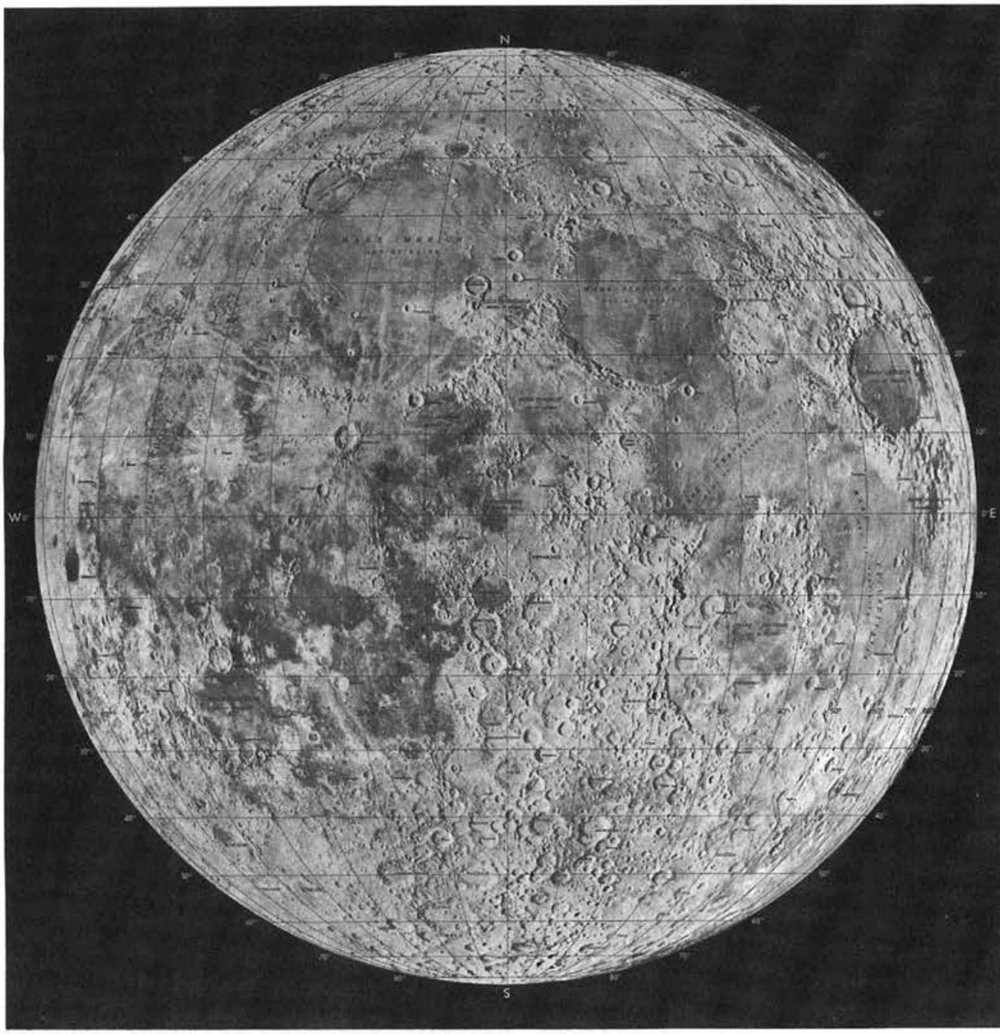
To a Rocky Moon



Photomosaic of lunar near side, probably the most frequently used lunar chart, published by the U.S. Air Force (ACIC) in November 1962 (LEM 1-A, 3d ed.). Mare Imbrium, Mare Serenitatis, Mare Nectaris, and other nearly circular volcanic maria are bordered by arcuate mountain ranges belonging to impact basins.

