THE GEOLOGIC HISTORY OF THE MOON

Astronaut David Scott at station 6, Apollo 15 landing site. Apollo 15 frame H–11514.

The Geologic History of the Moon

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with sections by JOHN F. McCAULEY
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A comprehensive review of lunar science and evolution from the viewpoint of historical geology, based on data from both photogeologic observations and lunar-sample analysis

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PREFACE

The Moon held little interest for most scientists after its basic astronomic properties had been determined and before direct exploration appeared likely (Wright and others, 1963; Baldwin, 1978). Speculations about its internal structure, composition, and origin were only broadly constrained by cosmochemical data from meteorites and solar spectra, and by astronomic data about its size, shape, motions, and surficial properties (Urey, 1951, 1952; Kuiper, 1954). Most investigators who were active before the space age began in 1957 believed that significant new advances in lunar knowledge required acquisition of additional data.

One analytical technique, however, was insufficiently exploited before the 1960's. Few scientists since the geologist Gilbert (1893) had studied the lunar surface systematically from the historical point of view. Those who did immediately obtained important new insights about the Moon's postaccretion evolution (Baldwin, 1949, 1963; Kuiper, 1959). Then, the pioneering work of E.M. Shoemaker and R.J. Hackman focused the powerful methods of stratigraphy on lunar problems (Hackman and Mason, 1961; Shoemaker, 1962a, b; Shoemaker and Hackman, 1962). Stratigraphy is the study of the spatial distribution, chronologic relations, and formative processes of layered rocks. Its application to the Moon came relatively late and met resistance, but the fundamental stratigraphic approach (Albritton, 1963) was, in fact, readily transferable to the partly familiar, partly exotic deposits visible on the lunar surface (Mutch, 1970; Wilhelms, 1970b).*

Stratigraphic methods were applied systematically during the 1960's in a program of geologic mapping that aimed at reconstructing the evolution of the Moon's nearside (McCauley, 1967b; Trask, 1969, 1972; Mutch, 1970; Wilhelms, 1970b; Wilhelms and McCauley, 1971). Order was discovered among the seemingly diverse and random landforms of the lunar surface by determining the sequence in which they were emplaced. The stratigraphic sequence and the emplacement processes deduced therefrom provided a framework for exploration by the Apollo program and for the task of analyzing the returned samples.

During the 1970's, the sophisticated labor of hundreds of analysts was brought to bear on the wealth of material returned by the American Apollo and the Soviet Luna spacecraft. Our present perception of the Moon has emerged from the interplay between sampling studies and stratigraphically based photogeology. These two approaches are complementary: Photogeology contributes a historical context by viewing the whole Moon from a distant vantage point, whereas the samples contain information on rock types and absolute ages unobtainable by remote methods. Neither approach by itself, even the most elaborate program of direct surface exploration, could have yielded the current advanced state of knowledge within the relatively short time of two decades (Greeley and Carr, 1976).

This volume presents a model for the geologic evolution of the Moon that has emerged mainly from this integration of photogeologic stratigraphy and sample analysis. Other aspects of the vast field of lunar science are discussed here only insofar as they pertain to the evolution of visible surface features. Chemical data obtained by remote sensing supplement the photogeologic interpretations of some geologic units (see chap. 5), and geophysical data obtained both from lunar orbit and on the surface constrain hypotheses of the origin of many internally generated structures and deposits. Studies of the same data that treat the Moon as a whole, including speculations about the intriguing but unsolved problem of its origin, have been adequately covered in other reviews (Hartmann, 1972b, 1983; Taylor, 1975, 1982; French, 1977; Wood, 1979; Basaltic Volcanism Study Project, 1981; Cadogan, 1981; Glass, 1982).

This volume is written primarily for geoscientists and other planetologists who have examined some aspect of lunar or planetary science and who want a review of lunar science from the viewpoint of historical geology. It should also provide a useful summary for the advanced student who is conversant with common geologic terms. It may, furthermore, interest the geologist who has not studied the Moon but who wishes to see how his methodology has been applied to another planet.

