Scientific Exploration of the Moon

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The exploration of the Moon has involved a highly successful interdisciplinary approach to solving a number of scientific problems. It has required the interactions of astronomers to classify surface features; cartographers to map interesting areas; geologists to unravel the history of the lunar crust; geochemists to decipher its chemical makeup; geophysicists to establish its structure; physicists to study the environment; and mathematicians to work with engineers on optimizing the delivery to and from the Moon of exploration tools. Although, to date, the harvest of lunar science has not answered all the questions posed, it has already given us a much better understanding of the Moon and its history. Additionally, the lessons learned from this endeavor have been applied successfully to planetary missions. The scientific exploration of the Moon has not ended; it continues to this day and plans are being formulated for future lunar missions.

The exploration of the Moon undoubtedly started with the naked eye at the dawn of history,[1] when mankind hunted in the wilderness and settled the earliest farms. Our knowledge of the Moon took a quantum jump when Galileo Galilei trained his telescope toward it. Since then, generations of researchers have followed suit utilizing successively more complex instruments.[2] The most significant quantum jump in the knowledge of our only natural satellite came with the advent of the space age,[3] when the Moon became the object of one of the most intensive scientific research programs of all time.

To plan exploration of the Moon from spacecraft, the United States[4] and the Soviet Union[5] called upon specialists from numerous disciplines. The process of determining the best scientific objectives of a given mission was conducted in three stages: First, specialists in the same field gathered to discuss the best ways and means of acquiring answers to questions related to their own discipline. Second, scientists representing the various disciplines met to bargain with each other as to the relative importance of their requirements. Third, the overall scientific requirements had to be reconciled with mission capabilities through discussions with engineers. This interdisciplinary approach was the best means of assuring a thorough investigation of our nearest neighbor in the sky.

CONTACT WITH THE MOON

Forty-six successful missions, that is missions that have returned scientific data, have been flown near to or landed on the Moon since the flight of the Soviet Luna 1 in January 1959. During the same year, Luna 2 made the first hard impact on the Moon, and Luna 3 provided the first glimpse of the lunar far side. After these significant steps, the American space program began its contribution to lunar exploration with the Ranger 'hard landers' from 1964 to 1965. These missions provided us with the first close-up views (nearly 0.3 m resolution) of the lunar surface by transmitting pictures until just before crashing.[6] The pictures confirmed that the lunar dark areas, the maria, were relatively flat and topographically simple.

Much information was provided by the success of Surveyors 1, 3, 5, 6 and 7 (1966–1968). After touchdown on the Moon, these 'soft landers' took photographs, studied the environment, and analyzed the chemistry of the soil.[7] Another very successful series of spacecraft, the five Lunar Orbiters (1966–1967), provided high resolution images of the landing sites selected for the first manned landings, and moderate resolution photographs of nearly the entire Moon.[8] Scientists studying disturbances of the polar orbits of Lunar Orbiters 4 and 5 discovered gravity anomalies or mascons in the nearside maria.[9]

The manned Apollo landing missions constituted the most significant phase of lunar exploration (1969–1972). Apollo 11 provided us with the first samples, apart from meteorites, from another body in the solar system. From mission to mission, payload capability, lunar stay-time, and astronaut operational radius increased bringing the interdisciplinary approach to its highest level on Apollo 17. During the Apollo era, the unmanned Soviet Luna 16 and 20 also returned samples from the Moon; Lunokhod 1 and 2 roved on the surface and sent back close-up views; and Zond spacecraft transmitted orbital images. After the conclusion of the Apollo program, the Soviet Luna missions continued, and Luna 24 returned the last samples from the Moon. As of this writing, the two countries engaged in lunar exploration have each sent 23

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Table 1. Successful Moon Probes

	Spacecraft	Launch date	Remarks
1.	Luna 1	2 January 1959	Flyby, within 6000 km of the Moon
2.	Luna 2	12 September 1959	First probe to impact on the Moon
3.	Luna 3	4 October 1959	First probe to photograph the far side
4.	Ranger 7	28 July 1964	Impacted after taking lunar surface photographs
5.	Ranger 8	17 February 1965	Impacted after transmitting close-up photographs
6.	Ranger 9	21 March 1965	Impacted in Alphonsus crater; returned pictures
7.	Zond 3	18 July 1965	Transmitted pictures of lunar far side
8.	Luna 9	31 January 1966	First successful landing by USSR; returned pictures
9.	Luna 10	31 March 1966	Achieved lunar orbit; made physical measurements
10.	Surveyor 1	30 May 1966	Soft landing; transmitted pictures of lunar surface
11.	Lunar Orbiter 1	10 August 1966	Equatorial orbit; photographic mission
12.	Luna 11	24 August 1966	Achieved lunar orbit; transmitted data
13.	Luna 12	22 October 1966	Achieved lunar orbit; transmitted pictures
14.	Lunar Orbiter 2	6 November 1966	Equatorial orbit; photographic mission
15.	Luna 13	21 December 1966	Soft landing; transmitted soil density data
16.	Lunar Orbiter 3	4 February 1967	Equatorial orbit; photographic mission
17.	Surveyor 3	17 April 1967	Soft landing; transmitted pictures and soil data
18.	Lunar Orbiter 4	4 May 1967	Polar orbit; photographed all of near side
19.	Explorer 35	19 July 1967	Measured Earth's magnetic tail in lunar orbit
20.	Lunar Orbiter 5	1 August 1967	Polar orbit; photographic mission
21.	Surveyor 5	8 September 1967	Soft landing; transmitted pictures and chemical data
22.	Surveyor 6	7 November 1967	Soft landing; transmitted pictures and soil data
23.	Surveyor 7	7 January 1968	Soft landing; transmitted pictures and chemical data
24.	Luna 14	7 April 1968	In lunar orbit
25.	Zond 5	15 September 1968	First circumlunar mission with spacecraft recovery
26.	Zond 6	10 November 1968	Unmanned circumlunar mission
27.	Apollo 8	21 December 1968	First manned circumlunar flight
28.	Apollo 10	18 May 1969	Second manned circumlunar flight
29.	Luna 15	13 July 1969	Orbital mission
30.	Apollo 11	16 July 1969	First manned landing and sample return
31.	Zond 7	8 August 1969	Unmanned circumlunar flight
32.	Apollo 12	14 November 1969	Second manned landing and sample return
33.	Luna 16	12 September 1970	Unmanned mission; returned soil samples
34.	Zond 8	20 September 1970	Unmanned circumlunar flight
35.	Luna 17	10 November 1970	Unmanned lander with automated roving vehicle
36.	Apollo 14	31 January 1971	Third manned landing and sample return
37.	Apollo 15	26 July 1971	Fourth manned landing and sample return
38.	Luna 18	2 September 1971	Orbital mission
39.	Luna 19	28 September 1971	Orbital photographic mission
40.	Luna 20	14 February 1972	Soft landing; returned soil samples
41.	Apollo 16	16 April 1972	Fifth manned landing and sample return
42.	Apollo 17	7 December 1972	Sixth manned landing and sample return
43.	Explorer 49	10 June 1973	Radio and magnetic data from lunar far side
44.	Luna 21	8 January 1973	Soft landing; automated roving vehicle
45.	Luna 22	29 May 1974	Lunar orbital mission
46.	Luna 24	9 August 1976	Soft landing; returned soil core sample

successful missions to the Moon and its vicinity (Table 1).

The lunar scientific data[10] indicate that the Moon is a well preserved museum of ancient impact physiography. Some 4.6 thousand million years ago, when the solar nebula condensed, part of its material gathered to form the Moon. As the moonlet grew in size, its upper 100–300 km was melted by accretionary energy. Denser fractions settled downward, and lighter material floated to form the crust. Leftover bodies struck the light colored solid crust, now represented by the lunar highlands, leav-

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ing giant basins. The last basins to form make the basic features of 'The Man in the Moon'. The youngest of these basins was formed about 3.9 thousand million years ago. A volcanic episode followed and basaltic lavas flooded the giant impact scars and nearby lowlands, and thus formed the dark colored maria. Volcanism lasted from approximately 3.8 to about 3.1 thousand million years ago. Since that time, the Moon's face has been changed only slightly by increasingly smaller impact events.[11]

The harvest of Apollo science did not answer all the questions regarding the Moon. Three theories of lunar origin are still competing for first place: The Moon is either Earth's wife, captured from some other orbit; or daughter, fissioned directly from a proto-Earth; or sister, accreted from the same binary system. Additional interdisciplinary data synthesis and correlation will lead to a greater maturity of lunar science.[12]

A proposed lunar polar orbit mission in the 1980s would permit a new global look at the Moon through the sensors of a sophisticated unmanned probe. Such an unmanned orbiter is viewed as a precursor of a family of spacecraft that will be designed for future exploration of all the terrestrial planets of the solar system.

THE FIRST EXPLORERS

Mankind has always been fascinated by the Moon, and with the growth of technology it has become the object of intense study and investigation. Early humans used the Moon's motion and apparent changes in shape as a timekeeper. The waxing and waning of the Moon and its full cycle from a thin crescent to a disc and again to a crescent were used to develop an astonishingly accurate calendar to record past events and to plan for the future. Since the dawn of history, the Moon has played a significant role in planting and harvesting crops.

The shape of the dark spots on the lunar disc also provided fertile ground for the imagination of mankind. To Europeans, these spots identified 'The Man in the Moon'. To the people of the Orient the spots appeared in the shape of a rabbit or a banyan tree. However, these figures remained hazy and possessed irregular boundaries until it was possible to see the Moon's surface with a resolution beyond the abilities of the naked eye.

The oldest surviving document of the first attempt to map and name lunar surface features is a map prepared by William Gilbert (1540–1603). This great English physician and physicist who published the classical treatise *De Magnete* in 1600, drew his map of the Moon from naked eye observations, and named some of its features. However, he identified the predominant bright regions on the Moon as seas and the dark regions as continents. Possibly, he thought that seas predominated on the Moon as they did on the Earth.[13] This view was the opposite of that held by all the investigators that followed him.

When Galileo Galilei (1564–1642) looked at the Moon with a telescope, a new era had begun. From that moment on, it was possible to characterize the Moon as an irregular body with small spots or cavities and protruding eminences, which he described in *Sidereus Nuncius*, 'The Starry Messenger', published in 1610. Galileo was able to recognize that the areas that form the features of 'The Man in the Moon' are smoother than their surroundings. Suggesting that these dark areas were like Earth's oceans, he called them *maria* (the plural of mare, the Latin name for sea). The surrounding highlands or uplands he called *terrae*, the plural of terra, the Latin name for land.

Galileo had planted the seeds of generations of lunar mapping and nomenclature.[14] Since his time, numerous maps of the Moon have been made with varying degrees of detail and accuracy (Fig. 1). The naming of lunar features became an important part of the process of mapping, and three distinct systems were introduced by Langrenus (1645), Hevelius (1647) and Riccioli (1651). Langrenus used mainly the names of scientists and members of royalty and nobility. Hevelius correlated the Moon's features to the map of the then known parts of the world. Riccioli restricted the names to astronomers, philosophers and other scientists whose names were associated with the Moon.[15]

During the 18th century, Johann Schröter (1745–1816) charted the lunar surface in more detail than before, and added 70 new names and subsidiary letter designations. W. Beer and J. H. Mädler followed with a map in 1834, which is the basis of lunar nomenclature to this day. In 1921, the newly formed International Astronomical Union (IAU) undertook the task of standardizing the naming of lunar features. The resulting map and catalog by Blagg and Müller was completed in 1935, and a later more complete catalog was published by the Lunar and Planetary Laboratory of the University of Arizona in 1966.[15] The practice of mapping the Moon in ever increasing detail, and therefore adding new names, continues to this day under the auspices of the IAU.[16]

THE TOOLS OF EXPLORATION

Scientific investigation of the Moon has taken many forms and employed various tools. The development of these tools relied both on the ingenuity of the researchers and on the knowledge gained from the results of previous successes and failures. For these reasons the tools that were used in the exploration of the Moon reached higher and higher degrees of sophistication, culminating in the Apollo manned missions (Fig. 2).

