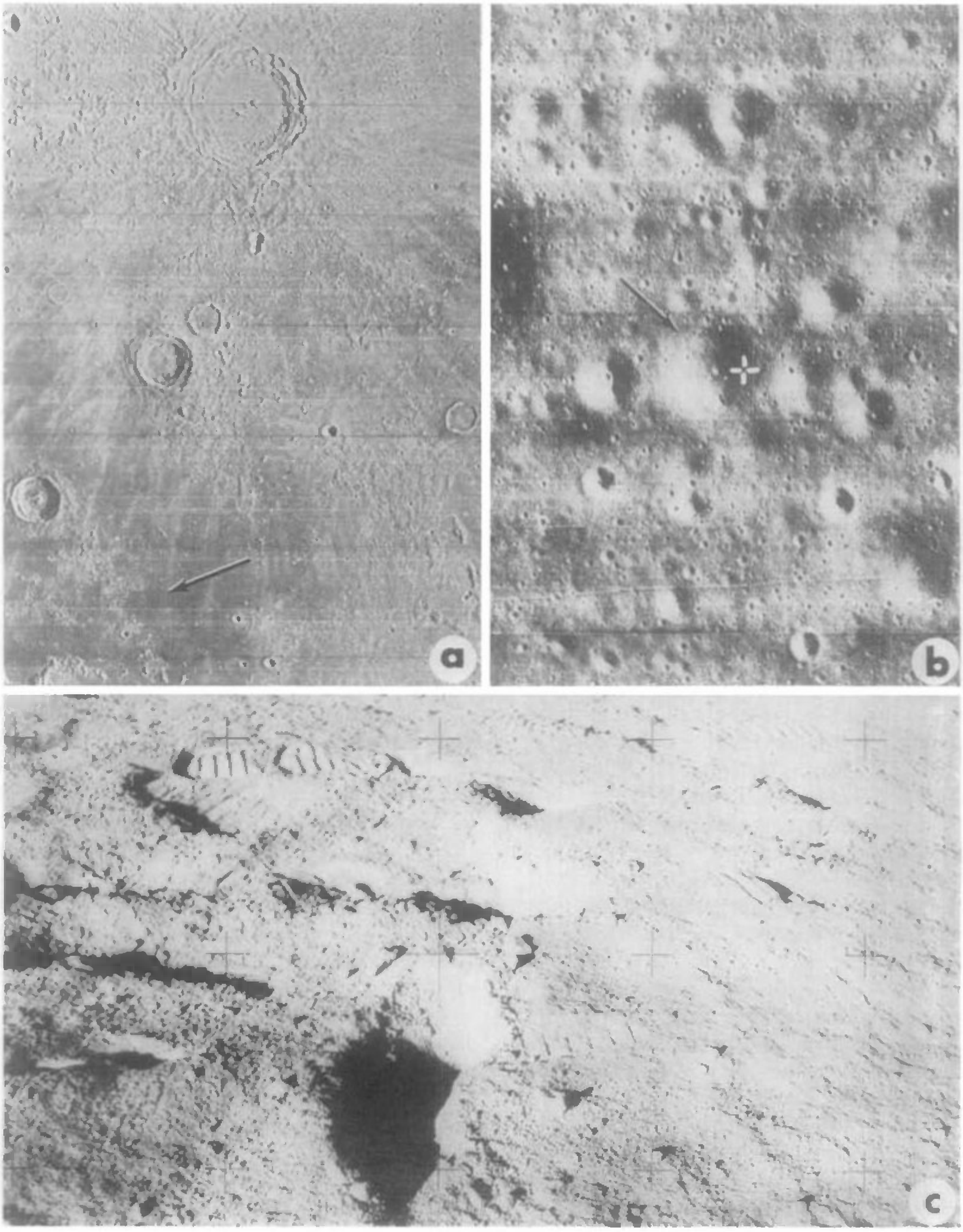


FIG. 3. Apollo 12: (a) The landing site area (arrow) in southeastern Oceanus Procellarum. Note that the area is covered by a bright ray from the crater Copernicus near the top of the photograph (Lunar Orbiter IV frame M-126); (b) Close-up view of the landing site showing a cluster of craters named "Snowman" with the Surveyor crater in the middle. The position of the Surveyor III spacecraft is shown by a cross and the Apollo 12 LM by an arrow (Lunar Orbiter III, frame H-137); (c) Exposures of white soil in the Apollo 12 site that may be part of the Copernicus ray material (Apollo 12 frame 7052).

rock and soil, the Apollo 12 astronauts brought back parts of the Surveyor spacecraft to be studied for effects of the lunar environment.

Basaltic igneous rocks, breccias, and soil were collected from a variety of the geologic features in the Oceanus Procellarum site. The igneous rocks show many differences from the Tranquillitatis basalts. The rocks of Apollo 12 are predominantly crystalline, whereas the Apollo 11 rocks are half crystalline and half microbreccias (LSPET, 1970). The Procellarum basalts show greater variation in grain size; some are very coarse grained. This was explained to be the result of segregation during crystallization in relatively thick lava flows or shallow intrusive dikes or sills (LSPET, 1970). Later, geologic evidence was developed indicating that these rocks were samples from several distinct basalt units, perhaps at least three (Sutton and Schaber, 1971). This is supported by petrographic evidence of various types of sampled basalts, including a porphyritic basalt that is made up of large crystals of olivine and pyrozene in a fine-grained matrix. From the chemical–mineralogical point of view, according to Melson and Mason (1971), the Tranquillitatis basalts show a greater abundance of titanium, lower anorthite content of the plagioclase, lower hyperstene:diopside ratio, and a predominantly quartz–normative mineralogy when compared with the Procellarum basalts.

Some of the fine-grained material collected at the 12 site is of much higher albedo than the surroundings (Fig. 3c). Soil and breccia samples from this high albedo unit contain fragments of unusual composition. According to Mayer *et al.* (1971), these occur as ropy and sculptured glasses, glassy matrix breccias, and annealed fragments with a predominance of orthopyroxene. The composition of these materials is essentially basaltic, but with greatly enriched trace element contents of potassium (K), rare earth elements (REE), and phosphorus (P). This resulted in coining of the acronym KREEP by Hubbard *et al.* (1971).

This chemistry makes the KREEP component a foreign one to the basalts of Oceanus Procellarum. For this reason, and because of the association with the light-colored soil, it is interpreted as part of the ejecta from the crater Copernicus, i.e., the result of penetration of the mare fill and ejection of the underlying pre-mare highlands by the crater Copernicus (Fig. 3a).

One Apollo 12 rock, number 13, proved to be the most unusual lunar sample yet obtained. It is a very heterogenous mixture of light and dark components with various degrees of mixing between them. The light component is granitic in composition, consisting predominantly of potassium-rich feldspar and quartz with plagioclase and pyroxene. The dark component is similar to the basaltic microbreccias of the Apollo 11 site consisting of angular fragments of plagioclase and pyroxene in a fine mixture of plagioclase, pyroxene, and ilmenite. One simple model of rock 13 (Albee *et al.*, 1970b) suggests that the dark basaltic component was permeated and assimilated to varying degrees by the light, granitic component.

The age of this rock, 4.0 billion years, was ascribed to the time when the light material intruded and reacted with the dark component (Albee *et al.*, 1970b). Both the chemistry and the age indicate that "rock 13" is foreign to the Procellarum basalts. The crystallization ages of these basalts as obtained by rubidium–strontium method varied between 3.1 and 3.3 billion years (Papanastassiou and Wasserburg, 1971).

Among the most important conclusions that could be drawn from the findings of Apollo 12 are the following.

1. The chemistry of the two mare landing sites, Apollo 11 and 12, resembles the findings of Surveyor V and VI (see Fig. 1 for locations). This chemistry distinguishes lunar basalts from basaltic meteorites and terrestrial basalts.

2. At least two, probably three or more, mare units were sampled on Apollo 12 based on petrologic and petrographic evidence. This confirms photogeologic interpretations that suggest the presence of more than one lava flow in the landing site area.

3. The age of the Apollo 12 basalts, which is approximately 3.2 billion years, attests to the fact that the lunar maria are geologically very old. The wide difference between the ages of Mare Tranquillitatis and Oceanus Procellarum basalts (600 million years) indicates a prolonged episode of mare filling on the Moon.

4. The high albedo material collected in the fine samples as well as rock 13 appear to be foreign to the Procellarum basalts. These light-colored materials seem to be part of the Copernicus ray. KREEP components in the Apollo 12 site may, therefore, be part of buried Fra Mauro Formation materials. If so, KREEP basalts should be an important component in the Apollo 14 rocks, which they are.

C. *Fra Mauro Formation*

The site selected for Apollo 13 and later Apollo 14 after the former was aborted is in the Fra Mauro Formation. This unit covers a substantial part of the near side of the Moon as a broad belt that surrounds the Imbrium basin; the Formation is interpreted to be an ejecta deposit from the impact that created the basin (Eggleton, 1964). It is characterized by broad ridges that form a characteristically hummocky terrain (Fig. 4a), with the major orientation being radial to the Imbrium basin. The thickness of this ejecta blanket is judged to be several kilometers by the calculated depth of the craters which are almost completely obscured by it (Eggleton, 1964; Eggleton and Offield, 1960).

The Apollo 14 LEM landed about 1100 meters west of Cone crater which is a sharp-rimmed crater, 350 meters in diameter, that apparently penetrated one of the characteristic ridges of the Fra Mauro Formation (Fig. 4b). The sampling traverse was planned with the ejecta of Cone crater in mind, i.e. to collect fresh exposures of the ridgy material excavated by this relatively recent event. Study of the photographs taken on the lunar surface indicates that large blocks in the area are composed of breccias in which dark and light clasts are set in a light-colored matrix (Fig. 4c). The returned rocks show that brecciation and presence of clasts in the large boulders are also exhibited in collected samples.

Inspection of the returned samples and study of thin sections (LSPET, 1971; LSAPT, 1972, 1973) confirmed the brecciated nature of almost all the returned samples. Many generations of brecciation were observed, that is breccias within breccias within breccias. This suggests that, before excavation of the Imbrium basin, the host rock had been subjected to earlier impacts. The effects of the Imbrium impact on the rock appears to be recrystallization, mineral reactions, and incipient fusion, characteristics that are to be associated with shock metamorphism due to a large impact. This shock metamorphism may be in part due to a base-surge like environment described in volcanic eruptions on Earth (Moore, 1967).

A recent study of the Orientale basin and the surrounding ejecta by Moore *et al.* (1974) shows that there are six facies of ejecta around its outer rim, the Cordillera Mountains: concentric, radial, smooth-plained, grooved, secondary impact cratered, and fissured. The transport of these ejecta (based on photogeologic mapping, terrestrial crater analogs, and experimental data) occurred by the following processes: block-riding, landsliding, debris flow (possibly by base-surge), viscous flow, and ballistic ejection. In their view of the dynamic transport mechanisms, therefore, mixing of ejecta and substratum materials must have occurred. Extrapolation of this model to Imbrium suggests a wide distribution of ejecta from this basin. Moore *et al.* (1974) point out that the locations of Apollo 14, 15, 16, and 17 permit the presence of Imbrium ejecta of considerable thicknesses at all these sites.

Chemically, the Apollo 14 samples have consistently lower contents of iron oxide and higher contents of aluminum oxide than mare basalts. The iron content is more like most terrestrial basalts. The concentration of minor or trace elements, such as potassium, rubidium, uranium, thorium, barium, yttrium, and europium are much higher than those found in mare basalts. The closest compositions are those of the Apollo 12 KREEP basalts and

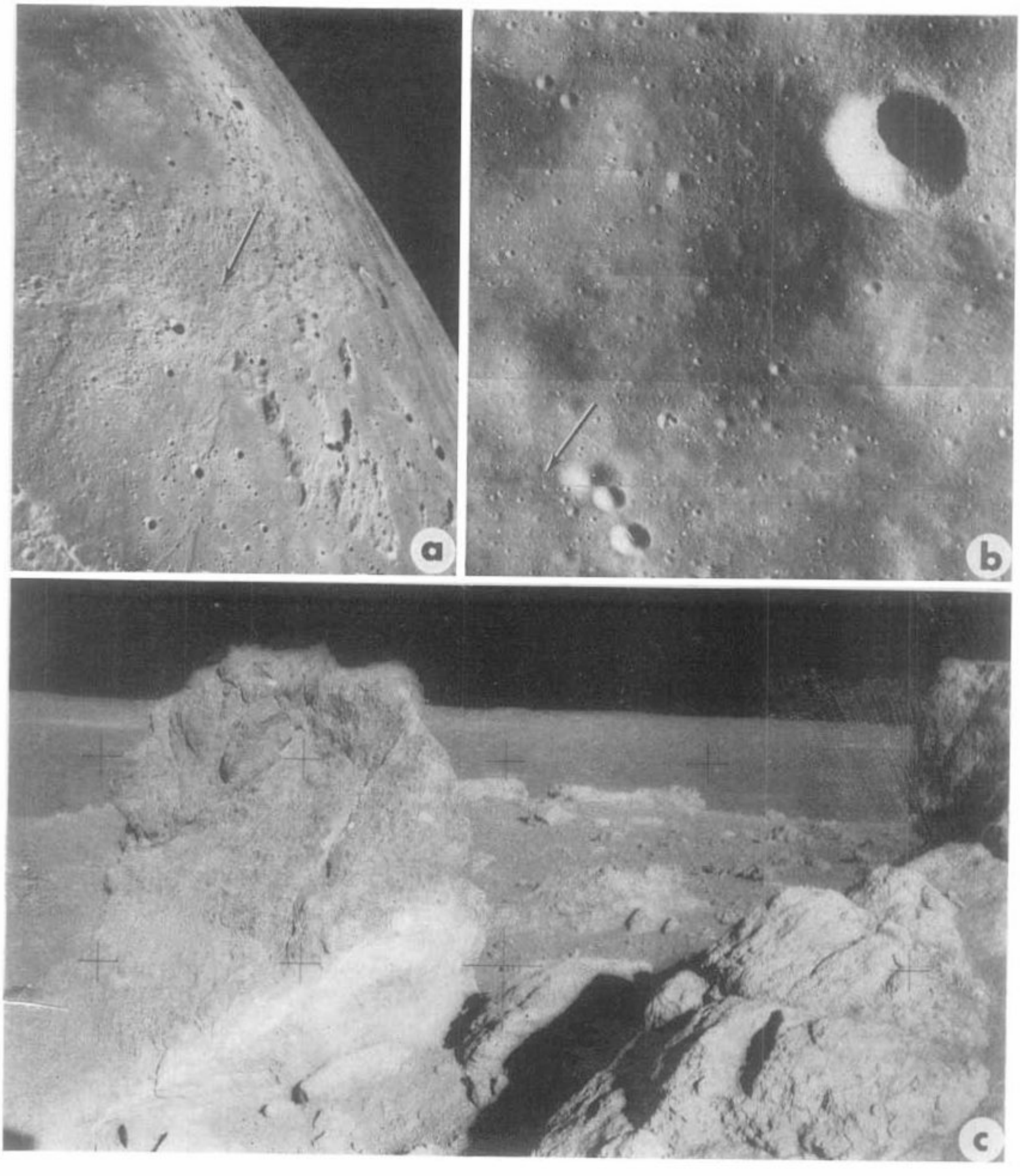


FIG. 4. Apollo 14: (a) Oblique view showing the ridgy Fra Mauro Formation (middle part of the frame) within which the Apollo 14 LM landed (arrow) (Apollo 16 metric frame 2507); (b) Close-up view of the landing site (arrow) southwest of Cone crater (upper right part of photograph). Cone crater, which is about 350 meters in diameter, apparently penetrated one of the Fra Mauro Formation ridges (right half of photograph) (Lunar Orbiter III frame H-133); (c) Large blocks, several meters across, near the rim of Cone crater showing dark and light clasts of breccia set in a light-colored matrix. The brecciation appears to be the result of impact metamorphism (Apollo 14 frame 9449).

the dark portion of "rock 13." The chemical composition of the soil closely resembles that of the fragmental rocks, except for the fact that some trace elements are somewhat depleted in the soil (LSPET, 1971).

