Chapter 1

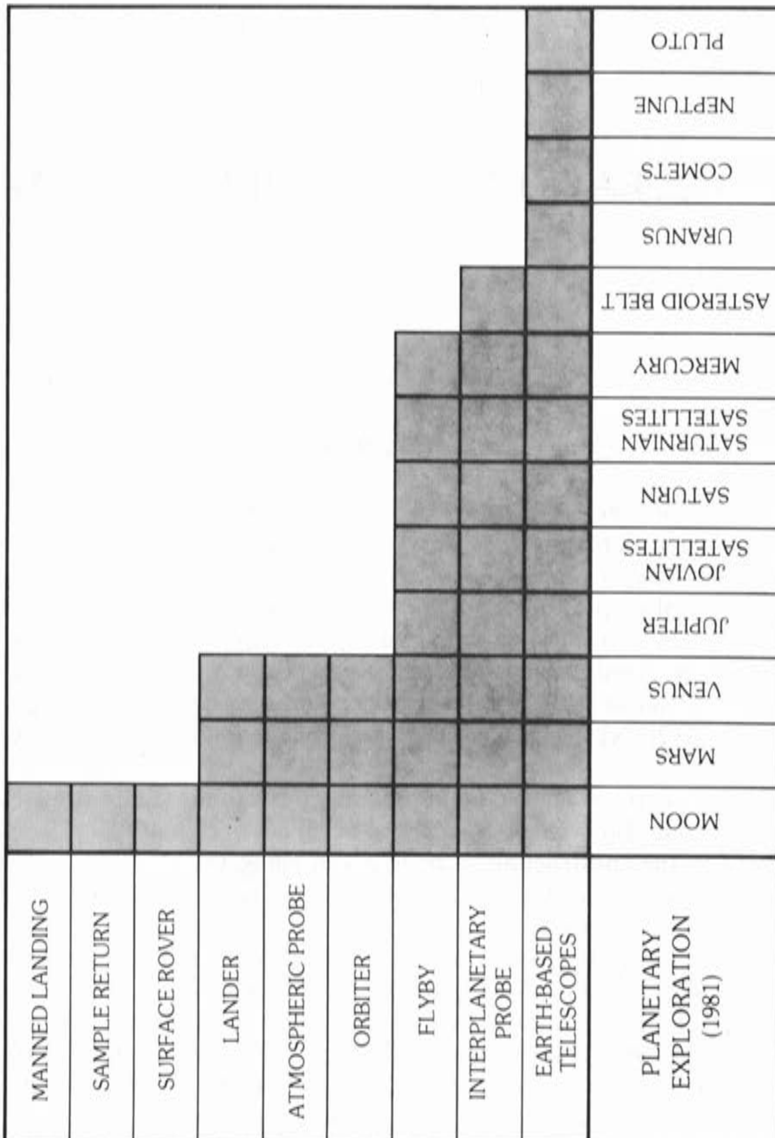
THE EXPLORATION OF THE SOLAR SYSTEM

1.1 Early Influences

In 1419, Henry the Navigator (1394–1460) founded, at Sagres on the southwestern tip of Portugal, what we would now call an Institute of Maritime Research. This date conveniently marks the commencement of the heroic age of oceanic exploration and of our understanding of the geography of this planet. Under Henry's sponsorship, the Portuguese captains discovered the Canary and Cape Verde Islands and sailed as far south as Sierra Leone, dispelling medieval terrors that the edge of the world lay just south of Cape Bojador (latitude 26° N), which accordingly marked the southern limit of safe navigation [1].

This exploration was made possible not only through the administrative skills of Henry but also because of technical advances in ship design. These advances led to the construction of truly ocean-going vessels such as the caravel, and to improvements in navigational devices, of which the magnetic compass was the most important.

We are now at an analogous stage in history. The advances in technology, which have resulted in rockets, spacecraft, computers and rapid data transmission have, in two or three decades, enabled an unparalleled exploration of the solar system. This has opened perspectives so new that we are still endeavoring to assimilate and comprehend the information. The present state of planetary exploration is shown in Fig. 1.1. This figure emphasizes the fact that we have orders of magnitude less information for each successive planet or satellite, knowing most about the Moon, but almost nothing about Pluto. This book reflects our current state of knowledge which is heavily influenced by the extensive lunar data. We are more fortunate now than in our studies of the planets in pre-Apollo time, when all our direct experiences and analogies were confined to the Earth.



1.1 The current status of exploration of the solar system. The amount of information increases by orders of magnitude for each step upwards on the vertical scale.

For example, our experience in dating surfaces by crater counting techniques, although well understood by some workers, was so insecurely based or accepted that estimates varying by orders of magnitude appeared in the literature as late as 1969. Such uncertainties persist as we voyage toward the outer reaches of the solar system, where the meteorite flux rates become less well understood [2].

