7

Geologic mapping

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> "On first examining a new district [planet] nothing can appear more hopeless than the chaos of rocks [landforms]; but by recording the stratification and nature of the rocks and fossils [morphologic patterns] at many points, always reasoning and predicting what will be found elsewhere, light soon begins to dawn on the district [planet], and the structure of the whole becomes more or less intelligible."
>
> Darwin (1958), p. 77
> (called to my attention and paraphrased by John F. McCauley).

7.1. INTRODUCTION

Many scientists as well as laymen are surprised to learn that geologists study the Moon and planets. The surprise may abate when they consider that these extraterrestrial bodies consist of rock. But both the layman and the uninitiated professional geologist may find it harder to understand how planetary crusts can be deciphered without direct field study or sampling. In fact, the basic architecture and postformational history of the impact-scarred, relatively stable Moon, Mercury, Callisto, and Martian and Saturnian satellites, the tectonically deformed Ganymede, the constantly changing Io, and the richly diverse Mars have been determined on the basis of remotely obtained data.*

A major tool for unravelling the secrets of these distant objects has been geologic mapping. A geologic map is a two-dimensional representation of the three-dimensional spatial relations and chronologic sequences of the materials and structures of a planetary crust. In constructing a map, the geologist organizes and summarizes a seemingly bewildering planetary scene into a comprehensible picture. A properly constructed map distinguishes the planet's essential rock framework from irrelevant detail. Like the graphs of more quantitative sciences, geologic maps are economical media for documenting the observations of the mapper and communicating the results to others.

The success of planetary geologic mapping rests on the analytical power of the uniquely geologic perspective on which it is based: the perspective of *history* (Albritton, 1963). Fundamental to geology is the science of *stratigraphy,* which determines the sequence of emplacement of the planet's three-dimensional building blocks, its *geologic units.* Geologic maps also show the age relations of these material units to the structures created by *tectonic* deformation by internal forces. The principles that guide this mental look beneath the surface and back in time are elementary: that younger rock units usually lie on older rock units and structures and that younger structures and erosional surfaces cut across older rock units, structures, and erosional surfaces. These principles can be applied not only to Earth but to the solid surfaces of all planets because the relevant geometric relations can commonly be observed on images. Geologists accustomed to physical contact with the rocks of Earth can readily transfer their basic approach to other planets once they have learned the peculiarities of the new data set. There are no separate sciences like "selenology" or "ganymedology."

This chapter outlines the general principles and methods by which geologic maps of the planets are constructed from images. It also briefly shows how other remote sensing data are incorporated into the mapping. Section 7.2 summarizes the principles of geologic mapping for a general audience. Some familiarity with geologic principles and with the planets is helpful but not essential to the reading of this section. Section 7.3 briefly discusses some difficulties that have been encountered in viewing planetary images. Section 7.4 presents detailed guidelines for the construction and review of maps for those who intend to map actively.

Most examples are taken from lunar mapping because extraterrestrial mapping techniques were evolved for this second geologically mapped planet and because the lunar techniques, in turn, have been adapted to the other planets. The lunar and general examples are based largely on several earlier papers by the author and his colleagues in the U.S. Geological Survey's Branch of Astrogeology (Shoemaker, 1962a; Shoemaker and Hackman, 1962; McCauley, 1967; Wilhelms, 1970, 1972, 1980, 1987; Wilhelms and McCauley, 1971; Carr, 1984). These studies were almost entirely funded by the U.S. National Aeronautics and Space Administration (NASA). Section 7.4, in particular, draws heavily on an informal document prepared in 1972 for the use of geologic mappers participating in the program of lunar and planetary mapping conducted for NASA under the guidance of the Geological Survey (Wilhelms, 1972). A perceptive analysis of the logic of geologic maps in general is given by Varnes (1974). Guest and Greeley (1977) have contributed many insights about geologic mapping in their summary of lunar geology. This chapter and all other considerations of extraterrestrial stratigraphy and geologic mapping also owe a great debt to the lucid presentation by the late and much mourned Tim Mutch (Mutch, 1970).

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* Henceforth in this chapter, the term "planet" includes satellites as well as true planets.

I am much indebted to B. K. Lucchitta for her thorough critical review of an earlier draft of this chapter. R. J. Baldwin, R. M. Batson, J. E. Guest, and C. J. Hayden also contributed valuable comments.

Statements of scientific fact or interpretation given in this chapter are intended only to illustrate the mapping and are not fully supported or referenced here. The reader interested in their background and further reading is referred to books edited by Morrison (1982), for the satellites of Jupiter, and by Carr (1984), for the terrestrial planets.

7.2. RATIONALE AND GENERAL METHODS

7.2.1. *The geologic unit*

The process of geologic mapping is simple in principle. It rests on the fundamental concept that a planetary crust is composed of discrete three-dimensional bodies of rock called geologic units. The rocks of each unit formed, relative to those of the neighboring units, (a) by a discrete process or related processes and (b) in a discrete timespan. The unit concept reduces the complex internal detail of each body of rock to a more comprehensible entity.

On Earth geologic units are detected in vertical exposures or on the ground surface, where they can be reconstructed from outcrops or soil fragments. Vertical sections are also sometimes observed on Mars but very rarely on the other planets. Certain lunar geologic units have been mapped on the surface by means of the overlying fragmental material *(regolith)* that was derived from the bedrock units. Mostly, however, planetary geologic units are detected by their topographic expression and other remotely observed surface properties. Despite the differences in data and geologic style among planets, the procedures for recognizing geologic units are basically the same for all planets.

Planetary mapping can begin when a mapper decides that a certain terrain has been formed by a uniform set of processes and in a specific timespan, even if the exact processes and absolute time are unknown. The mapper looks for distinctive surface morphologies (coarse features) or textures (fine features) that are similar or regularly gradational over the whole terrain. For example, a flow lobe, or a repetitive pattern of flow lobes of the same general size and shape, probably reflects a unit (Figure 7.1).The lobes may consist of lava, but this interpretation is not essential to identification of the unit. A common type of gradational deposits are those that surround the innumerable craters observed on planets. The deposits of many craters consist of rough, concentrically textured material near the crater rim, grading through radial ridges or lobes farther out, to chains, loops, or clusters of pits at greater distances (Figure 7.2). The radial and concentric arrangement of these textures shows that they are related to the crater. Studies have shown, further, that the crater deposits contain *ejecta* that was excavated from the crater during the *primary* impact of a projectile from space. The small satellitic pits are *secondary-impact* craters formed by impacts of this primary ejecta. Deposits of the secondaries are also geologic units that may be mixed with the primary ejecta. Again, these interpretations are not essential to the recognition of a crater deposit as a unit, although they help considerably in refined mapping, as will be shown. No matter what its origin, the whole textured area around the crater is the expression of a complex geologic unit that consists of horizontally gradational *facies* (physically different parts of the same deposit).