The Apollo 14 rocks are dated at 3.95 billion years (Tera *et al.*, 1973). These rocks (samples of the Fra Mauro Formation) most probably represent ejecta from the Imbrium basin, where the impact event must have reset the radioactive clocks. Therefore, the 3.95 billion years age represents the last stage of recrystallization of the Imbrium basin ejecta. In summary, important results of the study of the Apollo 14 samples are:

1. The complex history of shock metamorphism of all the rocks, for which there are three probable causes: (a) excavation by the Imbrium impact of preexisting brecciated materials; (b) formation of breccia within breccia during the Imbrium event, and the base-surge that resulted from it; and (c) local cratering events superposed on the Imbrium event.
2. The composition of the Fra Mauro Formation rocks is different from the mare rocks of Apollo 11 and 12. The highland or KREEP basalts of Apollo 14 are characterized by a lower iron oxide content and higher aluminium oxide and trace element concentrations than those of mare basalts.
3. Since the recrystallization age of the Apollo 14 rocks is about 3.95 billion years, and if the Fra Mauro Formation is indeed ejecta of the Imbrium basin, then we have established the absolute age of the Imbrium event which shaped much of the near side of the Moon.

D. Apennine–Hadley

The Apollo 15 lunar module landed on the mare surface of Palus Putredinis on the eastern part of Mare Imbrium, which is rimmed by the Montes Apenninus. The landing site is strategically situated such that the astronauts were able to sample the mare material, the highland massif Hadley δ or its regolith, and the sinuous Rima Hadley (Fig. 5a). The mare material of Palus Putredinis is very similar in texture, appearance, and number of craters per unit area to the mare of Oceanus Procellarum in which Apollo 12 landed, and, therefore, it was believed to be of the same relative age (Carr *et al.*, 1971). Hadley δ, which is part of the Apennine Mountains was believed to include material that was uplifted from the subsurface at the time of the formation of the Imbrium basin (Shoemaker, 1962, among many others).

First to be studied were the large numbers of photographs returned by the Apollo 15 crew. Both surface and orbital photographs were used to decipher local stratigraphic relationships. For example, high resolution panoramic camera photography showed meters thick layers on the walls of Rima Hadley (Fig. 5b). These layers, which confirm the theory of filling of mare basins by successive lava flows, were also depicted on high resolution surface photographs (LSAPT, 1972). Also, a highland prominence, informally called Silver Spur, within the Apennine chain of mountains and hills showed several strata (Fig. 5c). Each layer is about 100 meters thick, and the layers may be ejecta from the Imbrium basin (Swann *et al.*, 1970).

The mare material returned by Apollo 15 was found to be basalts similar to that returned from Oceanus Procellarum. Material of Hadley δ was found to be chemically different from both the mare basalts and the KREEP basalts of Apollo 14. It is mostly anorthositic rock; some of the returned samples are crystalline rocks which indicates that brecciation was not as extensive as at the Apollo 14 site.

The anorthositic rocks are held by most lunar investigators to represent a large part of the lunar crust. The chemistry of this material is similar to that of the light-colored fine particles collected in the soil from several sites [for example, Apollo 11 (Wood *et al.*, 1970) and Luna 16 (Vinogradov, 1971)]. Unlike the Fra Mauro KREEP this material does not show high concentration in radioactive elements. One anorthositic crystalline rock from the highland regolith samples on Apollo 15 and named "Genesis Rock" gives an age of 4.1 billion years (LSAPT, 1972). This is the oldest rock sampled on that mission.

Study of the samples collected from the

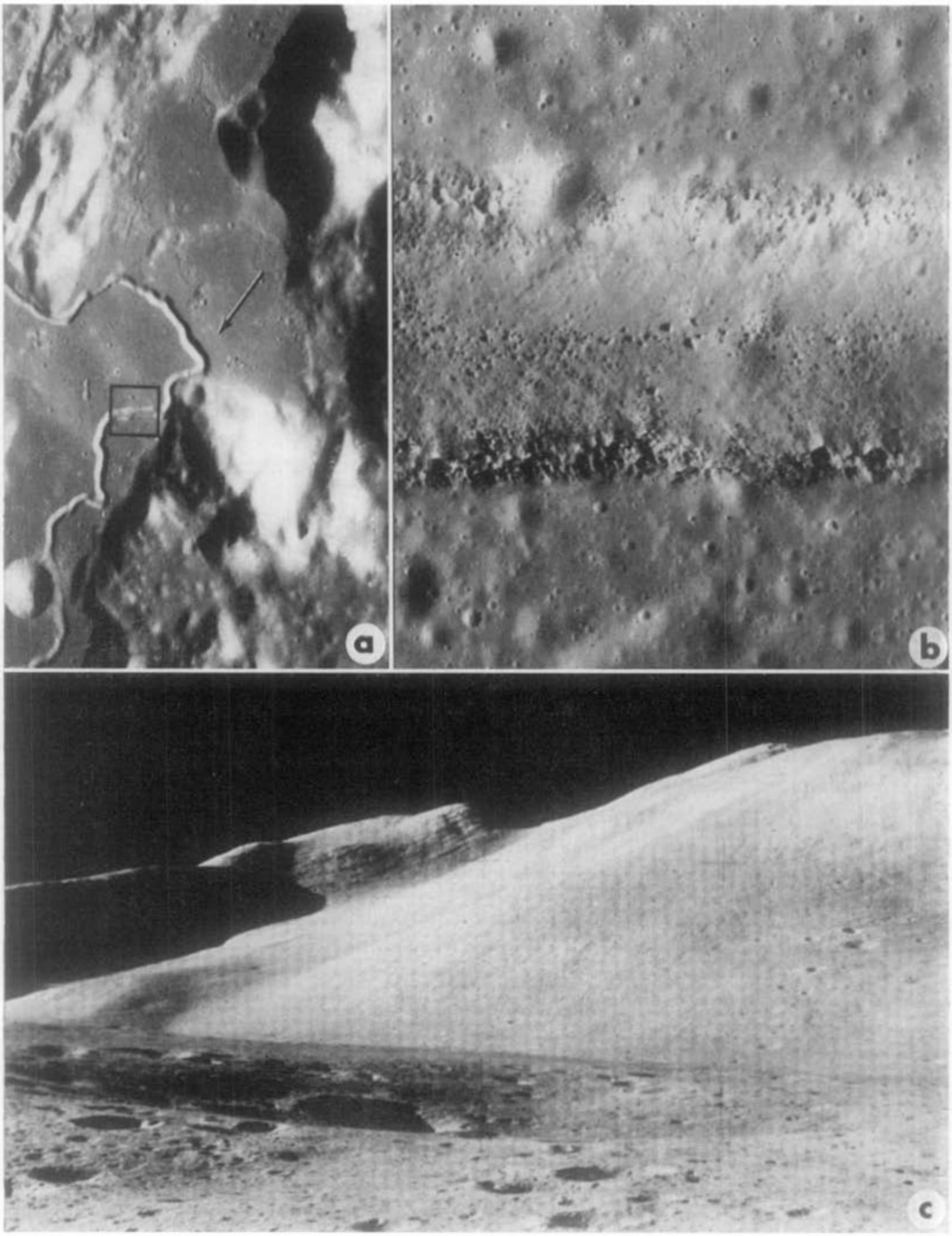


FIG. 5. Apollo 15: (a) Photograph of the landing site (arrow) in Palus Putredinis. The site is west of the Apennine Mountain chain and east of the sinuous Hadley Rille (Apollo 15 frame 12811); (b) High resolution photograph of part of Hadley Rille that is marked by a square in Fig. 5a. Note the ledge of bedrock near the top and the numerous blocks that accumulated at the bottom of the V-shaped rille (Apollo 15 panoramic camera frame 9342); (c) Photograph of the layered Silver Spur (near center of horizon) at Hadley δ as viewed from the LM (Apollo 15 photography 11371).

rim of Rima Hadley failed to add any significant insight into the origin of the structure. The morphological characteristics of this sinuous depression may best be explained as the result of drainage of lava into a conduit whose top part may have congealed and later collapsed to form the rille (Greeley, 1971; Carr *et al.*, 1971; Howard *et al.*, 1972). However, the data are not conclusive, and the origin of this and other sinuous rilles remain somewhat enigmatic.

Among the most significant results of the Apollo 15 mission are the following.

1. The basalts of the Apollo 15 site are similar chemically and texturally to the Apollo 12 basalts. Both mare basalts are also about 3.2 billion years old. They constitute the youngest group of sampled basalts. The luna 16 and Apollo basalts are 3.5 and 3.7 billion years old, respectively. The oldest basalt is one of the Apollo 14 rocks, number 53, which is 3.95 billion years old (LSAPT, 1972).
2. Rocks and soil samples of Hadley δ are in general terms anorthositic gabbros and gabbroic anorthosites. Some of these are crystalline rocks, which indicates that brecciation was not as extensive at the rim of the Imbrium scar as it was farther out on the ejecta blanket (Apollo 14 breccias).
3. The lunar highlands are indeed older than the maria, which is in agreement with photogeologic interpretations. The fact that "Genesis Rock" is 4.1 billion years old is very significant, in that the rock is older than the Imbrian basin, and was not metamorphosed by that event.
4. Although samples and close up photographs were taken of Rima Hadley, no new information was gathered on the origin of that sinuous rille. All existing theories of sinuous rille formation are still competing, and there may be many modes of origin for these rilles.

E. Descartes Highlands

Apollo mission 16 was dedicated to sampling and exploration of part of the central lunar highlands north of the crater Descartes (Fig. 1). Two distinctive units were recognized and mapped before the mission (Fig. 6). The first is a relatively flat unit which resembles in gross appearance old mare units but displays a much higher albedo and a denser population of craters, the plains-forming Cayley Formation. The second is a topographically higher unit which is characterized by hilly, grooved, and furrowed terrain. The latter ("Descartes") unit is morphologically similar to some terrestrial volcanic deposits. Hence, it was interpreted as a representative of volcanism in the lunar highlands; relatively viscous volcanic materials could be responsible for the formation of the hilly topography (Milton, 1968; Wilhelms and McCauley, 1971; El-Baz and Roosa, 1972; Milton and Hodges, 1972; and others). If this interpretation is correct, one would expect an abundance of crystalline highland rocks at the Apollo 16 site.

During the mission, however, the astronauts observed that most of the rocks they encountered were breccias rather than crystalline or igneous rocks. Examination of the returned samples confirmed that the vast majority of the samples are breccias and only a few are unmetamorphosed igneous rocks (LSPET, 1973a). There is an abundance of high aluminum and calcium rocks: many are monomict breccias approaching pure calcic plagioclase composition. These crushed anorthosite breccias are unlike other lunar breccias, displaying no evidence that they are mechanically produced mixtures of preexisting rocks. The Apollo 16 breccias probably formed from coarse-grained anorthosites by impact metamorphism (LSPET, 1973a).

Ray materials and ejecta derived from two bright rayed craters in the area, North Ray and South Ray (Fig. 6), appear to mantle much of the traversed surfaces, and, therefore, dominate the sampling locations. Because of this there is some uncertainty whether the material of the hilly terrain was sampled. It was clear, however, that premission theories of a volcanic origin were probably incorrect. After the mission, several theories were advanced relating the majority of Apollo 16 rocks to Imbrium basin ejecta (Hodges *et al.*, 1973), Orientale basin ejecta (Chao *et al.*, 1973), material generated by secon-

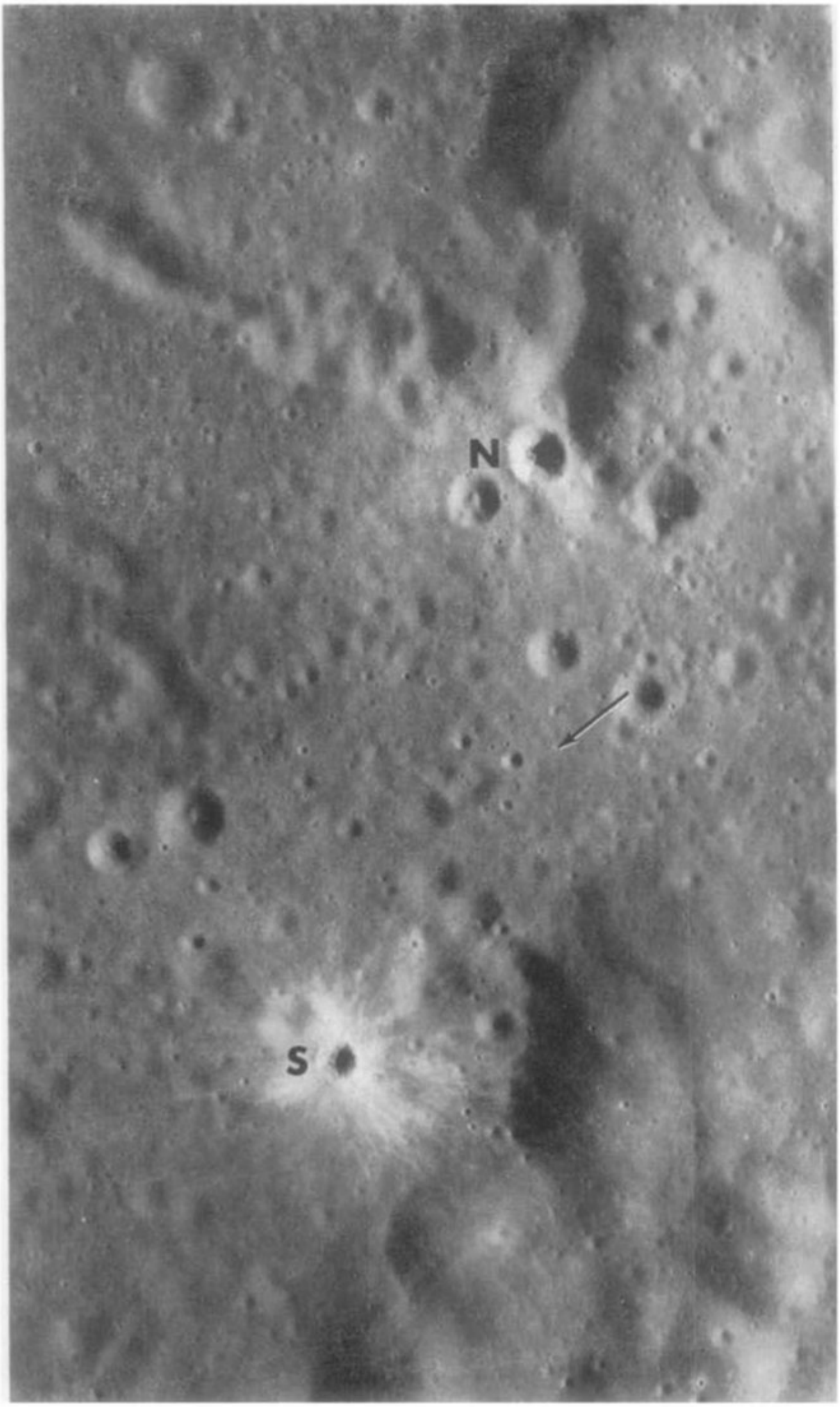


FIG. 6. High resolution photograph of the Apollo 16 landing site area. The landing point (arrow) is approximately midway between two bright craters, 800 meters in diameter, North Ray (N) and South Ray (S). The latter is the younger and therefore the brighter of the two. Ejecta from both was collected on the mission in addition to materials of the light plains (Cayley Formation) in which the LM had landed (Apollo 16 panoramic camera frame 4623).

dary craters of Imbrium (Oberbeck *et al.*, 1974), and Nectaris ejecta and locally generated deposits (Head, 1974).