To a Rocky Moon

A Geologist's History of Lunar Exploration

Don E. Wilhelms

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Dedicated to the amazing Ralph Baldwin,
who got so much so right so early

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Preface

The Moon, which has always ruled Earth's nights, was first viewed by telescope in 1609, first touched by machines in 1959, and first visited by human beings in July 1969. It was the object of intense scrutiny for the quarter of a century centered on that incredible visit and its five successors. It may become so again. In the meantime it has receded into its ancient roles as raiser of the tides and keeper of the months. Those of us who played a role in exploring it should now write down what we remember and what we can reconstruct from the record as a guide for the next generation of lunar explorers.

That magnificent if momentary reach toward another world has already been viewed from the viewpoint of the brilliant engineering, mission operations, and administrative organization that helped land men safely on the Moon in the decade of the 1960s as President John F. Kennedy had challenged his country to do. Memoirs by astronauts Buzz Aldrin, Frank Borman, Mike Collins, Walt Cunningham, Jim Irwin, and Wally Schirra describe their thoughts and experiences. The science-engineering conflict within Apollo has recently been traced by historian David Compton. A number of books have summarized the status of lunar science after Apollo, and writer Andrew Chaikin is preparing a definitive scientific summary from the astronauts' viewpoint.

My book also relates the history of lunar science in the Space Age, but with major differences. It offers a detailed historical view by a scientist deeply involved in the lunar program before, during, and after the manned landings. More than half of the book is devoted to the long period preceding those landings, beginning with the initially sporadic, then increasingly determined investigations that preceded the first robot spaceflights. It shows how these unmanned precursors set the stage for our arrival on the Moon while adding to our store of knowledge. Finally, it discusses all six successful manned landing missions in detail.

Some personal history will establish the emphasis. When I am asked, "What do you do?" and I answer, "Study the geology of the Moon," the usual response is, "Oh, you mean you are an astronomer?" The Moon did indeed once belong to astronomy, the study of distant reaches where humans have not yet gone. Astronomy was my first love also; not its astrophysical or mathematical aspects but the quiet starry night. I had contemplated the Moon through a telescope and in the planetarium since childhood. But twentieth-century professional astronomers do not stare through telescopes at the constellations. They measure, count, calculate, and theorize. To concentrate on the subjects they must master, I changed my college major from astronomy to mathematics after the first year. But I cannot use mathematics. I was saved for science when I took an undergraduate course in geology from an excellent teacher, John Sewall Shelton, and changed majors. Whatever part of the brain it is that does geology works better in me than the part that does mathematics. I can learn from messy rocks and photographs but not from numbers, equations, or graphs.

The opposite is true of the physicists and other quantitatively minded scientists who once dominated space science. If their dominance had continued, I would have gone into some other business. The approach of lunar exploration during the 1960s, however, destined the Moon to become not only a globe to be measured and tracked, or a surface to be scanned by instruments, but also to become known as a world of rock. Lunar science increasingly became geological science. The later Apollo missions were elaborate geologic field trips. My geologist friend and colleague, Jack Schmitt, walked on the Moon and hammered on its boulders. So a geologist, especially one already primed by a childhood interest in astronomy, could play a role in the grand new venture if he happened along at the right time, as I did.

This book, then, tells how people figured out what the Moon rocks are made of, and how and when these rocks were shaped into what we see through our telescopes. And in tracing the development of scientific interpretation of the surface features, it sheds some light on the conflict between the more quantitative "hard" sciences like physics and the more qualitative so-called soft sciences like geology.

When people are told that I am a Moon geologist, they usually ask, "So you've studied the Moon rocks?" Then I have to say no, neither I nor most of my closest colleagues have studied the samples the astronauts brought back — unless you count viewing them briefly on public display or in someone else's laboratory. Our job, instead, was to assemble an overall picture of the Moon's structure and history by examining it first through the telescope and later in photographs taken by spacecraft. We could then recommend where on the lunar surface the fieldwork should be conducted and the samples collected, and assess the results. In our opinion, the "hard science" experiments deployed on the surface or carried in lunar orbit are also best interpreted in relation to the lunar geologic framework. Not having firsthand knowledge of the Moon rocks, I have spent considerable time over the last 15 years reading the technical literature, attending conferences, and talking to those who actually analyzed the samples. Chapters 11–18 include findings from the analyses that bear most directly on geological matters and also touch on findings about the primordial Moon accessible only through the sample record.