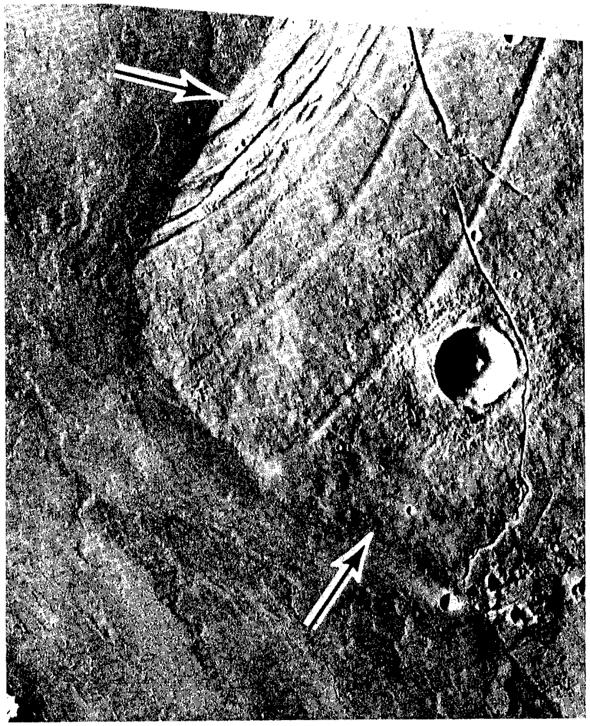

Figure 7.1
Distinct contacts between geologic units on Mars. Upper arrow, scarp contact; lower arrow, pinchout contact. Lobes of younger unit (left) suggest lava origin. The left sector of the crater's ejecta subdues an older, broad fault graben, whereas the right sector is cut by a younger, sharp fault graben. The relative ages demonstrated by these relations are confirmed above the crater, where the sharp graben cuts the broad graben. Viking orbiter frame 623A09, 99 km high by 82 km wide, centered at 26.6° N, 127.4° W.

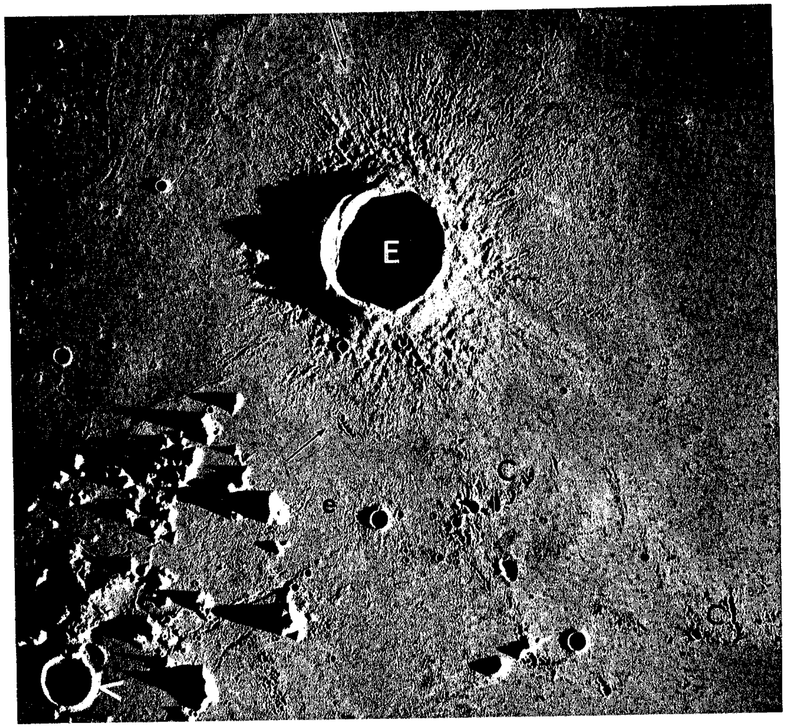

Figure 7.2
Stratigraphic relations near lunar crater Euler (E; 28-km diameter; 23.3° N, 29.2° W) in southern Mare Imbrium. A. Photograph. Lobate, channeled mare lavas evident to left (west) of Euler. These and other young mare materials truncate the deposits and secondary craters of Euler (arrows), whereas the Euler materials northeast of the crater are completely developed and superposed on an older mare unit. A belt of mare at lower arrow, containing sinuous rille, separates an outlying fan of Euler ejecta (e) from the main outcrop. Mare surface sharply abuts smaller crater (white arrowhead, lower left) and mountains (parts of Imbrium basin). C, secondary craters of Copernicus, centered 450 km to SSE, superposed on Euler and mare deposits; the most conspicuous craters of each secondary cluster lie closest to Copernicus. Apollo 17 mapping frame 2293.
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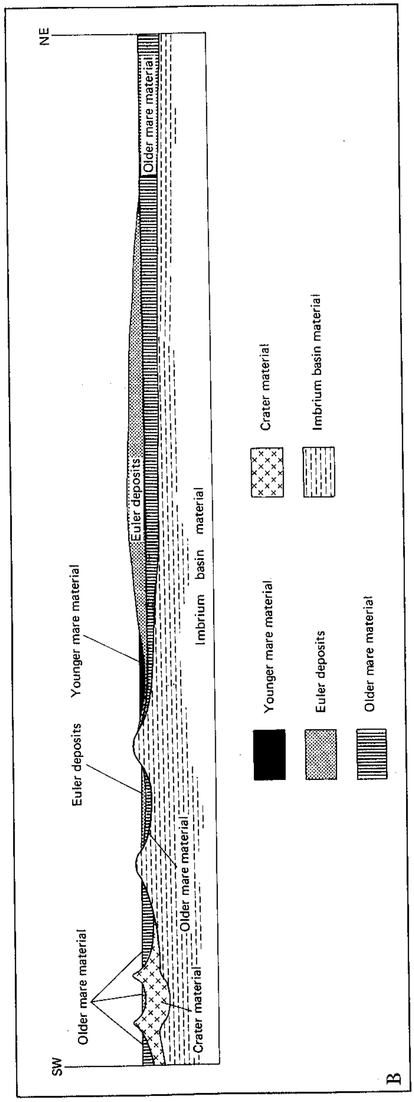

Figure 7.2 (cont.)
B. Diagrammatic geologic cross section drawn from lower left (southwest) corner to upper right (northeast) corner of 7.2A. Basement unit is Imbrium-basin material, which crops out in the mountains. The crater in the southwest is superposed on this basement. This crater and the rest of the Imbrium-basin basement are flooded by the older mare material. Euler deposits are superposed on this mare material and drape over parts of the Imbrium mountains. Parts of the Euler deposits are flooded by the narrow belt of younger mare material (lower arrow in A).

Although detected from surface properties, a geologic unit is not a surface, a geomorphic terrain, or a group of landforms. Instead, it is the sheetlike, wedgelike, or tabular body of rock that underlies the surface. Each geologic unit has a limited horizontal extent that can be mapped and a limited vertical extent that can be inferred. Thus, geologic mapping concerns the layered section of rock beneath a planar area more than the plain itself, and it concerns the deposits of a crater more than the cup-shaped topographic depression. Craters and their larger relatives, the multiringed impact basins, are the sources of identifiable deposits and are not merely assemblages of rings, ridges, troughs, and other topographic features. Even old, largely undistinctive surfaces like the lunar terrae (uplands, highlands) are not underlain by homogeneous masses of material but by discrete units, although such terrains may have to be assigned noncommittal designations temporarily, such as "undivided terra material," until their stratigraphy is learned (see Section 7.2.7).

The most significant units are those whose defining characteristics result from the units' emplacement process and not from later modifications. The flow lobes and ejecta textures already illustrated are examples of such intrinsic textures. Erosional morphology, faults, and superposed craters are examples of postdepositional modifications. Properties resulting from modifications may be used to define units (Sections 7.2.3, 7.2.5, 7.2.6), but are subject to reassessment when the true depositional units are recognized.

