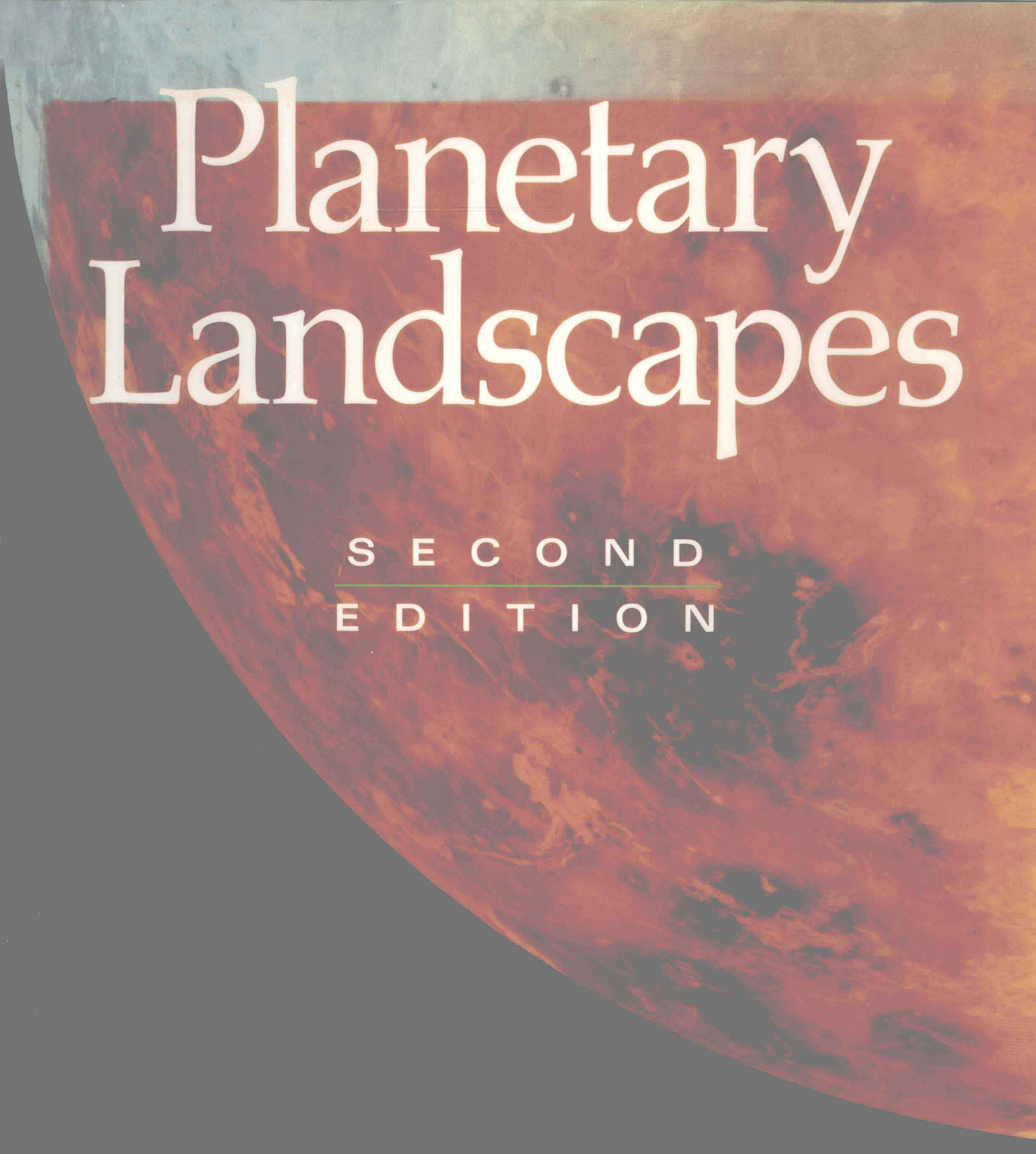

Planetary Landscapes

SECOND EDITION

R. GREELEY

CHAPMAN & HALL

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Ronald Greely

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Preface

The objective of this book is to introduce the surface features of the planets and satellites in the context of geomorphic processes. Introductory chapters include the "hows" and "whys" of Solar System exploration and a review of the primary processes that shape our planet, Earth, and which appear to be important to planetary sciences. The remaining chapters describe the geomorphology of the planets and satellites for which data are available. For most of these objects, the general physiography and terrain units for each are introduced, then the geomorphic processes that are inferred for the development of their surfaces are described. Each chapter then ends with a synopsis of the geologic evolution of the surface. The principal sources of information on the geomorphology of the planets and satellites are spacecraft photographs. These are usually shown in the book oriented so that the illumination is from the upper left or left side (so that craters will appear correctly as holes to most readers!), although this means that north orientation may not be toward the top.

Because the level of knowledge is not uniform for all of the objects in the Solar System, the individual treatment varies among the chapters. For example, it was difficult to decide what to leave out of the chapter on Mars because so much is known about the surface, whereas data are rather limited for Mercury.

In addition to introducing the geomorphology of planetary objects, this book is intended to be a "source" for obtaining supplemental information. References are cited throughout the text. However, these citations are not intended to be exhaustive but rather are given to provide a "springboard" for additional literature surveys.

Finally, it must be pointed out that planetary sciences are in their infancy and the techniques for analyzing the geomorphology of extraterrestrial objects are still evolving. I hope that the reader will find these extraterrestrial worlds as fascinating and as exciting as I do and, together with my colleagues, we are pleased to share the results of Solar System exploration with our readers.

R. Greeley
September 1992

Acknowledgments

Preparing a book is a formidable project. Without the help of many people it is doubtful that this project would have been completed. I wish to acknowledge the following individuals and thank them for their contributions: Jeffrey Moore and Curtis Manley for research assistance in preparation of the first edition; Loretta Moore for helpful comments on early drafts of the manuscript; Daniel Ball, Joo-Keong Lim, and Joseph Riggio for photographic support; Maureen Geringer for her accurate and speedy word processing of countless draft versions, and Shana Blixt for word processing material for the second edition.