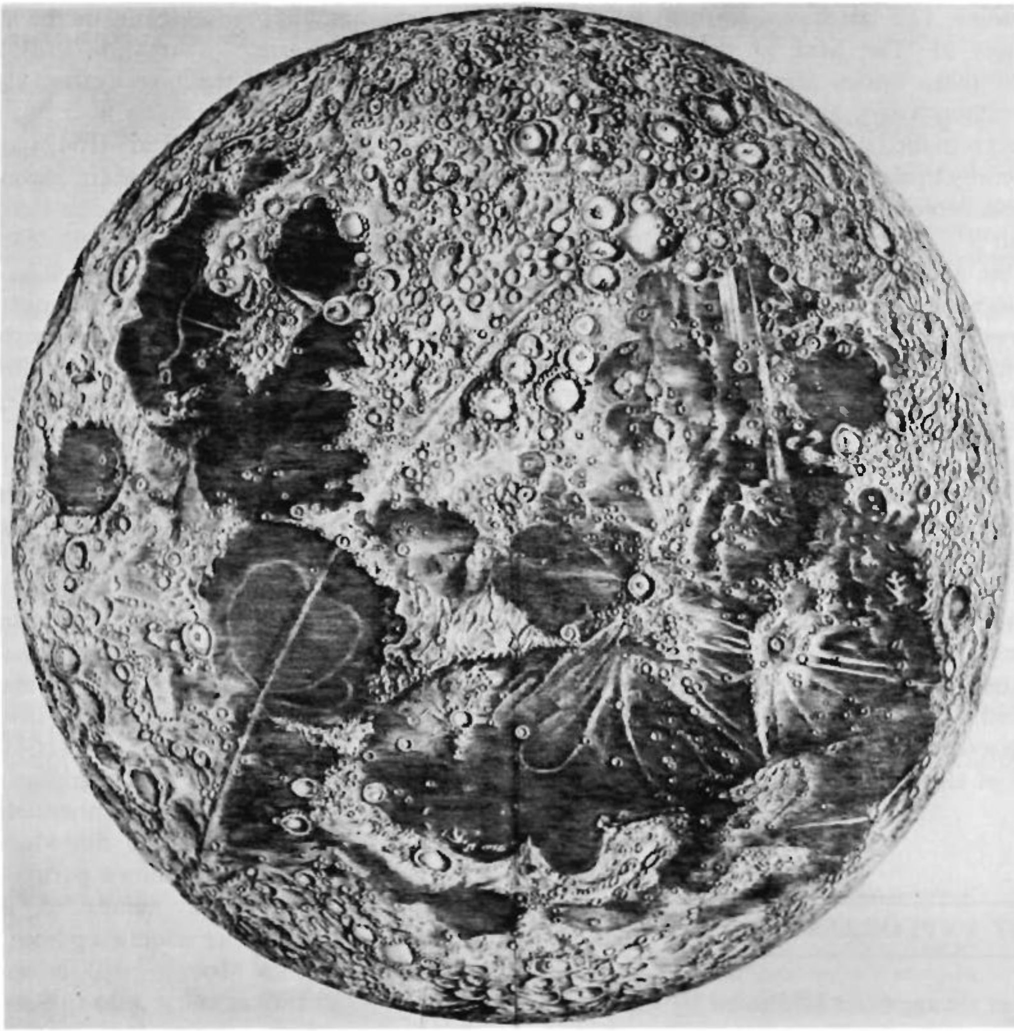


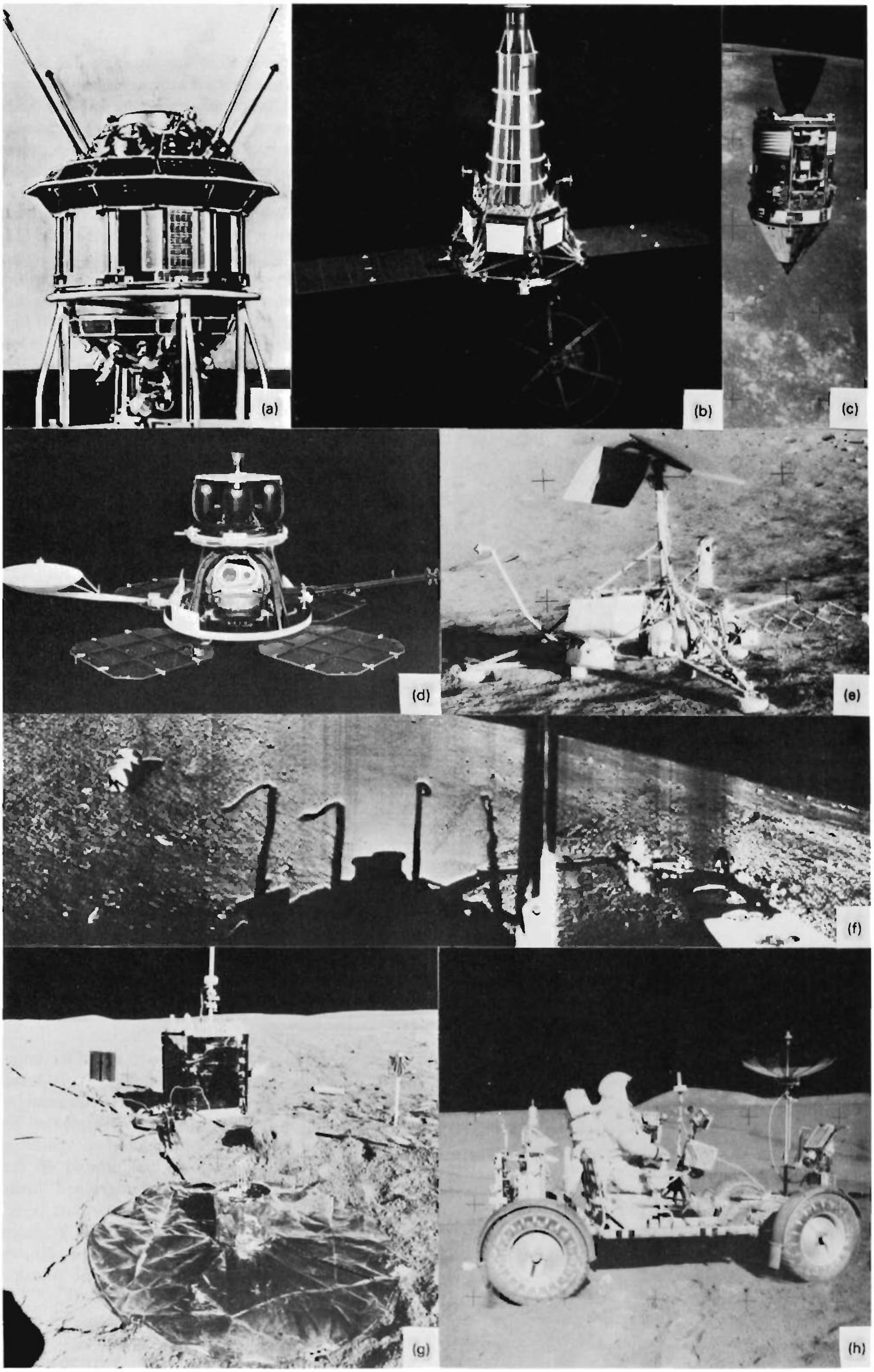
Figure 1. Map of the lunar near side by Giovanni Cassini (1625–1712), the Italian astronomer who was invited by Louis XIV to become the first director of Paris Observatory, where he studied and charted the Moon. It was engraved in 1680 by Claude Mellan (1598–1688) one of the great early craftsman of this technique. Only five of the originals have survived, making it the rarest of the early Moon maps, treasured both for its artistic beauty and astronomical accuracy.

Earth-based Remote Sensing

The building of telescopes shifted lunar observations from studies of its appearance and motions to investigations of the nature of its surface features. Telescopic observations produced an excellent library of photographs of the Moon's near side. Also, photometric studies of the lunar surface albedo showed that reflectance values vary from as low as 6% for the darkest areas to up to 22% for the brightest terrae.[17]

In addition to optical telescopes other instruments helped in the lunar investigations. For example, a spectrograph could be used to separate reflected sunlight into various wavelengths and to record the resulting spectra. The latter helped identify certain chemical elements that are abundant in the lunar surface material. Also multi-spectral imaging provided hints of the chemical composition of the Moon.[18] Additionally, radar astronomy was born in 1946 when radio signals were sent from the Earth, and bounced off the lunar surface. The radar investigations helped determine relative roughness of the lunar surface units[19] and, together with thermal infrared data,[20] were used to select landing sites for spacecraft.

Figure 2. Examples of the tools used to explore the Moon: (a) Luna 3 spacecraft, which provided the first photographs of the Moon's far side; (b) Ranger 7,.which photographed the Moon prior to crashing; (c) Apollo command module that gathered data from lunar orbit as astronauts explored the surface; (d) Lunar Orbiter, the spacecraft that provided nearly full photographic coverage of the Moon; (e) Surveyor 3 as photographed by the Apollo 12 astronauts who revisited its landing site; (f) Panorama of the lunar surface as seen by the Luna 13 spacecraft; (g) The package of scientific instruments deployed on the Moon by the Apollo 16 astronauts to monitor moonquakes and other geophysical and environmental parameters; (h) A lunar rover, which allowed the astronauts to extend their exploration area. (Photographs courtesy of NASA.)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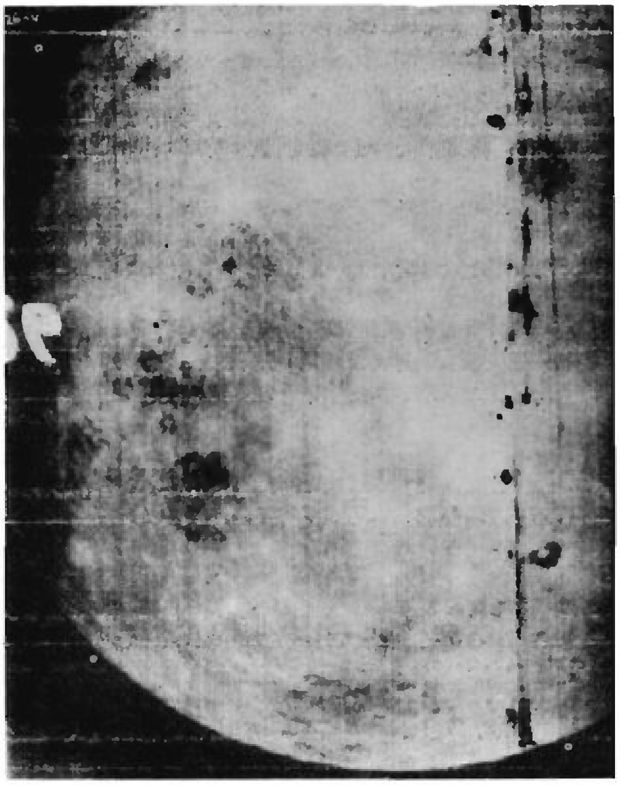

Figure 3. One of the historic photographs of the far side of the Moon taken by Luna 3. (Photograph 6 in *Atlas of Far Side of the Moon*, Nauka Press, Moscow (1959).)

Today, even with the largest telescope on Earth, it is impossible to distinguish features on the Moon with dimensions less than 500 m. The immense distance between the Earth and the Moon has hampered detailed investigations, even when telescopes are flown on airplanes at altitudes of 12 km to make observations in infrared wavelengths unhindered by atmospheric absorption.

Unmanned Spacecraft

To get closer to the Moon, both the Soviet Union and the United States sent remote sensing instruments on board several types of spacecraft (Fig. 2). First among these were the lunar 'flyby' missions which were the least expensive. Because such spacecraft spent less than a few hours near the Moon and observed only a small area, the amount of information these missions sent back to Earth was limited. Still, it was richer in detail than Earth-bound data and increased our knowledge manyfold. For example, the Luna 3 photograph of the Moon's far side shows it to be very different from the familiar Earth-facing hemisphere as the dark maria are very rare on the far side (Fig. 3).

Another type of a relatively simple mission was the one in which the probe headed on a collision course with the Moon. In the last part of its 500 000 km voyage, before impacting the lunar surface, the probe transmitted images before meeting its violent fate. These missions were labeled hard landers as opposed to soft landers, which slowly descended to the surface and started investigating it from a close-up vantage point. Sophisticated soft landers had wheels to increase the area of operation. More highly sophisticated soft landers had the capability of return to the Earth after collecting a lunar sample. The latter mode of sample collection was employed by the Soviet Union in its vigorous lunar exploration program until 1976, when the last spacecraft sampled the Moon.

When we consider the knowledge of the lunar surface features, the most important of all missions were the orbital photographic ones. Simpler missions traveled around the Moon once and then returned to Earth, thus called 'circumlunar'. The more sophisticated missions remained in orbit around the Moon for a long time. Naturally, the closer the craft came to the poles, the more its orbital coverage. Significant findings of specific US and USSR unmanned lunar exploration programs[21] are given below.

Ranger Project. The remarkable successes of the Mercury, Gemini and Apollo programs make it easy to forget that the US space effort has not always run so smoothly. Project Ranger is a good example.[6] The first six Rangers all malfunctioned in some aspect of their mission. However, the ultimate goal of the project, which was to photograph the Moon at resolutions vastly better than those obtained by Earth-based telescopic observations, was achieved on Rangers 7, 8 and 9 (Table 1).