As on Earth, the age of a planetary deposit and the ages of its components may or may not be entirely the same. Most flood lavas or pyroclastic blankets that cover old surfaces constitute geologic units that consist of juvenile materials newly melted in the mantle. Absolute ages determined from samples of these units usually date the surface emplacement of the unit. An impact deposit, however, consists of material that was created before the impact by other impacts, volcanism, or other processes. The projectile that formed each crater penetrated, violently disrupted, and ejected older units from its target. The impact may or may not "reset" the radiometric "clocks" of these older components. Nevertheless, the ejecta forms a new unit when it falls upon the older surface surrounding the crater. In this respect, impact ejecta is like a terrestrial clastic sedimentary rock. On planets where water and ice are agents of both erosion and deposition, transported materials similarly contain old material but may create new deposits that take new stratigraphic positions above their source units. This distinction between the "origin" of a unit's constituents and the "origin" of its emplacement as a three-dimensional rock body has been a source of misunderstanding between stratigraphers on the one hand and geochronologists, petrologists, and geochemists on the other.

7.2.2. *Relations between units*

Determination of the relations between geologic units is at the heart of the geologic approach. The *contacts* between units therefore command particular attention during geologic mapping. They summarize and abstract many observed details; all the terrain enclosed by a contact has been determined to belong to one unit and the terrain on the other side to a different unit or units. The geometric relations of the contacts reflect the depositional patterns and age relations of the units. They may also reveal much about the nature of the materials of the units they bound. For example, cohesive materials, such as lava flows, are commonly bounded by distinct scarps (Figure 7.1, upper arrow), whereas particulate material grades imperceptibly with the subjacent units. When all contacts are drawn and interpreted, a geologic map is nearly complete.

The presence of two units in contact is generally suggested by topographic contrasts that are not explicable by variations within a single unit. Some of these contrasts are lateral and the contacts between the two adjacent units are abrupt. Termination of a plains deposit against a mountain range or against a crater rim or wall is a common type of abrupt contact (Figure 7.2A, lower left). Contrary to appearances, this abrupt termination does not reflect the abutment of two blocks with limitless depth, but rather the superposition of a layer of younger plains material on other, older layers. As shown in Figure 7.2B, the buried layers consist of crater ejecta and basin material that continue laterally beneath the plains. Subtle flooding of the ridged ejecta or satellitic craters of a crater reveals a similar overlap of the plains material on the crater (Figure 7.2A, black-and-white arrows).

The buried layers are commonly invisible at the surface. Their existence is then inferred either from nearby outcrops or from independent knowledge of the stratigraphy. For instance, an extensive ejecta blanket that has been flooded by younger lava may appear in several unflooded windows. Its identity as a unit is established by the exposure in each window of similar textures, similarly oriented linear features, progressive gradations in texture, etc. (Figure 7.2A, radial ejecta of Euler at *e*, below the belt of mare).

Other lateral contrasts in topography are gradational, and the underlying unit is partly visible. The textures of the underlying unit may grade from distinct near the contact, where the superposed deposit is thin or absent, to invisible, where the superposed deposit is thick. The deposits of superposed craters are very common gradational units. Their radially ridged ejecta and the underlying topography may both be expressed (Figure 7.3A, letter *E*). More commonly, the superposed deposit retains no texture of its own and merely smooths the underlying unit. Crater deposits commonly pinch out to a vanishing point that is hard to locate and map precisely. Nevertheless, their superposition on other units is demonstrated where their ejecta is fully developed, with no facies missing (Figure 7.2A, northeast of *E*).

Similar criteria establish the relations between geologic units and structures. Sharp truncation or total obscuration of a fault by a deposit indicates, of course, that the fault is older than the deposit (Figure 7.1, upper arrow). An older fault may be partly expressed topographically as a sag in an overlying younger deposit (Figure 7.1, left of the crater). Where a deposit terminates abruptly against a fault and does not reappear on the other side, the fault is

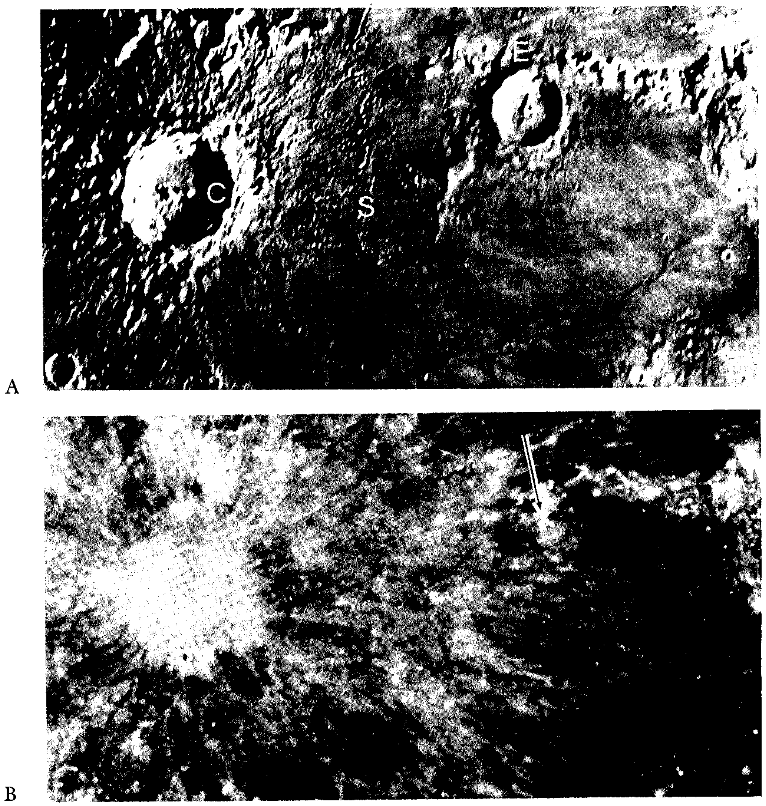

Figure 7.3
Telescopic photographs of Copernicus–Eratosthenes region of the Moon. See Figure 7.5 for location. A. Low-sun illumination. C, *Copernicus (93-km diameter);* E, *Eratosthenes;* S, *crater Stadius and Stadius chain of craters, extending to top of picture; Montes Apenninus at right (east). At* E, *deposits of Eratosthenes soften peaks of the Apennines and extend onto mare surface. Mt. Palomar Observatory photograph. B. High-sun illumination (near full Moon). Copernicus at left; arrow, Eratosthenes (barely visible). U.S. Naval Observatory photograph.*

also probably older than the deposit and has blocked its lateral expansion. Where a sharp fault interrupts a deposit's continuity but does not appear to have influenced the deposit's emplacement, the fault is probably younger than the deposit (Figure 7.1, right of the crater). Intersections of faults may reveal the faults' relative ages (Figure 7.1, above the crater).

These relations illustrate the laws of stratigraphy that were enunciated for Earth by Nicolaus Steno in 1669 (Gilluly et al., 1951): Each new sedimentary deposit (1) was deposited on older deposits and remains above them unless subsequently disturbed (law of superposition), (2) was deposited approximately horizontally and approximately parallel to the underlying surface (law of original horizontality), and (3) spread out laterally until it pinched out or was blocked (law of original continuity). These simple principles, which seem not to have been obvious before 1669 even for Earth, are still worth remembering during planetary work. A test of whether a given terrain consists of one unit is to consider whether the observed morphology can be explained by one laterally continuous rock body. If it cannot, what additional adjacent or subjacent rock bodies, postdepositional deformations, or erosional truncations can explain its appearance? The third dimension should be continuously kept in mind by drawing vertical cross sections.