Numerous colleagues very kindly provided photographs and illustrations as noted in the figure captions. Jurie Van der Woude of the Jet Propulsion Laboratory is gratefully acknowledged for providing access to planetary images. The Regional Planetary Image Facilities also aided greatly in providing images for this book and I would especially like to thank Linda Jaramillo and Conni Alexander (Arizona State University), Leslie Pieri and Marion Rudnyk (Jet Propulsion Laboratory), Gail Georgenson (University of Arizona), and Jody Swann (US Geological Survey).

Reviews of individual chapters and helpful discussions were provided by Paul Spudis (US Geological Survey), John Guest (University of London Observatory), Alan Peterfreund and James Garvin (Brown University), George McGill (University of Massachusetts), Peter Schultz (Lunar Planetary Science Institute), Michael Malin (Malin Space Science Systems), Victor Baker (University of Arizona), and Peter Cattermole (University of Sheffield).

I thank Conni Alexander and Andrea Seelinger for their careful proofing of the second edition. Finally, I acknowledge with gratitude the editorial assistance of Cynthia Greeley.

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1 Introduction

The mid-1960s witnessed two fundamental revelations that resulted in the beginning of an era which continues to have profound effects on the geologic sciences. Although the basic ideas of continental drift had been proposed nearly a half century earlier by Alfred Wegener, it was not until the late 1950s and early 1960s and the development of modern instruments to measure sea-floor spreading, to date rocks radiometrically, and to conduct accurate geophysical surveys, that the concept of crustal plate tectonics was accepted. At the same time as the gradual acceptance of plate tectonics, a similar, equally profound, view of the Solar System was emerging. Just as the ideas of continental drift were hampered by the lack of data, Solar System studies were also limited until the space age. Prior to the return of results from space probes sent to the Moon and planets, views of most planetary objects (except the Moon) were limited to little more than fuzzy blurs or tiny pin-points of light, even when viewed with the most powerful Earth-bound telescopes (Fig. 1.1).

Primitive by today's standards, the first probes sent to the Moon by the Soviets ushered in a new scientific era which has brought the surfaces of the planets within the grasp of study. For the most part, the study of planetary surfaces has passed from the astronomer to the geologist and has resulted in the establishment of the new discipline, **planetary geology**. Planetary geology is defined as the study of the origin, evolution and distribution of matter which forms the planets, natural satellites, comets and asteroids. The term "geology" is used in the broadest sense and is considered to mean the study of the solid parts of the planets. Aspects of geophysics, geochemistry, geodesy and cartography are all included in the general term.

This book is concerned with one aspect of planetary geology—the geomorphology of the planets. For simplicity, the term "planet" is also applied to natural satellites, such as the Moon. Geomorphology, a discipline long established in the earth sciences, seeks to determine the form and evolution of the Earth's surface. This same goal

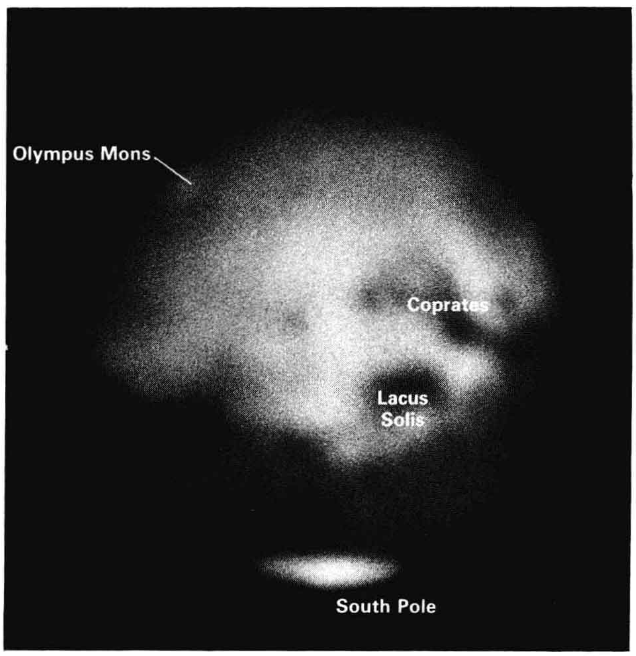
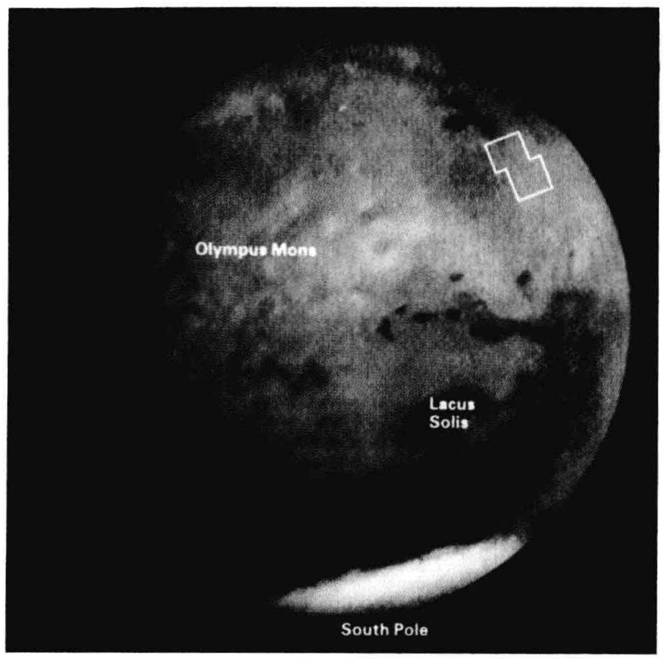
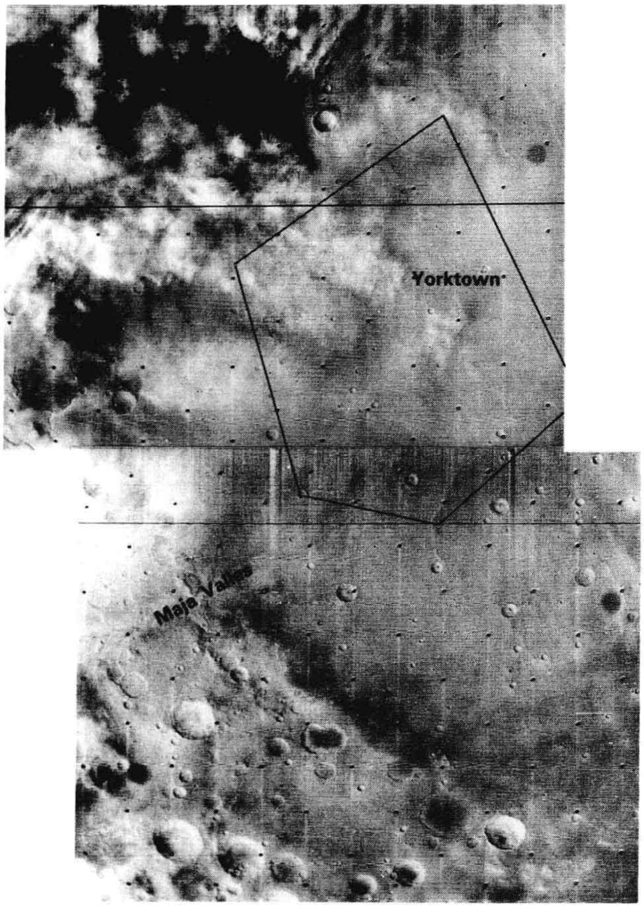