These Rangers were hard landers that were built to take and transmit thousands of close-up photographs shortly before lunar impact – Ranger 7 provided 4300 frames in about 17 minutes. They carried six cameras: four narrow-angle 'P' cameras providing only partial coverage, and two wide-angle 'F' cameras giving full coverage. The signals were transmitted to the tracking station at Goldstone, California, where they were recorded on film and magnetic tape. The best resolution achieved in these photographs was 0.3 m in the last frames from Ranger 9.

The Ranger photographs showed a surface inundated with craters caused by meteoroid impacts. Scientists were able to distinguish between primary craters and secondary craters that were created by the impact of debris from the original cratering event. The numerous impacts had ground up the lunar terrain so that a layer of fine-grained 'lunar soil' was created. This was the famous 'dust layer' which prompted the well-publicized fears of spacecraft sinking beneath the lunar surface. The pictures from Ranger 9 also revealed evidence of volcanic activity on the floor of the crater Alphonsus.

Surveyor Program. The next step in the US lunar effort was a soft landing. This was the goal of the Surveyor Program. Seven attempts were made, of which five were successful (Table 1). Four landing sites were in the relatively smooth and level maria, the best bet for a safe manned landing. On the last mission, planners decided to risk the hazards of rough terrain to satisfy scientists' desire for some knowledge about the as yet unexplored highlands.

On all but one of the missions the engines were used to slow the Surveyor and were then turned off at an altitude of about 4 m to prevent surface disruption. The resulting landing velocity was about 3–4 $m\,s^{-1}$ vertically and about 0.5 $m\,s^{-1}$ horizontally.[7] On Surveyor 3 one engine failed to shut down and the spacecraft bounced twice before coming to rest.

The Surveyor cameras provided over 86 000 photographs of the lunar terrain at resolutions as good as 1 mm. In addition to the cameras, Surveyors carried several experiments to test the chemical and physical properties of the soil and rocks at the landing sites. For example, the alpha-scattering experiment was a device that gave off alpha particles, which were scattered and absorbed by the lunar surface. It then measured the reflected particles, which contained the signatures of elements present.

The results showed that the lunar maria were similar in composition to terrestrial basaltic rocks. Highland composition was found to be lower in iron than the maria.[7] A scoop was used to test the physical properties of the soil; trenches were dug and impact tests were performed. The scoop proved to be a very versatile tool; it was even used on Surveyor 7 to dislodge a stubborn piece of equipment.

Lunar Orbiter. The Lunar Orbiter Program consisted of five orbital photographic missions (Table 1). Their primary purpose was to scout out lunar landing sites, but in the process the Lunar Orbiter missions taught us much about the surface geology of the Moon. Most of the landing site work was completed on the first three missions, allowing the last two to be more science-oriented. Lunar Orbiter 4 photographed the entire near side (Fig. 4), while Lunar Orbiter 5 was targeted to specific areas of interest and completed medium resolution coverage of the lunar far side.[8]

The photographic system had two cameras, which provided a medium resolution frame and a nested high resolution frame; the best resolution for the first three missions was 1 m; for mission 4, 60 m; and for mission 5, 4 m. The film was processed and scanned on the spacecraft; this scanning process produced the distinctive banding of Orbiter photography. The images were then radio-transmitted to Earth. In addition to the surface photographs, the Lunar Orbiters also gave us information about the

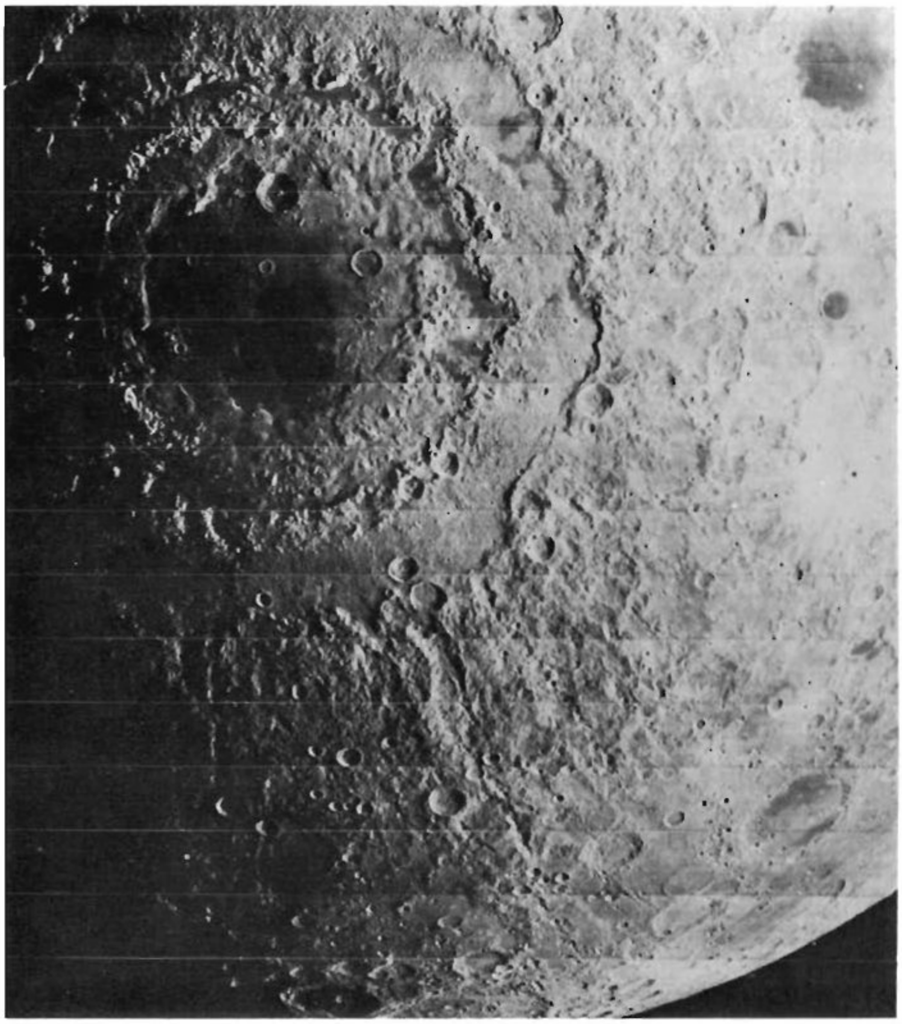

Figure 4. Lunar Orbiter 4 photograph (M-184) depicting the Orientale multi-ringed basin, with dark fill within the central ring, and linear grooves and radial ejecta beyond the outer ring (930 km across).

Moon's gravitational field, and carried micrometeoroid and radiation detectors.

Zond Program. The Soviet Zond flights were flyby and circumlunar missions that photographed the Moon, particularly the far side and west limb. According to D. R. Woods the Zond missions apparently were to be forerunners of a never-realized manned lunar program.[5] The lunar Zond program consisted of five successful missions. Zond 5 through 8 returned to Earth and were recovered. Because the Zond spacecraft did not achieve a lunar orbit, but only passed by or circled once around the Moon, the number of photographs was limited. About 44 are available in the United States as prints or in atlases.[21] Some of these reveal the Moon in excellent detail, for example the photographs of the far side crater Aitken (Fig. 5).

Luna Missions. The Luna missions constitute the major Soviet exploration program. This program was first known by the name Lunik and was later changed to Luna after the third mission. This unmanned program covered nearly the entire gamut of exploration ways. It included flyby missions, photographic orbiters, soft landers (some with roving capability), and sample return missions, which obtained a total of 320 g of lunar soil.

Of special significance were the two rover and the three sample return missions (Fig. 6). The rovers were carried on Luna 17 and 21. Luna 17 landed in Mare Imbrium at latitude 38°17'N and longitude 33°W, and carried the first lunar roving vehicle, Lunokhod 1. The rover was operational for 10.5 months, working only during the lunar day, and provided over 20 000 close-up photographs of the lunar surface. These photographs were essential to steering the remotely-controlled Lunokhod towards a safe travel route. In addition, the rover tested the physical and chemical properties of the soil and carried a cosmic ray detector and an X-ray telescope. During its 10.5 km trek the rover traversed overlapping lava flows.

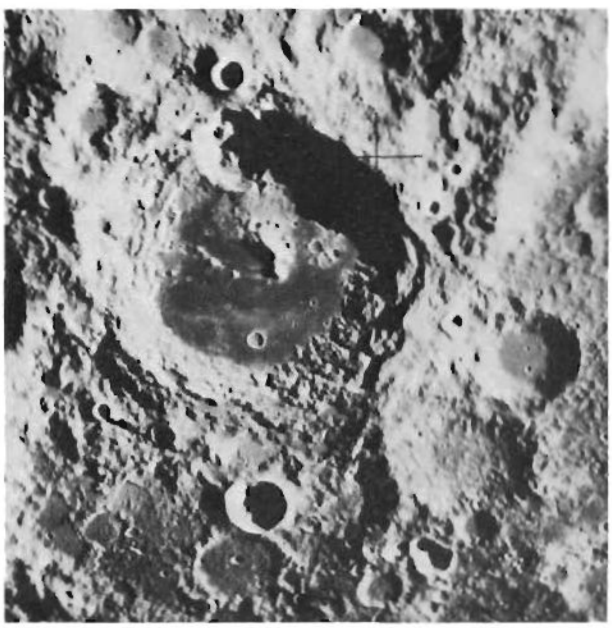

Figure 5. Zond 8 photograph of part of the lunar far side. The large crater in the upper center is named Aitken and is 150 km in diameter. Note the dark floor of Aitken and the thin, linear grooves trending north-northeast from the crater's rim.

Luna 21 with Lunokhod 2 on board landed at latitude 25°51'N and longitude 30°27'E within the southern part of the 55 km wide le Monnier, a degraded crater flooded with mare material. This landing site was on the eastern edge of the Serenitatis basin about 170 km north of the point where Apollo 17 had landed about a month earlier. By commands from the ground, Lunokhod 2 traveled southward across the dark mare plain to the transition zone near the southern rim of le Monnier and then eastward to a long rille in its floor (Fig. 7). During the 37 km route, an X-ray spectrometer made an analysis of lunar soil. In addition, the mechanical properties of the soil were also determined by a penetrometer.[22]

Luna 16 landed in northeastern Mare Fecunditatis at latitude 0°41'S and longitude 56°18'E. It returned to Earth a core 35 cm deep, the depth at which the drill hit hard rock; this core did not exhibit layering but did show an increase in coarse material with depth. Studies show that compositionally the Luna 16 mare material is similar to samples from Apollo 11 and 12, especially the latter.[23] Highland materials in the core may have been derived from rays that are present in the area of the landing site. Possible source craters for these rays are Langrenus, Taruntius, Theophilus and/or Tycho.[24]

Luna 20 returned a sample from the highlands between Mare Fecunditatis and Mare Crisium at latitude 3°32'N and longitude 56°33'E. The sample is composed primarily of a light colored rock similar to terrestrial anorthosite, and it corresponds in bulk composition to the Apollo 16 rocks and soils.[25] Ejecta from the small, young crater Apollonius C may be present in the Luna 20 material.