The volume's organization reflects the stratigraphic practice of first identifying and interpreting geologic units, then ranking them in chronologic sequence over the whole planet. Chapter 1 presents what may be considered the raw data by briefly describing the major surface and subsurface lunar features and defining some common terms. Chapter 2 explains the general philosophy of stratigraphy by showing how it has been applied to some critical past and contemporary lunar problems. Chapters 3 through 6 are devoted to the four major classes of lunar features—craters, basins, maria, and tectonic structures—with emphasis on craters and basins. These four chapters contain descriptions and interpretations that apply to the rest of the volume; except for some new hypotheses concerning basin origin and lithospheric thickness, these chapters are based mostly on existing literature and should be of use mainly to the reader unfamiliar with lunar geology. The rest of this volume is organized around the dimension of time. Chapter 7 reviews general guidelines for ranking lunar deposits in order of relative age. Chapters 8 through 13 trace the histories of the craters, basins, and igneous materials belonging to each of the six main divisions of the lunar stratigraphic column. These six chapters constitute the core of the original contribution of this volume and contain information for all of its intended audience. The volume is summarized in chapter 14 and in 12 maps of the two lunar hemispheres (pls. 1–12) at the end of this volume.

ACKNOWLEDGMENTS

This volume is dedicated to Eugene M. Shoemaker, who, more than any other individual, was responsible for the incorporation of geology into the American space program. First, in his study of Meteor Crater in Arizona, he developed a physical theory of the impact process on which subsequent cratering investigations have been based, and established the structural and petrographic indicators of impact later used on the Earth and the Moon (Shoemaker, 1960, 1963; Chao and others, 1960). With his colleague Edward C.-T. Chao, he applied these criteria in establishing an impact origin for the previously enigmatic Ries crater (Rieskessel), Germany (Shoemaker and Chao, 1961), which has become a model for larger lunar craters. Then, in four major papers written over two years (1960–61), he (1) put lunar geologic mapping on the firm stratigraphic footing that still supports it (Shoemaker and Hackman, 1962); (2) championed the impact interpretation of large fresh lunar craters by the most convincing combination of arguments yet advanced (Shoemaker, 1962b); (3) accurately appraised the objectives and future course of lunar exploration, including the forerunner role of the small, dry, and airless Moon in comparative planetology (Shoemaker,

*Use of the prefix "geo-" for lunar and planetary studies has been criticized, but it is justified by: (1) applicability to all other solid bodies of the geologic principles developed for the Earth; (2) elimination of the need for new terms for every new world observed at geologically useful scales, whose number now exceeds 20; (3) the Greek etymology, which includes the meanings "land" or "ground"; and (4) two decades of usage (Shoemaker, 1962a, p. 117; Ronca, 1965; Mutch, 1970; Wilhelms, 1970b). The prefix "seleno-" is no longer used by professional lunar scientists except in some terms referring to coordinates, control points, or the global figure (selenographic, selenodetic). Although "astrogeology" was chosen as a convenient and appropriate name (Milton, 1969) for the U.S. Geological Survey's branch devoted to lunar and planetary studies, "lunar (planetary) geology" is more commonly used. "Planetology" is a broader term that includes such nongeologic sciences as atmospherics and planetary astronomy.

1962a); and (4) attacked the problem of extraterrestrial absolute ages by means of the impact-cratering rate on the Earth (Shoemaker and others, 1962a). As chairman of the Joint Working Group responsible for recommending a detailed program of scientific exploration (Hall, 1977, p. 163) and by daily contacts at the U.S. National Aeronautics and Space Administration (NASA) headquarters in 1962 and 1963, he was able to implement many of his sound and visionary concepts of exploration strategy. He has followed up his earlier interests by definitive studies of the lunar regolith, primary- and secondary-crater populations, and the impact flux from interplanetary space (Shoemaker, 1965, 1966, 1971, 1981; Shoemaker and others, 1967a, b, 1968, 1969a, b, 1970, 1979; Shoemaker and Morris, 1970). He was the geologist on the experimenter team for the Ranger program, the principal experimenter for the Surveyor television experiment, and the leader of the field geology teams for Apollos 11, 12, and 13. He has continued to guide and inspire those of us fortunate enough to have been associated with him during the development of lunar geologic investigations.