None of these theories fully explains all the observations, although all the considered impacts may have contributed to the terra deposits in the Descartes site. However, the study of the Orientale basin ejecta by Moore *et al.* (1974) may provide additional support for this theory of Imbrium basin ejecta origin for the Apollo 16 materials. Moore *et al.* (1974) state that Imbrium-related debris more than 500 meters thick at the Apollo 16 site is quite possible, and is consistent with the photogeologic evidence in the Orientale case. This, however, does not preclude the presence of some Orientale and other basin ejecta at the site. Moore *et al.* (1974) expect a thinner deposit of Orientale materials in the Descartes region. Locally generated debris must also be present, e.g., ejecta blankets and rays of North and South Ray and older craters.

If we are to accept the theory of Imbrium basin ejecta for the Descartes site, two fundamental questions will remain unanswered: First, why are the rocks of the Apollo 16 site so different morphologically, petrologically, and from the metamorphic history point of view than the Apollo 14 breccias (which are also believed to be ejecta from Imbrium)? Second, why are the concentrations in KREEP basalts so much higher in the Fra Mauro Formation rocks than in the Descartes highlands, if both are mostly Imbrium ejecta deposits?

Some of the samples of North Ray crater ejecta appear to have a rustlike coating. Studies of the opaque mineral assemblage in these rocks revealed the presence of an iron hydroxide, goethite, in that coating. According to El Goresy *et al.* (1973), goethite occurs as a thin film around metallic Fe/Ni and infiltrates the silicate grain boundaries in the vicinity of the Fe/Ni metals. These observations lead to the conclusion that goethite was formed on the lunar surface by hydrothermal or similar reactions between troilite and water vapor, perhaps during a cometary impact, the water being a component of the cometary tail. Therefore, a cometary impact may have formed North Ray crater.

From studies of the Apollo 16 samples, the following results are most significant.

1. Photogeologic interpretations by many investigators, including myself, of landforms in the Descartes region were proved incorrect. The hilly and grooved topography in that area is probably unrelated to terra volcanism and most likely to the accumulation of basin ejecta.
2. Although the Imbrium basin appears to be the most likely source of the Descartes area deposits, differences between the Apollo 16 and 14 rocks are still not fully understood.
3. The ages of Apollo 16 rocks (about 3.9 billion years, Tera *et al.*, 1973) are consistent with an Imbrium origin, although some samples dated by argon 40-argon 39 give crystallization ages of approximately 4.1 to 4.2 billion years (Husain and Schaeffer, 1973).
4. The high aluminum and calcium rocks of the Apollo 16 site are crushed anorthosite breccias, probably derived from cataclysmic metamorphism of an anorthositic complex containing 70 to 90 percent plagioclase.
5. Although the lunar environment is completely void of water and is characterized by exceedingly low oxygen pressure, goethite was formed in the Apollo 16 rocks as a mineral reaction rim. The water vapor may have been part of the impacting (cometary) projectile that formed North Ray crater.

F. Taurus–Littrow

The Apollo 17 site is located on a dark unit that fills a valley between two large massifs on the southeast rim of Mare Serenitatis (Figs. 1 and 7). This flat unit is among the darkest of all lunar surface materials (albedo value about 6–7%; Pohn and Wildey, 1970). As mapped by Carr (1966) this unit was believed to be younger than the inner mare fill of the Serenitatis basin. Also, according to Greeley and Gault (1973) this unit is so moderately cratered that it was considered among the youngest marelike units on the near side of the Moon. It displays a very

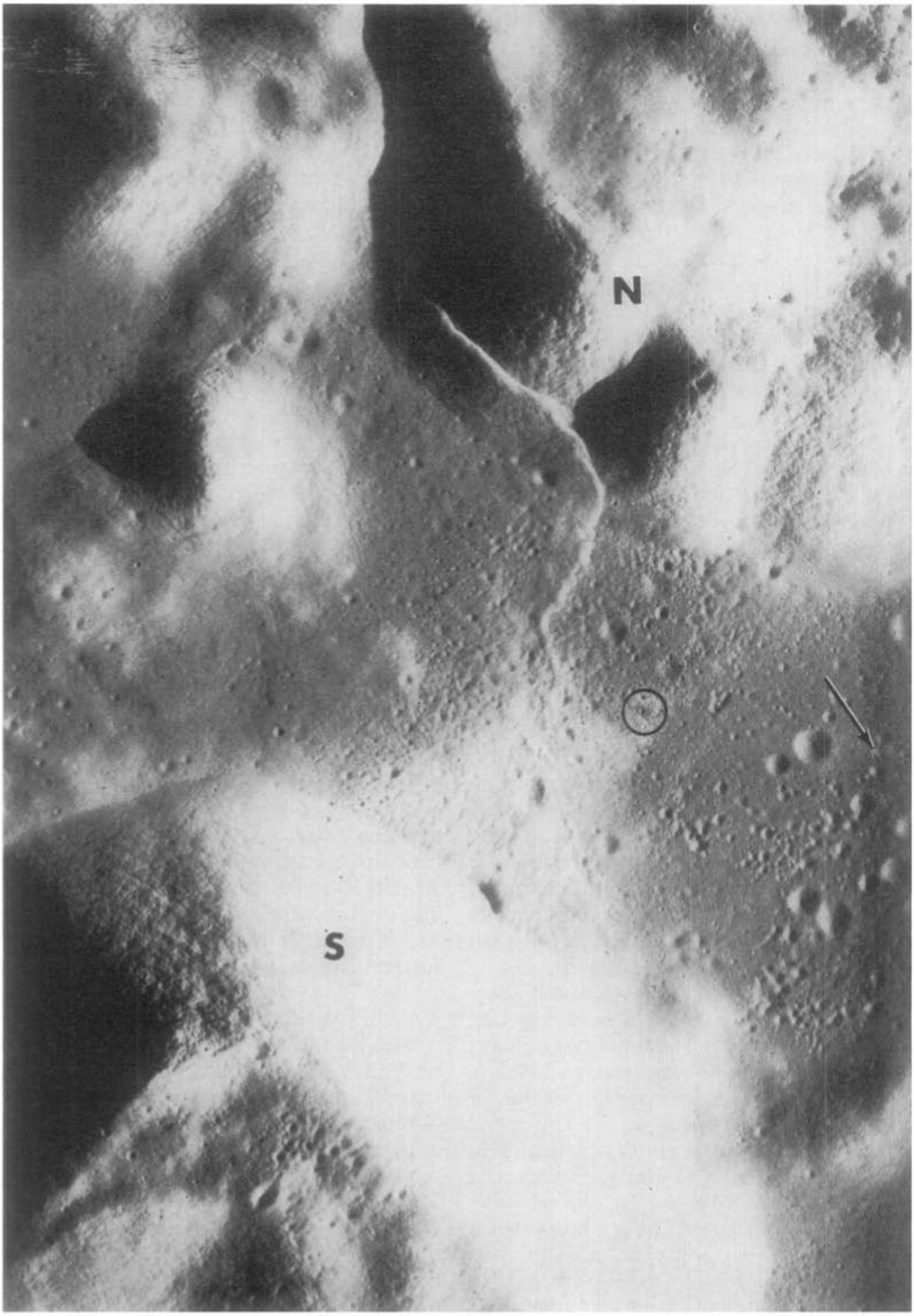


FIG. 7. Area of the Apollo 17 exploration site. The LM (arrow) landed in the dark plain between two highland massifs, North Massif (N) and South Massif (S). Samples were collected from the plains, the two massifs, the landslide near South Massif, the scarp between the two massifs, and Shorty crater (circle) (Apollo 17 panoramic camera frame 2314).

smooth surface which was interpreted to be the result of a thin pyroclastic mantle (El-Baz, 1972a). This interpretation was endorsed by the sighting in this vicinity, from the Apollo 15 orbit, of small smooth-rimmed craters which were interpreted as cinder cones (El-Baz *et al.*, 1972). Part of this unit is covered with a relatively thin layer of light-colored material which is believed to be a landslide from the South Massif (El-Baz, 1972b; Scott *et al.*, 1972).

The massif units measure up to two kilometers in height and display relatively fresh surfaces with numerous blocks. A large population of blocks could also be seen at the base of the massifs, indicating unstable slopes and much downslope movement of material. Crossing the site in a north-southerly trend is a scarp with mare ridgelike segments. This scarp is interpreted as a fault scarp with en-echelon segments producing the ridgelike appearance. Muehlberger (1974) interprets it to be an asymmetric compressed fault, part of postmare structural adjustments in southeastern Serenitatis.

Observations made at the site indicate that the dark unit is composed of igneous rock which is similar to the mare basalts; a thick pyroclastic mantle was not obvious. The observations were confirmed in the laboratory where the basalts showed a high titanium content in the form of the mineral ilmenite much like the Apollo 11 basalts (LSPET, 1973b). This tends to support the studies by Adams and McCord (1971) which suggest that the albedo of the mare unit depends partly on chemical composition. In this case the darker the unit, the higher the titanium content.

At Shorty crater (Fig. 7), the astronauts encountered an orange-colored layer of fine grained material which appeared during the mission to be the result of fumarolic activity, i.e., alteration by oxidation of the host rock. This observation, however, did not hold in the laboratory and the orange material was found to be made of very fine grained glass spheres, yellow, orange, brown to black in colour with high lead, copper, zinc and chlorine content (LSAPT, 1973). Although some investigators believe that the glass spheres may be impact produced (Roedder and Weiblen, 1973), most agree that they represent a product of volcanic eruption (Reid *et al.*, 1973, among others). Orange-colored deposits and ejecta blankets are apparently not restricted to the Apollo 17 landing site area; orbital observations on Apollo 17 indicate that they abound in the Sulpicius Gallus region on the western Serenitatis rim (Evans and El-Baz, 1973; Lucchitta and Schmitt, 1974).

The highland materials collected at the Apollo 17 site show several suites of anorthositic rocks. Although petrologically complex, massif rocks may be divided into two chemical suites: (a) noritic breccias which include the petrologic varieties of green-gray, blue-gray, and light gray breccias; and (b) anorthositic gabbros, which petrologically are brecciated gabbroic rocks. The second group occurs both as clasts in noritic rocks and as isolated samples. Although the noritic breccias are broadly similar to KREEP rocks, they contain only one-half the minor and trace element content (LSPET, 1973b).

The ages of Apollo 17 basalts were found to be close to those of the Apollo 11 site, about 3.7 billion years old (Tera *et al.*, 1974). The highland rocks gave crystallization ages of approximately 4.0 billion years (Tera *et al.*, 1974). However, age dating of highly crushed dunite fragments of a clast in a South Massif boulder sample (72435) gave a model age of 4.48 billion years (Albee *et al.*, 1974). From its composition and old age, these authors tentatively conclude that the rock must represent a very early differentiate derived from the upper lunar mantle, and that it represents a cumulus formed during early lunar differentiation and associated differential gravitational settling.

Particle-track measurements on target materials carried to the lunar surface on Apollo 17 have provided new data on heavy ions from solar and galactic cosmic rays in the low energy range (LSAPT, 1973). Previously unknown "quiet time" fluxes of ions from carbon to iron in the energy range of .05 to 1 million electron volts per nucleon were observed. Also, the large