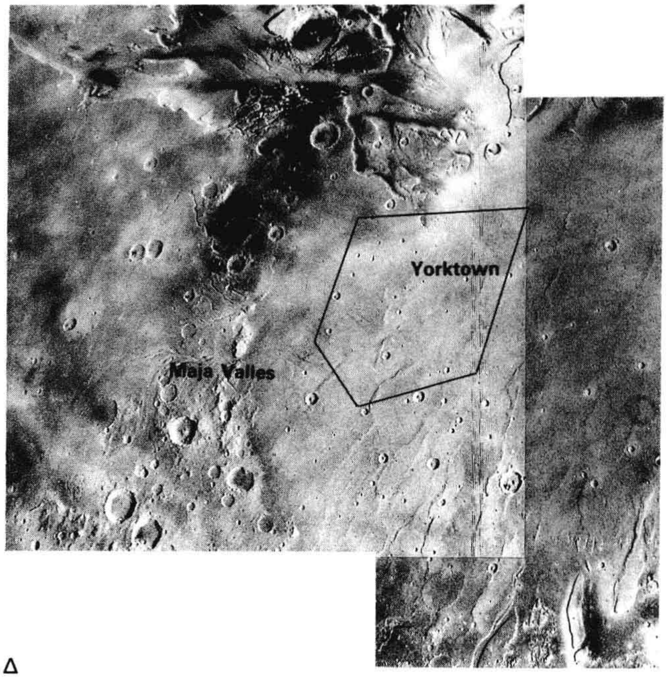
Figure 1.1 Progressively higher-resolution views of Mars. **(a)** Earth-based telescopic photograph of the western hemisphere of Mars taken 16 August 1971 by the University of Arizona, Lunar and Planetary Laboratory using the Catalina Observatory Telescope (courtesy of the Lunar and Planetary Laboratory).



(b) A global view of Mars similar to Figure 1.1a, imaged by Mariner 7 on 4 August 1969 from a distance of 495 086 km; outline shows location of Figure 1.1c and d (Mariner 7 7F71).



(c) Mariner 9 images of the Kasei region of Mars taken from 2835 km; resolution ~1.5 km/pixel; area shown is 650 km by 1000 km; outline shows location of Figure 1.1e (Mariner 9 DAS 07543588 and DAS 07543518).



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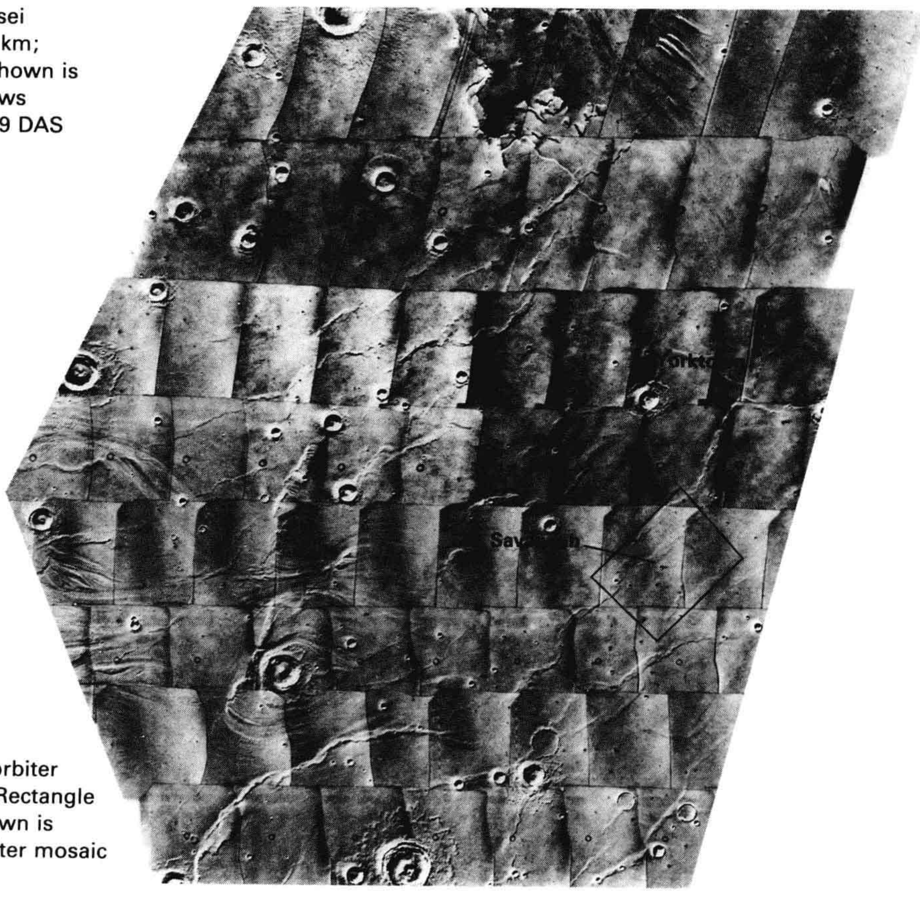
(d) Viking orbiter images of about same region as shown in Figure 1.1c; the significant improvement in overall picture quality results primarily from an improved imaging system. Area shown is about 1200 km across. The outline locates Figure 1.1e (Viking Orbiter 666A04, 666A06).