One variation on these laws encountered in planetary work is that some units, namely secondary-impact craters and the bright rays that emanate from them on many planets, were discontinuous when deposited. Each patch of ray or secondary ejecta obeys Steno's laws, but the patches are collectively treated as a unit. The primary crater that was the source of the secondaries can often be established by mapping or simple inspection of the rays' radial patterns. Units on which the rays or secondaries are superposed are older than the primary crater. Units superposed on the rays or secondaries are younger than the primary. Clusters of secondary craters whose rays are no longer visible can be used similarly because they contain clues to the direction in which the primary lies: The largest secondary craters are concentrated on the side of the cluster nearest the primary, and secondary ejecta with distinctive herringbone textures is concentrated at the opposite side (Figure 7.2A, letter *C*). Such relations greatly extend the range over which primary impact craters can be dated. The criteria are particularly useful where the primary source is a giant ringed impact basin.

The process of distinguishing significant units and establishing relative ages is well illustrated by the first modern lunar geologic maps that were constructed by stratigraphic principles (see Chapter 2). Mapping of the Copernicus region by Shoemaker (1962a, b; Shoemaker and Hackman, 1962) yielded a clear stratigraphic succession, from oldest to youngest: Imbrium-basin material, mare material, deposits of the crater Eratosthenes, deposits of the crater Copernicus. This sequence can be observed even on a relatively crude photograph that shows the rays of Copernicus crossing Eratosthenes, the deposits and rayless secondary craters of Eratosthenes crossing the adjacent mare surface, and mare embayments abutting Montes Apenninus, which mountains are part

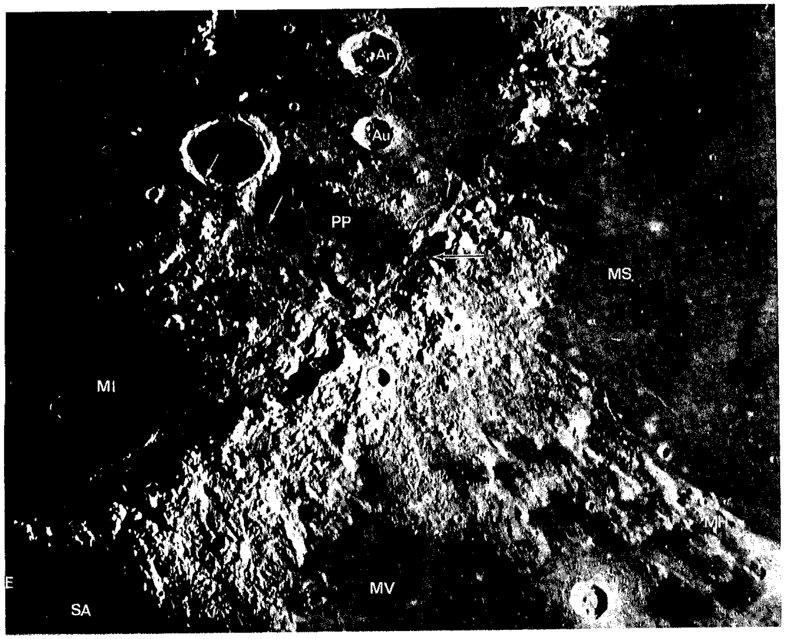

Figure 7.4
*Montes Apenninus (rugged range dominating picture), Montes Haemus (*MH*, lower right), Mare Imbrium (*MI*), Mare Serenitatis (*MS*), Mare Vaporum (*MV*), Palus Putredinis (*PP*) including Rima Hadley and Apollo 15 landing site (black-and-white arrow), Sinus Aestuum (*SA*), and craters Archimedes (white arrows), Aristillus (*Ar*), Autolycus (*Au*), and Eratosthenes (*E*, barely visible at lower left; compare Figure 7.3A). White arrows show flooding of Archimedes interior and secondary craters by mare materials; at lower white arrow, Archimedes secondary craters are superposed on nonmare plains deposit, which is also flooded by mare material but which embays Montes Apenninus. See Figure 7.5 for location. Catalina Observatory photograph 1894.*

of the rim of the Imbrium basin (Figure 7.3). In a neighboring area, this sequence was augmented by observations of stratigraphic relations near the crater Archimedes (Figure 7.4). Mare material so deeply floods Archimedes in some sectors that only part of the crater wall and rimflank are exposed. Elsewhere, the deposits and secondary craters of Archimedes are well exposed and are superposed on a nonmare plains deposit that, in turn, surrounds or abuts outlying hills of Montes Apenninus (Figure 7.4, lower arrow). The sandwiching of the Archimedes deposits between the mare and nonmare plains materials shows that a finite amount of time elapsed between the formation of the Imbrium basin and the deposition of the mare materials. Thus, the impact that created the basin did not create the mare, which is volcanic basalt (Baldwin, 1949; 1963). This important discovery appeared as novel in an era when the mare and basin were often confused.

Stratigraphic relations in a nearby region convincingly prove this basin–mare distinction and illustrate the power of stratigraphic principles to solve problems of planetary geology (Figure 7.4). Montes Haemus are part of the circular basin that contains Mare Serenitatis. The surface of the mountains is distinctly scoured by grooves and ridges that radiate from Montes Apenninus. Mare Serenitatis is not thus affected. Clearly, therefore, the Imbrium basin postdates Montes Haemus and the rest of the Serenitatis basin but predates Mare Serenitatis (Baldwin, 1949, pp. 210–13). Thus, Mare Serenitatis did not form simultaneously with either the Imbrium basin or the Serenitatis basin. The mare lavas can furthermore be subdivided by overlap relations and crater densities.

A stratigraphic sequence of no fewer than eight major units can be readily constructed in the region of Figures 7.3 and 7.4, from oldest to youngest: (1) Montes Haemus and other Serenitatis basin deposits, (2) the Imbrium basin materials, including those atop Montes Apenninus and those that created the surface lineations of Montes Haemus, (3) the nonmare plains deposit, (4) Archimedes deposits, (5) an older mare unit exposed along the margin of Mare Serenitatis that undoubtedly extends beneath the younger mare of central Serenitatis, (6) the mare units in central Mare Serenitatis and in Palus Putredinis between Archimedes and Montes Apenninus, (7) Eratosthenes deposits, and (8) Copernicus deposits (Figure 7.5). These relations can be portrayed in realistic cross sections showing the third dimension (Figure 7.5B). Their validity has been further confirmed by analyses of samples collected by Apollos 15 (Figure 7.4) and 17 from (1) mountains that are part of the eastern Serenitatis rim (3.87 ± 0.03 aeons), (2) the foot of Montes Apenninus (3.85 ± 0.03 aeons), (3) part of the border material of Mare Serenitatis (3.72 ± 0.05 aeons), and (4) the mare basalt of Palus Putredinis (3.29 ± 0.05 aeons).*

7.2.3. *Correlations of units*

A major goal of planetary geologic mapping, like terrestrial mapping, is to integrate local stratigraphic sequences ("columns") of geologic units into a stratigraphic column applicable over the whole planet. When any part of this global column is calibrated with absolute ages obtained from samples at spot localities, approximate absolute ages can be matched with the rest of the relative ages (Shoemaker, 1962a; Greeley and Carr, 1976). For example, dating the samples obtained by Apollos 14 and 15 from Imbrium-basin ma-

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* 1 aeon = 10^9 years.