The scientific exploration of the solar system represents the culmination of a process whose roots go back to the earliest stages of human thought and development. The strange motions of the planets, wandering among the fixed stars, the monthly waxing and waning of the Moon, the cycles of the seasons, the occasional occurrences of eclipses, and the apparition of comets provided an incentive to record and understand all those celestial events.

In this context the Moon, as the closest and most obviously variable heavenly body, has played a dominating role [3]. Tantalizingly out of reach to poets and princesses alike, its features are sufficiently intriguing to stimulate not only myth-making and the production of calendars, but also the construction of telescopes and spacecraft.

1.2 Lunar Sampling

Six Apollo missions returned a total of 382 kg of rocks and soil from the Moon. Three Russian unmanned landers brought back 250 gm (see Table 1.1 for details of the lunar landings and Table 1.2 for a listing of successful planetary missions). Various questions arise from these visits: (a) Was the sampling adequate? (b) How much can we tell about the Moon from nine suites of samples? (c) Were the manned landings necessary [4,5]?

The sampling sites for the lunar missions are shown in Fig. 1.2. The Apollo 11 mission collected 22 kg rather hurriedly within about 30 m of the Landing Module (LM). This first landing on that distant and alien shore was brief. The accessible surface, the regolith, contained rocks excavated by meteorite impacts of varying depths from the local mare basalts; bedrock in the terrestrial sense lay several meters deeper. The ubiquitous debris blanket—the regolith—however, mirrors with reasonable faithfulness the local bedrock so that extended field work in many different sites was a useful and productive exercise. The development of a lunar vehicle, the Rover, enabled the astronauts to traverse distances up to 20 km on Apollo missions 15, 16 and 17. Accordingly, detailed collecting of specialized samples from differing terrains became possible, particularly since precise navigation (Fig. 1.3) enabled landings to be carried out in narrow valleys (e.g., Apollo 15 at Hadley-Apennines and Apollo 17 in the Taurus-Littrow region) adjacent to mare-highland boundaries. These achievements enabled the collecting of samples which reasonably can be related to various mappable formations.

Table 1.1 Lunar exploration by spacecraft.

Successful Pre-Apollo Lunar Landings

Spacecraft	Date	Landing site	Data returned
Ranger 7	August, 1964	Mare Cognitum	Photographs
Ranger 8	February, 1965	Mare Tranquillitatis	Photographs
Ranger 9	March, 1965	Crater Alphonsus	Photographs
Luna 9	February, 1966	Western Oceanus Procellarum	Photographs
Surveyor I	June, 1966	Oceanus Procellarum, north of Flamsteed	Photographs
Luna 13	December, 1966	Western Oceanus Procellarum	Photographs; soil physics
Surveyor III	April, 1967	Oceanus Procellarum (Apollo 12 site)	Photographs; soil physics
Surveyor V	September, 1967	Mare Tranquillitatis (25 km from Apollo 11 site)	Photographs; soil physics; chemical analyses
Surveyor VI	November, 1967	Sinus Medii	Photographs; soil physics; chemical analyses
Surveyor VII	January, 1968	Ejecta blanket of Crater Tycho (North Rim)	Photographs; soil physics; chemical analyses

Apollo Lunar Landings

Mission	Landing Site	Latitude	Longitude	EVA duration (hours)	Traverse distance (km)	Date	Sample Return (kg)
11	Mare Tranquillitatis	0°67′N	23°49′E	2.24	—	July 20, 1969	21.7
12	Oceanus Procellarum	3°12′S	23°23′W	7.59	1.35	Nov. 19, 1969	34.4
14	Fra Mauro	3°40′S	17°28′E	9.23	3.45	Jan. 31, 1971	42.9
15	Hadley-Apennines	26°06′N	3°39′E	18.33	27.9	July 30, 1971	76.8
16	Descartes	8°60′S	15°31′E	20.12	27	April 21, 1972	94.7
17	Taurus-Littrow	20°10′N	30°46′E	22	30	Dec. 11, 1972	110.5

Russian Lunar Sample Missions

Mission	Landing site	Latitude	Longitude	Date	Sample Return (grams)
Luna 16	Mare Fecunditatis	0°41′S	56°18′E	Sept. 1970	100
Luna 20	Apollonius highlands	3°32′N	56°33′E	Feb. 1972	30
Luna 24	Mare Crisium	12°45′N	60°12′E	Aug. 1976	170