(e) High-resolution Viking orbiter mosaic of the Kasei region. Rectangle locates Figure 1.1f. Area shown is ~400 km across (Viking Orbiter mosaic 211-5015).

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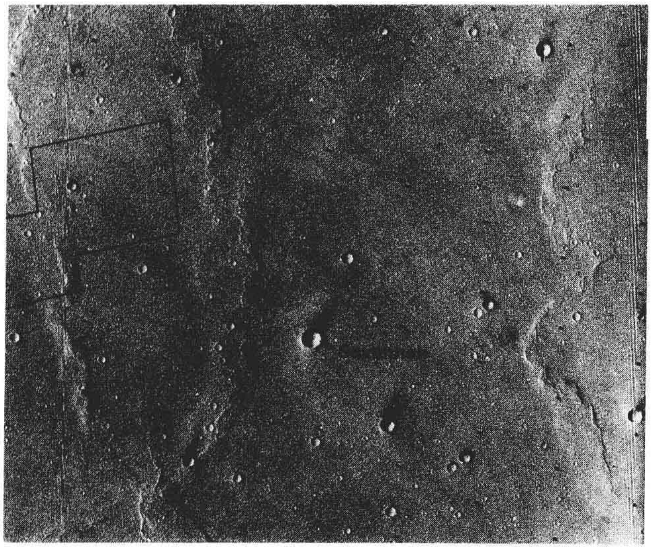
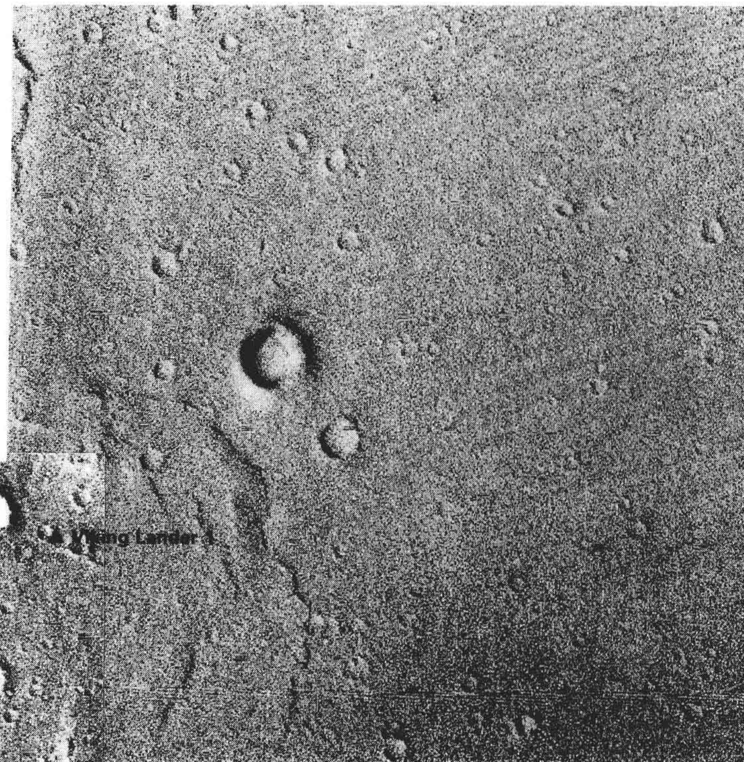
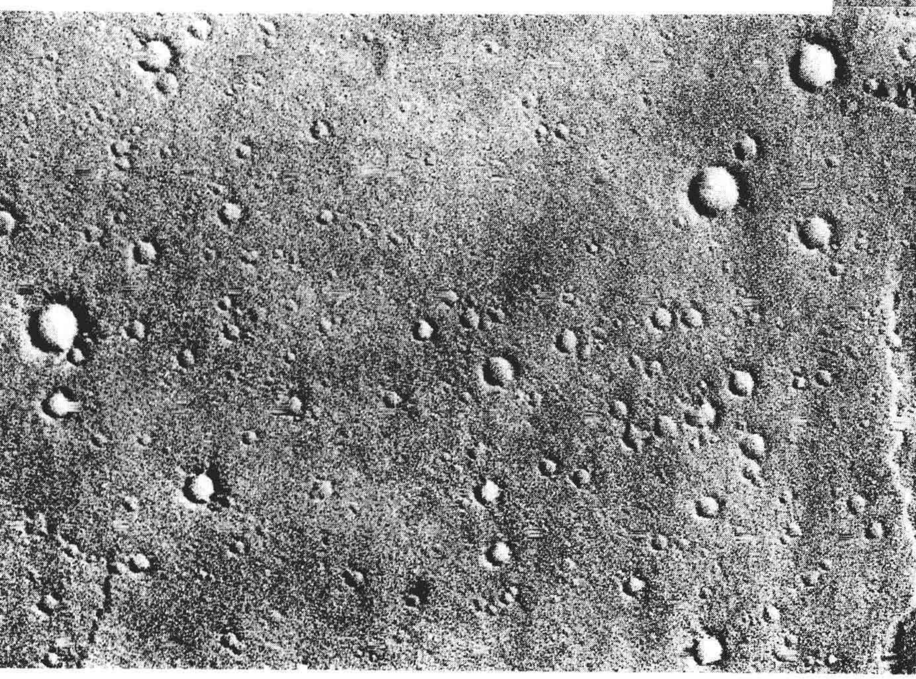
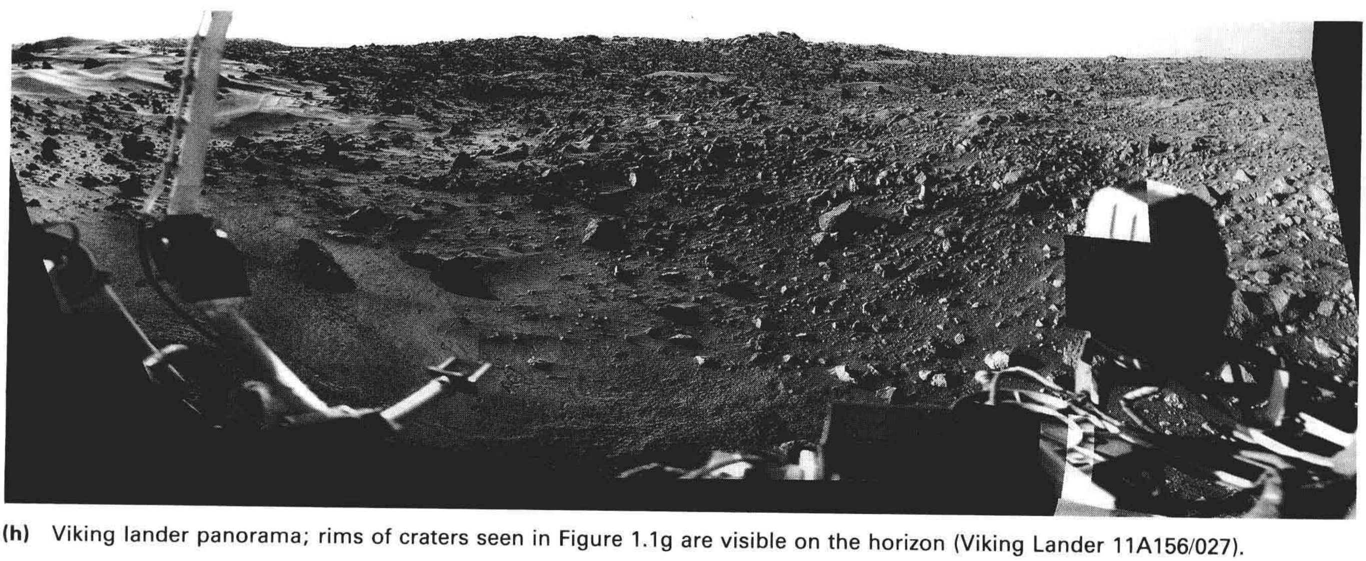