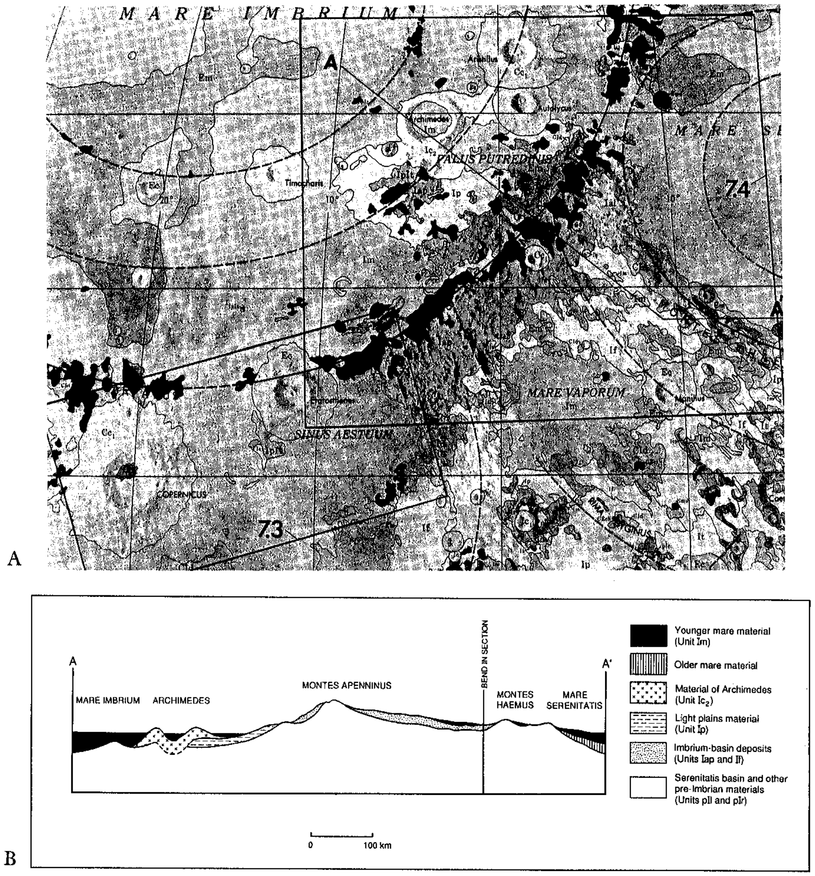

Figure 7.5
Geologic relations on part of the lunar nearside. A. Geologic map (Wilhelms and McCauley, 1971) including areas of Figures 7.3 and 7.4. Scale: each 10 degrees of lunar latitude covers 300 km. B. Geologic cross section along line A–A' of 7.5A. The "older mare unit" is shown on the map as Eratosthenian (unit Em) but was demonstrated by Apollo photography to be older than unit Im in Mare Serenitatis. Great vertical exaggeration; lunar curvature ignored.

terial has divided the entire lunar stratigraphic column into two blocks, one older and one younger than the 3.85-aeon age of Imbrium. Samples from other geologically mapped planets will similarly bracket their major historical episodes.

The local stratigraphic columns are generally determined during mapping in the ways that have been discussed. Where possible, local units are dated relatively to extensive units like the deposits and secondary craters of ringed basins, which serve as stratigraphic datum planes for large parts of many planets. However, not all units contact these datum planes. Even some units quite close to basins have been missed by the basin ejecta, which forms lobes of unequal length. Lava flows provide excellent local stratigraphic reference planes but are less useful for regional correlations because of their limited extent. Furthermore, no unit covers an entire planet.

Supplementary means of dating are therefore needed. On Earth, age relations of units that are not in contact can be reconstructed from fossils. On most other planets – though not the ice-covered Europa or the volcanically hyperactive Io – the ages of the units correlate with the density of smaller superposed impact craters (Basaltic Volcanism Study Project, 1981, Chap. 8). Heavily cratered units are usually older than less heavily cratered units (provided that the superposed craters were formed by primary impacts from space, which are spatially almost random and accumulated in proportion to time, and not by secondary impacts, which are concentrated around a primary and formed in a burst when the primary forms). Craters employed as counters in this way are modifiers of other units.

Craters are, of course, also stratigraphic units in their own right. As such, they can be dated by smaller superposed craters. Impact craters on airless planets can also be approximately dated on the basis of their morphology, which is initially similar for a given crater size. Topographically sharp craters are younger than craters that have only bland, rounded topography (Section 7.2.7; Pohn and Offield, 1970; Trask, 1971). Crater morphology is a less satisfactory means of dating than crater frequency, but it has been used successfully on the Moon and Mercury. It is a less reliable guide to age on Mars, where more diverse degradational processes have operated and where crater morphology also depends on latitude and target material (volatile-rich or volatile-poor).

7.2.4. *Time-rock units*

Ideally, each successively younger stratigraphic unit has successively fewer and morphologically sharper superposed craters. As with the dating of terrestrial sediments by fossils, this ideal correlation is not always attained. A formal stratigraphic practice has been developed for terrestrial geology to accommodate the distinction between the geologic units mapped on the basis of physical characteristics and the "clocks" that indicate elapsed time (North American Commission on Stratigraphic Nomenclature, 1983). Distinctions

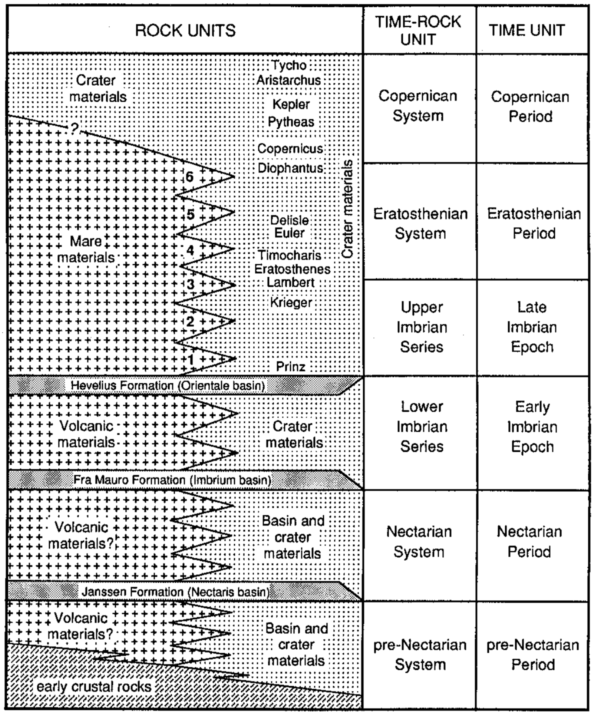

Figure 7.6
Lunar columnar section indicating interfingering rock units of crater materials and mare materials (examples from Mare Imbrium and Oceanus Procellarum; Wilhelms, 1980) and relations among rock, time-rock, and time units.

among *rock, time-rock,* and *time* units based on this Stratigraphic Code have benefitted planetary geology (Figure 7.6).*

Rock (rock-stratigraphic or lithostratigraphic) units are the three-dimensional physical units that may be directly observed and mapped. The fundamental rock unit is the *formation;* formations can be combined into *groups* and divided into *members.* For example, several individual deposits of the lunar Orientale basin are considered formations (Hevelius Formation, Montes Rook Formation, Maunder Formation), which collectively constitute the Orientale Group (Scott et al., 1977). In contrast, maps may treat each facies of an individual crater as a member, all the facies of each crater together as a formation, and several such formations of related craters as a group. Each formal rock unit is defined in a *type area* to which other occurrences can be compared.