Although it is a history and not a textbook, I hope the book will leave you with an idea of what the Moon is like. Histories of science and exploration often reveal more about their subject than does the scientific literature. Formal scientific reports are usually written as if sprung full-blown from the forehead of some Goddess of Truth instead of gradually emerging from the groping minds of fallible human beings. I have tried to write a book that can be read by anyone interested in the Moon, the space program, the history of science, or the application of geology to planetology. Each new concept or technical term is explained when first mentioned, and the introduction gives some background on the main scientific issues for the nonscientist or nongeologist. Scientists may or may not learn new facts about the Moon here, but they will see how certain ideas became dominant, and why certain spaceflights were targeted as they were. Skeletons in closets provide some of the critical clues.

This book may be biased a little—I hope not too much—by my view from inside the U.S. Geological Survey (USGS). My professional career was spent entirely in that venerable organization, which was established in 1879 to consolidate scientific exploration of the American West, so I feel I should report the inner workings of its lunar program in some detail. The USGS was preeminent in lunar geology in the 1960s, before it was joined in the effort by hundreds of other geologists, petrologists, geochemists, and geophysicists as the time for the Apollo landings approached. Longer histories than this one will be required to do justice to them all.

Several sections derived mostly from the literature discuss lunar spaceflights conducted by the Soviet Union. Although they summarize the Soviet contribution to lunar geology only briefly, they serve as reminders that the United States probably would not have had a lunar program if the Soviet Union had not had one first.

Scientific research is not conducted in isolation. Without exploration by spacecraft, the rocky Moon would have remained an object for speculative contemplation—an activity meaningful only to the contemplator. Science needs facts, though it often proceeds without them, and the facts need to be the common property of a community of scientists. The kinds of facts that are collected depend on the sort of instruments we use to collect them. And the choice of hardware depends as much on the technological "state of the art" as on what scientists or engineers think they need to know. So this book includes enough of the history of lunar spaceflight to show how the data that interested us were assembled, what effect the sequence and type of flights had on our conclusions, and how, or whether, our conclusions influenced what flew next. Moreover, spacecraft do not fly unless someone has a good reason to pay for them. Politics, not science, instigated and nourished lunar exploration, and this is why I mention the political and social environment at points when it affected the direction taken by the U.S. lunar program. The program was launched by politics in the late 1950s, slowed by the Vietnam War in the late 1960s, and curtailed by economics in the 1970s. Whether it will be revived remains to be seen.

Contrary to its media-cultivated public image, science is always influenced by random or chance factors and by the quirks of scientists. Scientists are no more objective or dispassionate than people in general. Other writers have already revealed that secret, and this book will add much to corroborate it. Lunar geology did not progress neatly toward some predetermined result but was torqued by unpredictable convergences of personalities and timing. This history follows a number of scientists who strongly influenced the course of lunar geology. The chain that led to today's understanding of the Moon was forged, in my opinion, mainly by G. K. Gilbert, Ralph Baldwin, Harold Urey, Eugene Shoemaker, and Gerard Kuiper—geologist Gilbert and astronomer Baldwin by their scientific insight, chemist Urey and astronomer Kuiper by their timely promotion of critical programs, and geologist Shoemaker by both. These men and their intellectual progeny are emphasized in this book at the expense of people and ideas seen, in hindsight, as less influential.