(f) High-resolution Viking orbiter image of the Viking 1 landing site taken from 1551 km; resolution ~350 m/pixel. The polygon outline locates Figure 1.1g. Area shown is 46 km across (Viking Orbiter 27A33).





(g) Highest-resolution (10 m/pixel) orbiter images of Viking 1 landing site. Craters near the site can be seen in the lander panorama (Fig. 1.1h); also seen is the crater formed by the impact of the Viking thermal shield (O. de Coursac and J. Garvin, personal communication, 1990). Area shown is about 12 km across (Viking Orbiters 452B11 and 452B10).



(h) Viking lander panorama; rims of craters seen in Figure 1.1g are visible on the horizon (Viking Lander 11A156/027).

applies to all the planets. Because much of our knowledge of the planets has been gained by remote sensing—primarily spacecraft pictures—we are, in fact, using landforms to interpret much of the geology of the planets. The approach commonly employed is first to determine the physiography of each planet and then to interpret the processes that have shaped the landforms that are observed on the pictures.

1.1 Objectives of Solar System exploration

The question is often asked, "Why study the Solar System?" During the mid-1960s, the United States National Academy of Sciences addressed this question and defined three principal goals for the exploration of space: (a) to determine the origin and evolution of the Solar System; (b) to determine the origin and evolution of life; and (c) to clarify the nature of the processes that shape humankind's terrestrial environment. The US National Aeronautics and Space Administration (NASA) has refined these objectives and derived a plan for Solar System exploration through the year 2000 (SSEC 1983).

Planetary geology and geomorphology figure prominently in all three of these goals, as discussed in detail by Greeley and Carr (1976). Let us consider the first goal. There are two ways to approach the study of the origin and evolution of the Solar System. The first is to model the possible conditions of Solar System formation and then follow the evolution through a series of stages leading up to the present time. This approach is typically employed by astronomers and uses observations of stars that are thought to represent various stages of evolution. The second approach is to begin with the present state of the Solar System and try to work backward in time. This is the approach typically taken by the planetary geologists—it is basically a geologic approach. Of course, the final goal will probably be reached through a combination of these two approaches. Astronomical modeling is probably the better approach for the early stages of formation and for that part of the early record missing in geologically derived histories; the geologic approach is better for the later stages of Solar System evolution represented by the rock record preserved on the surfaces of planetary objects.

The geology of planetary surfaces also relates to the second goal of Solar System studies, the origin and evolution of life. The planetary environment, including rock and mineral compositions and active geologic processes, has a direct bearing on the starting conditions for life and influences the process of natural selection.

And what of the third goal? Many fundamental geologic problems on Earth might be solved by detailed comparisons with other planets where the relative effects of different sizes, compositions and atmospheres on the evolution of the planets could be assessed. For example, very little is known of the early history of the Earth. Only the last 0.5 eons of the estimated 4.6 eon history is readily available for study because so much of our planet is constantly attacked and altered by tectonic, weathering and erosional processes, and the remainder is covered by water. On the other hand, because the Moon has no erosive atmosphere and the crust has been stable for several eons, it displays a surface that is commonly five to eight times older than most of the Earth's surface. In this older surface is stored and available for study the early history of the Moon and probably the Earth as well. Thus, through the study of the Moon, we are better able to understand the processes that contributed to the early history of the Earth (Fig. 1.2).