Time-rock (time-stratigraphic or chronostratigraphic) units include all the rock units emplaced on a planet within a given timespan. Time-rock units consist of rock units and are defined on the basis of specific rock units in specific type areas. Thus, the time-rock unit is a physical unit. The basic time-rock unit is the *system,* which can be divided into *series* (and finer subdivisions in terrestrial geology). The deposits of the lunar Imbrium basin (more specifically, the Fra Mauro Formation) define the base of the Imbrian System, and the Orientale Group divides this system into lower and upper series (Wilhelms, 1987). The Lower Imbrian Series includes the materials of both basins and whatever other materials intervene stratigraphically on the whole Moon. Older systems are the pre-Nectarian (informal) and the Nectarian (Stuart-Alexander and Wilhelms, 1975). For want of a better criterion, the top of the Imbrian System and of the Upper Imbrian Series is defined by certain rock units of mare basalt, and geographically separated rock units are correlated by comparing their crater densities with those in the type areas. Younger systems are the Eratosthenian and Copernican (Shoemaker and Hackman, 1962). Time-rock units do not overlap; the upper boundary of one is the lower boundary of the next. This exclusivity is not always true of rock units, which commonly intergrade laterally (e.g., clastic and carbonate sediments on Earth, groups of lavas and crater deposits on other planets) (Figure 7.6).

Time (geochronologic) units are defined as the time during which a corresponding time-rock unit was deposited and are not physical units. *Periods* correspond to systems, and *epochs* to series (e.g., Imbrian Period, Early Imbrian Epoch).

These distinctions facilitate geologic mapping. Many rock units can be mapped from their distinctive textures or remote-sensing properties without knowing their ages. In other cases, relative ages of a terrain can be determined from crater frequencies before the individual rock units are fully delineated. These two types of information then converge when time-rock units are devised. The separation of rock and time-rock concepts also allows one or the other assignment to be changed without overthrowing the entire system of stratigraphic nomenclature.

The history of lunar mapping again provides illustrations. Although the stratigraphic scheme devised by Shoemaker and Hackman (1962) was conceptually powerful and generally very successful, its nomenclature implied too close a correspondence between rock and time-rock units. Shoemaker and Hackman (1962) concluded from telescopic crater counts that all lunar mare materials had about the same age as those that lie stratigraphically between the materials of Archimedes and Eratosthenes (Figure 7.4, *MI;* Figure 7.5). The rock unit "mare material" on the whole Moon was equated with the time-

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* Although this 1983 edition of the Stratigraphic Code recommends the terms *lithostratigraphic, chronostratigraphic,* and *geochronologic,* the simpler terms are used here.

rock unit "Procellarian System," which intervened between the "Archimedian Series" (mostly the Archimedes-type craters) and the Eratosthenian System. In fact, however, many mare units are older than Archimedes or younger than Eratosthenes. To accommodate this wide spread in mare ages, the Procellarian System was dropped, and mare units (and other lunar rock units) are assigned to whatever system their crater densities, crater morphologies, and stratigraphic relations indicate they belong (McCauley, 1967; Wilhelms, 1970).

Similar distinctions between rock and time-rock units can help avoid prejudgments about the histories of other planets. A scheme based on the lunar scheme has been devised for the geologically similar planet Mercury (Spudis, 1985). The two oldest systems are divided by the Goya Formation, the lineated peripheral material (probably ejecta) of the Tolstoj basin, into the pre-Tolstojan and Tolstojan Systems. These are parallel to the lunar pre-Nectarian and Nectarian Systems. The top of the Tolstojan System lies at the base of the Caloris Group (McCauley et al., 1981), which includes all materials of the Caloris basin. The Calorian System includes extensive light-colored plains, which may be either contemporaneous with or younger than the Caloris basin. The stratigraphic scheme flexibly allows for both possibilities by allowing the plains deposits to be mapped as rock units without requiring a decision about their exact stratigraphic position. The top of the Calorian System lies below the deposits of the crater Mansur. The two youngest systems are the Mansurian and Kuiperian, which, like the lunar Eratosthenian and Copernican, include craters that are slightly degraded and bright-rayed, respectively. Although morphology and rays are physical distinctions that are not entirely time dependent, they are a useful basis for approximate time-rock units.

Three systems organize the more complex Martian stratigraphic column (Scott and Carr, 1978). The oldest, the Noachian System, includes the relatively intact, ancient, basin- and crater-rich uplands including "cratered plateau material," which is basically undivided uplands material recalling the lunar "undivided terra material." The intermediate and younger systems, the Hesperian and Amazonian, respectively, include diverse plains deposits, extensive channel deposits, lobate flows of lava and other materials, probable and possible eolian deposits, and a great variety of other deposits that characterize this diverse planet. These three systems are defined on the basis of type areas of key units but are less well defined than those of the Moon and Mercury because extensive stratigraphic datum planes are rare on Mars. Most Martian rock units are therefore assigned to systems on the basis of crater densities, which are correlated with the crater densities measured in the type areas. Many groups of martian rock units cross the time-rock boundaries. Despite the approximate nature of the systems, they usefully provide a first-order classification for the complex martian rock-unit stratigraphy.

No formal time-rock schemes have been devised for the four highly diverse Galilean satellites of Jupiter (Morrison, 1982). All the identifiable stratigraphic datum planes on Io are local, and many are so young that they were created between the flybys of the two Voyager spacecraft. The relatively featureless

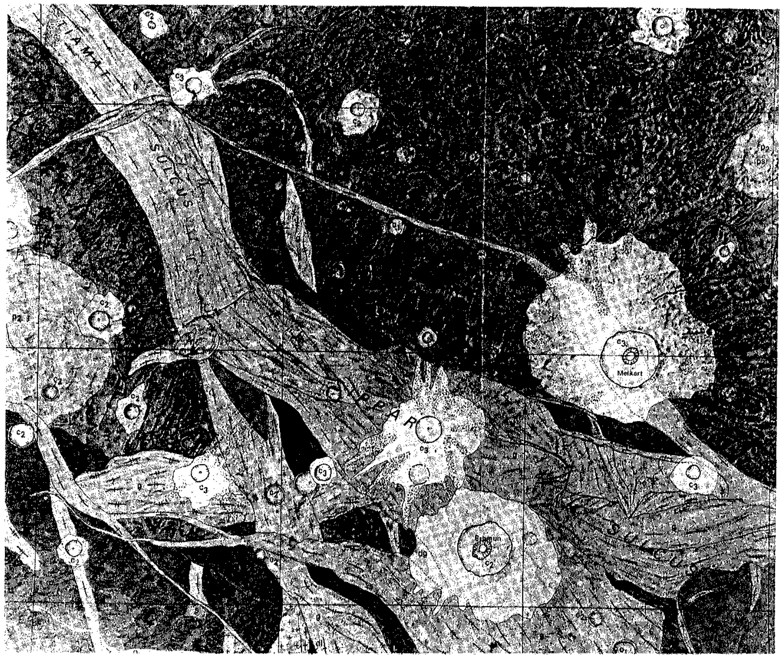

Figure 7.7
Geologic map of part of the Uruk Sulcus quadrangle of Ganymede, showing truncation of older, darker, indistinctly structured terrain by younger, brighter, closely grooved terrain. Several crater units also mapped. Air-brushed base; approximate boundaries 4°N–22°S, 180°–212° W. (Guest et al., 1988).

Europa consists of two basic units, extensive light-colored materials and streaks and patches of dark material. Descriptive rock-stratigraphic schemes probably suffice for these two satellites. The materials of Ganymede are divided into two basic groups that approximately correspond to time-rock units: a generally older, darker, lineated-to-hummocky group and a younger, brighter, grooved-to-smooth group (Figure 7.7). The ejecta and secondary craters of the basin Gilgamesh provide an excellent local stratigraphic reference plane that is a potential planetwide correlation reference for Ganymede. Callisto is characterized by multitudes of craters and by impact basins with more concentric rings than are known on any other planet. The larger of these basins are also potential stratigraphic markers.