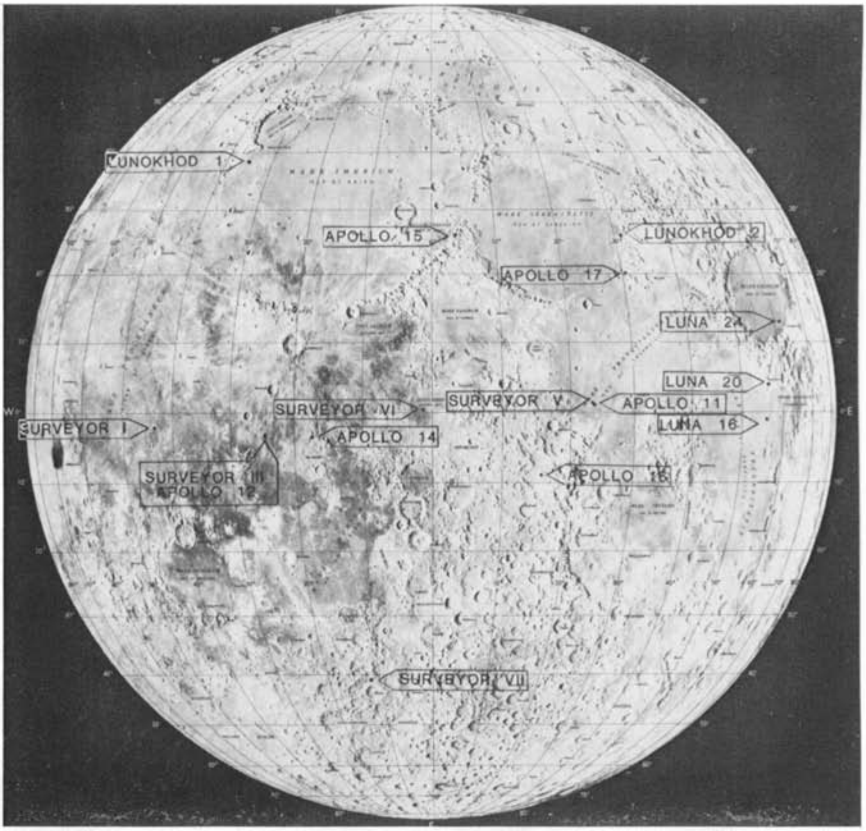
Russian Lunar Traverse Vehicles

Vehicle	Landing site	Date	Traverse Length
Lunokhod 1 (Luna 17)	Western Mare Imbrium	Nov. 1970	20 km
Lunokhod 2 (Luna 21)	Le Monnier Crater, Eastern Mare Serenitatis (180 km north of Apollo 17 site)	Jan. 1973	30 km

Table 1.2 Planetary exploration.†

Mission	Launch Date	Target	Encounter Date
Pioneer 5	March 1960	Interplanetary	—
Mariner 2	August 1960	Venus flyby	Dec. 1962
Mariner 4	Nov. 1964	Mars flyby	July 1965
Pioneer 6	Dec. 1965	Interplanetary	—
Pioneer 7	August 1966	Interplanetary	—
Venera 4	June 1967	Venus landing	Oct. 1967
Mariner 5	June 1967	Venus flyby	Oct. 1967
Pioneer 8	Dec. 1967	Interplanetary	—
Pioneer 9	Nov. 1968	Interplanetary	—
Venera 5	Jan. 1969	Venus landing	May 1969
Venera 6	Jan. 1969	Venus landing	May 1969
Mariner 6	Feb. 1969	Mars flyby	August 1969
Mariner 7	March 1969	Mars flyby	August 1969
Venera 7	August 1970	Venus landing	Dec. 1970
Mars 3	May 1971	Mars landing	Dec. 1971
Mariner 9	May 1971	Mars orbit	Nov. 1971
Pioneer 10	March 1972	Jupiter flyby	Nov. 1973
Venera 8	March 1972	Venus landing	July 1972
Pioneer 11	April 1973	Jupiter	Nov. 1974
		Saturn	Sept. 1979
Mars 5	July 1973	Mars orbit	March 1974
Mariner 10	Nov. 1973	Venus flyby	Feb. 1974
		Mercury flyby	March, Sept. 1974 March 1975
Helios	Dec. 1974	Sun approach	—
Venera 10	June 1975	Venus landing	Oct. 1975
Viking 1	August 1975	Mars landing	July 1976
Viking 2	Sept. 1975	Mars landing	Sept. 1976
Helios 2	Jan. 1976	Sun approach	—
Voyager 2	August 1977	Jupiter	July 1979
		Saturn	August 1981
		Uranus	Jan. 1986
Voyager 1	Sept. 1977	Jupiter	March 1979
		Saturn	Nov. 1980
Pioneer Venus 1	May 1978	Orbiter	Dec. 1978
Pioneer Venus 2	August 1978	multiprobe	Dec. 1978
Venera 11	Sept. 1978	Venus flyby and probe	Dec. 1978
Venera 12	Sept. 1978	Venus flyby and probe	Dec. 1978