To achieve the goals of Solar System exploration, data are obtained through a series of steps that begins with Earth-based observations, progresses through reconnaissance missions and ultimately ends with manned exploration. Obviously, we are a long way from completing this sequence, even for a small fraction of the Solar System, as indicated in Table 1.1. Nevertheless, sufficient data are available to begin analyses and to formulate ideas on the origin and evolution of the planets and their geologic histories.

Table 1.1 Sequence of planetary exploration.

Type of mission	Mercury	Venus	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto	Comets	Asteroids
Earth-based	x	x	x	x	x	x	x	x	x	x	x
Flyby	x	x	x	x	x	x	x	x		x	x
Orbiter		x	x	x	(1)						
Unmanned landers		x	x	x							
Sample return			x								
Manned landings			x								

(1) Anticipated Galileo mission.

Figure 1.2 Apollo 17 view of the eastern part of the Moon ("farside" is to the right) showing heavily cratered uplands and dark mare areas (circular zone in upper half is Mare Crisium). The samples from the uplands have been dated by radiometric techniques as having been formed in excess of 4 eons ago and thus represent geologic events from the earliest history of the Solar System. Because of the proximity of the Moon, it is presumed that Earth experienced a similar period of heavy cratering, but because of tectonic and erosional processes, most of the early record on Earth has been lost (Apollo 17 AS 17-152-23308).

1.2 The geologic approach

With each step in the exploration of the Solar System, three primary geologic questions are asked: (a) What is the present state of the planetary object observed? (b) What is its geologic history? (c) How do the present state and geologic history compare with other objects in the Solar System? The keys to addressing these questions involve the interpretation of planetary processes, the derivation of geologic histories through mapping and comparative planetology.

1.2.1 Present state

An understanding of the present state of a planetary object requires knowledge of its composition, interior properties, exterior environment and the geologic processes which may be currently active. Knowledge of the composition—at least of the surface—can be obtained directly by measurements made on returned samples (Fig. 1.3), or *in situ* by various instruments on landed spacecraft (Fig. 1.4), or indirectly by various remote-sensing techniques (Fig. 1.5). Information on the interior, such as lithosphere–mantle–core configurations, can be obtained from instruments, such as seismometers, or from geophysical models based on knowledge of the planetary density, size, moment of inertia and shape. Information on the exterior environment includes the temperature range, mechanical and thermal properties of the surface materials, the influence of various external processes (such as impact cratering), solar wind flux and the presence or absence of an atmosphere and, if present, its composition and density. Finally, knowledge is required of the various active processes which may be operating on the planetary object, such as volcanism.

1.2.2 Past state of the planets

This objective is to trace the processes, events and characteristics of the planets from their origin to the present; in other words, to determine their geologic histories. The approach for meeting this goal is met primarily through geologic mapping, in which surface materials (rock units) are identified and placed in a time sequence. In planetary geology, mapping is accomplished primarily by photogeologic techniques; however, as we shall see later, this method is not without some problems. Despite the difficulties, the level of mapping which is attainable at least provides a broad framework for the derivation of geologic histories.

1.2.3 Comparative planetology

Once knowledge is gained—even if incomplete—of the present and past states of the planets, it is then possible to begin to compare the planets to see how they are similar to and different from each other. Such comparisons help to meet the objectives of Solar System exploration by enabling a better understanding of the evolution of all

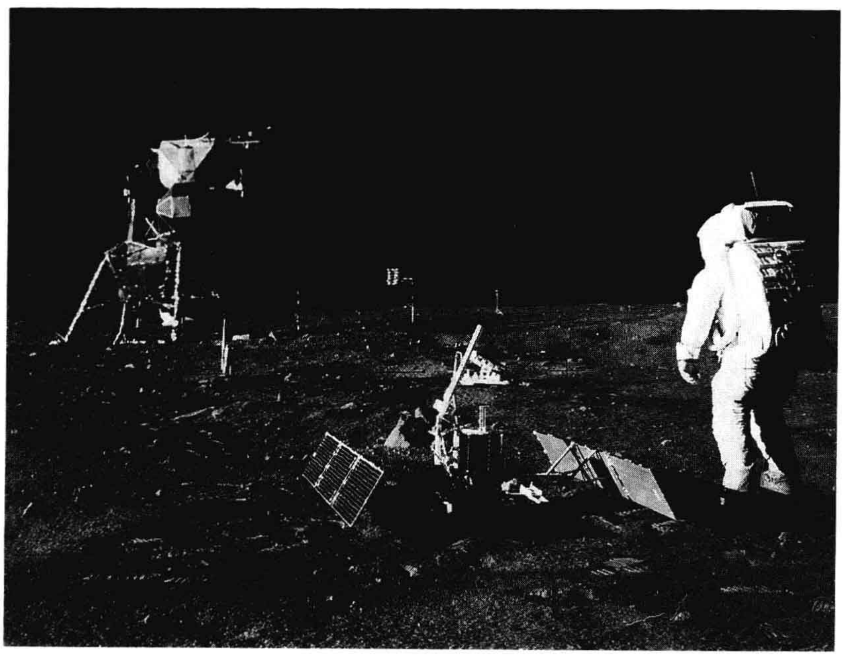


Figure 1.3 Apollo 11 astronaut on Moon, showing various experiments deployed around the lander. Samples returned from the Moon by the Apollo 11 crew enabled for the first time detailed compositional determination and dating of the ages of emplacement of mare lavas (Apollo 11 69-HC-898).

the objects in the Solar System and of the processes involved in their formation and evolution.

1.3 Relevance of geomorphology

Ideally, the various geologic objectives of Solar System exploration would be met by carrying out the entire sequence of missions and measurements, as indicated in Table 1.1. Limited resources prevent the completion of this strategy for Solar System exploration, at least in the foreseeable future. Meanwhile, nearly all previous and near-term anticipated missions have been equipped with **imaging systems** to acquire pictures of planetary surfaces. Aside from the obvious appeal of pictures, it is generally recognized that imaging science can yield answers to a broader range of questions than any other single instrument which might be carried on board spacecraft.