The small satellites of Mars and Saturn display stratigraphic sequences of heavily cratered uplands and more lightly cratered units (Figure 7.8) (Smith

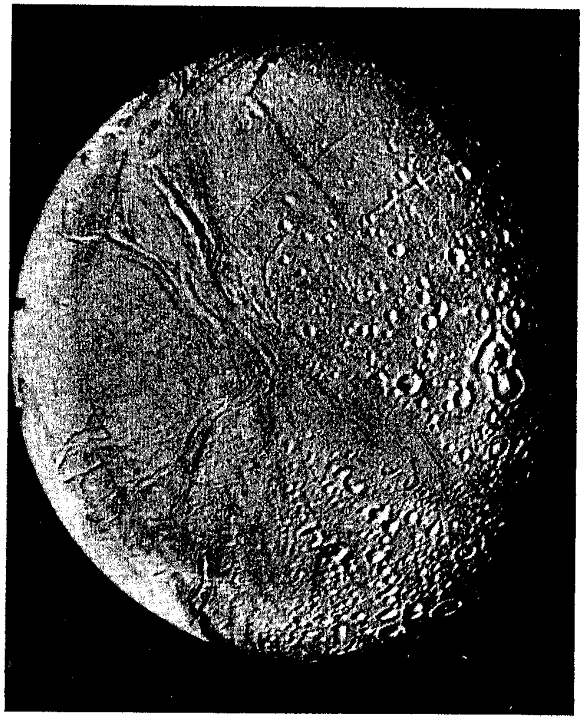

Figure 7.8
Saturnian satellite Enceladus, showing a densely cratered unit and younger smooth and structured units (Smith et al., 1982, p. 520). This geologic diversity was unexpected on such a small body (502-km diameter). Voyager 2 frame 1715S2-001.

et al., 1982; Plescia, 1983) that could be formally recognized as time-rock units if it were considered useful. Local stratigraphic relations are abundantly clear in the Soviet radar images of Venus (see Chapter 2), and the future unraveling of the complex geology of this fascinating planet will probably benefit from the establishment of a time-rock scheme.

7.2.5. *Structures and structural units*

Tectonic structures modify material stratigraphic units on all planets – to the greatest extent on Earth, Venus, and Ganymede; the least on some of the small icy or rocky satellites. Investigation of the spatial and temporal relations of structures is an integral part of geologic mapping. Structures and structural patterns should be related to specific rock or time-rock units and therefore to the evolutionary history of the planet.

Linear features are often plotted on rose diagrams and the like for apparent objectivity. However, many such features are not true structures but are artifacts of lighting angle and other subjective factors. Features known to be true structures should be mapped where possible. Individual structures are mapped by line symbols adapted from terrestrial mapping (see Section 7.4.5). Treatment of extensive tectonically deformed terrains requires more attention here.

Because structures commonly cut across several rock units, the Stratigraphic Code does not allow for mapping of units on the basis of their structural modification alone. Where the rock units of a highly faulted or otherwise deformed terrain are recognizable, they should be mapped as separate rock units. Sometimes, however, the deformed rock units are not recognizable. In this case it is better to map such structural units as "fractured plains material" (Figure 7.9) than to ignore the presence of the structures in order to adhere strictly to the Code.

Some structures are closely tied with material units. Both of the major types of unit on Ganymede that are characterized mainly by tectonic patterns and albedo (Figure 7.7) probably consist of similar ice-rich materials. However, the younger, lighter, grooved and smooth units probably consist of new or recycled material that broke through the surfaces of the older, darker, lineated or hummocky units. Mapping these units and subdivisions by structural patterns conforms with the Stratigraphic Code because the material coincides with the structural pattern.

Martian chaotic terrain illustrates the question of material versus structural units and also the relation between mapping conventions and scale. The chaotic topography results from loss of coherence of other units. Large tracts of this terrain are visible on medium- and low-resolution images and are mappable at scales of 1:15,000,000 or 1:5,000,000 as chaotic material (Figure 7.10). Some blocks and block-bounding fractures that are included with the chaotic material at 1:15,000,000 scale can be mapped individually at 1:5,000,000 scale. The higher the resolution and the larger the map scale, the more numerous are the blocks of the chaotic material that can be mapped separately as "plateau material," "plains material," or whatever unit broke up chaotically.* Despite its origin by a quasi-structural process, the chaos may be considered a new material unit, because its source materials have been physically reconstituted at the scale of mapping. A terrestrial analogy is landslide breccia consisting of jostled blocks that are commonly derived from

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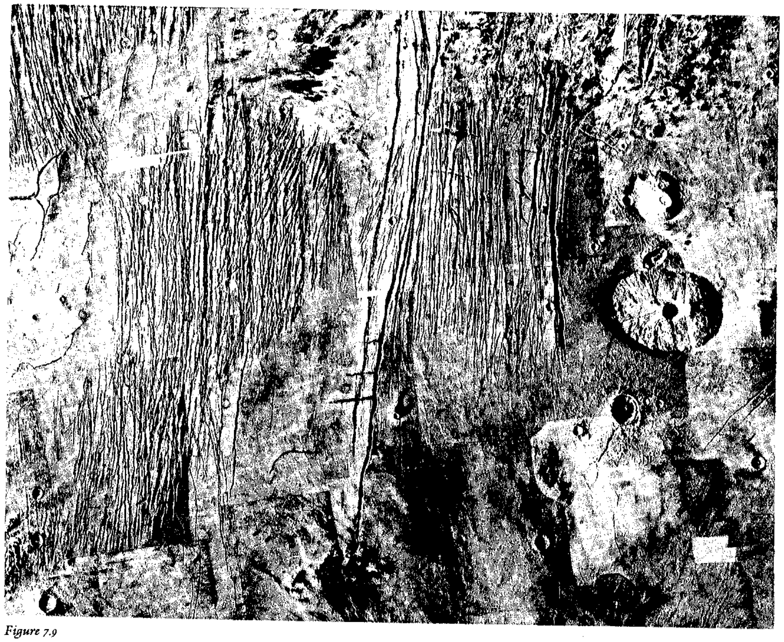
* Scales are referred to here as "small" or "large" according to their numerical value. Thus, 1:15,000,000 is a smaller scale than 1:5,000,000. By this convention, a map at a small scale covers a larger area than a map at a large scale.



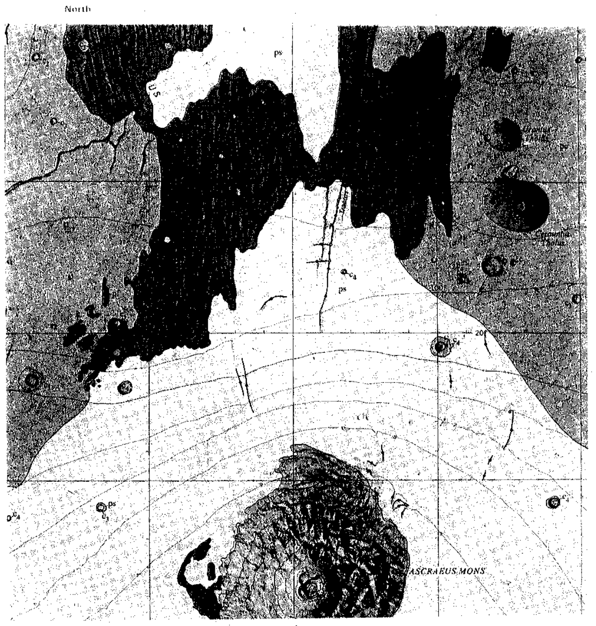
A

Figure 7.9
Heavily fractured and smooth units in the Alba–Tharsis region of Mars. A. Part of photomosaic of the Tharsis NE quadrangle (M 2M 22/101 CM, MC9 NE) (U.S. Geological Survey; original scale 1:2,000,000).
(Continued)

different units. In the final analysis, all terrestrial and planetary geologic units are recycled, to different degrees, from older units (see Section 7.2.1). Some recycling is physical; some, chemical.