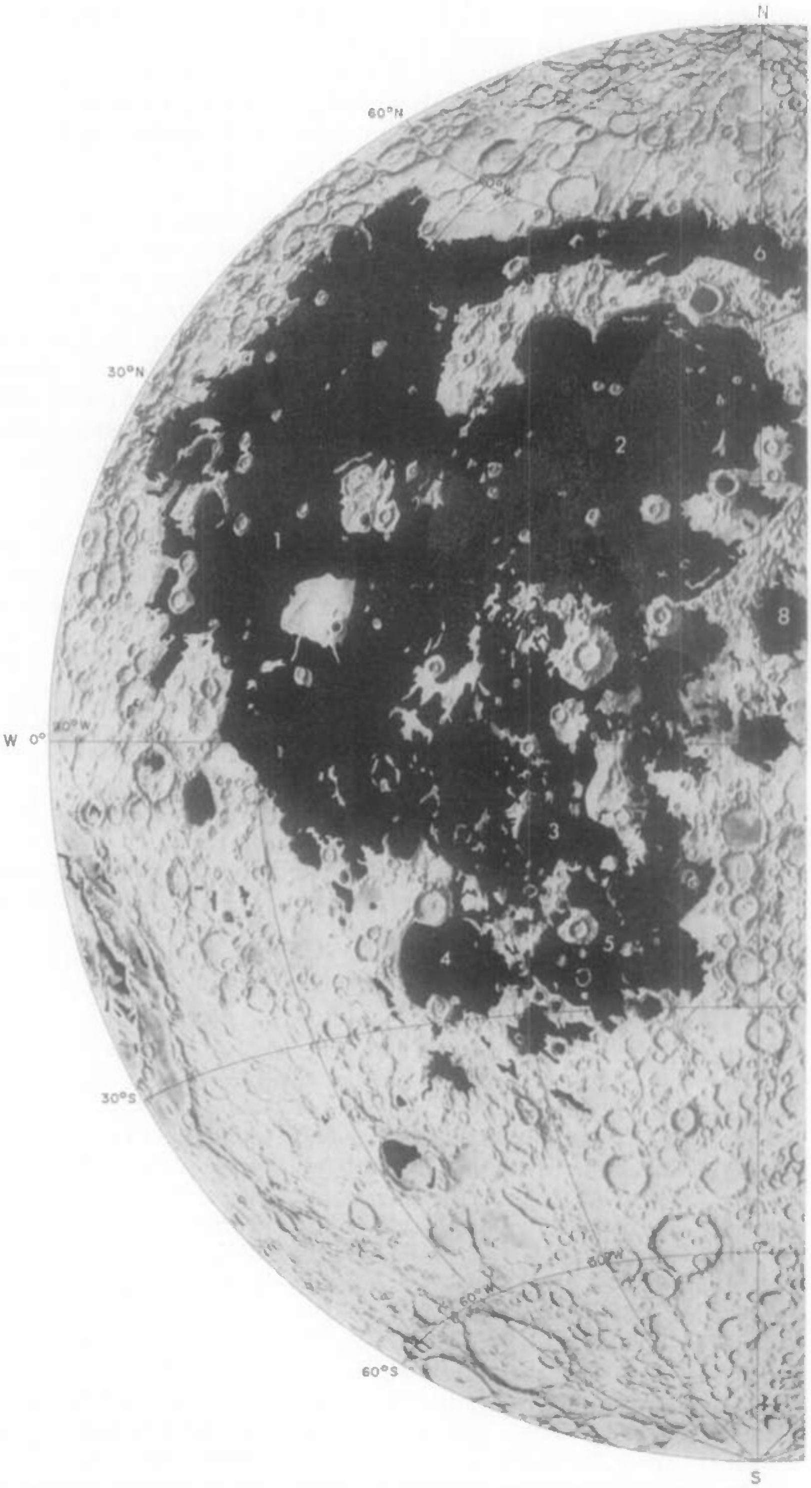
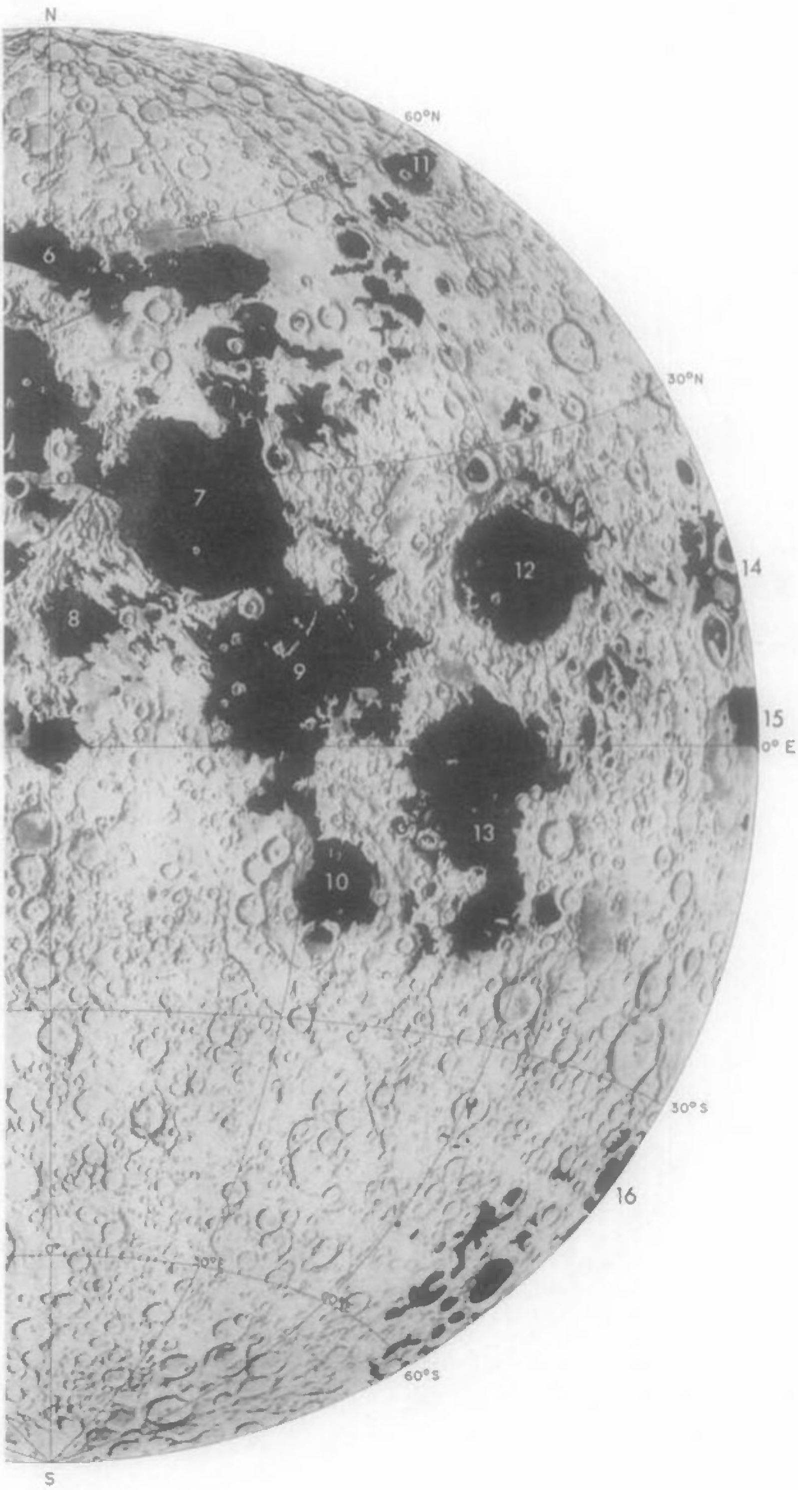


FIG. 8a. Distribution of mare material on the near side of the Moon. The mare material is concentrated in multiringed circular basins (Hartman and Kuiper, 1962) and in their peripheral troughs. Kaula *et al*. (1973) have determined a 2 to 3 km offset toward the Earth of the Moon's center of mass from its center of figure. They ascribe this to a variable thickness of low-density highland crust, thinner on the near side than on the far side. The maria are therefore concentrated on the near side



because the mare basalts could more easily penetrate the thinner crust. Numbered are Oceanus Procellarum (1) and the maria of Imbrium (2), Cognitum (3), Humorum (4), Nubium (5), Frigoris (6), Serenitatis (7), Vaporum (8), Tranquillitatis (9), Nectaris (10), Humboldtianum (11), Crisium (12), Fecunditatis (13), Marginis (14), Smythii (15), and Australe (16). (Drawing from Masursky *et al.*, 1975; base map by the National Geographic Society).

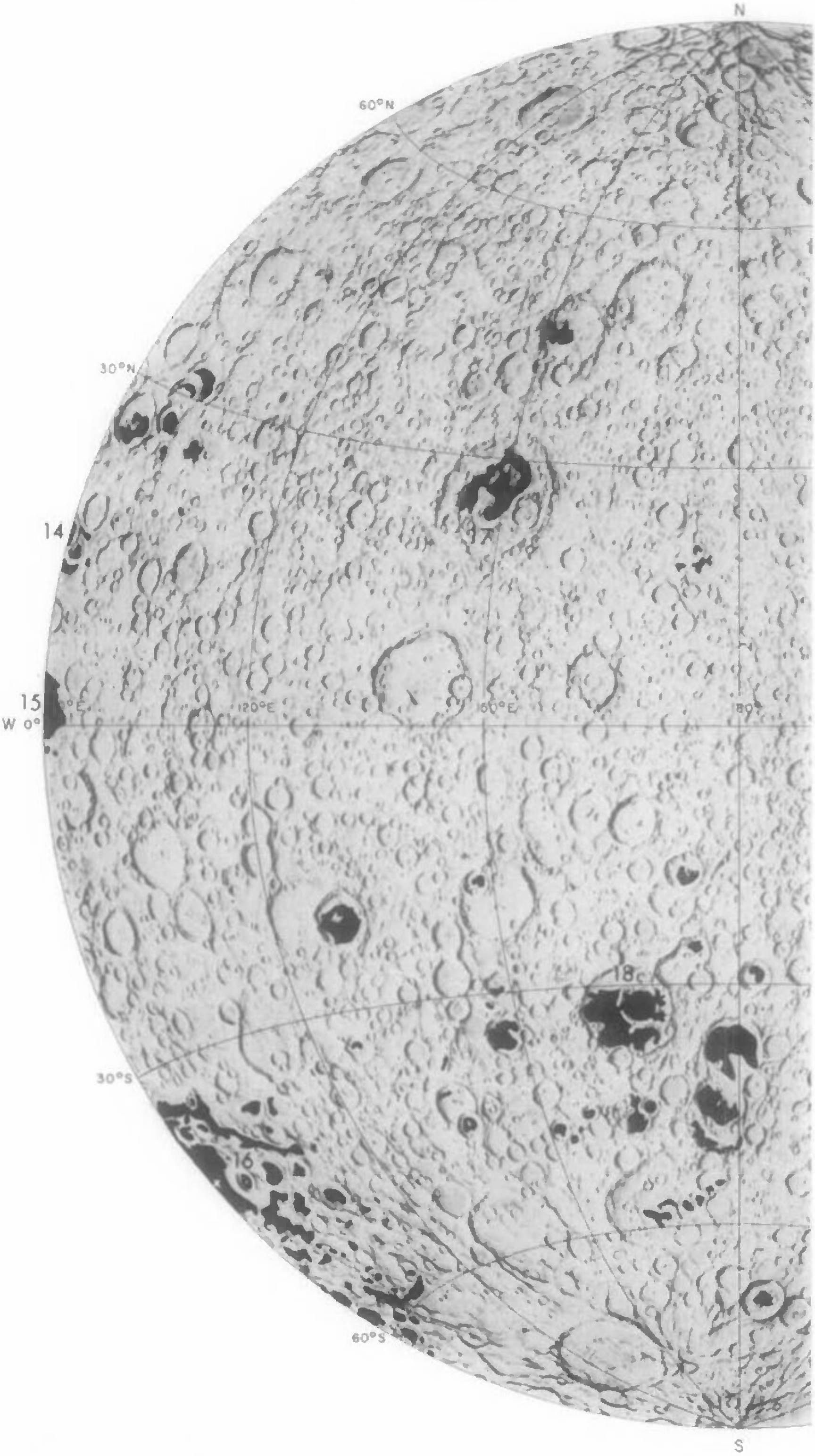
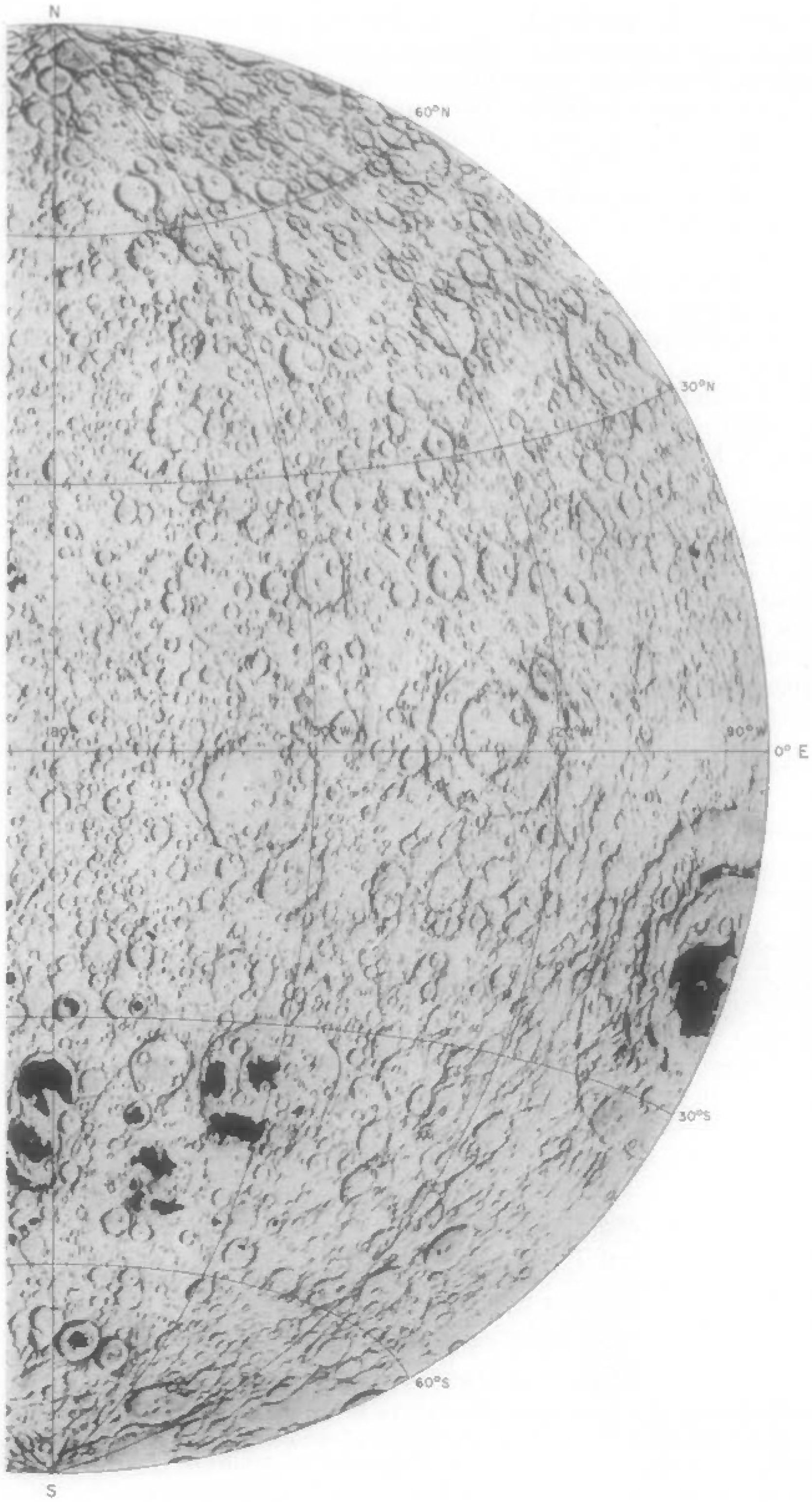


FIG. 8b. Distribution of mare material on the far side of the Moon. The presence of fewer mare regions on the far side than on the near side is ascribed to a thicker highland crust (Kaula *et al.*, 1973); basaltic lavas would have more difficulty in penetrating a thicker crust to reach the surface. Local thinning of the crust through excavation by basins, and particularly by craters within the



basins, may explain the observed distribution of maria on the far side (see also Fig. 12). Numbered are the maria of Marginis (14), Smythii (15), Australe (16), Moscoviense (17), Ingenii (18), and Orientale (19). (Drawing from Masursky *et al.*, 1975; base map by the National Geographic Society.)

solar flares of August 1972 produced relatively large amounts of radioactivity in the Apollo 17 samples. These flares were shown to have a larger average particle energy and greater intensity than any flare in the past fifteen years (LSAPT, 1973).

In summary, among the most important findings of the Apollo 17 surface exploration are the following.

1. The basalts contained in the Taurus-Littrow Valley are grossly similar to those from Mare Tranquillitatis in their high content of titanium, as well as in their age. The age of these basalts, about 3.7 billion years, contradicts earlier expectations that the Apollo 17 basalts would be young.

2. Orange, brown and black spheres of glass that are probably the product of volcanism are also 3.7 billion years old. They may represent a more complex history of volcanism in that region. High concentrations of volcanic glass spheres may be responsible for the apparent smoothness of the dark mare unit.