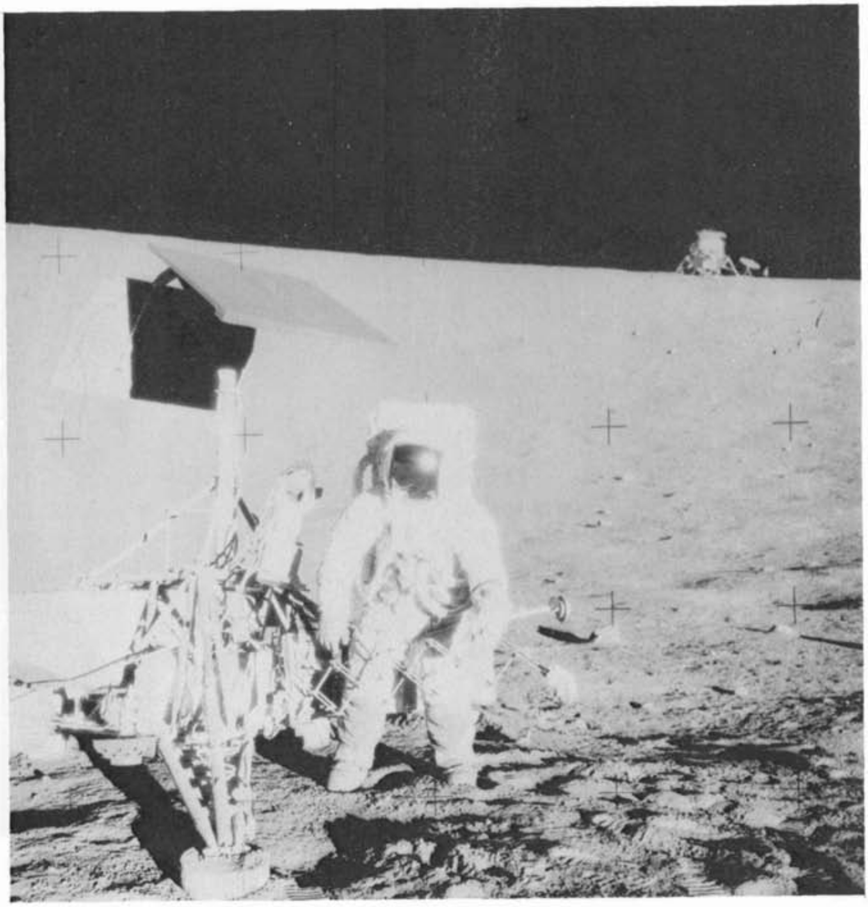
†Mariner, Pioneer, Viking and Voyager were US missions. Helios was a joint US/Federal Republic of Germany mission, and Mars and Venera were USSR missions.
Note: Only successful missions are listed.



1.2 Surveyor, Apollo, Luna and Lunokhod landing sites on the Moon.

The sampling was thus adequate for us to obtain a first order appreciation of the nature of the lunar surface and of the varying stratigraphic relationships. The limited number of missions has raised a number of detailed stratigraphic problems whose resolution can only be achieved by further missions. Such problems include the evolution of the early highland crust and the detailed sequence of the gigantic basin collisions—pressing intellectual questions of much significance for the early history of the solar system.

In this book, the claim is made that the data from the nine lunar missions provide a key to unlock both lunar evolutionary history and to shed light on the restricted and circumscribed information from the other planets and satellites. This claim would not be valid for the Earth where no combination of three spot samples and six from areas of a few square kilometers could, without hindsight, have led to a synthesis of terrestrial geological processes.



1.3 Astronaut Pete Conrad at the Surveyor III lander, during the Apollo 12 mission. The Lunar Landing Module is in the background.

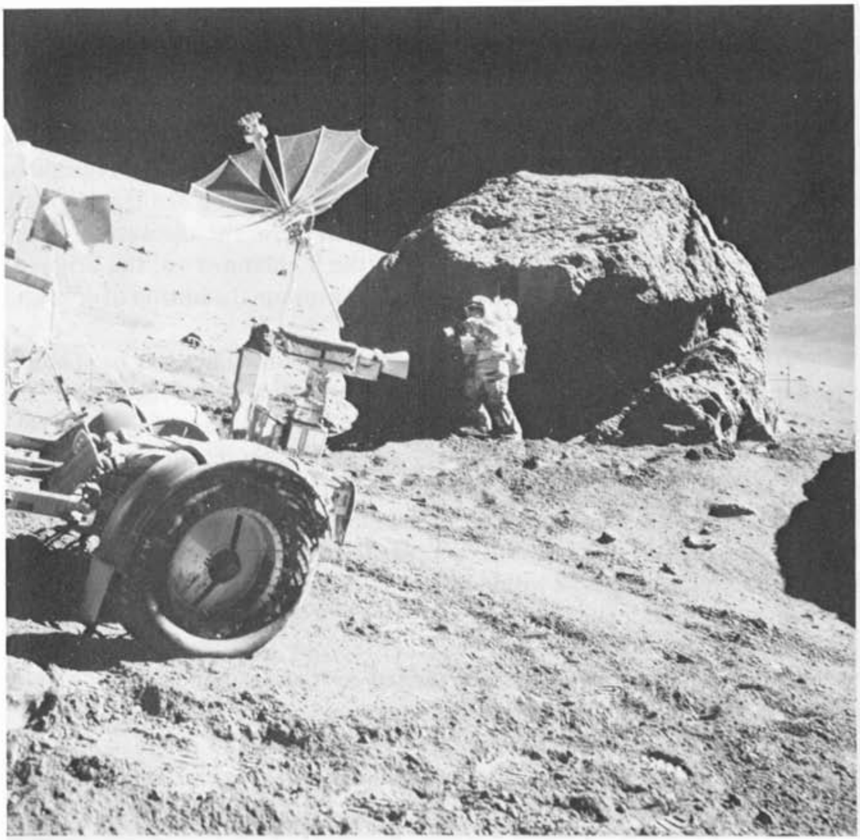
The overall geology of the Moon is much simpler, with a basic two-fold division into the dark maria and the highlands. Sampling of the basalts has yielded about 20 varieties, but these are related by reasonably well-understood variations in chemistry. An important conclusion is that they are not all uniform, but indicate some heterogeneity, again within our comprehension, deep in the lunar interior.