The manuscript was prepared with the help of numerous other scientists who are or were active in lunar research as members of the U.S. Geological Survey's Branch of Astrogeology. John F. McCauley contributed much of chapter 4, was codeveloper with me of many of the concepts of stratigraphy and basin formation embodied in this volume, and furnished valuable reviews of chapters 1 through 8. Odette B. James and Paul D. Spudis helped fill gaps left by my ignorance of lunar petrology and kindly supplied photographs of lunar rocks and thin sections. James submitted the first version of the section on mare-basalt samples and suggested major beneficial changes in all the sections on petrology. Spudis contributed drafts of the sections on Apollo 15 in chapter 10, read two versions of the entire manuscript, and contributed many valuable suggestions to every part. Richard J. Pike and Joseph M. Boyce contributed drafts of the sections on complex craters (chap. 3) and the D_L method (chap. 7), respectively. Baerbel K. Lucchitta and David H. Scott contributed drafts of much of chapter 6. Perceptive reviews were furnished by Maurice J. Grolier and Carroll Ann Hodges of chapters 3 and 4, respectively. Jay L. Inge prepared the shaded-relief base for the two-hemisphere maps (pls. 1–12). Donald E. Davis prepared most of the artistic illustrations. Gary D. Clow helped with the mathematics. The manuscript furthermore benefited from the first-hand experience of Survey geologists Gordon A. Swann, George E. Ulrich, and Edward W. Wolfe as leaders or members of the field geology teams for Apollos 14, 15, 16, and 17. Non-Survey experts also generously helped with sections outside my fields of research. Discussions with Gunther W. Lugmair (University of California, San Diego) and S. Ross Taylor (Australian National University, Canberra) clarified many aspects of geochronology and petrology. Carle M. Pieters (Brown University) contributed figures and a valuable review of the section on remote sensing in chapter 5.

I am most deeply indebted to Albert Estrada and David B. Snyder. Estrada provided indispensible help in preparing the photographic illustrations and gave valuable counsel about scope. Snyder read two versions of the manuscript in sequence from beginning to end and greatly improved its clarity by his careful scrutiny and insight.

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ABSTRACT

More than two decades of study have established the major features of lunar geologic style and history. The most numerous and significant landforms belong to a size-morphology series of simple craters, complex craters, and ringed basins that were formed by impacts. Each crater and basin is the source of primary ejecta and secondary craters that, collectively, cover the entire terra. The largest impacts thinned, weakened, and redistributed feldspathic terra-crustal material averaging about 75 km in thickness. Relatively small volumes of basalt, generated by partial remelting of mantle material, were erupted through the thin subbasin and subcrater crust to form the maria that cover 16 percent of the lunar surface. Tectonism has modified the various stratigraphic deposits relatively little; most structures are confined to basins and large craters.

This general geologic style, basically simple though complex in detail, has persisted longer than 4 aeons (1 aeon = 10^9 yr). Impacts began to leave a visible record about 4.2 aeons ago, after the crust and mantle had differentiated and the crust had solidified. At least 30 basins and 100 times that many craters larger than 30 km in diameter were formed before a massive impact created the Nectaris basin about 3.92 aeons ago. Impacts continued during the ensuing Nectarian Period at a lesser rate, whereas volcanism left more traces than during pre-Nectarian time. The latest basin-forming impacts created the giant and still-conspicuous Imbrium and Orientale basins during the Early Imbrian Epoch, between 3.85 and 3.80 aeons ago. The rate of crater-forming impacts continued to decline during the Imbrian Period. Beginning in the Late Imbrian Epoch, mare-basalt flows remained exposed because they were no longer obscured by many large impacts. The Eratosthenian Period (3.2–1.1 aeons ago) and the Copernican Period (1.1 aeons ago to present) were times of lesser volcanism and a still lower, probably constant impact rate. Copernican impacts created craters whose surfaces have remained brighter and topographically crisper than those of the more ancient lunar features.