3. The highland rocks from the massifs show more petrologic variety than any other group collected on previous sites. These rocks might represent both materials uplifted at the rim of the Serenitatis basin as well as ejecta from both Serenitatis and Imbrium.

4. The age of the highland rocks of Apollo 17 (about four billion years) lends support to the idea of a cataclysmic event or events which affected much of the near side of the Moon around 3.9 to 4 billion years ago as suggested by Tera *et al.*, 1973 and Albee *et al.*, 1974. However, discovery of older dunite fragments (about 4.48 billion years old) also indicates that earlier differentiates may still be preserved in the lunar crust.

III. GLOBAL CHEMISTRY

Mare materials form only about one-fifth of the lunar surface. The distribution of maria is an obvious indication of the asymmetry of the Moon, more mare

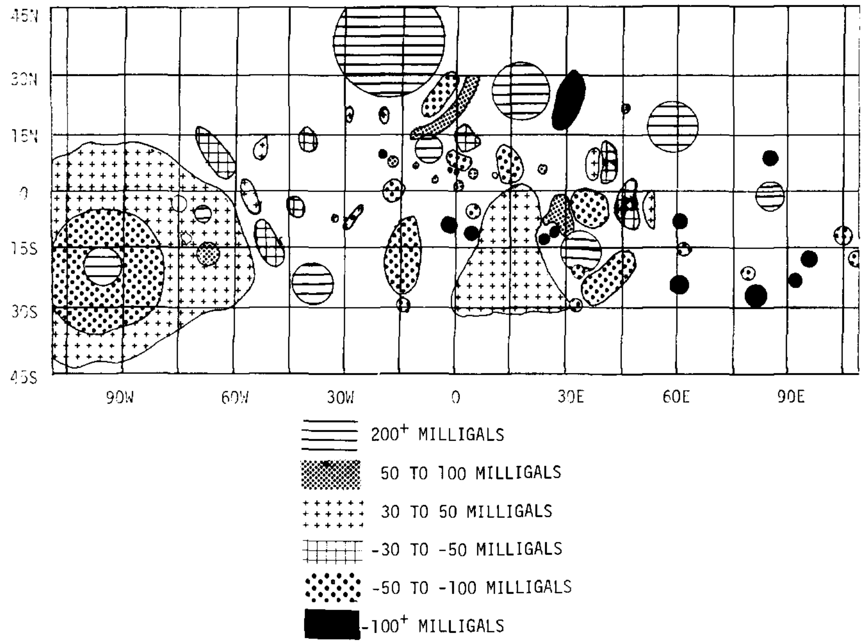


FIG. 9. Gravity anomalies on the lunar near side and limb regions. Mascons (circular areas) have mass excesses of 800 kilogram/m^2. These occur in multiringed circular basins and are interpreted by Sjogren *et al.* (1974), to be near surface, disc-shaped features. A circular or ring structure is evident at Mare Orientale on the western limb of the Moon; other ring structures are less evident near the other mascons. (Courtesy of W. L. Sjogren, Jet Propulsoin Laboratory.)

material on the near side than on the far side (Fig. 8).

Large exposures of mare materials can be divided into two types of occurrences: (1) the probably thick (tens of kilometers) inner fill of circular basins; and (2) the relatively thin (a few kilometers) cover of basin troughs and other low-lands. As first discovered by Muller and Sjogren (1968), the first occurrences display large positive gravity anomalies or mass concentrations (mascons). The gravimetric data, which are available for the nearside and limb regions, show mascons underlying the maria of Smythii, Crisium, Nectaris, Serenitatis, Imbrium, Humorum, and Orientale (Fig. 9). However, large mare expanses of irregular shape, such as Oceanus Procellarum, do not show a positive gravity anomaly; both topography and gravimetrics indicate that the mare material in this region formed only a shallow veneer.

The basaltic composition of mare materials, although suggested by telescopic observations and photogeologic interpretations, was first indicated by the α-scattering elemental analyses made by Surveyors V and VI (Fig. 1) in Mare Tranquillitatis and Sinus Medii, respectively (Turkevich *et al.*, 1969). The widely spaced locations of the Surveyor V and VI sampling sites, as well as Apollo missions 11, 12, 15, 17, and Luna 16 sites (Fig. 1), leave no doubt that basalts are the major component of all the lunar maria.

Although Jackson and Wilshire (1968) point out that there are gross similarities between lunar basalts and flood basalts on Earth (e.g., Columbia River Plateau basalts), Melson and Mason (1971) and Wood (1974a, b) discuss differences between the lunar basalts, terrestrial basalts and basaltic meteorites. The basic difference between lunar and terrestrial basalts is that the former are depleted in sodium, along with all other volatile elements.

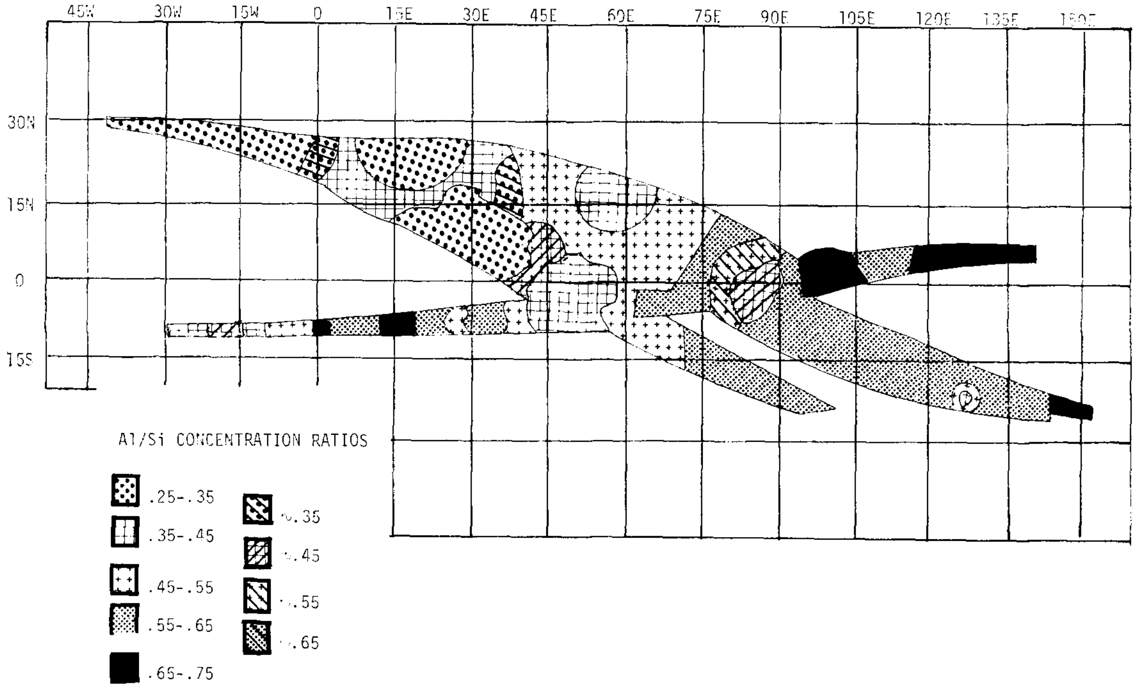
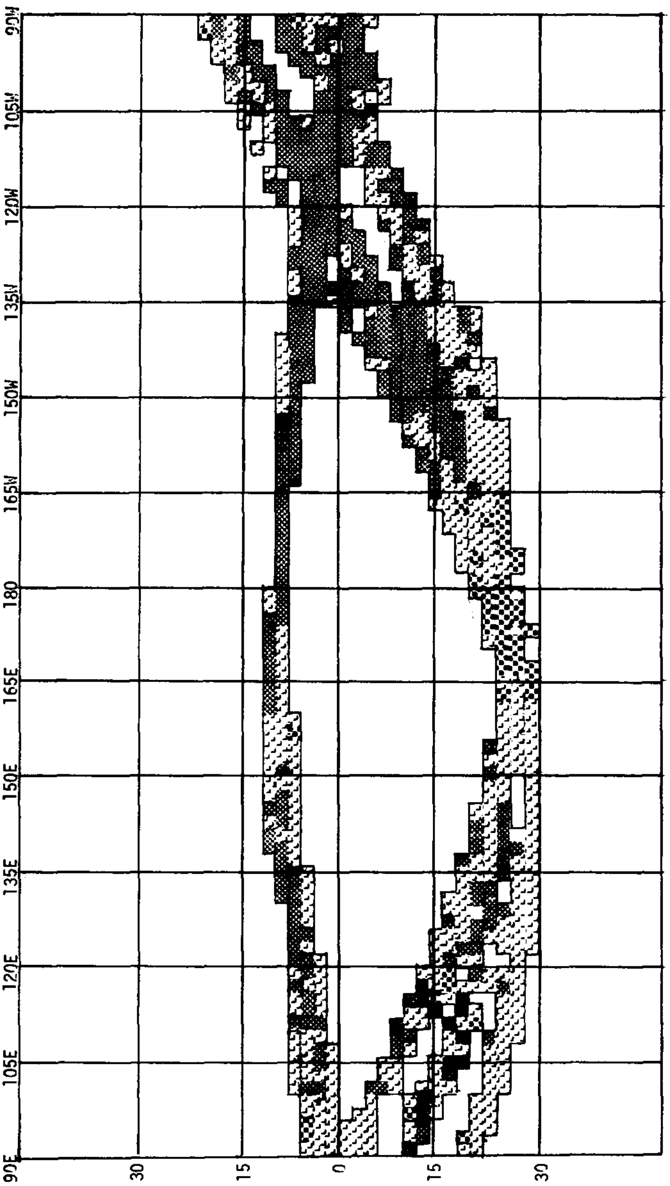


FIG. 10 Aluminum: silicon concentration ratios as detected by the X-ray experiments on Apollo missions 15 and 16 (Adler *et al.* 1973). Higher values for aluminum show over highland areas and lower values over maria; intermediate values occur where there is much mixing between the two types of materials. The magnesium: silicon concentration ratios show a converse relationship—higher values over maria and lower values over highlands. (Courtesy of I. Adler, University of Maryland.)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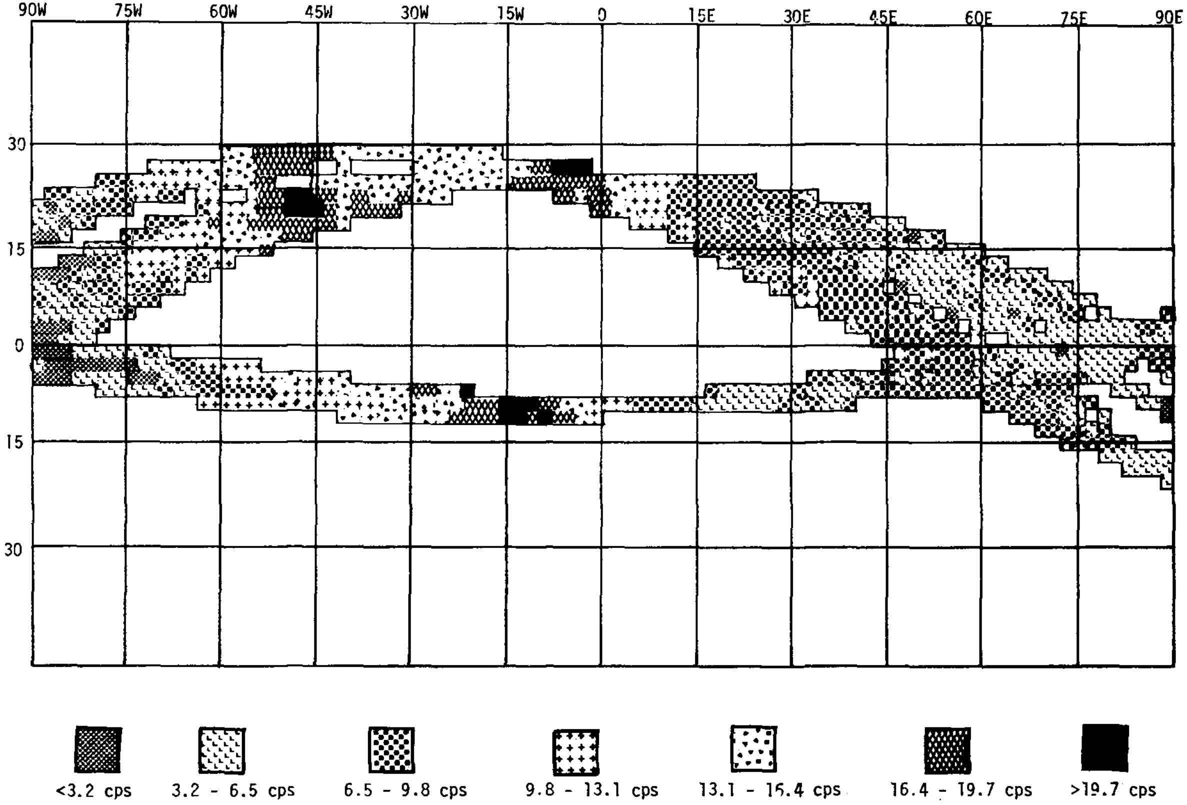

FIG. 11. Natural lunar radioactivity of both far side (top or left) and near side (bottom or right), as mapped by the gamma ray spectrometer on Apollo missions 15 and 16. The three "hot spots" on the western near side of the Moon (black areas) correspond roughly to about 10 ppm thorium; the lowest radioactivity (dotted area) is less than 1 ppm Th. (After Metzgar *et al.* 1973.)

Therefore, the plagioclase of lunar basalts contains lesser amounts of the albite component.

As discussed above, lunar mare basalts are not compositionally or texturally uniform within a given site or between sites. Variations are common in grain size, crystallinity, and vesicularity, as well as in detailed composition. These variations are most probably due to minor differences in the source materials beneath the surface, as well as to variations in thickness and cooling rates of individual lava flows.

Mare basalts contain greater amounts of iron and titanium than do the anorthositic and feldspathic highland materials, which are enriched in aluminum and calcium. These iron-rich basalts are also depleted in radioactive elements. The presence of some iron-rich intermediate rocks, particularly in the Apollo 14 site (samples 14053 and 14072) prompted Gast (1973) to suggest that the typical mare basalts may be derived from iron-rich source regions that have been subjected to previous partial melting.

Highland materials, which make up about four-fifths of the lunar surface are chemically and petrologically more complex than the mare materials. In general, the sampled highlands are feldspathic breccias. The common brecciation, recrystallization, and apparent partial melting is consistent with patterns of overlapping ejecta from numerous impacts. The major rock types are: feldspar-rich rocks, especially the type called anorthosite; KREEP basalts with a relatively high concentration of radioactive elements; "Very High Aluminum" (VHA) basalts (Hubbard *et al.*, 1973) which are common in the Apollo 16 samples; and the anorthositic gabbros of Apollo 17. There are several variations in rock types, where petrographers recognize at least a half dozen categories of highland breccia rocks (LSAPT, 1973). A number of truly igneous rocks have also been collected in the highlands, but only a few of these may have crystallized from internal lunar melts; most are undoubtedly the product of impact melting.