Planetary pictures also play a key role from the standpoint of engineering. During mission operations, flight engineers use pictures taken by the spacecraft for celestial navigation in guiding the probe in its journey through space. For missions involving landers, pictures of potential landing sites play a key role in the selection of safe sites.

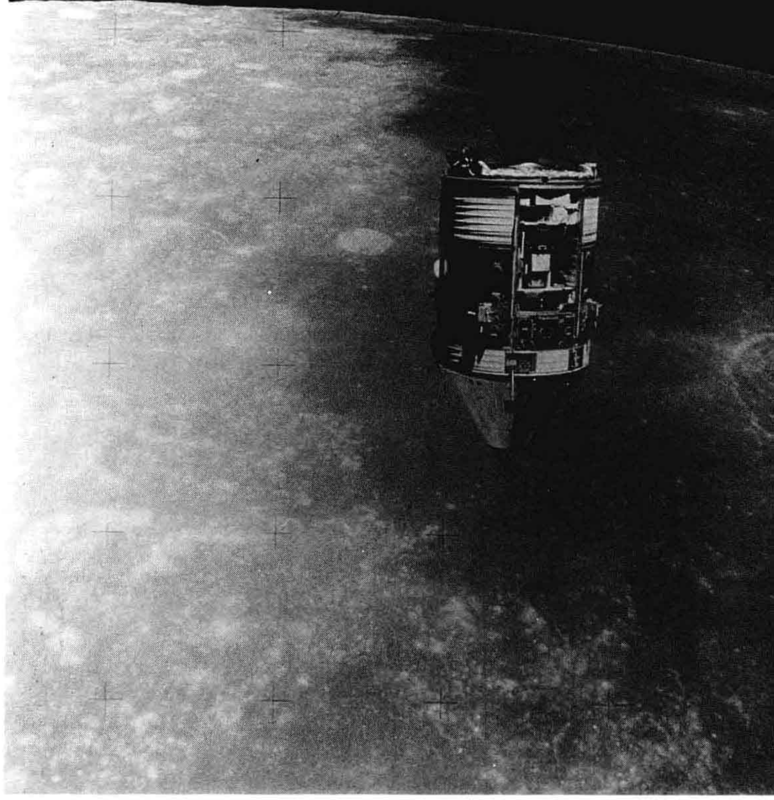
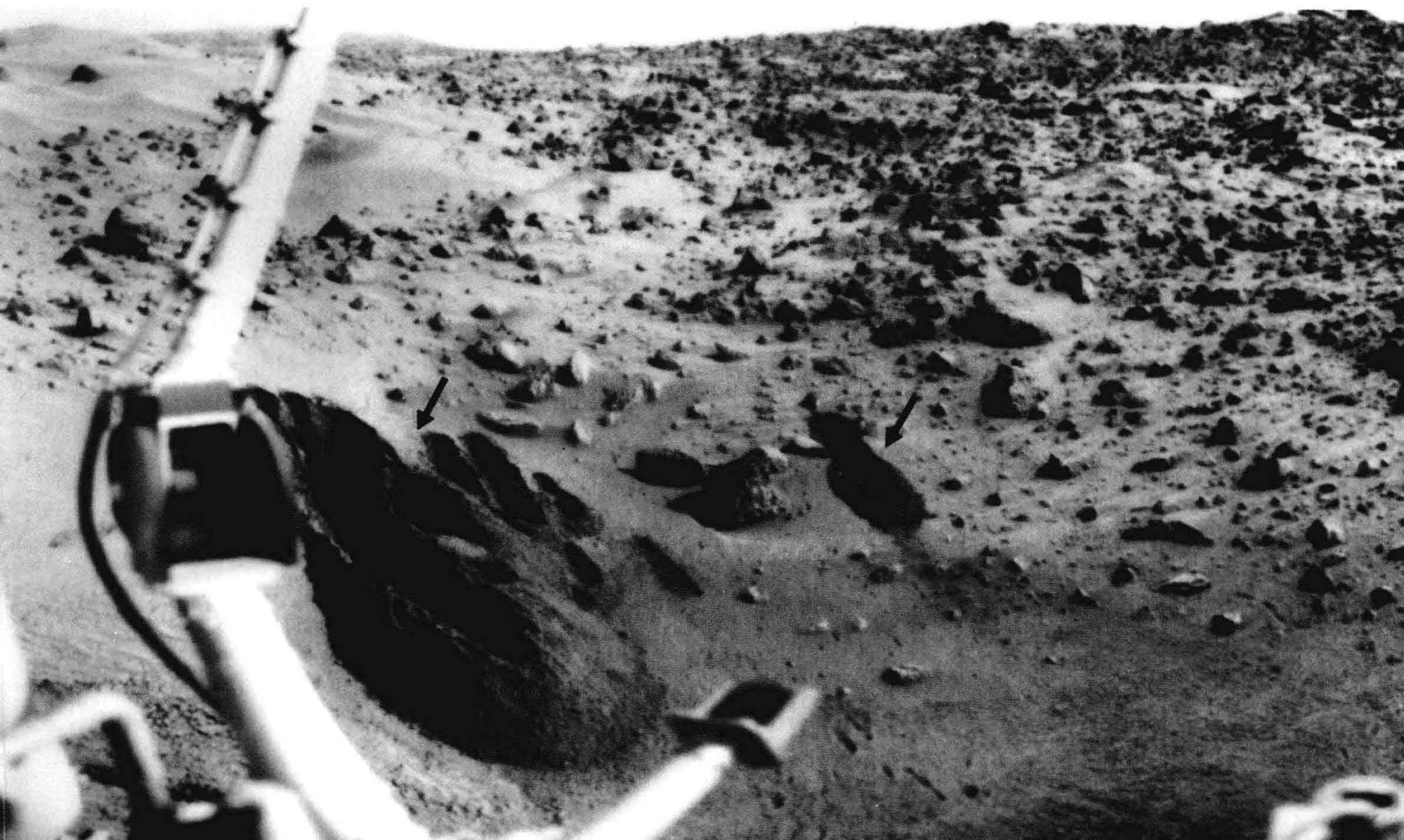


Figure 1.5 Apollo 15 photograph of the Service Module taken from the Landing Module, showing the Scientific Instrument Module (SIM) containing various remote-sensing experiments, including cameras, alpha, gamma-ray and X-ray spectrometers (Apollo 15 AS 15-88-11972).