Luna 24 landed in southeastern Mare Crisium at latitude 12°45'N and longitude 60°12'E. The landing site is 40 km from the mare–terra boundary and is inside a series of ridges and scarps that mark the inner concentric ring of the Crisium basin. The returned core is 160 cm long and contains 170 g of material. It is layered and has been divided into four zones. The principal rock types present are coarse grained as well as fine grained basaltic fragments mixed with volcanic glass.[26] Chemical studies have shown the presence of very low titanium basalt, which is uncommon in other returned samples. Most of the ejecta in the core may have come from the craters Langrenus and Taruntius in the highlands and Fahrenheit in the mare.[27]

The success of the Luna sample return missions (16, 20 and 24) has been used as a strong argument for promoting unmanned planetary exploration. During the Apollo program, many scientists ex-

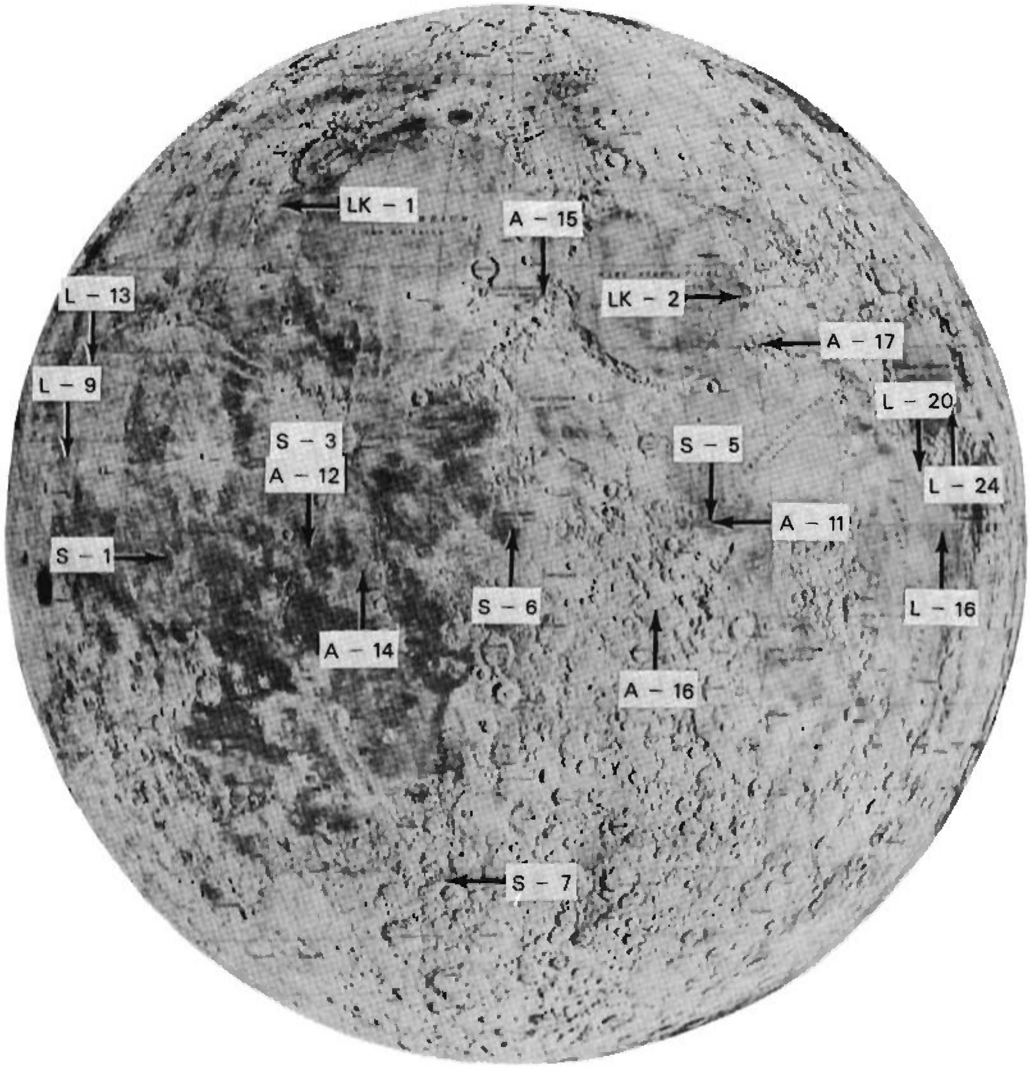

Figure 6. Landing site map showing the location of all successful soft landed spacecraft on the Moon. These include from the United States the five Surveyors (S) and the six Apollo lunar modules (A); and from the USSR two Lunokhod roving vehicles (LK) and five Luna missions (L) of which three (Luna 16, 20 and 24) returned samples to Earth.

pressed the opinion that the cost of accommodating astronauts on the lunar missions was not worth the gain. Others, including myself, held the opinion that the ability of a human being to observe, interpret and select added an invaluable dimension to these missions.

Nonetheless, the three soil samples returned by the Luna missions, although small and nonselective, have added much to our knowledge of the lunar surface materials. This is particularly true when these samples are viewed within the context of the information gained from the larger amounts and the more diverse rock and soil samples that were selected by the Apollo astronauts.

Apollo Manned Missions

The Apollo program, which landed 12 astronauts on six lunar sites, is generally considered as one of the greatest technological endeavors in the history of mankind.[28] For the first two missions, emphasis was placed on the engineering aspects of 'landing a man on the Moon and returning him safely to Earth'.[28] However, following the momentous success of the Apollo 11 mission, more attention was directed to scientific research. Mission after mission witnessed an increase in payload capability, lunar stay-time, operational radius, number of experiments performed, and amount of samples returned (Fig. 8).

Apollo 11. The first two astronauts to walk on the Moon landed their spacecraft at latitude 0°37′N and longitude 23°30′E in southern Mare Tranquillitatis. The landing site was selected in a flat, smooth area to assure the safety of the astronauts. In spite of this, many boulders were encountered in the area due to a small impact crater.

The scientific returns from this mission were momentous. From the first manned lunar landing, we learned that the mare site was covered with a layer of fragmented rock called regolith, which was at least 1 m thick. In this regolith, the rocks kept a record of a violent impact history. Most of them

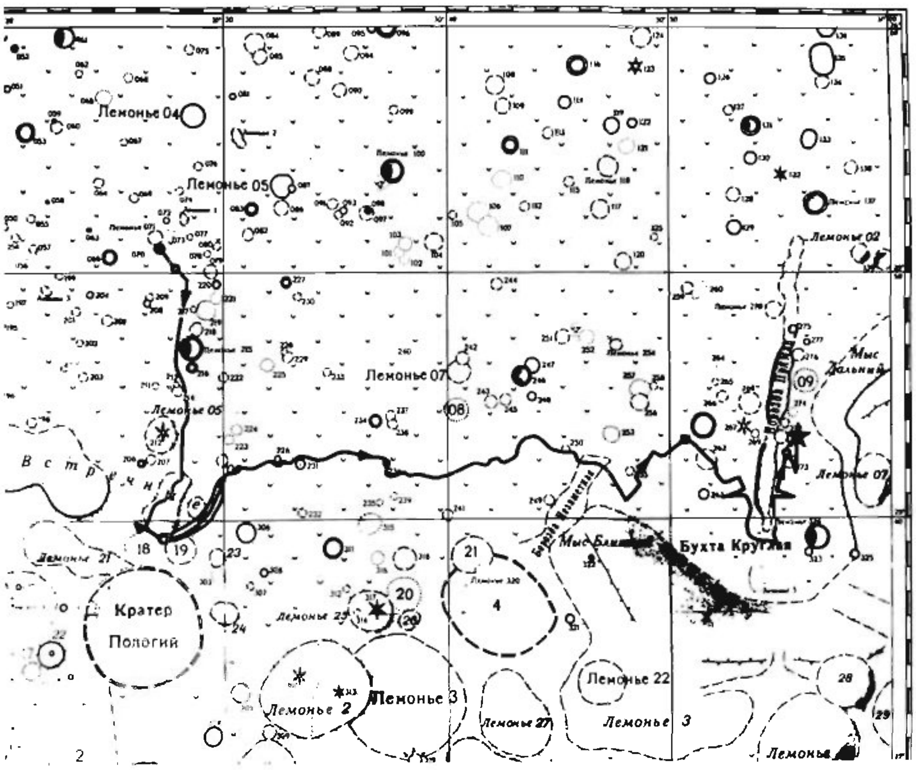

Figure 7. Part of the 1:50 000 scale *Topographic Map of the Lunokhod 2 Operating Region* in the southern floor of the crater le Monnier, published by the Soviet Mapping Agency, Moscow (1973). The thick black line marks the 37 km traverse of the roving vehicle.

were fragmented and displayed angular, coarse fragments in a matrix, resulting in a texture that necessitated labelling them breccias. Many had a glass-like coating from partial melting by impact. The composition of most of those rocks was generally similar to that of dark volcanic rocks on Earth, basalt. These samples proved beyond doubt the subsurface origin of the dark lunar maria. The old age of the Apollo 11 samples was also very significant. The Moon rocks turned out to be much older, 3.7 thousand million years, than anything dated on Earth.

Apollo 12. The first lunar landing proved the capability of the system and the ability of the astronauts to perform scientific tasks on the surface of the Moon. However, Apollo 11 was off target by about 7.5 km when it touched down on the lunar surface. Later missions were scheduled for more rugged sites such as those of Apollo 15, 16 and 17. With these landing sites in mind, it was necessary to establish the capability of making a pinpoint landing on the Moon.

The site chosen for Apollo 12, latitude 3°36'S and longitude 23°41'W, was in southeastern Oceanus Procellarum, an area now called Mare Insularum, where Surveyor 3 had landed within a crater two years earlier. A pinpoint landing was successfully accomplished less than 100 m from Surveyor 3. The success of this pinpoint landing on the second lunar landing mission greatly advanced the strategy for subsequent lunar exploration by proving the capability of landing within walking distance of specific sampling objectives.

The Apollo 12 samples were also from volcanically produced basaltic rocks. As predicted by pre-mission photogeologic interpretations, they had a slightly different chemistry, particularly lesser amounts of titanium, and were somewhat younger than the Apollo 11 basalts. A different kind of sample was also brought back, along with the Moon rocks and soils, when the astronauts walked to the Surveyor craft toward the end of their second surface traverse and retrieved parts of it. These were returned to Earth to study the effects of nearly three years of exposure to the lunar environment.

Apollo 14. The Apollo 14 mission landed in the Fra Mauro Formation at latitude 3°40'S and longitude 17°28'W. Pre-mission analysis of the available data showed that this formation was characterized by subparallel ridges that were radial to the Imbrium basin. Ridges and gentle swales gave it an undulating character and a much rougher look than the mare sites of Apollo missions 11 and 12. Most of the ridges were about 100 m high and many could be traced for over 100 km. The general setting of this unit, and its textural and structural characteristics, suggested that it consisted of deposits ejected from the Imbrium impact site.

Based on this interpretation, materials of the Fra Mauro Formation would have included deep-seated rock, perhaps derived from as deep as 100 km. It was then important that the astronauts sample rocks from the actual formation, and not from materials that may have blanketed it. To make certain of this, the landing site was selected within walking distance of a 350 m crater that was named 'Cone' because of the shape of the hill on which the crater was made. Cone crater must have penetrated through the regolith and exposed chunks of rocks from the Fra Mauro Formation.

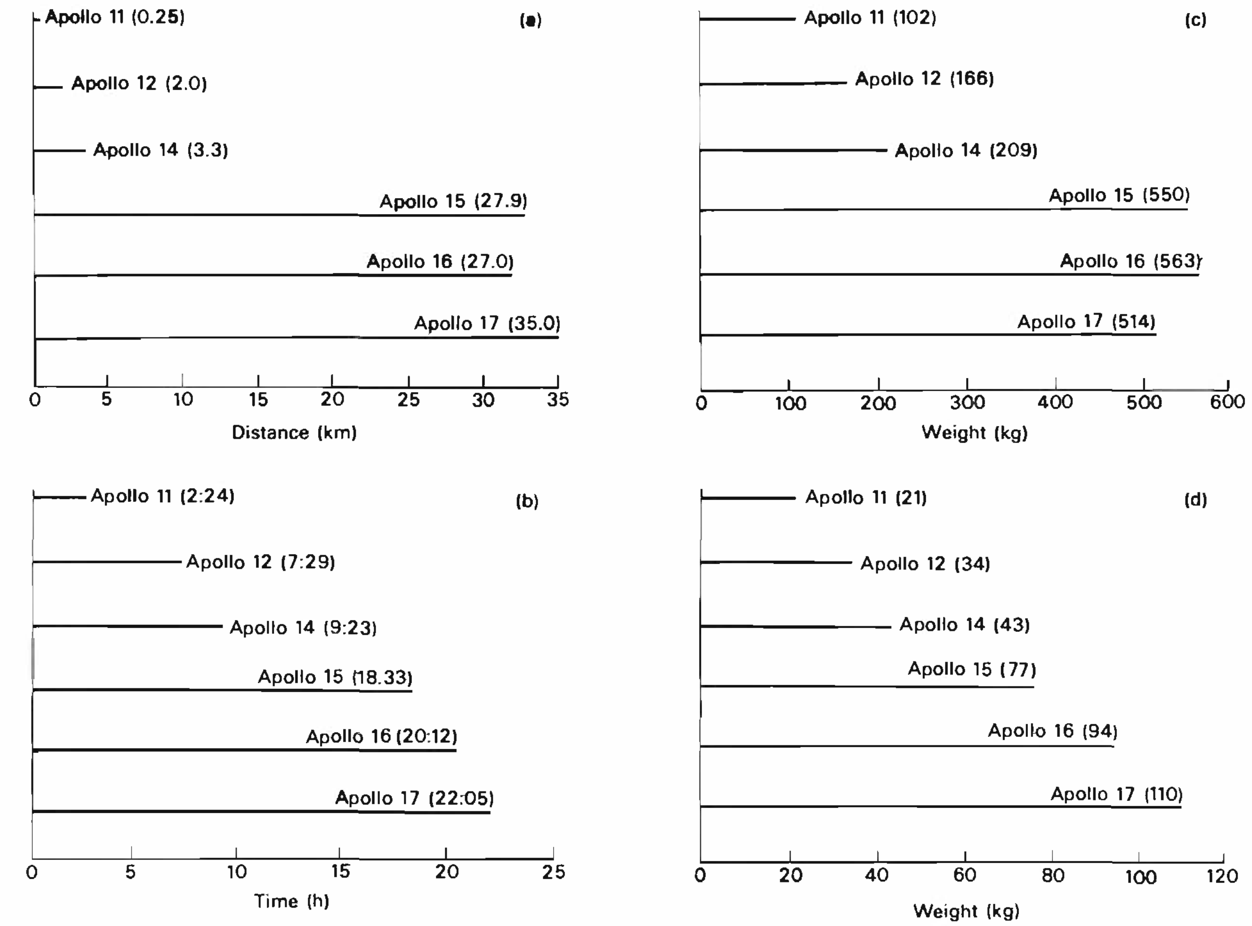

Figure 8. Graphs illustrating the step-by-step increase in the scientific capabilities of the Apollo missions. The comparisons are made of: (a) total surface traverse distance; (b) time the astronauts spent on the lunar surface; (c) weight of scientific instruments delivered to the Moon; and (d) weight of returned lunar rock and soil, as summarized in the 'Apollo 17 Preliminary Science Report,' NASA SP-330 (1973).