All the lunar rock and soil returned by Apollo and Luna missions originated from differentiates; they have the specialized chemical compositions that are characteristically produced by magmatic differentiation. This indicates that the part of the Moon that was sampled had been molten at one time or another. The basic pattern of primary differentiation may have been relatively simple, but the picture has been greatly complicated by the tendency of large cratering events and lava eruptions to transport and mix chemical entities during and after the original differentiation (LSAPT, 1973).

The chemical pattern that was developed by studying the returned samples was confirmed by the orbiting geochemical sensors on Apollo missions 15 and 16, which carried X-ray and γ-ray spectrometers. The X-ray sensor measured the characteristic fluorescence signatures of aluminum, silicon, magnesium, and iron that were excited by impinging solar radiation (Adler *et al.*, 1973). The Al/Si intensity profiles clearly show low Al/Si values over the lunar maria, and higher values over terra materials, especially on the lunar farside (Fig. 10). Intermediate Al/Si values usually correspond with boundaries between the basaltic mare units and the anorthositic highlands. A reverse correlation generally exists in Mg/Si ratios, where mare units show a higher value than the highlands (Adler *et al.*, 1973).

The γ-ray spectrometer measured concentrations of natural radioactive emissions from the lunar surface (Fig. 11). The highest counts, which correspond roughly to about 10 ppm thorium, are confined to the western near side of the Moon, namely two regions in Mare Imbrium and Oceanus Procellarum (Metzger *et al.*, 1973). Based on the aforementioned discussion of sample compositions at Apollo 12 and 14 sites, this high radioactivity probably is due to the presence of KREEP basalts. This leads to the conclusion that the areas of high radioactivity must contain exposures of ejecta from the Imbrium basin. The latter is the largest of the impact basins on the lunar near side, and, therefore, may have penetrated through originally radioactive parts of the crust. A high radioactive spot in the vicinity of the crater Van de Graaff on the far side is also within a very old and large basin, even larger than Imbrium (Stuart-Alexander, 1975). The localization of the highly radioactive rocks supports the deduction that they cannot represent average lunar surface materials.

Groundtruth derived from the study of returned samples from six Apollo missions and two Luna missions are, therefore, extrapolated, by "orbital truth" data, to larger areas of the Moon.

IV. Evolution of the Surface

Before the return of lunar samples, geologists were limited to establishment of a relative time scale to describe events and major provinces on the Moon. This relative age time scale can effectively be applied to the entire Moon, most of which will not be sampled. The absolute time scale, which is based on age dating measurements of the lunar rocks, can now be used to calibrate the relative time scale, as will be discussed below.

A. *Relative Ages*

Global morphology of the Moon is controlled by the large features of impact origin known as multiring circular basins (Fig. 12). From the time of its formation, the crust of the Moon has probably been repeatedly shaped by basin and crater formation (Baldwin, 1969; El-Baz, 1973; Howard *et al.*, 1974). Materials of those basins and smaller craters compose most of the lunar highlands. As discussed above, mare materials, of later volcanic origin, are concentrated in the basins and their peripheral troughs, and the nearby lowlands.

Thus, the main surface sculpting mechanisms on the Moon appear to be meteorite bombardment and the downslope movement of fine-grained debris from higher to lower levels, aided by tectonic and/or seismic shaking. Study of fresh-appearing and young-looking features can, therefore, help in understanding relatively older ones. As discussed in detail by Wilhelms and McCauley (1971), subtly expressed forms can be recognized and often confidently identified as older equivalents of more clearly expressed features.

Several attempts have been made to classify features by relative age according to topographic and morphologic characteristics. A stratigraphic sequence was first developed by Shoemaker (1962) and Shoemaker and Hackman (1962) of an area around the crater Copernicus. This sequence was later modified and applied to most of the near side of the Moon by U.S. Geological Survey mappers as summarized by McCauley (1967), Wilhelms (1970), Wilhelms and McCauley, (1971), and Mutch (1972). Also, it was recently realized that an extension of the nearside lunar stratigraphy could be employed on the far side as well (e.g., EL-Baz, 1974; Wilhelms and El-Baz, 1975).

At the present time, a Moon-wide time-stratigraphic sequence exists, where surface units belong to one of the following, in the order of decreasing relative age.

1. Pre-Nectarian. All materials formed before the Nectaris basin and as far back as the formation of the Moon are classed as pre-Nectarian. The majority of pre-Nectarian units are distinguished on the lunar far side. These include materials of very old and subdued basins such as Al-Khwarizmi (El-Baz, 1973), and mantled and subdued craters cuch as Pasteur (Wilhelms and El-Baz, 1975).

2. Nectarian System. This system includes all materials stratigraphically above and including Nectaris basin materials, up to and not including Imbrium basin strata (Stuart-Alexander and Wilhelms, 1974). Ejecta of the Nectaris basin that can be traced near the east limb region allows recognition of these materials as a stratigraphic datum for the farside highlands. Younger than Nectaris ejecta, hence grouped under the Nectarian system, are materials of such basins as Humboldtianum, Moscoviense, and Mendeleev. Some plains units, particularly on the far side, are believed to be Nectarian in age (Wilhelms and El-Baz, 1975).

3. Imbrian System. A large part of the lunar surface is occupied by ejecta surrounding both the Imbrium and Orientale basins. These form the lower and middle

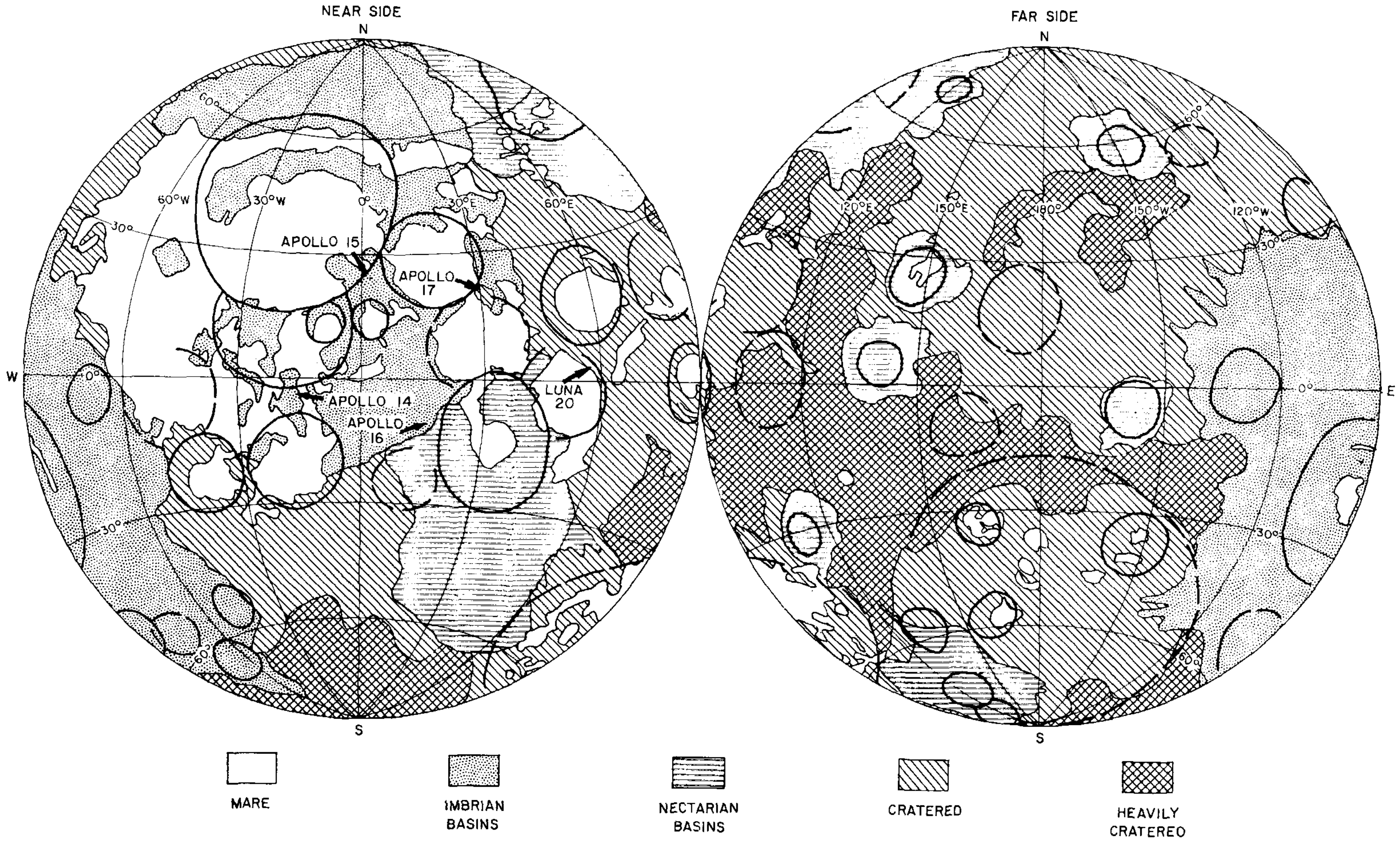

FIG. 12. Thematic map of the major geologic provinces of the Moon. The map clearly shows that lunar physiography is controlled by the large, circular basins and their overlapping ejecta blankets. Mare materials are enclosed in the circular basins and their peripheral troughs. Note asymmetry in the distribution of maria (more on the near side than on the far side). (See also Figs. 8a and b.) Refer to text for description of Nectarian and Imbrian basins and materials. (After Howard *et al.*, 1974.)

parts of the Imbrian System, including units such as the Fra Mauro Formation, Hevelius Formation, and Cayley Formation, the latter being light-plains material of Imbrian age. Two-thirds of the mare materials belong to the Imbrian System, particularly in the eastern maria of Crisium, Fecunditatis, Tranquillitatis, Nectaris, the dark annulus of Serenitatis, as well as most mare occurrances on the lunar far side. This system also includes materials of numerous large craters such as Plato, Arzachel, Petavius, and Tsiolkovskij.

4. Eratosthenian System. This system includes materials of rayless craters such as Eratosthenes. Most of these are believed to have once displayed rays that are no longer visible because of mixing due to prolonged micrometeorite bombardment as well as solar radiation. The system also includes about one-third of the mare surface materials on the lunar nearside. These are generally concentrated in Oceanus Procellarum, in western Mare Ibrium, and possibly the central region of Mare Serenitatis.

5. Copernican System. This is stratigraphically the highest and, hence, the youngest lunar time-scale unit. It includes materials of fresh-appearing, intermediate to high albedo, bright-rayed craters. The system also includes exposures of very high albedo material on inner walls of Copernican and older craters, as well as other scarps. Brightness in these cases is interpreted as the result of fresh exposure by mass wasting and downslope movement along relatively steep slopes. The Copernican System also includes isolated occurrences of relatively small dark-halo craters. Many of these are probably impact craters, however, the possibility that some may be volcanic in origin cannot be discounted.

B. Absolute Ages

As previously discussed, many techniques have been employed in absolute dating of lunar rock and soil, sometime yielding different results. However, some generalizations could be made particularly from the strontium–rubidium and uranium–lead data.

One age about which most investigators agree is the model age of the lunar soil, 4.6 billion years. As pointed out by Tatsumoto and Rosholt (1970), this age is comparable with the age of meteorites and with the age generally accepted for the Earth. The same figure presumably represents the age of the Moon; however, the "Lunatic Asylum" of the California Institute of Technology files a complaint that the age of the Earth and the Moon are lower than the accepted age of meteorites by 0.1 billion years (Tera *et al.*, 1974).

It was shown above that there are chemical–petrological indications of an early differentiation resulting in the formation of the Moon's crust. Age-dating results of highland rocks give indirect indications of the same thing. Studies by Nyquist *et al.* (1973) suggest differentation ages of 4.3–4.4 billion years. Tera *et al.* (1974) conclude from all the available absolute age data that planetary differentiation processes took place between 4.6 and 4.3 billion years, and that the crust is 4.43 billion years old.

The solid crust must have continued to receive impacting projectiles. Reshaping of the lunar physiography, accompanied by resetting of the radioactive clocks, continued with each major impact erasing most of the earlier history within its sphere of influence. From the uranium–lead evolution data on highland rocks from the four Apollo sites, 14, 15, 16 and 17, Tera *et al.* (1974) confirm that a major lunar cataclysm occurred at 3.9 to 4.0 billion years on the near side of the Moon.

In addition to other materials, ejecta of the Imbrium basin has most likely been sampled at all four Apollo sites. The ages of rocks from the Fra Mauro Formation (Apollo 14), a distinct ejecta unit of the Imbrium basin, cluster at 3.95 billion years (Tera *et al.*, 1973). It is, therefore, probable that the 3.9–4.0 billion year old cataclysm is either: (1) the formation of the Imbrium basin itself, or (2) the formation in quick succession (within 0.1 billion years) of the large nearside basins, i.e., Serenitatis Nectaris, Imbrium and possibly Orientale.

The majority of sampled mare basalts

show ages between 3.2 and 3.7 billion years. The distinction is very clear between at least two ages of mare basalts. One group clusters around 3.2 billion years, representing samples of Apollo 12 and 15 basalts. The second group gives ages around 3.7 billion years, representing basalts of Apollo 11 and 17. The Luna 16 basalts of Mare Fecunditatis are closer to the latter group, being about 3.5 billion years old. This quite convincingly correlates with the two major mare episodes discussed earlier that belonged to the Eratosthenian and the Imbrian systems. The Apollo 12 and 15 basalts are Eratosthenian in age (3.1 to 3.3 billion years old) and the Apollo 11 and 17 and Luna 16 basalts are Imbrian in age (3.5 to 3.7 billion years old).

In addition to rock ages, the times of formations of lunar craters have also been determined radiometrically (LSAPT, 1972). For example, the crater Copernicus on the south rim of Imbrium was formed about one billion years ago, if the noritic glass component of the Apollo 12 soil is correctly interpreted as Copernicus ray material. Cosmic-ray exposure ages of rocky debris from Cone crater, the dominant landmark at the 14 site, show that it was excavated about 25 million years ago. Similarly, in the four billion year old highland units, cosmic-ray exposure ages of rocks and boulders ejected from the craters in the Apollo 16 site (Fig. 6) show that North Ray crater was excavated 50 million years ago while South Ray crater occurred only 2 million years ago (LSAPT, 1973). The time of formation of Shorty crater in the Apollo 17 site, based on the exposure age of orange and black soil samples, was determined to be 20 to 30 million years ago (Eberhardt *et al.*, 1974).