The selection of sites for manned landings is a good example of the randomness of scientific progress. Apollo exploration followed an intricate, evolving, and mostly unwritten script that took only one of many potential paths. At first, science was only a tool for achieving what really mattered to NASA: the success of the first landing. Later, Project Apollo also responded to what the scientists had in mind. The choice of landing sites was based in large part on geologic interpretations made without benefit of rock samples. As the study of Lunar Orbiter photographs and the first Apollo data proceeded, some scientific goals were satisfied, others came into prominence, and others disappeared for lack of continued interest. The evolution of geologic knowledge resulting from sampling at one landing site influenced the choice of the site for the next landing. This book relates the site-selection process in detail, bragging about geologists' successes or owning up to their mistakes as the case demands. Little of this history has been recorded before, and it is time to do so before the brains and bodies of those who contributed to it wear out.

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San Francisco, California
May 1992

Acknowledgments

This book originally was planned as a cut-and-dried chapter in my book *The Geologic History of the Moon*, written between 1977 and 1982 but published in 1987. Hal Masursky (late of the USGS) and Farouk El-Baz (then of the Smithsonian Institution and now at Boston University) reviewed the sections on site selection in that draft. Their influence has survived the ten-year gap and total rewrite between that version and the present one, which was written after my retirement from the USGS in August 1986. A sketchy version was reviewed by one of the history's heroes, Ralph Baldwin of the Oliver Machinery Company, and by Rich Baldwin (no known relation), C. J. Hayden, and Paul Spudis of the USGS. Farouk El-Baz, Charles Wood of the Johnson Space Center, free-lance copy editor Mindy Conner, and editor Barbara Beatty of the University of Arizona Press provided valuable guidance about what the book should emphasize. Editor Jennifer Shopland of the University of Arizona Press was a solid rock of support and a source of skilled help during the preparation of the manuscript for publication. The semifinal manuscript was reviewed in its entirety by Paul Spudis; its first half was reviewed by Jeff Moore of Arizona State University (now at NASA Ames Research Center), its second half by Gordon Swann, USGS, retired, and chapters 13–17 by Lee Silver of the California Institute of Technology. Jack McCauley, USGS, retired, reviewed a later version of the first half plus chapters 16 and 18. All of these geologists devoted much time to their reviews and helped greatly in detecting errors and misplaced emphasis. I am especially indebted to astronomer Clark Chapman of the Planetary Science Institute at Tucson, Arizona, who reviewed what I thought was a nearly final manuscript for the University of Arizona Press. Clark's insight greatly improved the readability of the book for the general reader and corrected many points of scientific fact, history, and philosophy.

The recollections of several key figures in the history were indispensable in preparing this book. Current or former USGS geologists Ed Chao, Dick Eggleton, Jack McCauley, the late Hal Masursky, the late Annabel Olson, Gene Shoemaker, and Lorin Stieff supplied critical information from the pre-Apollo period. Ray Batson (USGS) and Norm Crabill (formerly of the NASA Langley Research Center) helped greatly with Surveyor and Lunar Orbiter, respectively. To compensate for my absence from the science "back rooms" of NASA's Manned Spacecraft Center in Houston (now JSC) during the landing missions, I have picked the memories of the geologists who were on the USGS field geology support teams, most of whom are my friends and colleagues. Prime among these were Tim Hait, Gordon Swann, George Ulrich, and Ed Wolfe of the USGS, Bill Muehlberger of the University of Texas, and Lee Silver of Caltech. Silver granted me a full day of his busy life, and Swann contributed major pieces of information at several stages of the writing. Fred Hörz, Gary Lofgren, and Bill Phinney of the Johnson Space Center filled in essential information about NASA's participation in the geology training and back-room support. Former USGS geologist, NASA astronaut, and U.S. senator Jack Schmitt clarified a number of important items from his various careers. Free-lance writer Andy Chaikin generously provided me with quotes gleaned from his many interviews with the astronauts and from listening to all the Apollo voice tapes. I also thank Jim Burke (Jet Propulsion Laboratory, retired), Bob Dietz (Arizona State University), Don Gault (NASA, retired), Richard Grieve (Geological Survey of Canada), Jeff Moore, John O'Keefe (Goddard Space Flight Center), Bob Strom (Lunar and Planetary Laboratory), Ewen Whitaker (Lunar and Planetary Laboratory, retired), Don Wise (University of Massachusetts), and many others for contributions credited at appropriate places.