Figure 1.4 View of the martian surface from Viking Lander 1, showing meteorology boom (left side, extending out of view toward top) used to measure wind speed and direction, temperature and atmospheric pressure, and sample arm (lower middle) used to obtain samples for analysis. Arm could dig into surface (trench for sample acquisition is marked with arrow) to retrieve the sample and dump it into a hopper on the spacecraft for analysis.



The first phase of most planetary geologic studies involves the classification of various landforms observed through images and the production of **physiographic maps** (Fig. 1.6). The next step is to derive geologic maps using various photogeologic techniques. Color, **albedo** (reflective properties of the surface), texture and other remotely sensed characteristics are used to distinguish possible rock formations. Then, using various geometric relationships, such as superposition, embayment and cross-cutting relations, the identified formations are placed in a relative sequence. These techniques have been long established in photogeologic studies of the Earth. An additional technique useful in planetary geology for relative dating of some surfaces is to establish the size–frequency distribution of impact craters. The idea is that surfaces act as impact "counters": the older the surface, the higher the frequency of superposed craters (Fig. 1.7). This concept will be discussed in more detail in Chapter 3.

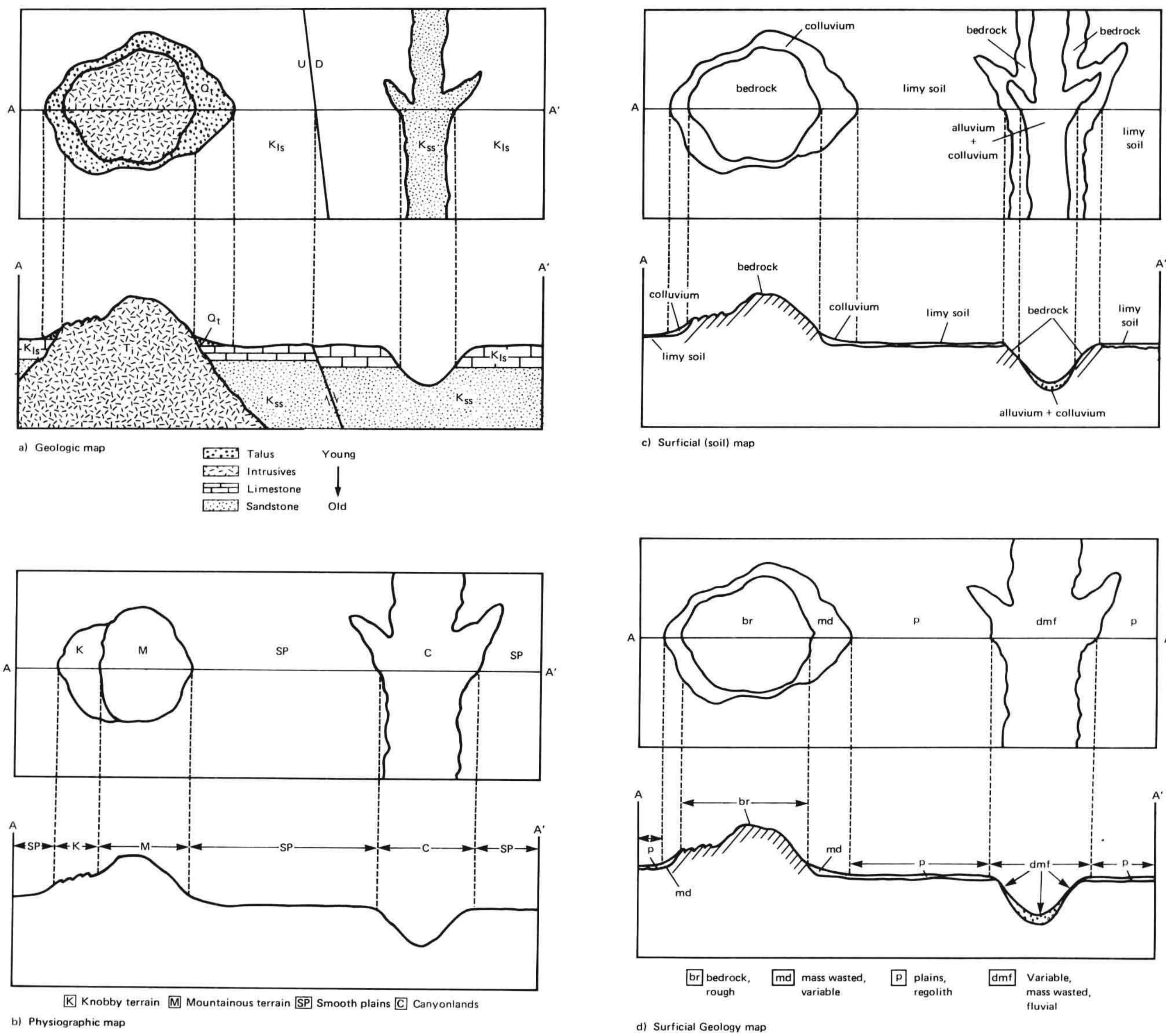


Figure 1.6 Diagrams showing types of maps commonly used to portray planetary surfaces (from Spudis & Greeley 1976). (a) *Geologic maps* show three-dimensional rock units in space and time, plus structural features such as folds and faults. They portray the surface of the planet as though all vegetation, soil and other surficial materials were stripped away; sequences of geologic events can be derived from this type of map. (b) *Physiographic maps* show landforms such as hills, valleys and plains. (c) *Surficial (soil) maps* show the distribution only of surficial covers or the lack thereof and do not show topography or terrain types. (d) *Surficial geology maps* which characterize the local geologic and surficial geology of a given area. Note that this map presents all the data of the physiographic (terrain) and surficial (soil) maps, but with a substantial reduction in map complexity.

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