Pre-mission interpretations were proven correct. Samples from the Apollo 14 mission were complex rocks that kept a record of a violent impact history. Generations of breccias within breccias were recognized as the result of repeated impacts. These rocks were so complex that if they had been the first to come back from the Moon they would have defied explanation. The step-by-step understanding of lunar rocks and surface processes helped unravel the history of the multistage impact events that produced these breccias.

Apollo 15. The Apollo 15 landing site was located at latitude 26°06′N and longitude 3°39′E at the foot of one of the Moon's highest mountain ranges. The astronauts landed on the eastern boundary of Mare Imbrium near Montes Apenninus and a meandering gorge called Rima Hadley. This landing site provided an opportunity for the astronauts to explore and sample a mare basin, a mountain front, and a lunar rille on a single mission, thus adding to the variety of the returned lunar rocks.

The Apennine Mountains are about 5 km high. It was believed that they contained ancient material predating the formation and filling of the major mare basins. It was also thought that this ancient material was exposed during the excavation of the Imbrium basin and, thus, was in some way related to the Fra Mauro Formation of Apollo 14. Samples from the Apennines were less shocked and were simpler in texture and composition than the Apollo 14 breccias. This result was in agreement with pre-mission interpretations.

The origin of sinuous rilles was a mystery. It was believed that their formation was due to the erosive action of some type of fluid, possibly volcanic, or to the fluidization of the lunar surface materials by degassing from the interior. Rima Hadley, a V-shaped sinuous rille, provided an opportunity to study these features. The rille originates from an elongate depression in an area of associated volcanic domes and meanders northward across Palus Putredinus, a part of Mare Imbrium, named the 'Swamp of Decay'. It merges with a second rille approximately 100 km to the north. The rille averages about 1.5 km in width and about 400 m in depth. The astronauts sampled and photographed layered basaltic rocks near its rim. The layering confirmed the theory that mare basins were successively filled by numerous, thin lava flows.

Without the lunar rover it would have been impossible to undertake the planned geological investigations on the Apollo 15 mission. The three traverses that were planned for the Apollo 15 astronauts were the most elaborate yet. The astronauts were able to test the full capability of the lunar rover by driving it on undulating terrain and even to the edge of Rima Hadley. The rover was able to get to distant as well as difficult-to-reach sampling locations. Its use on Apollo 15 and the two subsequent missions greatly enhanced their scientific returns.

Apollo 16. The scientists involved in lunar landing site selection agreed from the start on the need to send one of the Apollo missions to the midst of the lunar highlands. The photographic coverage of the terrae in the southern part of the Moon was less than adequate, in addition to the fact that most areas were too rough for a safe landing. It became obvious that additional orbital photographs had to be obtained of the relatively smooth regions in the south-central part of the Moon. After many attempts the necessary high resolution photographs were obtained on Apollo mission 14, and a mission plan was laid out. A landing site with a smooth plain and within reach of a relatively bright and undulating formation was selected north of the crater Descartes. The bright formation and the smooth plains were interpreted to be of probable volcanic origin.[29] This made the site exceedingly interesting, because no volcanic rocks had been sampled from the lunar terrae.

The Apollo 16 crew landed at latitude 9°S and longitude 15°31′E and embarked on their exploration. Instead of encountering the crystalline volcanic rocks, the astronauts described only impact breccias.

This was the first signal that pre-mission photogeologic interpretations might be wrong. Examination of the returned samples confirmed the astronauts' opinion. The impact breccias from that site, however, were unlike others from Apollo 14 and 15 in that they displayed no evidence of mechanical mixing. The Apollo 16 rocks were formed from coarse grained rocks of anorthositic composition that were metamorphosed by impact cratering.

Apollo 17. The landing site of the last manned lunar mission was by far the most complex. The site was located between massifs, at least 2 km high. When we first suggested this locality on the eastern edge of Mare Serenitatis, we encountered resistance from the NASA engineers who dubbed the site 'box canyon'. With much discussion and give-and-take, the trajectory experts finally agreed to and planned for a landing at latitude 20°10′N and longitude 30°46′E.

The high massifs, part of the Taurus Mountains, were believed to be ancient highland crustal rocks that were emplaced by uplift at the time of formation of the Serenitatis basin. A large landslide had spread light colored material from one of the massifs. This landslide offered an excellent opportunity to sample the old massif material without having to climb its steep slopes.

Before the mission, the dark materials in the valley floor were thought to be much younger than the mare basalts sampled on Apollo missions 11, 12 and 15. This interpretation was based on the generally smooth appearance and on the small number of impact craters. However, as post-mission analyses showed, these characteristics were the result of the presence of much fine grained volcanic glass in this mare. In spite of their unexpectedly old age, these basalts and interlayered glasses provided us with much new data on lunar volcanism.

Scientific Experiments on the Moon. In addition to the selection of rocks from the landing sites, the Apollo astronauts conducted numerous experiments while orbiting the Moon and on the lunar surface (Table 2). Surveys from orbit included photography

Table 2. Apollo Lunar Experiments

Experiment	Mission 11	12	14	15	16	17
Orbital experiments						
Gamma-Ray Spectrometer				X	X	
X-Ray Fluorescence				X	X	
Alpha-Particle Spectrometer				X	X	
Mass Spectrometer				X	X	
Far Ultraviolet (UV) Spectrometer				X	X	
Lunar Radar Sounder						X
S-Band Transponder			X	X	X	X
Bistatic Radar			X	X	X	
Infrared Scanning Radiometer						X
Subsatellite						
Particle Shadows/Boundary Layer				X	X	
Magnetometer				X	X	
S-Band Transponder				X	X	
Window Meteoroid Detector			X	X	X	X
UV Photography of Earth and Moon				X	X	
Gegenschein from Lunar Orbit			X	X		
Surface experiments						
Passive Seismic	X	X	X	X	X	
Active Seismic			X		X	
Heat Flow Measurement				X	X	X
Suprathermal Ion Detector		X	X	X		
Cold Cathode Ion Gauge		X	X	X		
Cosmic Ray Detector					X	
Lunar Neutron Probe						X
Lunar Dust Detector		X	X	X		
Lunar Ejecta and Meteorites						X
Charged Particle Lunar Environment			X			
Surface Electrical Properties						X
Lunar Atmospheric Composition						X
Solar Wind Composition	X	X	X	X	X	
Solar Wind Spectrometer		X		X		
Far UV Camera/Spectroscope					X	
Lunar Surface Magnetometer		X		X	X	
Portable Magnetometer			X		X	
Lunar Surface Gravimeter						X
Lunar Gravity Traverse						X
Lunar Seismic Profiling						X
Laser Ranging Retro-Reflector	X		X	X		
Soil Mechanics			X	X	X	X

from the command module windows and by sophisticated metric and panoramic cameras mounted on a special bay in the service modules of Apollo missions 15, 16 and 17. Fifteen other experiments, conducted mainly on these last three missions, obtained geochemical and geophysical data pertaining to overflown parts of the Moon which is about 20% of the surface area.

Collection of rock and soil samples on the Apollo missions was part of the 'Field Geology Experiment'. In addition to this, the astronauts conducted 23 experiments on the lunar surface (Table 2). Some required data collection while the astronauts were on the Moon, such as obtaining heat flow measurements and measuring lunar surface magnetism via a portable instrument. Other instruments, for example the passive seismometer, were so sensitive that the motion of the astronauts disturbed their measurements.

The network of long-life passive seismometers at five stations (Apollo sites 11, 12, 14, 15 and 16) provided the most significant data on the deep interior of the Moon. These instruments remained active far beyond their expected lifetime of two years. NASA recently had to shut them off after more than five years since deploying the last seismometer. This was done due to the lack of funds to continue monitoring them and processing their data.

THE SCIENTIFIC HARVEST

The lunar exploration tools have gathered a plethora of information about the Moon. Returned to Earth were some 2000 individual samples of rock and soil weighing nearly 400 kg. The photographic record included some 30 000 orbital photographs and many more surface photographs that depicted the Moon in various details. Added to these were reams of data collected on the surface from seismometers, magnetometers, gravimeters, and a host of other scientific instruments; the amount of data defied filing and cataloging. This treasure of data was studied in a preliminary fashion to gain a general understanding. However, much of this information is still being investigated at numerous scientific laboratories in many countries. In the following section, a brief account is given of the more significant findings.

Moon Rocks and Soil

Much excitement accompanied the arrival of the first samples of the Moon from Apollo 11. The samples and the astronauts were quarantined for three weeks. In an elaborate facility named the Lunar Receiving Laboratory at the Johnson Space Center, Houston, Texas, specialists studied the lunar samples for possible microscopic life forms. As medical doctors examined the astronauts for possible lunar germs, animals and plants were exposed to the rocks and were injected with lunar dust. This flurry of activities had been planned to make certain that the returning humans and their loot would not import germs or diseases of lunar origin to the Earth. As most scientists believed, however, the sterile lunar environment, with no protection from the Sun by an atmosphere, did not support any forms of life. All that came back from the Moon were rocks and soil similar in composition to rock types known on Earth, such as the following.

Basalt. Most of the rocks collected from the dark maria (Apollo missions 11, 12, 15 and 17, and Luna missions 16 and 24) are generally similar to what geologists call basalt. The lunar basalts are fine grained volcanic rocks, which solidified from lava that was extruded onto the surface of the Moon. In most maria, the vents from which the lavas erupted cannot be located, and features of lava flows are absent. However, distinct, relatively young lava flows are particularly evident in Mare Imbrium. With their lobate margins, these flows resemble lava flows on Earth. In the low gravity of the Moon, lava flows in Mare Imbrium extend for great distances from the center of extrusion; in some cases, this is more than 1000 km.

The fact that basalts flowed onto the surface of the Moon can be seen not only in photographs of the lunar surface but in the textures of the rocks themselves. In some basalts, small and partially formed minerals occur in a matrix of glass. Rapid chilling of the molten lava near the surface of a flow arrested the growth of the minerals and produced glass. At times, as the lava rose to the surface, volatile gases were released producing bubbles called vesicles (Fig. 9), which were frozen in the basalt.

These rocks were crystalline rather than glassy, and therefore cooled and solidified slowly, though near the surface as the vesicles attest. Gases trapped in the vesicles often reacted with the rock to line these cavities with delicate, beautifully formed crystals. Still other lunar basalts are entirely crystalline and somewhat coarse grained. These must have cooled very slowly, perhaps near the bottom of a thick lava flow beneath the insulating cover of already solid basalt.

In their textures and mineral contents, the lunar basalts are similar to rocks found on Earth. There are, however, some striking differences in their chemical compositions. On the whole, compared with terrestrial rocks, the lunar basalts have lower concentrations of some volatile elements, for example sodium and potassium, and are enriched in refractory elements, for example chromium and titanium. Lunar basalts are also similar to one class of basaltic meteorites, the eucrites.