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Technicalities

The text is organized chronologically as far as possible, though some overlap is inevitable to avoid fragmentation of topics. Acronyms and abbreviations that appear repeatedly are listed at the front of the book, and a selected bibliography that includes books, review articles, and other works of general interest appears at the end. Works of a more technical nature that are cited only once or twice appear in the endnotes only. Definitions of technical terms can be tracked down through the index.

The metric system is used throughout, except where English units are thoroughly ingrained; for example, not many people refer to the Lick Observatory 36-inch refractor as the 91.4-cm refractor. To cleave to original usage in most other cases would require the reader to look up such units as "nautical mile," for NASA and the astronauts preferred that unit for altitudes and distances traveled by their craft in space.

Names of lunar features are usually given in the form most commonly employed by scientists. Hence, usually "the Apennines" rather than the international Latin "Montes Apenninus," but "Mare Fecunditatis" rather than the "Sea of Fertility" preferred by NASA and the astronauts.

All spacecraft and spaceflights are designated with Arabic numerals except in some references and direct quotations. Roman numerals were often used, but no consistent convention was ever agreed on, and the Arabic numbers seem to be replacing the Roman in current literature. Terms like *manned spaceflight* might offend today's reader, but desexing them would be historically inaccurate.

Common Acronyms

AAP	Apollo Applications Program
ACIC	Air Force Aeronautical Chart and Information Center
AES	Apollo Extension System
AFCRL	Air Force Cambridge Research Laboratory
ALS	Apollo landing site (preflight early Apollo designation)
ALSEP	Apollo Lunar Surface Experiment Package
AMS	Army Map Service
ASSB	Apollo Site Selection Board
CMP	command module pilot
CSM	command and service module
EVA	extravehicular activity (space walk or surface traverse)
GLEP	Group for Lunar Exploration Planning
GMT	Greenwich mean time
JSC	Johnson Space Center
LM	lunar module
LMP	lunar module pilot
LOPO	Lunar Orbiter Project Office
LPL	Lunar and Planetary Laboratory (University of Arizona)
LRL	Lunar Receiving Laboratory (MSC and JSC)
LSAPT	Lunar Sample Analysis Planning Team
LSPET	Lunar Sample Preliminary Examination Team
MOCR	Mission Operations Control Room
MSC	Manned Spacecraft Center (now Johnson Space Center)
NASA	National Aeronautics and Space Administration
OMSF	Office of Manned Space Flight (NASA)

OSS	Office of Space Science (NASA; now OSSA)
OSSA	Office of Space Science and Applications (NASA)
PET	Preliminary Examination Team
SFOF	Space Flight Operations Facility
SOUC	Surveyor/(Lunar) Orbiter Utilization Committee
SPE	Surface Planetary Exploration Branch (USGS)
SPS	service propulsion system (the CSM's engine)
USGS	U.S. Geological Survey

To a Rocky Moon

Introduction

People often ask what we learned by going to the Moon. Did we find anything useful? What did scientists get out of Project Apollo and its precursors besides a share of mankind's and America's pride in a magnificent technical achievement? Perhaps nothing useful was learned in the practical sense of locating valuable minerals (though that remains to be seen). I do believe, however, that we got plenty that was useful in the sense of satisfying human curiosity about the second most obvious object in the sky. We found out what created the Moon's surface features, to what extent it resembles the Earth, whether it is hot or cold, how old its crust is, what it is made of, and, I think, how it originated.