Age sequences like these could be used to calibrate the relative age time scale already established among time-stratigraphic and

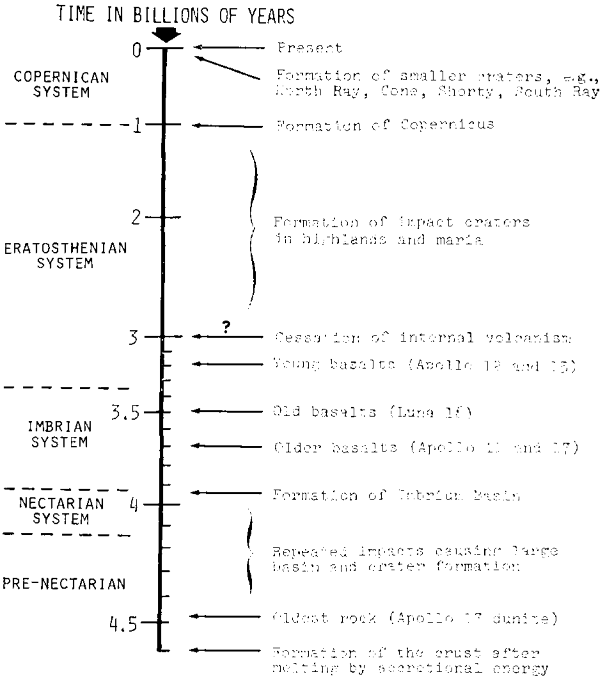

FIG. 13. Schematic illustration of the evolution of the lunar surface. The absolute time scale in billions of years as deduced from age and exposure date techniques is shown along the median line. On the right, major events and episodes of material emplacement are shown; on the left is the lunar-wide relative age scheme based mainly on superposition relationships of geologic units.

rock-stratigraphic units. An attempt is made here (Fig. 13) to correlate the relative age scheme derived mainly from stratigraphic relations and photogeologic interpretations with the absolute ages of returned rock and soil samples.

In a nutshell, the Moon is assumed to have formed 4.6 billion years ago; global planetary differentiation processes took place between 4.6 and 4.3 billion years ago. As the solid anorthositic crust was formed it kept a record of moonlets that struck it leaving numerous scars (pre-Nectarian time). The last of the impact basins were formed on the near side about 4.0 to 3.9 billion years ago (Imbrian System, starting about 3.95). Volcanic eruptions filled the basins and low lands with basalts from 3.7 to 3.2 billion years ago (Imbrian and Eratosthenian time). Postbasalt history included transport and mixing of the lunar materials, mostly by impact craters, that continues to the present day (Copernican System).

V. Layers of the Moon

A. The Outer Skin

Details of the broad-scale topographic relief of the lunar surface were provided by laser altimeter measurements made on Apollo missions 15 through 17. The altimeter measured precise altitudes of the orbiting Command Service Module above the lunar surface (Wollenhaupt and Sjogren, 1972). Measurements were made at points spaced every one to one-and-a-half lunar degrees, or every 30 to 45 km on the surface. The agreement between measurements on the three missions emphasizes the accuracy of the profiles.

Figure 14 is one example of an Apollo 15 profile where the measurements were made in a plane inclined at approximately 26° with respect to the lunar equator. Lunar elevations were computed relative to an assumed mean lunar radius of 1738 km. It is clear from Fig. 14 that the far side is over 4 km higher than the near side on the

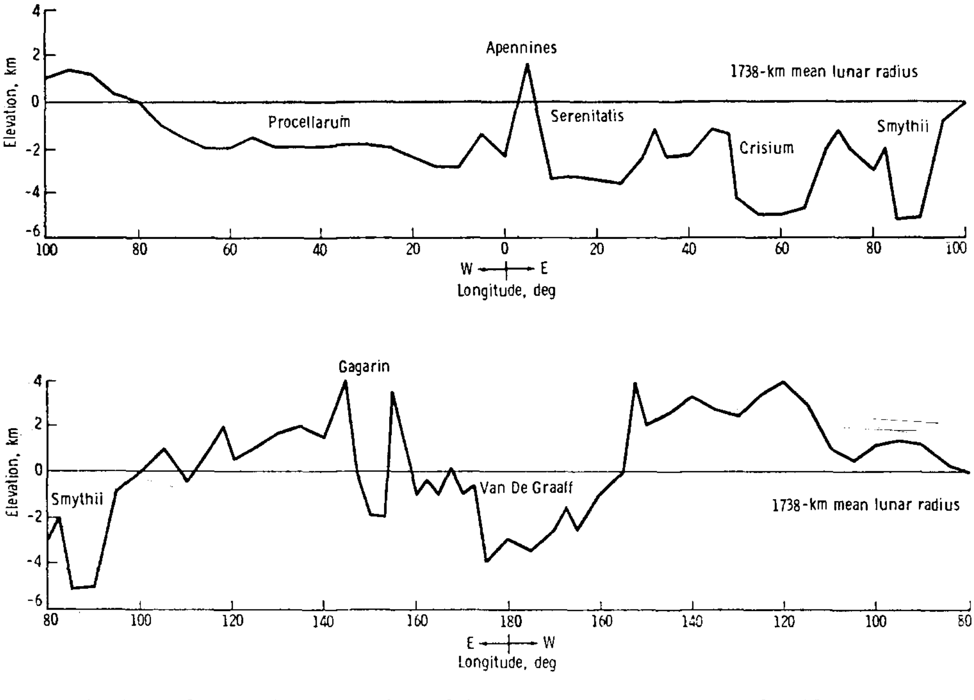

FIG. 14. Apollo 15 laser latimeter profiles of the lunar near side (top) and far side (bottom). Elevation data are computed relative to a sphere of 1738 km radius with respect to the lunar center of mass. (After Robertson and Kaula, 1972.)

average. Figure 14 (top) also shows the greatly depressed mare basins, on the near side, e.g., Smythii, Crisium, and Serenitatis.

Another method of generating elevation profiles of the lunar surface was provided by the lunar sounder (Phillips *et al.*, 1973). The sounder which was carried on Apollo 17 consists of a three-frequency coherent radar (5, 15 and 150 MHz). Continuous surface profiles were optically recorded and show excellent details of the outer skin of the Moon, e.g., Fig. 15.

Brown *et al.* (1974) have recently used the 5 MHz radar data to generate profiles with an estimated absolute accuracy of 130 m, and an estimated relative accuracy of 5 m over mare surfaces. The same authors compared the radar profiles with the Apollo 17 laser altimeter measurements. Although these two sets of data were not acquired simultaneously, they agree within 150 meters over mare surfaces. Brown *et al.* (1974) used a 1738 km sphere about the lunar center of mass and the center of figure, as well as a 1734 km sphere about what they termed "center of maria" (Fig. 16). To generate the latter, they used the mare surfaces of western Procellarum, Serenitatis and Crisium; they found that Mare Smythii falls within 40 meters of that circle.

This suggestion of a center of maria gives credence to the idea that lunar lavas rose only to a certain level, at least in large quantities. Examination of Fig. 16c shows that the northern floor of the large basin on the far side at about 180° is near the same mare level. This basin encloses the largest concentration of mare patches on the far side (Gornitz, 1974, and Stuart-Alexander, 1975). As mentioned previously, it also contains the highest γ-ray activity on the far side (Metzger *et al.*, 1973), and the strongest intrinsic magnetic field as measured by the subsatellite magnetometer of Apollo 15 (Russell *et al.*, 1973). Lunar magnetism, its cause and probable origins are discussed by Fuller (1974), and its relationship to the interior of the Moon by Dyal *et al.*, (1974).

From both the laser altimeter and radar sounder profiles, it is clear that the impacts that formed the multiringed circular basins resulted in an enormous loss of mass from

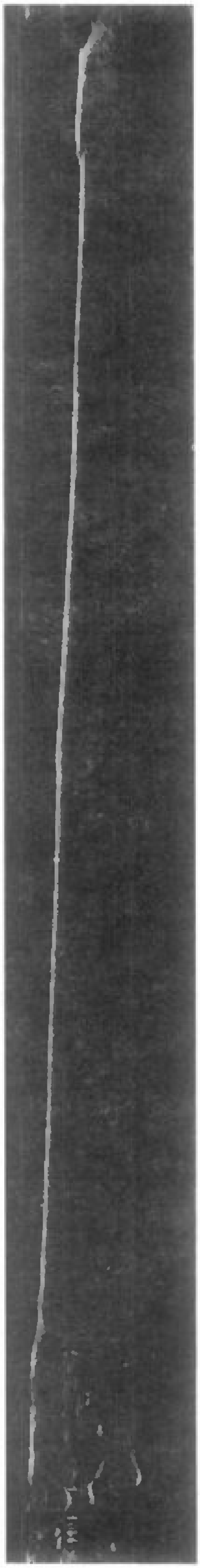

FIG. 15. Very high frequency radar image of Mare Crisium that was obtained by the Apollo 17 lunar sounder. This profile of a circular basin shows the mountain chains that form the basin rim as well as the benches that border it, which are covered by mare fill. The topographically low, inner part of the basin fill corresponds with the boundaries of the gravity anomaly of Crisium. The apparent eastward slope of the basin and its mare fill is not real. (Courtesy of H. S. Ward, University of Utah.)

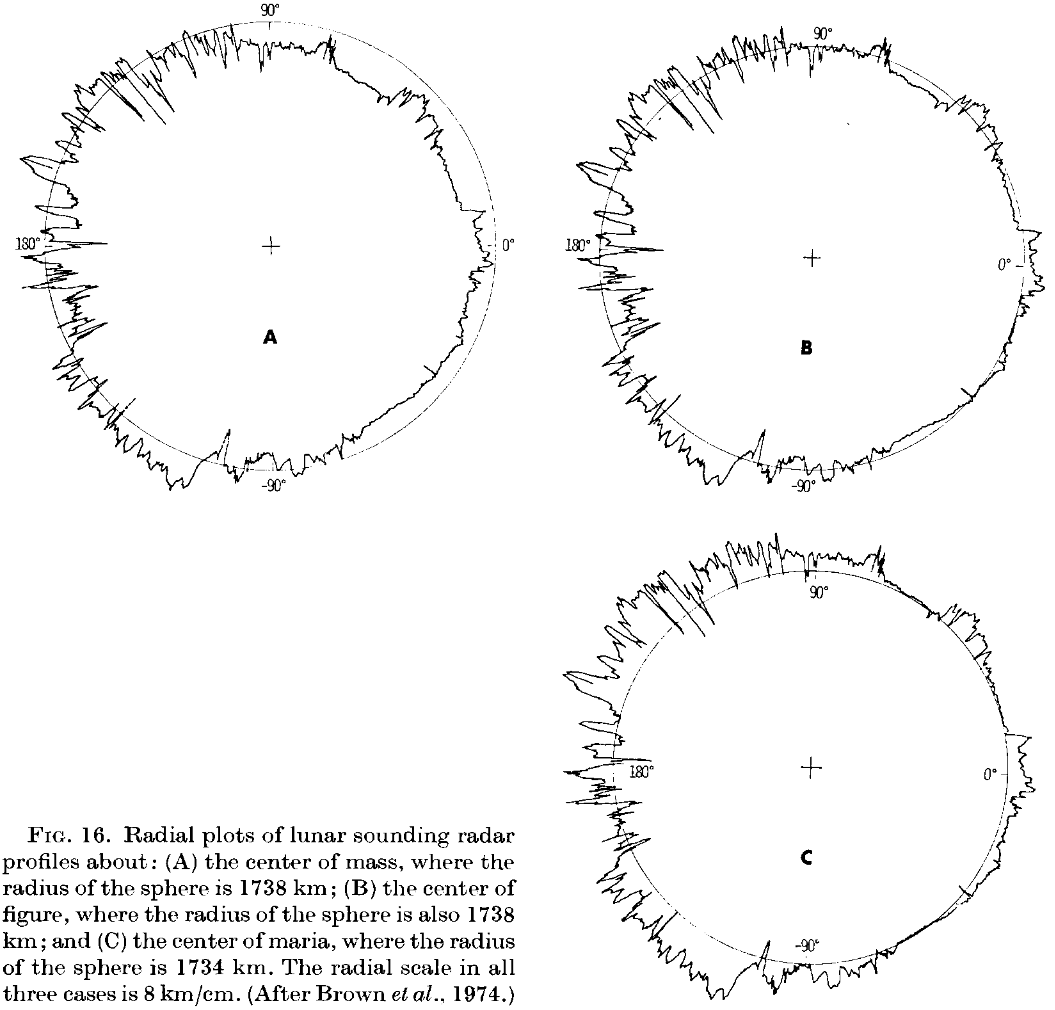

FIG. 16. Radial plots of lunar sounding radar profiles about: (A) the center of mass, where the radius of the sphere is 1738 km; (B) the center of figure, where the radius of the sphere is also 1738 km; and (C) the center of maria, where the radius of the sphere is 1734 km. The radial scale in all three cases is 8 km/cm. (After Brown *et al.*, 1974.)

the impact sites. These same basins, as discussed earlier, display large mascons. Some older basins were probably formed early enough to be essentially obliterated by intense cratering and volcanism (Stuart-Alexander and Howard, 1970). Others were formed by the impact of very large objects in a solid lunar crust which was underlain by an upper, partially plastic mantle. The partially plastic mantle may have allowed for an upward movement to isostatically compensate for the lost mass and its redistribution by the impact. At a later time, upward moving volcanic lavas used as channelways the fractures that were created by the impacts. The lavas erupted to the surface to fill the circular depressions, and also topographically low plains. The additional weight of tens-of-kilometers thick, dense basalts would, therefore, contribute to the positive gravity anomaly within the isostatically compensated circular impact basins (Wise and Yates, 1970; and Wood, 1970).

B. The Lunar Interior

With respect to the shallow lunar interior, it was realized from the first seismometer measurements of impacts on the lunar surface that the travel times are relatively low (Latham *et al.*, 1970). The observed travel times, and the relatively low seismic velocity in lunar near-surface rocks, are interpreted by Watkins (1971) to mean either, (1) that lunar near-surface rock consists of cold, particulate, unfused material accreted from space; or (2) that lunar near-surface rock has fused at some time during the evolution of the Moon, but subsequently has been brecciated and fractured to considerable depth by meteorite impact. Although Watkins favors the cold accretion model, the second model is favored by most investigators: first, there is ample photogeologic and petrographic evidence of an early melting, and second, there is evidence of repeated fracturing and brecciation of the lunar rock to a depth from a few km to 25 km by meteoroid bombardment (Latham *et al.*, 1972).

Our knowledge of the deep lunar interior consists of inferences based on (1) the geophysical data provided by the network of geophysical stations or observatories at the Apollo sites 12, 14, 15 and 16 (Fig. 1); and (2) the chemistry and mineralogy of the surface samples. Of special importance are the recordings of natural moonquakes by the seismometer network which allowed the determination of their origin time, epicenter, and focal depth. Also, seismic data, mainly from man-made impacts, revealed a major discontinuity at a depth of between 55 and 70 km in eastern Oceanus Procellarum (Latham *et al.*, 1971). Additional data were obtained from a large meteoroid impact that occurred on the far side of the Moon on 17 July 1972, where direct shear-wave arrivals were not observed at some of the Apollo seismic stations. This led to the conclusion by Nakamura *et al.* (1973) that the material in the lunar interior at a depth of 1000 to 1100 km may be in a partially molten state.

From these data and an analogy with the Earth's interior, I previously summarized a model of the lunar interior (El-Baz, 1974) where the successive layers from top downward are as follows (Fig. 17).