Unlike terrestrial basalts, eucrites closely resemble lunar basalts in their sodium and potassium content. However, because of wide differences in the contents of refractory elements and of some minor elements, this resemblance between mare basalts

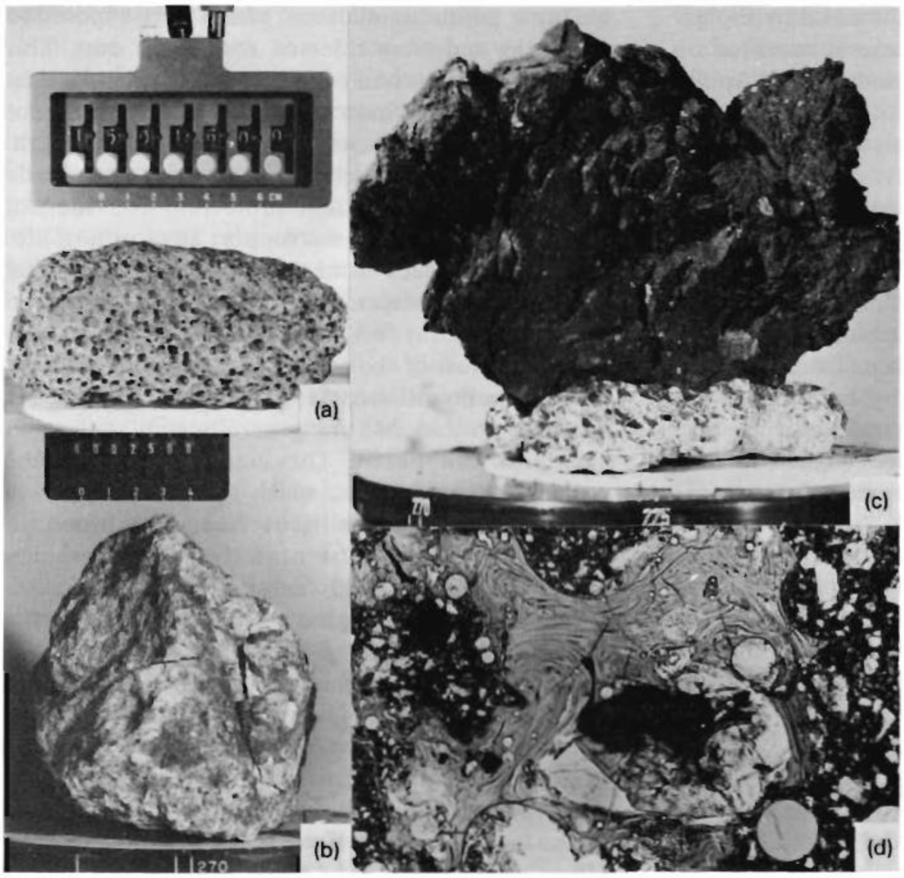

Figure 9. Three Lunar Receiving Laboratory photographs of samples representing the major types of Moon rocks: (a) basalt samples from the Apollo 15 site showing vesicles that were once occupied by gases; (b) light colored anorthosite rock from the Apollo 16 site; (c) breccia from the Apollo 17 site composed of light colored rock fragments in a dark matrix; and (d) photomicrograph of a rock thin section showing glass spheres and flow structures of a glassy matrix, which resulted from shock melting on impact.

and meteorites ends. Eucrites must have come from elsewhere in the solar system and not, as once proposed, from the Moon. Absent from the mare basalts and all other lunar rocks are any minerals that would indicate that either water or free oxygen had been present on the Moon. Detailed studies of the mineral and chemical compositions of lunar basalts show that the lava originated by partial melting of other rocks several hundred kilometers deep within the Moon.

Anorthosite. The Apollo 11 soils, collected in Mare Tranquillitatis, contained a small number of rock fragments that were not of mare basalt. If not from the maria, these rocks must have been from the lunar highlands. Some of these fragments were a different kind of basalt with high concentrations for the Moon of potassium (K), rare earth elements (REE) and phosphorus (P), for which the acronym KREEP was coined.

Most unusual of the highland fragments, however, were those of the light colored, calcium rich rock, anorthosite. Anorthosite, on Earth, is a rare and enigmatic rock; its discovery on the Moon was quite surprising. With all the pre-Apollo speculation on the composition of the lunar highlands, numerous rock types had been proposed but never anorthosite. Later, the study of samples collected in the highland regions and orbital remote sensing of the chemistry of the Moon's surface, did show the highlands to be dominantly of anorthositic composition.

A widely accepted model for the origin of the anorthositic crust involves fractionation of a partially molten Moon early in its history. Fractionation means that different minerals, as they crystallize from a melt would separate, fractionate, according to mass and form two different rock types. From a melt with the composition of the Moon, the first minerals to crystallize would be the heavier iron and magnesium rich minerals olivine and pyroxene, and the calcium plagioclase anorthite. The more dense olivine and pyroxene would sink in the molten rock material and the anorthite would tend to be concentrated near the top, perhaps by floating, to form a skin or crust of anorthosite. Of course, this model means that somewhere, deep within the Moon, there must be layers of more dense rock containing olivine and pyroxene. Such rocks were not collected, but inferences concerning their existence came from the Apollo seismometer network.

Breccia. The lunar surface is saturated with meteoroid impact craters ranging in size from microscopic 'zap pits' to giant multiringed basins over 1000 km in diameter. Such intensive bombardment of the Moon's surface has not left its rocks unscathed.

Crushing and grinding (brecciation) by the forces of impact are evident in most lunar rocks. The effects of shock run the gamut from simple fracturing and deformation to partial or even complete melting (Fig. 9). With extreme shock, rocks may be vaporized totally. This appears to have been the fate of the larger meteoroids that impacted the Moon.

Lunar rocks, composed of impact-derived fragments of other rocks, are called breccias. The materials of breccias were excavated from deep within the Moon by impact events – just how deep depends on the size of the crater – and strewn outward as ejecta, up to hundreds of kilometers for the largest lunar craters. The ejecta of large craters flowed and were deposited as hot, thick blankets, much in the manner of volcanic ash flows on Earth.

Fragments near the bottom were compacted by the weight of the ejecta blanket and were welded together by molten rock produced during the impact. In this way breccias were formed. Many rock fragments in lunar breccias are themselves breccias, which record a previous episode of fragmentation and reconstitution. As many as four generations of brecciation have been recognized in some lunar rocks, especially those collected at the Apollo 14 site.

In addition to the rocks themselves, the individual minerals show evidence of shock deformation. Shock disrupts the orderly arrangement of atoms in minerals and causes them to rearrange. For example, what had been a single uniform crystal before shock became twinned; in fact, it is made up of alternating lamellae or layers with somewhat different, but regular, orientations. Some minerals, such as the plagioclase in anorthosite, have been vitrified by the sudden pressure of impact; others have been converted to more dense crystalline forms.

Breccias, as well as lunar soils, provide samples of lunar rocks from areas farther than astronauts have roamed and from deeper than they could dig or drill. In the interpretation of their complicated histories lie the clues to much of the long and complex history of the Moon.

Soil. The lunar soil makes up the layers of fine material that blanket the surface of the Moon. Before the Apollo missions, estimates of the thickness of this surface covering, regolith, ranged up to tens of kilometers. The thickness of the unconsolidated soil layer was later found to be generally less than 10 m based on observations of exposures of rock in rilles and of the depths of craters that excavate to the level of bedrock.

The first human footprints on another world attest to these physical properties of the Moon's uppermost surface layer. As astronaut Neil Armstrong photographed his first step on the Moon, he described the regolith as follows: 'The surface is fine and powdery. I can pick it up loosely with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a fraction of an inch, maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine, sandy particles'.

The fine fragments that comprise the lunar soil are products of the bombardment of the Moon by meteoroids ranging from cosmic dust to bodies of asteroidal sizes. Some lunar rocks were crushed and pulverized by these impacts and were ejected from the craters formed. Finer materials from craters were scattered widely over the Moon, up to thousands of kilometers from the original crater. Layer by thin layer the lunar soil accumulated.

As might be expected, the lunar soil is composed largely of fragments of pre-existing lunar rocks and their minerals. At any spot on the Moon yet sampled, fragments from the underlying bedrock appear dominant in the soil, though a small number from afar are always present. In effect then, the Moon has been sampled more widely than the restricted areas visited by humans and their machines.

In addition to rock and mineral fragments, the lunar soil contains abundant glasses. Most of the glasses in the soil have originated by melting during meteoroid impacts, though there are some notable exceptions. Many of the impact produced glasses occur as rounded shapes that were caused by rotation during their flights. Other glasses are found as irregular splashes near zap pits formed by impacts of micrometeoroids.

Impact derived glasses commonly weld lunar soil particles into larger aggregates. This process tends to counteract the pulverization of the soil into smaller and smaller sizes by meteoroid bombardment. Although much has already been written about lunar rocks and soil,[30] scientists have a long way to go before reaching a complete understanding of what was returned from the Moon.

The chemistry of lunar rocks was also explored from lunar orbit. Apollo missions 15 and 16 carried X-ray and γ-ray spectrometers. The X-ray experiment provided Al/Si and Mg/Si intensity ratios for the top 20 microns of the surface along portions of the mission groundtracks.[31] Broad regional chemical variations, high Al/Si in the terrae and lower in the maria, as well as local differences were shown (Fig. 10).

The γ-ray experiment measured radioactivity. The highest counts are localized in small patches predominantly on the western near side of the Moon. The anomalies may be related to KREEP basalts, which may have been excavated by the impact event that created the Imbrium basin. Since

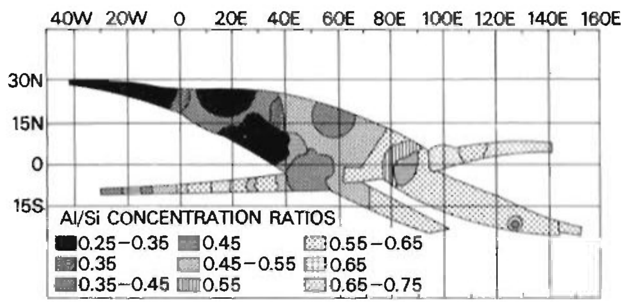

Figure 10. Example of compositional variations in lunar surface materials as detected by the X-ray fluorescence experiment flown on Apollo missions 15 and 16. The aluminum to silicon concentration ratios show larger amounts of aluminum in the lunar highlands particularly on the far side, and lesser amounts in the lunar maria.[31]

Imbrium is one of the largest lunar basins, it is feasible that it penetrated to a depth greater than the others. Another anomaly, around Van de Graff, may be the result of similar processes as this far side crater rests near a very ancient, exceedingly large basin. Knowledge of the gross chemical variations at this global scale is significant to the extrapolation of knowledge gained from the returned samples, and to the assurance that the returned samples are representative of large areas of the Moon, rather than representative of only local rocks and soil.

Ages of Lunar Materials

Before the return of lunar samples, geologists were limited to using a relative time scale to describe events and major provinces on the Moon. It was recognized early in the studies of the lunar surface that the Moon's global morphology was controlled by the large features of impact origin known as multiring circular basins. Materials of these basins and smaller craters compose most of the lunar highlands. Multiple flows of lava within these basins indicate that they were not filled in a single grand episode of volcanic activity, but in stages and over a long period of time. In the maria there are craters, such as Archimedes, that are themselves flooded by mare basalt. Such craters are younger than the basin in which they lie, but older than the basalts that cover their floors. Therefore, some time must have elapsed between the formation of the large basins and their flooding by basalt.

To decipher the relationships between impact basins, craters and volcanic maria, geologists pored over photographs to establish age sequences. Step-by-step and year-after-year a lunar stratigraphic column was established.[32] The lunar stratigraphy was based on the observable overlap relationships of the lunar surface materials (for example, see Fig. 11).

To establish a time-stratigraphic sequence for lunar events, it was important to select some prominent features on the near side of the Moon that display clear boundaries with the surrounding materials. Most highland units were considered relative to two basins: Nectaris, a relatively old basin in the southeast quadrant of the Moon, and Imbrium, a relatively young basin in the northwest quadrant of the Moon. Most mare materials were contrasted in age with the relatively old Eratosthenes crater, and the youngest of formations were compared with the bright rayed, sharp appearing Copernicus crater.