We always want to explain what we can see. Long before the invention of the telescope, all human cultures noticed dark splotches on the full moon and imagined in them some human or animal form like the "Man in the Moon." The Man's eyes and mouth are approximately circular, and other features are arcuate or seemingly irregular. The very first telescopic observations of the Moon, made in 1609 by Thomas Hariot (1560–1621) and Galileo Galilei (1564–1642), showed that the dark spots are smoother than the rest of the surface.[1] Johannes Kepler (1571–1630) also noted the two kinds of terrain and apparently gave them their present names of *maria* and *terrae*.[2] The maria (singular, *mare*) are one of four classes of surface features that keep reappearing in this history. Maria cover about 30% of the hemisphere that can be seen from Earth (the near side), and spacecraft have shown that they cover about 2% of the far side.

The telescopes of Hariot and Galileo revealed the second class of surface feature, *craters*, which have puzzled all observers of the Moon ever since. Any telescopic glimpse or photo of the Moon shows innumerable craters of all sizes but of one predominant shape: circular, with raised rims and deeply sunken floors. The main argument, as many readers already know, was whether the craters were created by impacts of objects from space[3] or by volcanic or other processes that originated inside the Moon. This history updates the debate whenever some progress toward its solution appears.

I have said that circular craters come in all sizes. The biggest ones have caused even more controversy than the little ones. Early telescopic observers noticed that the smooth, dark, circular maria are surrounded or bordered by circular or arcuate mountainous rings. The most observant investigators also noticed other rings concentric with the main rings in craters more than about 250 or 300 km across. Being rough and light-toned (technically, high in albedo), the rings are part of the second type of Keplerian terrain, the *terrae* (also called uplands, highlands, or continents). These are very great differences: dark and smooth, bright and rough. Nevertheless, almost everyone long assumed that the maria and the mountainous rings had the same general origin; either impact or volcanic, but not both. The mind needs to classify things but does not always pick the best criteria. The circularity of the maria and the rings apparently carried the day over the dark-smooth/bright-rough dichotomy, both in naming and in interpreting these major lunar features. Chapters 2 and 3 show that they differ as much as soup does from its bowl. Nevertheless, well into the 1960s even the technical literature employed the term *maria* for the mountainous rings as well as the dark, smooth, and flat true maria, and most popular literature still does. And the technical literature is stuck with the term *basin* (more specifically *ringed basin* or *multiringed basin*) for features that include not only the Moon's deepest depressions but also its highest mountains. The size and importance of basins earn them a place in this history as a third type of surface feature distinct from maria and craters.

The dominance of maria, craters, and basins in the makeup of the lunar crust was established by the pathway recounted in this book. But at points along that pathway, many additional landforms and rock types were thought to be important genetic keys. When you look at a lunar photograph, your eye is attracted by what I call *special features.* These include a whole variety of sinuous, arcuate, or straight *rilles* (long, narrow trenches), chain craters, "domes," "cones," "pits," ridges, and so on. All investigators paid them great heed while groping to explain the lunar scene. Many special features in the maria do exist, and they help explain the mare suite of rocks. As the big picture developed, however, more and more special features of the terrae were found to be illusory or to be related to basins. Special features assumed a greater role than warranted by what has proved to be their actual importance, not only in early telescopic work but in the selection of Lunar Orbiter and Apollo photographic targets and Apollo landing sites. Therefore they have earned a prominent place in our history, if not in the geologic structure of the Moon, as a fourth class of surface feature.

The topography of a fifth and last class of physical feature cannot be directly observed through a telescope: the material that coats the Moon's surface. The lunar surface worried engineers planning the first manned landings. Would it be strong enough to support a spacecraft and crew? Astronomers took the lead here, extracting clues about the surface material and environment with their optical, infrared, and radar instruments. Geologists joined in the search for answers to the practical question of landing safety and to the scientific question of how the material originated. If it is fragmental debris or dust, how thick is it? Does it consist of meteoritic material or pieces of bedrock broken up by meteorite impacts, or did volcanic eruptions blanket the whole scene? Are there real rocks that astronauts could pick up in their hands and assess from their knowledge of Earth rocks? Are there perhaps even actual outcrops of bedrock as on Earth?