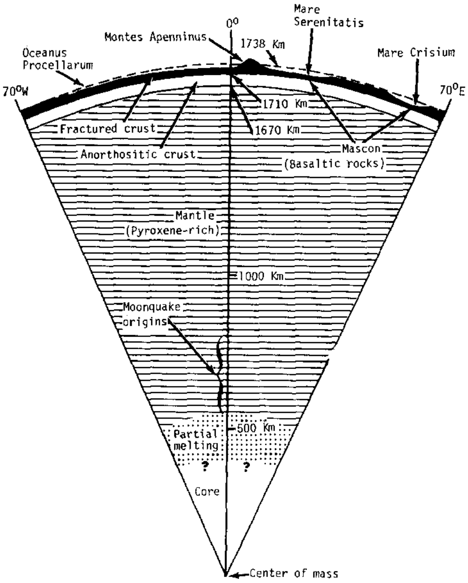

FIG. 17. Inferred cross-section of the lunar interior. It shows a crust 65 km thick, with a highly fractured upper 25 km; a mantle 1100 km thick; and a core that is either partially molten or includes a molten zone. This cross section represents a segment of the Moon drawn to scale from a sphere 1738 km in radius from the center of mass. Surface features correspond roughly to part of the near side topography shown in Fig. 14 (top).

1. Crust: a layer enriched in aluminum and calcium (anorthositic gabbros), approximately 60 km thick in the region of the Apollo seismic network, as compared to the 5 to 35 km thick crust on Earth. In this layer there are local mass concentrations of iron-rich rocks, and a rapid increase of velocity down from the surface due to pressure effects on dry rocks. There is also a minor discontinuity at a depth of about 25 km which may be related to intensive fracturing of the upper crust and/or to petrological differences. The seismic velocity is nearly constant (6.8 km $\sec^{-1}$) between 25 and 65 km (Toksöz *et al.*, 1972).

2. Mantle: at the major dicontinuity at about 65 km depth, there is a large increase in the velocity to about 9.0 km $\sec^{-1}$. This interface is comparable to the rise of velocity at the Mohorovičić discontinuity on Earth (Toksöz *et al.*, 1972). This layer appears to continue to the depth of 1100 km. Compositions of the surface rocks, the measured seismic velocities, and constraints imposed by the Moon's mean density and moments of inertia support a pyroxene-rich composition for the lunar mantle.

3. Core: the moment of inertia and the overall density of the Moon place an upper limit of about 500 km on the radius of the lunar core, if a core exists (Toksöz *et al.*, 1974). A molten or partially molten silicate zone or core below about 1100 km from the surface (Nakamura *et al.*, 1973) may be responsible for deep-seated moonquakes, which are focused between 800 and 1100 km deep. The data however, do not rule out the possibility of a small, 400 km radius, iron-rich (Fe–FeS?) core (Solomon and Toksöz, 1973).

VI. QUESTIONS OF ORIGIN

There are three basic theories of origin of the Moon. She is either Earth's wife, captured from some other orbit; daughter, fissioned directly from "proto" Earth; or sister, accreted from the same binary system.

Before Apollo, it was widely believed that the lunar exploration missions would provide the necessary information for a final answer to the question of origin. This did not happen. As discussed above, the primitive lunar crustal materials have been subjected to much metamorphism, due to large impacts.

Thus, the three basic theories of lunar origin (Fig. 18) are still competing, especially since all three have been modified to accommodate the new findings. Each theory has its share of positive points as well as shortcomings, and these vary depending on whose paper one reads. However, as discussed by Wood (1974b), one of the most important constraints on the theories of origin is the chemical makeup of the Moon. Any theory will have to account for the lower metal and volatile content, and the higher refractory element content in the lunar rocks, as compared to the compositions of terrestrial rocks and meteorites.

A. Capture

The basic attractiveness of the capture theory is the assumption that the Moon was formed somewhere else in the solar system, therefore, one does not have to explain chemical differences between the Earth and Moon.

In this theory the Moon is envisioned as a body that was captured from an orbit about the Sun to one around the Earth. As discussed by Wood (1974b) some authors believe that the Moon was captured intact; others suggest that in the capturing process, disruption and reaccumulation occurred. Proponents of this theory have looked for ways to decelerate the approaching Moon to allow capture by the Earth. This may be staged by tidal interaction between the two bodies, or by collisions between the approaching Moon with smaller objects circling the Earth (Kaula and Harris, 1973).

Other ways were sought for selective capture of small bodies into geocentric orbits without resorting to tidal or collisional deceleration (Öpik, 1972; Wood and Mitler, 1974). According to the latter, silicate-rich material can be captured and metal-rich bodies rejected into the heliocentric orbits. However, Wood (1974b) states that the process, being inefficient, would not result in complete rejection of metal-rich fragments.

B. Fission

The idea that the Moon came directly from the Earth was first proposed by Sir George Darwin in 1880. The theory is still viable and in recent years has been supported by Wise (1963 and 1969) and O'Keefe (1970).

The present concept of the fission theory starts with a fluid body rotating around the Sun. As heavier components settle at the core and lighter ones float on top, the spin is increased to cause rotational instability. The latter causes elongation of the body perpendicular to the spin axis, until creation of two separate bodies is achieved.

This theory accounts for the chemical differences between the two bodies. Fission would have occurred after the formation of a core in the part of the body that formed the Earth. The Moon-forming part of the body would then be depleted in metals. Binder (1974) believes that sampled lunar rock types could be made of materials that

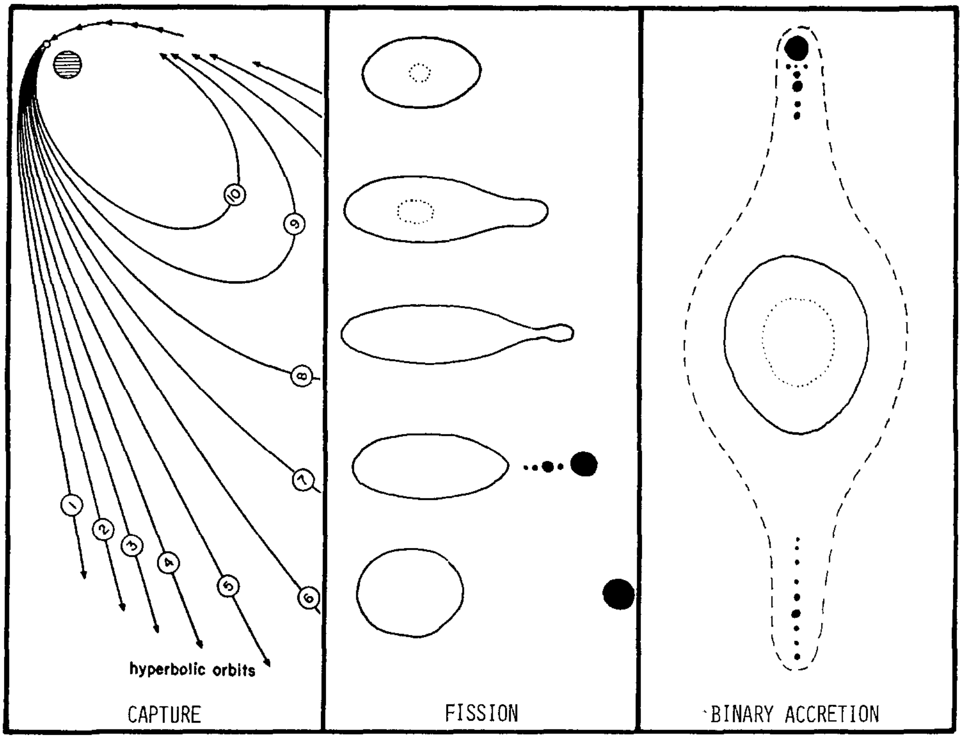

FIG. 18. Schematic illustrations of the three theories of lunar origin: (a) *capture*: selective capture by the Earth of bodies that accreted to form the Moon; fragments in orbits 1 to 5 are lost in hyperbolic orbits; those in orbits 6 to 10 are captured in elliptical orbits (from Wood and Mitler, 1974); (*b*) *fission* of the Moon from "mother" Earth as it was spun to instability during core formation (after Wise, 1963); and (c) *binary accretion* of both the Earth and Moon from the solar nebula. The Earth was formed first, and heavy metals settled to form a core. Lighter fragments in geocentric orbits accreted by collision to form the Moon (adapted from Ringwood, 1972).

are chemically equivalent to those of Earth's mantle.

Ringwood (1970) added a new dimension to the fission theory by proposing that the temperature of the accreting Earth could have been high enough to form a thick, hot atmosphere of metal and oxide vapors. These vapors could have been spun out of the equator to form the Moon as accretion proceeds in Earth orbit.

Whether fission occurred from a solid body or by escape of hot gases, it appears that the major objection to the theory is the excessive amount of angular momentum required for the process (Wood, 1974b).

C. Binary Accretion

This theory envisages both the Earth and Moon accreting together from the solar nebula along with the terrestrial planets. In this context, Wood (1974b) discussed the differences between what he termed the American and Russian schools of thought. The first (championed by Cameron, 1973) pictures a massive solar system nebula in which rapid accretion of the terrestrial planets causes extensive heating and melting. On the other hand, the Russian school (established by Schmidt, 1958) views the planets as accretionary products of slowly accumulating planetismals from a small solar nebula (Wood, 1974b). The global chemistry of the Moon indicates probable melting of at least the outer 100 km. Therefore, it seems logical to consider a rapid accretionary process to have caused such melting as the Moon formed.

In simple terms, one can envision a rapidly rotating accretionary system with a dense proto-Earth and a swarm of planetismals, dust and gases in geocentric orbits. Mutual collisions among the members of the swarm tended to round up their orbits and bring them into a common plane. From these colliding planetismals, a moonlet was formed. The moonlet swept the circum-terrestrial orbit by attracting more and more planetismals. The accretionary energy would have resulted in melting of the uppermost layers. Also, in the process much of the volatile elements would have been lost from the growing moonlet. This view of the binary accretion theory shares some aspects with the precipitation theory of Ringwood (1970 and 1972).

This theory requires the least number of assumptions. It also accounts for all the chemical differences between the Earth and Moon. For these reasons, it has been the most widely accepted theory among lunar scientists in recent years.

VII. Future Outlook

In the past decade, our knowledge of the Moon has evolved through the findings of Ranger, Surveyor, Lunar Orbiter, Luna and Apollo missions. However, six manned Apollo lunar exploration missions provided the most tangible of data. Our understanding of the Moon grew systematically and chronologically from the rich harvest of rocks and soil as well as remotely sensed information gathered by Apollo.

To me, the most important findings from Apollo lunar exploration are the following.

1. The lunar samples indicate that the Moon does not now, nor did it ever, host any water or life forms of any kind.
2. The Moon is made up of the same chemical elements as is the Earth, but in varying proportions. The lunar rocks are enriched in refractory elements and depleted in volatile elements.
3. The Moon is a differentiated body: extensive melting may have occurred in the upper layers of the Moon, to about 100 km depth, at the time of accretion. As the hot magma cooled, light plagioclase crystals floated to form the low-density crust leaving denser materials below.
4. The low-density highland rocks are exposed everywhere on the lunar crust except where covered by denser basalts. These are the products of internally generated volcanic melts which spread on the surface during a period of 600 million years (between 3.7 and 3.2 billion years ago).
5. There are many indications of the shaping of the Moon by large impacts, basin and crater formation being the major sculpting mechanism on the Moon. Shock effects on the rocks attest to the violent impact history. Although the bombardment is now continuing, the size and frequency of impacting projectiles were much larger in the early history of the Moon.
6. As confirmed by the orbiting geochemical experiments, samples collected at the landing sites most probably represent the whole Moon.
7. The figure of the Moon shows pronounced asymmetry; the far side is higher, and the near side is lower, relative to a mean lunar radius of 1738 km. Also, the center of mass is shifted about 2 km towards the Earth relative to the center of the figure.
8. There is lateral asymmetry in natural γ-ray radiation on the Moon. Pockets of radioactive materials are concentrated in the western near side; only a small anomaly in the vicinity of the crater Van de Graaff exists on the lunar far side.
9. The moon is probably layered into a crust, about 65 km on the near side and probably thicker on the far side; a solid mantle, about 1100 km thick; and a silicate core, about 500 km thick, that is in part molten or contains a partially molten zone.
10. The data so far collected do not provide enough proof for final conclusions regarding the origin of the Moon.

Only two years have passed since the last Apollo mission, and only about 10% of the lunar rocks and soil have been studied and analyzed in great detail. Much of the data obtained by sensors from lunar orbit is yet to be processed to fully extract all its meanings. It will perhaps take two years to process all of these data adequately, and two additional years for thorough interpretations and correlations. Geophysical data from five ALSEP stations on the Moon continue to yield new results about the lunar interior and the lunar environment. All of these stations are operating well and could continue to do so for several more years. Only then could concrete conclusions be drawn concerning the ultimate results of Apollo lunar exploration.

After four more years have passed, we may be fortunate enough to take another look at the Moon. The National Aeronautics and Space Administration (NASA) is now considering the possibility of a mission to the Moon. This would be an unmanned Lunar Polar Orbit mission, or LPO. This indeed appears to be perfect timing; by then, much of the Apollo information would have been assimilated and synthesized, at least to a first order synthesis.

To voice my opinion, some of the things that need yet to be done relate to three general fields: photogeology, geochemistry, and geophysics.

Contrary to widespread belief, the surface of the Moon has not yet been adequately photographed. Although Lunar Orbiter IV covered nearly all the near side of the Moon, this photography can neither be used for measurements nor is it stereo photography. We only have stereometric coverage of about 20% of an equatorial area of the Moon at 30 m resolution. Much is yet to be known and learned about the lunar surface features and their mode of formation. One of the most important localities to our understanding of large impact processes and the transport of materials on the lunar surface is that of the Orientale basin. The Orientale basin is not covered by stereographic photographs. Models of the Moon and of the transport of ejecta on the surface have all referred to Orientale because of its freshness as the type of locality to be studied. However, we lack the proper tools for the necessary studies. Stereographic photographs aided by laser altimetry are essential in measurements of the multiple rings of the Orientale basin and its ejecta blanket.

From the geochemical point of view, there is still much information to be gained about the Moon. Most important among these are the lunarwide natural gamma radiation fields. The γ-ray experiment has already shown that there is asymmetry in natural gamma radiation. The source and the distribution of this radiation will not be fully understood unless we have data covering almost the entire Moon. In addition to this, we also need to know more about the global chemistry of the Moon, both concerning the distribution of elements like aluminum, calcium, iron and magnesium in the highlands and in the maria, and also concerning the distribution of titanium in the maria. Chemical mapping of the maria should extend to the lunar far side, perhaps utilizing both X-ray and multispectral equipment.

From the geophysical point of view, two types of information appear to be most required. First is the definition of an equipotential gravitational surface on the Moon. For this, one needs to understand and measure gravitational anomalies or mascons on the lunar far side. Second is the measurements of the figure of the Moon including details of the figure at higher latitudes, including the polar regions.

It is hoped that the LPO mission will provide such information so that a comprehensive view of the Moon could be gained. If we are to apply the knowledge gained from lunar exploration to planetary exploration, that knowledge should be complete or near complete, so that when correlations are made they would be drawn from clear positions of strength. This is especially relevant since we know from the Mariner 9 data of Mars and the Mariner 10 data of Mercury, that the processes that acted on the Moon have also been responsible for many features of both planets.

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