The samples from the highlands were so smashed up by the early bombardment of the Moon that traces of the original crust are exceedingly difficult to identify. Nevertheless, the chemical composition survives to tell its tale of these events, close in time to the formation of the solar system. The moon-wide nature of these events lends special significance to the correlation of the surface sampling both with the photogeological mapping and remote-sensing data and with the orbital geochemical values obtained from XRF and gamma-ray experiments. The integration of all this information enables us to relate the surface sampling to the broad lunar perspective established by stratigraphic procedures. We are thus able to construct models, with the aid of the vital ages established on the returned samples, which are tantalizingly close to final answers. The question of a lunar core, the resolution of the magnetic puzzles, the detailed evolution of the highland crust, the origin of KREEP, and some other problems, await only a minimal addition of data and samples from future lunar missions.

Although manned exploration of the Moon sometimes has been considered superfluous, it was crucial to a proper understanding of the Moon. The reason lies in the nature of the lunar surface (and of the surfaces of other bodies which lack atmospheres). An automated sample return, in the current state of technology, obtains a small drill core of soil hopefully with a few rock fragments. Only our experience with the lunar samples enables us to extract correct information from such a sample. If our lunar sampling had been restricted to such material it would have been difficult and perhaps impossible to discern the true story. The lunar soil is a complex mixture, formed by the prolonged meteoritic bombardment of the lunar surface over a period of three to four aeons. The rock samples collected by the astronauts enable us to investigate the individual components of the mixture (Fig. 1.4).

The most critical observation was that of the age of the material. The basaltic rocks from the initial landing site had clearly established crystallization ages of 3.6–3.8 aeons. The complicated soil mixtures indicated *model* Rb-Sr ages of around 4.5 aeons, close to the accepted age for the formation of the solar system. This paradox was understood to result from a combination of a primordial differentiation of the basaltic source regions at about 4.4 aeons, and a small separation of Rb from Sr during the formation of the basaltic magma at the younger epoch. Thus the soils recorded the earlier event [6]. The redistribution of volatile Rb during meteorite impacts led to some apparent ages in excess of 5 aeons, while the addition of exotic components such as KREEP, rich in Rb or anorthosite with primitive $^{87}Sr/^{86}Sr$ ratios, all contributed to confuse the story. If the total lunar sample had been only a few grams, it might have been impossible to disentangle the true age sequences. An alternative scenario, difficult to disprove, would have compressed the entire lunar evolutionary story (formation of the highland crust, meteoritic bombardment and basaltic eruptions) into a time span of 100–200 million years producing a catastrophic picture of early planetary evolution, as misleading to planetology as the phlogiston theory was to chemistry.

Now, with the skill and experience obtained from lunar sample studies, it is possible to extract information from a few grams of soil and rock fragments



1.4 Astronaut Harrison H. (Jack) Schmitt collecting samples during the Apollo 17 mission.

as was demonstrated by the studies of the samples from Luna 16, 20 and 24. But these skills were not easily acquired. Faced with a minute amount of sample, two problems arise: (1) Which problems shall be attacked, and (2) which laboratories shall carry out the analyses? It was by no means clear in 1969 that the age and isotopic results, closely followed by the trace element chemistry, would provide the most significant information. The allocation of over 2 kg of sample for biomedical testing indicates a differing set of priorities, a scenario repeated in the Viking missions to Mars.