This debate about origins and the confusion of mare and basin were part of *the* central issue in lunar studies: Were the Moon's features created by impacts from space (*exogenic* activities) or by some process originating inside the Moon (*endogenic* activities)? Impact origins do not require (though they do not exclude) a Moon with a hot interior, so advocates of impact have often been called "cold-mooners." Internal origins do require heat, so their advocates are "hot-mooners." Speculations about surface-shaping processes once lodged almost exclusively in either the cold-Moon or the hot-Moon camp; *all* features were thought to be either exogenic or endogenic. The strict cold-mooners believed not only that impacts formed all craters, including the big ones that they called maria and we call basins, but furthermore that the dark mare plains were themselves the melted impactors or crustal rock melted by the impacts. The strict hot-mooners held that the mare plains were one kind of lava while the mountainous borders were another. Contrary to geological common sense, some could even imagine that the mountains were emplaced after the maria—the bowl after the soup. Many investigators active as late as the 1960s were willing to defend one of the camps to the death. As the late Tim Mutch pointed out in his 1970 book, the debate was oddly reminiscent of the one between "Neptunists" and "Plutonists" (or Vulcanists) at the dawn of geology during the late eighteenth and early nineteenth centuries. The Neptunists insisted that all rocks had to be sediments deposited in water. The Plutonists insisted that they were all *igneous* (from the Latin for "of fire" or "fiery" and meaning "formed from a molten magma"). Today it is just as obvious that both impacts and internal heat have shaped the Moon's face as it is that both igneous and aqueous agents have created Earth's rocks.

I have partly explained what geologists are doing studying the Moon by saying that each surface feature is made of rock. Not all geologists examine rocks as individual laboratory specimens. The ones who do that are a special breed called *petrologists.* On Earth, geologists can (and I think should) conduct their basic research outdoors, where most rocks are still joined together in the sedimentary layers or intrusive bodies in which they originated. Such layers and intrusions are the *geologic units* that collectively compose Earth's crust. The way the units are stacked, as well as the science that studies the stacks, is called *stratigraphy.* Here we have touched on the subjects that are most typically geologic: sequence, time, and age. Unlike physics and chemistry, geology is a profoundly historical science.[4] Moon geologists have transferred an interest in stratigraphy and the age of things to the Moon. If you think like a geologist while looking at a lunar photograph, your first impulse is to try to determine the relative ages of geologic units—say, a patch of mare or the blanket of debris thrown out of a crater (the *ejecta*). I, for one, spent most of my career working out the Moon's stratigraphy by the simple (in principle) procedure of observing which geologic units overlap which. My colleagues and I also tried to compare the Moon's features with those of Earth, although the attempt to do so was fraught with uncertainties and got some of us into as much trouble as it has the astronomers. This *photogeologic* research began during what we can call the first phase of lunar exploration, before July 1969, which depended on remote information obtained by the telescope and unmanned spacecraft.

This ready transferal of methods shows that geology is more a way of doing things than just the term for the study of the Earth. This is why we use the prefix *geo-* in reference to the Moon. At the beginning of the Space Age almost everyone preferred the prefix *seleno-*, from the Greek word for the Moon, so there were selenologists but no lunar geologists before 1957. One still sees the prefix in such terms as *selenodesy,* for measurements of the Moon's overall shape (*figure*). However, *ge-* ($\gamma\hat{\eta}$) in ancient Greek includes the many meanings of the English *land, ground,* and *soil* (lowercase earth) as well as the planet Earth.[5] The history of the Space Age has provided the clinching arguments for the use of *geo-*. Images have been obtained at geologically useful scales for over 20 solid planets and satellites, and by now the effort of coining names for this large number of planetary disciplines (venerophysics, deimology, callistography, or what have you) would have driven us crazy.[6]