Thus, a moonwide sequence of lunar surface materials was developed. It included 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

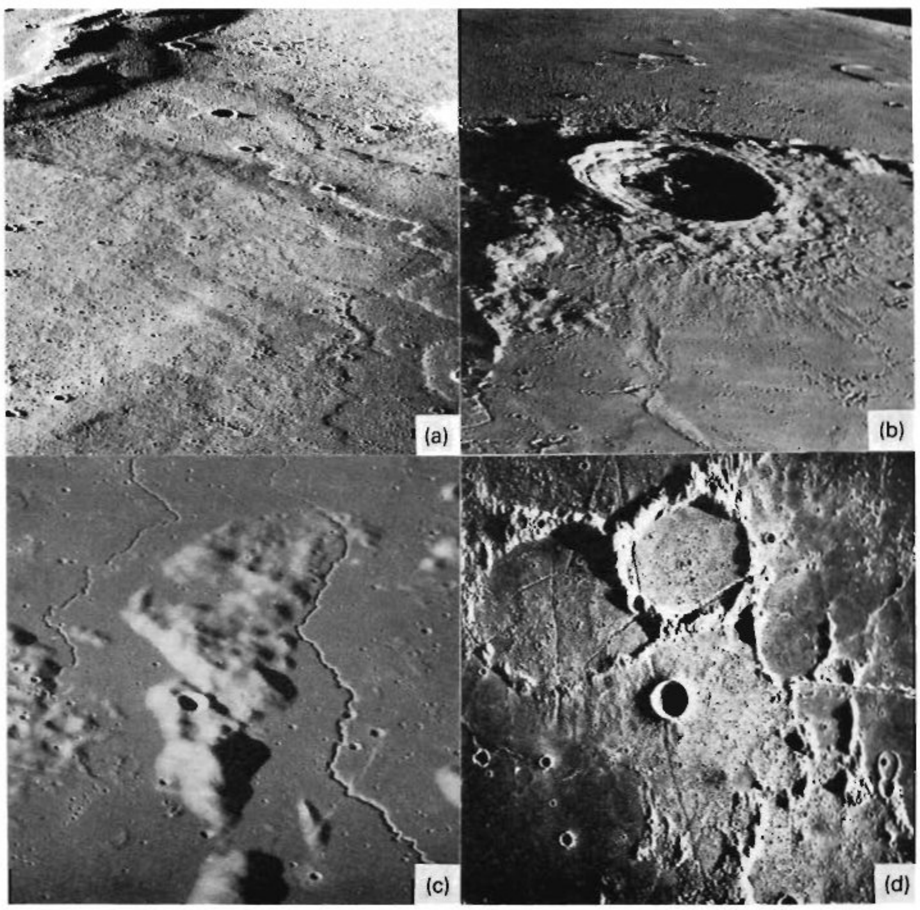

Figure 11. The Apollo astronauts obtained these four photographs that illustrate age relationships of lunar surfaces features: (a) relatively young lava flows superposed on older ones in Oceanus Procellarum; (b) ejecta from the crater Eratosthenes overlying older flat basalts in Mare Imbrium (near field) and Mare Insularum (far field); (c) Two sinuous rilles cutting across the mare plain as well as highland terrain in southern Oceanus Procellarum; and (d) Mare materials covering, and therefore postdating, straight rilles, light colored plains, and old depressions just south of Fra Mauro crater. (Photographs courtesy of NASA.)

majority of pre-Nectarian units are distinguished on the lunar far side. These include materials of very old and subdued basins and mantled and subdued craters.

(2) Nectarian System. This system includes all materials stratigraphically above and including Nectaris basin materials, up to and not including Imbrium basin strata. Ejecta of the Nectaris basin that can be traced near the east limb region serve as a stratigraphic datum for the far side highlands.

(3) Imbrian System. A large part of the near side of the Moon is occupied by ejecta surrounding both the Imbrium and Orientale basins. These highland units form the lower and middle parts of the Imbrian System. Two-thirds of the mare materials also belong to the Imbrian System, particularly in the eastern maria such as Crisium, Fecunditatis, Tranquillitatis and Nectaris, as well as most mare occurrences on the lunar far side.

(4) Eratosthenian System. This system includes materials of rayless craters that are similar to Eratosthenes. Most of these are believed to have once displayed rays that are no longer visible because of mixing due to prolonged micrometeoroid bombardment and solar radiation. The system also includes about one-third of the mare materials on the lunar near side. These are generally concentrated in Oceanus Procellarum and in Mare Imbrium.

(5) Copernican System. This is stratigraphically the highest and, hence, the youngest lunar time scale unit. It includes materials of fresh appearing, bright rayed craters. The Copernican System also includes isolated occurrences of relatively small dark halo craters. Many of these are probably impact craters; however, it is probable that some may be volcanic in origin.

This scale of relative age was applied effectively to the entire Moon. However, it did not provide the absolute time of the events and of the formation of the rocks. An absolute time scale had to await the return of lunar samples. Dating of the samples was done by measuring the amounts of certain isotopes that result with time from the decay of other isotopes. For example, the isotope uranium-238 decays with time to lead-206, potassium-40 decays to argon-40, and rubidium-87 decays to strontium-87.

All such reactions were measured to determine the age of lunar samples. The various techniques sometimes produced different results, but these were not so vastly different as to prohibit their correlation. Therefore, some generalizations could be made regarding the absolute ages of the lunar materials and, therefore, the events that shaped the Moon's surface (Fig. 12).

One age about which most investigators agree is the model age of the lunar soil, being 4.6 thousand million years. This age is comparable with the age of meteorites and with the age generally accepted for the Earth.

It was shown above that there are chemical-petrological indications of an early differentiation resulting in the formation of the Moon's crust and age dating of highland rocks gives indirect indications of the same effect. From all the available absolute age data it is probable that a planetary differentiation process took place within the Moon between 4.6 and 4.3 thousand million years and, thus, the solid anorthositic crust is 4.3 thousand million years old.[33]

This 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

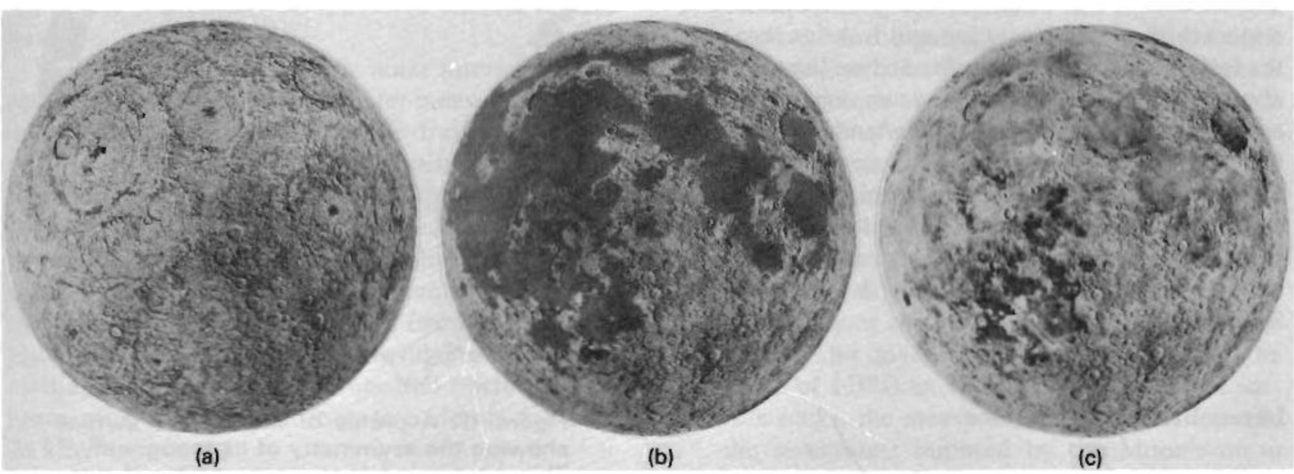

Figure 12. Three faces of the Moon since the formation of the Imbrium basin, the socket of the right eye of 'The Man in the Moon': (a) materials of the multiringed Imbrium basin overlie and subdue older formations; (b) the Moon's surface after the mare lava flooding that filled Imbrium, as well as older basins and other lowlands; (c) today's Moon with numerous post-mare craters. (Drawings by Don Davis, US Geological Survey.)

sphere of influence. For example, the ages of rocks from the Fra Mauro Formation (Apollo 14), a distinct ejecta unit of the Imbrium basin, cluster at 3.95 thousand million years.[33] It is probable, therefore, that the event that created the Imbrium basin, or the socket of the right eye of 'The Man in the Moon,' occurred 3.95 thousand million years ago. Therefore, older basins such as Nectaris must be 4 thousand million years or older.

The ages of lunar mare basalts were found to range from 3.15 thousand million years for an Apollo 12 rock to approximately 3.85 thousand million years for samples collected at the Apollo 11 and 17 landing sites. This range of about 700 million years is longer than the history of life that is preserved as fossils in the rocks of Earth, only 600 million years! The ages of mare basalts are all less than the ages of the mare basins. These age relationships seem to rule out the possibility that mare basalts solidified from material melted by the impacts that produced the large mare basins.

These ages also support the photogeologic observations that mare basalt emplacement falls into two divisions of the relative age scheme; the older maria of the Imbrian System, and the younger basalts of the Eratosthenian System. The Apollo 12 and 15 basalts are Eratosthenian in age (approximately 3.1 to 3.3 thousand million years old) and the Apollo 11 and 17 and Luna 16 basalts are Imbrian in age (approximately 3.5 to 3.8 thousand million years old).

Such age relationships could be used to calibrate the relative age scheme and to summarize the history of the Moon in terms of absolute age. It is reasonable to assume that the Moon was formed 4.6 thousand million years ago. Global planetary differentiation processes took place between 4.6 and 4.3 thousand million years ago to form a crust that is mostly anorthositic in composition. This solid crust kept a record of the moonlets that struck it leaving numerous scars during pre-Nectarian time. Large and small impacts continued to form basins and craters through the Nectarian and Imbrian Systems; the last of the impact basins formed on the near side about 3.9 thousand million years ago. Volcanic eruptions filled the basins and lowlands with basalts from 3.8 to 3.1 thousand million years ago in two episodes, Imbrian and Eratosthenian. Post-basalt history included the transport and mixing of the lunar materials, mostly by impact craters, and such impacts continue to the present day (Copernican System).

Layers Beneath the Surface

Details of the topographic relief of the lunar surface were provided by laser altimeter measurements made on Apollo missions 15 through 17. The altimeter measured precisely the altitudes of the orbiting Commond Service Module above the lunar surface. 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.[34]

Another method of generating elevation profiles of the lunar surface was provided by the lunar sounder.[35] The sounder, which was carried on Apollo 17, consisted of a three-frequency coherent radar using 5 MHz, 15 MHz and 150 MHz. Continuous surface profiles were recorded optically and show excellent details of the outer skin of the Moon. The 5 MHz radar was used to generate profiles (for example, Fig. 13) with an estimated absolute accuracy of 130 m and an estimated relative accuracy of 5 m over mare surfaces. These radar profiles were compared with the Apollo 17 laser altimeter measurements. Although the two types of data were not acquired simultaneously, they agree within 150 m over mare surfaces.

From both the laser altimeter and radar sounder profiles, it became clear that the impacts that formed the multiringed circular basins resulted in an enormous loss of mass from the impact sites. These same basins display large gravity anomalies or mascons.[9] As discovered from the tracking of orbiting spacecraft, particularly Lunar Orbiter 4 and 5, these large mascons were located only in the basins where the mare basalt fill is probably thick (Fig. 14). Mare materials that thinly cover basin troughs and other lowlands do not show gravity anomalies.

Calculations of the difference in the gravity value that must have been added by the relatively thick basaltic fill in the basins was not enough to account

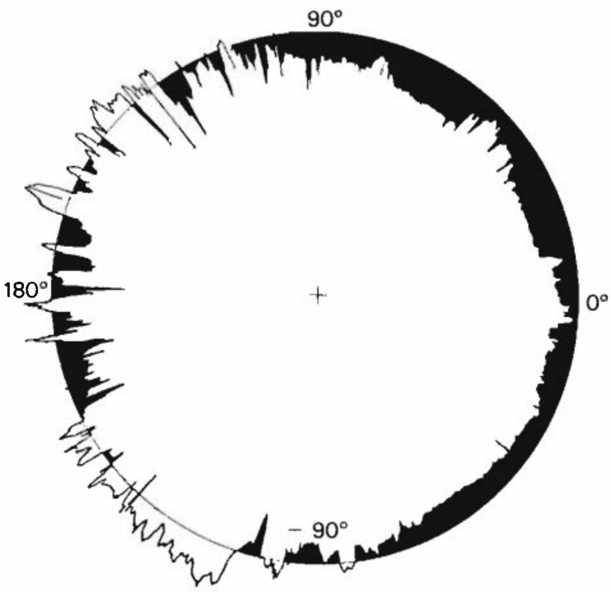

Figure 13. A profile of the Moon's surface showing the asymmetry of its topography.[35] The plot was made about the center of mass of the Moon with an assumed spherical radius of 1738 km. All of the near side (right half) falls well below the sphere, while the far side highlands (left half) are mostly above it. Vertical exaggeration about 70×.