It was also not clear in 1969 which scientific teams possessed or would develop the highest skills, for who "can look into the seeds of time, and say which grain will grow and which will not" [7]. The scientific community is reluctant to accept one result from one laboratory as the ultimate truth. One of the great benefits from the large amount of sample available from the Apollo missions, and of the enlightened policy of distribution established by NASA, has been the formation of a new science of planetology, comprising a scientific community rich in expertise, self-checking and self-regulating which contains many individuals, unknown in 1969, who have made significant contributions to our understanding. It has also been found that high quality scientific work can be carried out rapidly without loss of precision, accuracy or understanding [8]. It is to be hoped that the administrative successors to Henry the Navigator, will ensure the survival of this unique asset, in a society which shows some signs of relapsing into medieval patterns of thought.

Accordingly, the manned missions saved us from probable errors of interpretation and, with hindsight and experience, we now are capable of extracting significant information from a small sample return. The Viking experience on Mars, however, warns us that a soil sample from that planet is unlikely to contain useful rock fragments, but is more likely to resemble a wind-blown desert sand. Accordingly, some device for breaking off pieces of the abundant rocks—coupled with surface mobility extending to kilometer ranges at least—is required for a Martian sample return. Possibly, we may see an advancement in mass spectrometric techniques that will enable us to obtain reliable ages by remote sampling, but the experience even with a relatively straightforward technique such as X-ray fluorescence in obtaining chemical information from Mars illustrates the difficulties. The biological experiments indicate the problems in interpreting unusual or unexpected data in a mini-laboratory on a distant planetary surface [9].

A further question, which can be addressed with hindsight, is whether the Apollo sites and sampling techniques could have been different. The experience gained in the early missions was in practice rapidly incorporated into successive visits. The walking traverses of Apollo 11 and 12 were supplemented by a hand-drawn cart resembling a golf buggy, on Apollo 14, and by the roving vehicles on the final three missions. Each carefully selected site provided unique samples. In retrospect, more attention to magnetic and heat-flow measurements earlier in the missions would have provided useful information, but the major gaps would have been filled by the three cancelled missions. Most damage was done by the premature termination of the landing program and the decision to turn off the ALSEP experiments on September 30, 1977, when many instruments were still recording data [10]. The seismic data from one large impact on the far side on July 17, 1972, provided not only unique information about the lunar interior, but also the expectation of further such events. The most useful immediate information can now be gained from a polar orbiter, providing a moon-wide picture of the surficial distributions of the radioactive elements, the variations in Al/Si ratios in the highlands, the mapping of the differing mare basalt types, and the moon-wide variations in surface magnetism.

1.3 The Moon and the Solar System

In a celebrated comment, Newton said that if he saw further, it was because he stood on the shoulders of giants [11]. The Moon provides us with an analogous platform from which to comprehend the other planets and satellites.

The first, and possibly the most critical advantage, is that it provides us with a well-established stratigraphic sequence, to which an absolute chronology may be fixed by the radiometric dating of the returned samples. Such information, discussed in the next chapter, enables us to apply similar reasoning to the less accessible surfaces of other planets and satellites. This concept is of particular importance because of the ubiquitous evidence of extensive early cratering throughout the solar system. The cratering question has had a long and varied history, hampered by our experience of living on the surface of a planet from which most of the record has been erased. The efficiency of terrestrial erosion indeed made it difficult for the scientific community to recognize and accept impact processes. As T. H. Huxley remarked, "it is the fate of new truths to begin as heresies." Even now, vestiges of alternative internally generated processes appear [12], although the mineralogical evidence for instantaneous shock pressures exceeding 500 kbar at impact sites has removed internal volcanic explanations from consideration [13].

As discussed in Chapter 3, the Moon provides us with sequences of crater forms only dimly perceived on Earth. The great lunar craters have always excited interest. The recognition of the existence of a larger class of multi-ring basins, with diameters reaching thousands of kilometers, was a product of detailed lunar mapping and has provided critical evidence for the existence of large objects up to several hundred million years after the formation of the planets. This early bombardment record is interpreted to provide evidence in support of the planetesimal hypothesis for planetary growth. One lesson which has become apparent from the studies of the giant multi-ring basins, and of the large size of Martian canyons and volcanoes, is that much of our comprehension of geological processes based on terrestrial experience has been on too small a scale. Indeed, Sir William Hamilton perceived this truth in 1773 when he commented, after many years of observations of Mt. Vesuvius, that "we are apt to judge of the great operations of Nature on too confined a plan" [14]. Much of terrestrial geology, examined in road cut, drill core or thin section does encourage the development of expertise in the minutae of geology. In this context, the plate tectonic revolution was wrought by ocean-going geophysicists, perhaps accustomed to wider horizons, than by land-based stratigraphers and paleontologists.

The Moon has provided vital information on the nature of surfaces developed on rocky planets in the absence of atmospheres. Early ideas that the mare basins contain kilometer thicknesses of fine dust were dispersed by the

Surveyor evidence of a firm cohesive surface. The debate over the presence of water on the lunar surface was resolved only after the Apollo sample return. In this context, the mineralogical evidence in the large rock samples returned by the astronauts provided decisive evidence of a dry Moon in a way that the fine-grained, often glassy soils could not [15]. Among many other features of the lunar surface discussed in Chapter 4 is the possibility of establishing the long term history of the sun.