During the Space Age the Moon's composition and physical properties came under the scrutiny of two of geology's branches, geochemistry and geophysics. Geochemists trace the sources, migrations, and current resting places of individual chemical elements. Although the last three Surveyors (September 1967–January 1968) sent back compositional information that proved quite accurate, the geochemists and petrologists had nothing much to study until the six manned Apollo landings between July 1969 and December 1972 (chapters 11–17) and the three robotic Luna sample returns between September 1970 and August 1976 (chapters 13, 15, and 18). Some geochemists specialize in *geochronology,* a subject critical for geologists' favorite topic, history. *Relative* ages were learned from photographs, but *absolute* ages, expressed in this book mostly in a unit that is convenient for the ancient Moon, the *aeon* (1,000,000,000 years, or one billion years in American usage),[7] could only be learned from samples brought from the Moon to Earth's clean laboratories. A number of workers had correctly estimated the absolute ages of the lunar maria and other geologic units before the landings, but no one knew whose estimates were right and whose were wrong until the Apollo astronauts came home. A true understanding of how old the Moon's features are has come from hanging the findings from these tiny surface samples onto a framework of geologic units embracing the whole Moon. Most of this book's chapters trace the progress of relative or absolute chronologic studies.

Unlike geologists, geophysicists prefer to study what they cannot see but must infer from the data their instruments provide. They could begin to speculate on the basis of astronomical calculations and data from Moon-orbiting spacecraft, but they really needed instruments placed on the Moon's surface. An elaborate program of deployment by robotic spacecraft was planned but not carried out, so the job had to be done by the astronauts. Geophysicists attempt to determine from instrumental measurements such things as the densities, temperatures, and depths of the boundaries of a planet's crust, mantle, and core. Other geophysicists are concerned with physical properties of near-surface rocks such as magnetism and thermal conductivity. Theoretically, geologists can work with geophysicists by estimating what the three-dimensional structure of the Moon is like. But in reality, geophysicists usually lean more toward the -physics than the geo-, and the differences in mentality between them and geologists have long been the source of usually amusing but sometimes acrimonious conflict between supposedly brotherly geoscientists. A well-known joke describes the difference: "What is 2 plus 2?" The geologist answers, "Oh, about 4"; the geochemist answers, "4 ± 2"; the geophysicist answers, "What number do you want?" But we are all scientists.

Some scientists fit the popular image of reclusive monklike characters poring over musty books or staring at test tubes, while others prefer action, excitement, and influence. The first type waited patiently for the mission-related brushfires to die down so they could contemplate at their leisure the vast flood of data that had been obtained from the Moon. The planets and their satellites were waiting in line with new geologic styles and new challenges for the second type. The final chapter of this book follows the doings of the first type, those of us who occupied ourselves with making sense of the Moon in the 1970s and 1980s. The often-restated cliché that "mission *x* provided enough data to keep scientists busy for years" is not really true for most missions — certainly not for crash-landing Rangers or one-time flybys. But it is true of the Lunar Orbiter and Apollos collectively; the treasure trove of photographs and samples they returned has kept many of us gainfully employed for two decades. Scientific curiosity is never satisfied. No sooner is one question answered than more appear — a process that goes on with increasing refinement every time the senses are improved. Chapter 18 can therefore only touch on the highlights of the post-Apollo work.

Except for a "where are they now?" section in that last chapter (see chapter 18, Time's Flight), this history ends in the (fortunately non-Orwellian) year 1984 because it was then that a hypothesis for the origin of the Moon came on stage which, in the felicitous phrase of geologist Reginald Daly and geochemist Ross Taylor, "undid the Gordian knot" — cut all at once through the many insurmountable objections to all other theories. Before 1984 it was often said in jest born of frustration that the Moon cannot exist because none of the proposed formative mechanisms was possible. Although the origin of the Moon or the Solar System is the professional concern more of chemistry and astronomy than of geology, it was the ultimate quest of all of us. I think it has been attained, but the future will tell. I offer the final chapter additionally as a commentary on the great and too-transitory achievements in thought and engineering that placed the secrets of the Moon within our grasp.