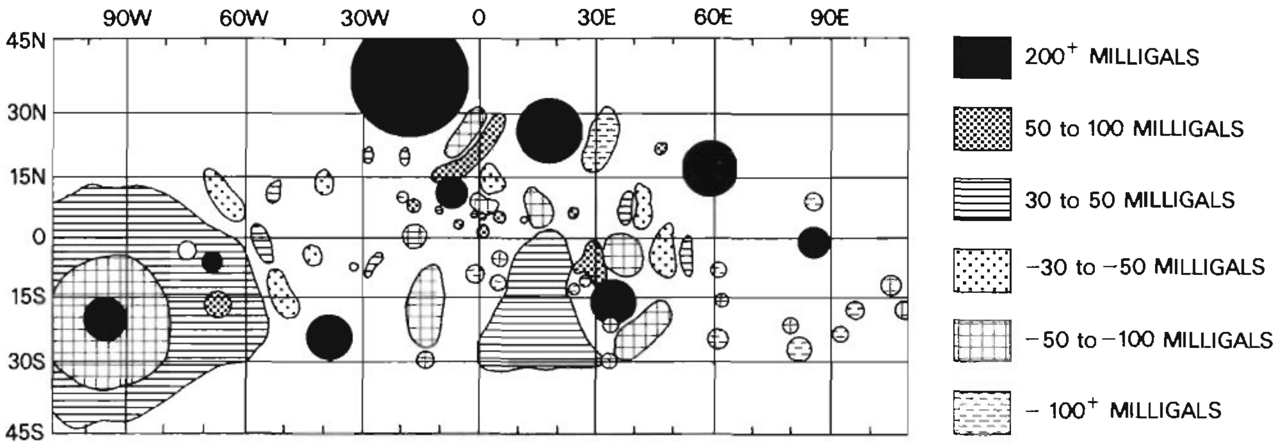

Figure 14. Gravity anomalies on the lunar near side and limb regions. Mascons (black circles) are positive gravity anomalies in the circular lunar basins.[9] They are interpreted as disc shaped features that have masses in excess of 800 kg cm^{-2}. (Courtesy of W. L. Sjorgren, Jet Propulsion Laboratory.)

for the value of the detected mascons. This was particularly true due to the loss of mass at the impact sites. Therefore, a mechanism was required to compensate for the loss of mass from the basins prior to their filling.

An idea that gained acceptance by many scientists contended that some of the very old basins were probably formed early enough to be essentially obliterated by intense cratering and volcanism. Others were formed by the impact of very large objects in a solid lunar crust that was underlain by an upper, partially plastic mantle. The partially plastic mantle may have allowed an upward movement to compensate isostatically for some of the lost mass and its redistribution by the impact. At a later time, upward moving volcanic lavas used the fractures that were created by the impacts as channelways. The lavas extruded on to the surface and filled the circular depressions and the topographically low plains. The additional weight of kilometers thick dense basalts contributed to the positive gravity anomaly within the isostatically compensated circular impact basins.

With respect to the shallow lunar interior, it was realized from the first seismometer measurements of impact generated waves that the travel times are relatively low. This relatively low seismic velocity in lunar near surface rocks was interpreted to mean that the upper layers, which had been fused during the evolution of the Moon, were subsequently brecciated and fractured to considerable depth by meteoroid impacts. This model is favored by ample photogeologic and petrographic evidence of an early melting, and by evidence of repeated fracturing and brecciation of the lunar rock to a depth down to 25 km.[36]

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 that were left by the Apollo astronauts at the sites of missions 12, 14, 15 and 16 (Fig. 6); and (2) the chemistry and mineralogy of the surface samples. Of special importance are the recordings of natural moonquakes by the seismometer network; the seismographs allowed the determination of the origin time, epicenter and focal depth of moonquakes. 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. Additional data were obtained from a large meteoroid impact that occurred on the far side of the Moon on 17 July 1972, when direct shear wave arrivals were not observed at some of the Apollo seismic stations. This led to the suggestion that the material in the lunar interior at a depth of 1000 to 1100 km may be in a partially molten state.

Based on seismic data,[37] and using the Earth as a model, it is reasonable to postulate that the successive layers of the lunar interior from top downward are as follows (Fig. 15).

(1) *Crust*: a layer enriched in aluminum and calcium, anorthositic composition, approximately 65 km thick in the region of the Apollo seismic network, as compared with the 5 to 35 km thick crust on Earth. In this layer, there are local mass concentrations of iron rich rocks. There is also a minor discontinuity at a depth of about 25 km that may be related to intensive fracturing of the upper crust and/or to compositional differences.

(2) *Mantle*: at the major discontinuity at about 65 km depth, there is a large increase in seismic velocity. This interface is comparable to the rise of velocity at the Mohorovičić discontinuity on Earth. This layer appears to continue to the depth of 1100 km. The compositions of the surface rocks, the measured seismic velocities, and the 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

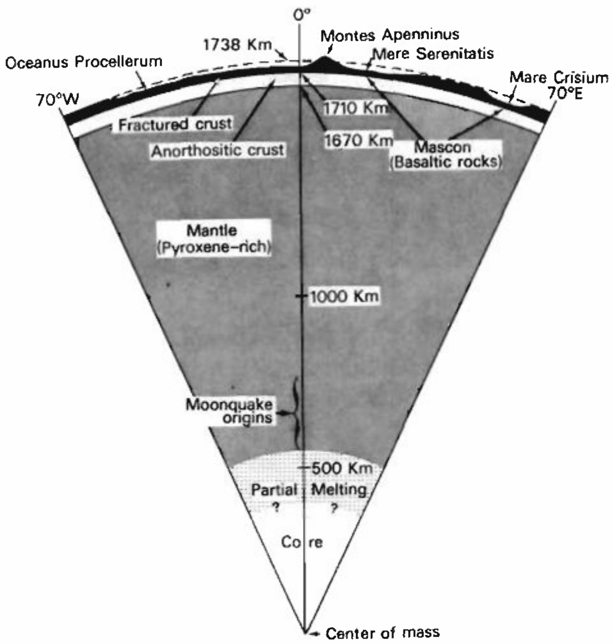

Figure 15. Diagram drawn to scale of the lunar interior based on inferences from seismic data. It shows a crust 65 km thick, with a highly fractured upper 25 km; a mantle 1100 km thick; and a core that is either partially molten or includes a molten zone. (After El-Baz[10].)

core exists. However, a molten or partially molten zone or core below about 1100 km from the surface is probable. It may be significant that moonquake origins are focused between 800 and 1100 km deep, a region of probable interaction between the solid mantle and a molten or partially molten zone or core.

Origin of the Moon

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. It was even believed that in the lunar materials were the records of the birth of the Sun. The Moon was described by some as 'The Rosetta Stone of the Solar System.' This did not happen. As discussed above, the primitive lunar crustal materials have been subjected to much metamorphism due to large impact events. These monumental events have erased the records of the Moon's birth.

Any theory for the origin of the Moon must be consistent with what we know about the Earth and the solar system, as well as about the Moon itself. Most importantly, any proposed mechanism must explain the great age of the Moon, 4.6 thousand million years, the same as Earth, and the differences in composition between the Earth and Moon.[38]

Today, the theories or models for the origin of the Moon may be divided into three general classes. The Moon is either Earth's wife, captured from some other orbit; daughter, fissioned directly from the Earth; or sister, accreted from the same cloud of dust as the Earth.

The capture theories propose that the Moon formed elsewhere in the solar system, or even beyond and that from an orbit that passed close to that of the Earth, the Moon was slowed down and captured into an orbit about the Earth. With the Moon a captive body, the differences in chemical composition between the Earth and Moon are easily explained. However, in order for it to be captured, the Moon would have to be in a very special orbit and, even then, to be slowed to nearly match the orbital speed of the Earth. The forces needed to slow the Moon would raise great tides in it and in the Earth. This, some scientists argue, would shatter the Moon to bits. At any rate, no record of the inevitable cataclysm of capture can be found in the rocks of either the Moon or Earth.

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 has received some support in recent years. The 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 the 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 the heavier elements. However, dynamic considerations similar to those considered in the capture case also apply to the formation of the Moon by fission. Even if the Earth had turned fast enough and was hot enough to spin off a large chunk, the newborn Moon could not have had the strength to resist being torn apart.

The third alternative, binary accretion, is that the Moon and Earth formed together in orbit about the Sun at the same time and from the same cloud or ring of debris left over from the formation of the solar nebula. The theory proposes that the two bodies would have formed with their own distinctive chemistry. It also explains the rarity of volatile elements in the lunar materials, which would have been lost by the heat of rapid accretion. Because of this, and because the theory requires the least number of assumptions in terms of dynamics, this is the most popular of the three theories. However, binary accretion is not without faults that many theorists find objectionable.

Thus, the three basic theories of lunar origin 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. Today we still must say that the Moon was formed in a manner and a place that we have yet to determine. Based on theory alone, it has been said that the Moon should not be there at all.

FUTURE EXPLORATION

The lunar exploration missions have changed the Moon from an unknown place to a familiar world. Our knowledge of the Moon evolved through the findings of the Ranger, Surveyor, Lunar Orbiter, Zond, Luna and Apollo missions. However, the latter provided the most tangible amounts of data. Our understanding of the Moon grew systematically and chronologically from the rich harvest of rocks and soil as well as from remotely sensed information gathered by the Apollo astronauts and their machines.

From all the data that were gathered on the lunar exploration missions we have learned the following basic facts:

(1) The lunar samples indicate that the Moon has never hosted any life forms of any kind. The samples also indicate that the lunar surface was never covered by water. However, we cannot rule out the possibility of some water trapped as ice in the permanently shadowed areas near the poles.

(2) The Moon is made up of the same chemical elements as 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 occurred in the outer layers of the Moon, to a depth of at least 100 km, most probably 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. The basalts are the products of internally generated volcanic melts that spread on the surface during a period lasting about 700 million years (between 3.8 and 3.1 thousand million 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 its surface. 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 much of the 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 1783 km. Also, the center of mass is shifted about 2 km towards the Earth relative to the center of the figure.

(8) There is also asymmetry in natural γ-ray radiation on the Moon. Pockets of radioactive materials are concentrated on the western near side; only a small anomaly in the vicinity of the crater Van de Graff exists on the studied part of the lunar far side.

(9) The Moon is probably layered into a crust, about 65 km on the near side and possibly thicker on the far side; a solid mantle, about 1100 km thick; and a 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 evidence for a final conclusion regarding the origin of the Moon.

It has been over six years since the last Apollo mission visited the Moon and as stated above, the scientific returns from the US lunar exploration program exceeded those from the Soviet program. However, the US program ended with Apollo 17, and the USSR program continues to this day. This comparison shows a characteristic trend in the programs of both countries. The United States' plans include spectacular programs with enormous returns that abruptly end with few follow-up plans. The Soviet Union, on the other hand, pursues a slow, but steady, step-by-step progress with many failures, but with a continuity that may be very significant in the long run.

Although the Soviet Union has sent three successful missions to the Moon since Apollo 17 (Table 1), the United States has no firm plans for future lunar exploration. NASA's own plans in this field are unclear. However, a proposal by lunar scientists has gained much support recently. This proposal is to launch a 'Lunar Polar Orbiter',[39] an unmanned probe that will expand our present knowledge to the entire lunar surface; at this time, orbital data coverage encompasses less than 20% of the Moon.

From data gathered during the past decade, we are now able to specify the gaps in our knowledge and the best ways and means of filling them. Pre-Apollo orbital spacecraft and Apollo orbital experiments have surprised us with sometimes unexpected results. Two particular examples are the extreme variations in the lunar gravitational field, discovered only after a review of tracking data for the Lunar Orbiter spacecraft in polar orbit; and the existence of a very weak magnetic field. These and many other scientific findings in the mid-latitude regions of the Moon have allowed us to speculate on the composition and physical properties far from the equator. The available data, however, do not provide the means for testing these hypotheses. What the lunar scientific community requires is a better understanding of areas outside the Apollo coverage.

This may allow the extrapolation of knowledge gained by the Apollo missions to the whole Moon.

The Lunar Polar Orbiter will provide the required data. It will take an interdisciplinary approach to gathering information on the entire lunar surface. Sensors aboard this mission will transmit multispectral, stereo images to map interesting regions and to distinguish rock composition including the concentration of titanium and iron. Geochemical spectrometers and other sensors will map the ratios of major elements such as aluminum, silicon and magnesium; the concentration of radioactive elements such as thorium, uranium and potassium; and the mineralogical species of the lunar rocks.

In addition, the Lunar Polar Orbiter will consist of the main spacecraft and a subsatellite that will monitor the larger craft as it circles the far side to provide gravity data. The subsatellite itself will also supply data on the gravitational field. Other sensors will collect data on the lunar magnetic field, internal heat flow, and thermal emission.

Gathering data in these ways can be considered a resource survey. In this context the Lunar Polar Orbiter is to the Moon what Landsat is to the Earth. This becomes important if we consider the possibility of utilizing lunar materials in future space endeavors, for example if a solar energy station is to be erected in space. The Lunar Polar Orbiter will allow resource evaluation of the lunar materials. These resources may include metals that can be extracted from the lunar soil, such as titanium, and water that may be frozen as ice in the permanently shadowed polar regions.

The Lunar Polar Orbiter can also be looked at as a precursor to future missions to the inner solar system, particularly Mars and Mercury. The mission will utilize a spacecraft that can be modified to fit the needs of planetary exploration. In this respect, additional lunar data will augment our knowledge of all the terrestrial planets and provide a basis for comparative planetology.

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