The nature and origin of differentiated crusts on planets was illuminated by the lunar missions. Early geochemical thinking had considered the Moon to be a primitive object, captured into Earth orbit and resembling the carbonaceous chondrites in composition (the Martian satellites, Phobos and Deimos, are probably examples of such objects). It will become apparent to readers of this book that the Moon has provided us with much more information than if it had been a large carbonaceous chondrite. The highly differentiated lunar crust was a surprise to most lunar workers and stimulated thinking in general about early planetary models. Clearly, if one had to produce a strongly chemically fractionated crust close on the heels of accretion of the planet [16], then considerable deviations from formerly accepted models of planetary formation were called for. Decisive evidence of the operation of crystal-liquid fractionation, rather than of gas-solid condensation processes, as described in Chapter 5, indicated early moon-wide melting processes. The feldspathic crust of the Moon, generated by flotation during crystallization, stands in great contrast to either the oceanic or continental crusts of the Earth, generated by varying episodes of partial melting from the mantle. Although the lunar highland crust bears a superficial resemblance to the terrestrial continental masses, the distinction in origin reminds us that each planet may be unique. The Mercurian crust may be closest to that of the Moon, but the differing densities and bulk compositions must engender caution until we have more geochemical and petrological data. Mars and Venus present different aspects of crustal genesis, so far as we can judge from the available evidence. The surfaces of the satellites of Jupiter and Saturn, lately revealed for our curious inspection, provided so many surprises that "the sense of novelty would probably not have been greater had we explored a different solar system" [17]. The tendency of solar system bodies to develop crusts distinct from their bulk composition by processes possibly unique in detail for each body provides a major stimulus to develop theories of planetary evolution.

Basaltic eruptions have long been familiar on the Earth [18], although their full extent was only realized with the discovery of the mid-oceanic ridges and of the basaltic composition of the oceanic crust. The lunar maria constitute a second example of the widespread occurrence of lavas generated by partial melting deep within planetary mantles. The Moon provided examples which indicated that terrestrial petrological experience was not all-embracing.

The surprising differences in titanium enrichments and europium depletions from familiar terrestrial lavas provided evidence for differing evolutionary histories for lunar and terrestrial mantles. The isotopic systematics told of extensive early differentiation of the Moon, while the trace elements revealed the complementary nature of the highland crust and the deep source regions of the mare basalts. The early assumptions that the lunar interior, in so far as it is sampled by the basaltic lavas, might be primitive, and so yield the bulk composition of the planet, gave way to models of zoned mantles of varying mineralogy (Chapter 6). These scenarios contrast strongly with our models of the terrestrial mantle. Accordingly, we must expect surprises from Martian lavas, even though Olympus Mons has a profile resembling that of Mauna Loa. The composition of basalts and possibly even of granites on Venus, for which the Venera gamma-ray data for K, U, and Th hold promise, is likely to provide unique information on the internal constitution of that planet. Basaltic volcanism on Mercury remains an enigma.

The state of planetary interiors, as discussed in Chapter 7, illustrates just how many data are needed to make unique interpretations from the geophysical data. We lack adequate resolution from the lunar seismic experiments [10] to decide whether the Moon has a core, and to pass judgement on the reality of discontinuities within the lunar mantle. The heat-flow data suffers from having only two measurements, although the frustrations of geochemists have been tempered somewhat by the realization that the bulk uranium content of a planet is not a simple function of the heat flux. The magnetic evidence has proven perplexing, but an understanding is slowly being reached with the development of techniques for preserving the magnetic memory of the sample (carried by fine-grained iron) in a wet oxidizing terrestrial atmosphere.

It is sometimes considered surprising that geochemists are bold enough to construct tables of planetary composition from a few basic parameters. As discussed in Chapter 8, various interlocking sets of constraints from isotopic and element ratios, coupled with the observation that planetary compositions differ in their contents of refractory, volatile and siderophile elements, enables a large degree of internal self-consistency to be achieved in these estimates. When integrated with geophysical parameters such as density, moment of inertia, magnetic properties and mantle structures revealed by seismology, significant statements can be made about bulk planetary compositions to an extent not possible before the lunar missions. The data from the meteorites, in all their complexity, are relevant to our understanding of much of early solar system history. The study of the lunar samples has shed much light on meteoritic problems, formerly so intractable that a distinguished geochemist, in 1965, pronounced the chemical evidence in the meteorites to be unreadable [19].

Chapter 9 addresses the basic intellectual question of the origin of the planets in the light of the evidence assessed in this book. A sober reading of the literature on this topic over the past three decades since the appearance of *The Planets* by Harold Urey might daunt the most accomplished reviewer, but progress in realistic scenarios and reduction in the numbers of free parameters is occurring rapidly. Although it is conventional to lament the complexity of modern knowledge and the difficulty of obtaining an overview, it should be recalled that the Renaissance scientists, often envied for working in a supposedly simpler situation, had to comprehend the complexities of medieval thought, if only to dismiss such topics as alchemy and astrology from rational consideration.

References and Notes

1. The Institute at Sagres was destroyed in 1587 in a raid led by Francis Drake, designed to disrupt preparations for the attack by the Spanish Armada. [Mattingly, G. H. (1959) *The Defeat of the Spanish Armada*, Jonathan Cape, London.]
2. See, for example, the controversy over the ages of Martian features. [Neukum, G., and Hillier, K. (1981) *JGR*. 86: 3097.]
3. The influence of the Moon on primitive art is illustrated with many beautiful photographs in Bedini, S. A., et al. (1973) *Moon*, Abrams, N.Y.
4. The traverses and details of sample collecting are described in the following sources: Apollo 11: LSPET (1969) *Science*. 165: 1211; NASA SP 214 (1969); NASA SP 238 (1971); USGS Map I-619 (1970); Beaty, D. W., and Albee, A. L. (1980) *PLC 11*: 23. Apollo 12: LSPET (1970) *Science*. 167: 1325; NASA SP 235 (1970); USGS Map I-627 (1971).
   Apollo 14: USGS Apollo Geology Team (1971) *Science*. 173: 716; NASA SP 272 (1971); USGS Map I-708 (1970).
   Apollo 15: USGS Apollo Geology Team (1972) *Science*. 175: 407; NASA SP 289 (1972); USGS Map I-723 (1971).
   Apollo 16: USGS Apollo Geology Team (1973) *Science*. 179: 62; NASA SP 315 (1972); USGS Map I-748 (1972); USGS Prof. Paper 1048 (1981).
   Apollo 17: USGS Apollo Geology Team Report (1973) *Science*. 182: 672; NASA SP 330 (1973); USGS Map I-800 (1972).
5. The lunar sample numbering system is described in Appendix IX.
6. Wetherill, G. W. (1971) Of Time and the Moon, *Science*. 173: 383.
7. Shakespeare, W. (1606) *Macbeth*, Act 1, Scene III (comment by Banquo to the three witches on the blasted heath).
8. Creative work can be accomplished in brief time scales, contrary to popular wisdom. Thus Handel wrote the Messiah between August 22 and September 14, 1741. Mozart produced his three final symphonies (No. 39 in E flat, K 543 ; No. 40 in G minor, K 550; and No. 41 in C minor, K 551) within a period of two months (early June–August 10, 1788). The G minor symphony has been considered by at least one critic to provide sufficient justification for the existence of Homo sapiens [Einstein, A. (1957) *Mozart: His Character, His Work*, 3rd ed., Cassell, London].
9. See Cooper, H. S. F. (1980) *The Search for Life on Mars*, Holt, Rinehart, and Winston, N.Y., for a readable account of these problems. See also Soffen, G. A. (1981)

Chapter 9 in *The New Solar System* (eds. Beatty, J. K., et al.), Sky Publishing, Cambridge, Mass.

10. Bates, J. R., et al. (1979) ALSEP Termination Report. NASA Ref. Pub. 1036. This publication provides a description of the Apollo Lunar Surface Experiments Package (ALSEP) for Apollo missions 11–17, of their operational history, and of the significant scientific results.
11. Letter to Robert Hooke, Feb. 5, 1675.
12. See introduction in Roddy, D. J., et al., eds. (1977) *Impact and Explosion Cratering*, Pergamon Press.
13. Such overpressures cannot be built up at shallow depths in the crust where the confining pressure at 40 km is only 10 kbar.
14. Hamilton, W. (1773) *Observations on Mt. Vesuvius, Mt. Etna and other Volcanoes*, T. Cadell, London, p. 161. This is one of the first modern works on volcanology. This distinguished naturalist is, alas, better known to history as the husband of Emma, Lady Hamilton.
15. A sample of terrestrial desert sand could be so used to infer the absence of water on Earth.
16. The Moon is commonly referred to as a planet in this text. The large size of the satellite relative to the primary justifies consideration as a double planet system. In addition, as suggested by one worker, it makes for simpler sentences.
17. Smith, B. A., et al. (1979) *Science*. 204: 951.
18. The igneous nature of basalt was demonstrated by James Hall (1805); See Lofgren G. E., in Hargraves, R. B. (1980) *Physics of Magmatic Processes*, Princeton, Chap. 11.
19. A recent review by J. V. Smith [(1982) Heterogeneous accretion of meteorites and planets especially the Earth and Moon. *J. Geol.*, in press] provides an excellent, if brief, statement of the significance of the meteoritic evidence, and much else.