7.2.6. *The role of erosion*

In mapping from images, one is faced with the necessity of distinguishing depositional from erosional surfaces. The distinction is particularly subtle in the case of undistinctive surfaces, such as plains and smooth uplands. If depositional, the exposed surface has the same age as the deposit. If erosional, the surface is younger than the unit or units that it exposes. Most of the outcrop patterns seen on Earth-satellite images were created by erosion, and the original depositional patterns of the stratigraphic units that compose these landforms must be reconstructed with allowance for the erosion.



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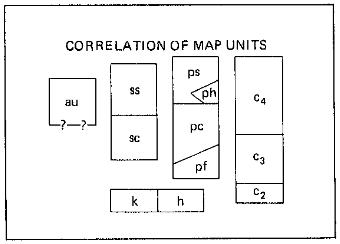

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Figure 7.9 (cont.)
B. Geologic map including area of 7.9A and additional area to south, based on Mariner 9 data (Carr, 1975). Scale: each 10 degrees of Martian latitude covers about 600 km. C. Part of explanation of 7.9B, showing interpretations of stratigraphic relations; au, Olympus aureole material; c_4, c_3, c_2, crater materials, in order of interpreted increasing age; h, hilly material; k, knobby material; pc, pf, ph, and ps, cratered, fractured, hilly, and sparsely cratered plains materials, respectively; sc and ss, cratered and sparsely cratered shield material, respectively.

Figure 7.10
Martian chaotic terrain, broken up into small, jumbled hills (lower part of picture) and separated into miniplateaus (upper part). At the scale of this image, the miniplateaus could be mapped individually whereas the small hills could not; at smaller scales (lower resolutions), the miniplateaus would also have to be mapped collectively as chaotic terrain. Viking orbiter frame 366S61, 254 km high, 284 km wide, centered 0.9° S, 34.8° W.

In contrast, depositional patterns dominate the visible surfaces of dry, airless, tectonically quiescent planets. However, the surfaces of these planets are exposed to erosion in the form of constant abrasion by impacting particles. Most slopes are covered by soft-textured deposits of fragmental material chipped from the bedrock. On the Moon, some of this material has crept downslope and accumulated at the slope bottoms in molding-like deposits (Figure 7.11). This material therefore constitutes three-dimensional units superposed on the older units from which it was derived and even on units that postdate the older units (Figure 7.11C). In this role of forming new units created from old materials, the slope debris is like the debris eroded and transported by water, ice, and wind on more active planets, except that it has remained close to its source.

The one imaged planet besides Earth where erosion is known to have played a major role is Mars. The present map patterns of many Martian units have been created by erosion. Truncated edges of strata, evocative of terrestrial geology, are exposed in erosional scarps. Irregular reentrants in the map plan of many deposits probably indicate that erosion has stripped back the edges of the deposits and exposed an underlying layer (Figure 7.12). As on conventional terrestrial geologic maps, the uncovered unit and the remaining parts of the eroded unit are assigned the ages of their deposition, not of their erosion. The age of the erosion surfaces may be shown by supplementary conventions (Milton, 1975).

On many planets, textures produced by erosion are often more evident than textures produced by deposition. In layered sections on Earth and Mars, resistant beds protrude and weak strata recede. Horizontal surfaces are also differently affected by erosion. For example, the wind may scour a soft Martian deposit while leaving an adjacent deposit untouched. Although not intrinsic to the unit's deposition, these erosional properties are valuable indicators of the units' lithologies.

A mapper is not always sure whether textures and morphologies are depositional or erosional in origin. The striated walls and floors of Martian channels or valleys are clear indications of the flow of some fluid material (water, ice, lava). However, the striations may be grooves scoured by erosion, the outcropping edges of strata exposed by the flow, or depositional features of the sediment deposited by the flow. The striated surfaces can be mapped descriptively but cannot be fully integrated into the Martian stratigraphic scheme if their origin is unknown. The striations may affect more than one depositional unit. They should be objectively mapped and approximately dated pending further information. A similar example is the mapping as "gullied terrain" of Martian upland terrains that are characterized by intricate valley networks. These terrains may or may not coincide with stratigraphic units.

7.2.7. *Interplay of mapping and theory – a lunar case history*

Determining emplacement mechanisms is assessed at two levels in two stages of mapping. The first, already discussed in general terms, establishes that a rock body is a unit by recognizing that its appearance and stratigraphic relations are consistent with formation by a single general process (radial deposition from a central source, mantling by particulate material of varying thickness, viscous flow, flooding of an extended surface, fluidlike movement in a restricted channel, etc.). Associations between units are another clue obtainable by mapping; consistent juxtaposition in large areas or the whole planet suggests that two units are genetically related. Mapping will also show whether a feature is part of an extensive unit and therefore significant to the planetary geologic style or is merely a unique eye-catching anomaly that need not de-

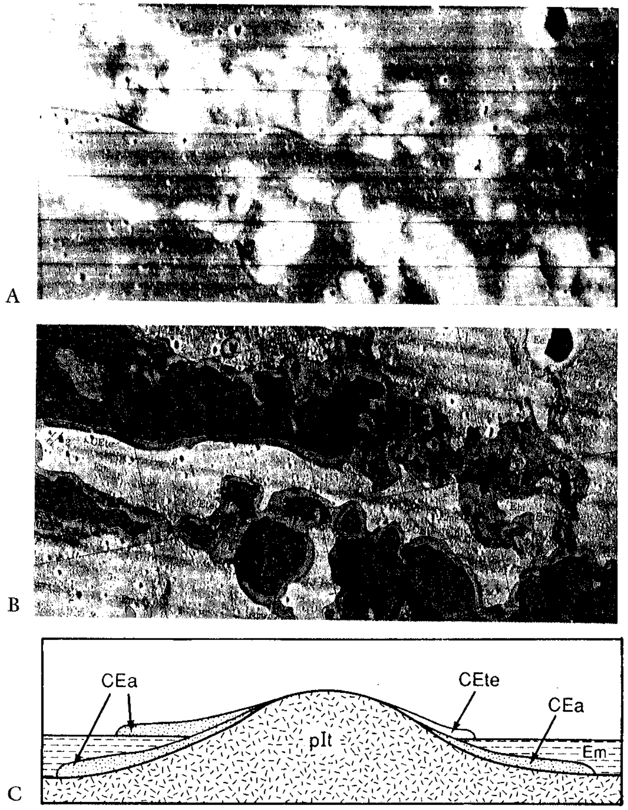


Figure 7.11
Part of premare lunar crater Flamsteed P, showing softened landforms and basal "moldings" resulting from downslope movement of particulate material. View centered at 1.75° S, 43.2° W; largest crater is 1.7 km in diameter. A. Lunar Orbiter 1 frame M-194. B. Geologic map (Offield, 1972). Debris forms Copernican or Eratosthenian units CEa (apron material) and CEte (terrace material) at bases of near-exposures of pre-Imbrian terra (crater) material (pIt). C. Diagrammatic cross section illustrating interfingering debris and mare-basalt units. Units CEa and CEte are superposed on unit Em; thus, old but recently mobilized material overlies relatively young unit. Earlier accumulations of unit CEa formed before, and are overlain by, unit Em.

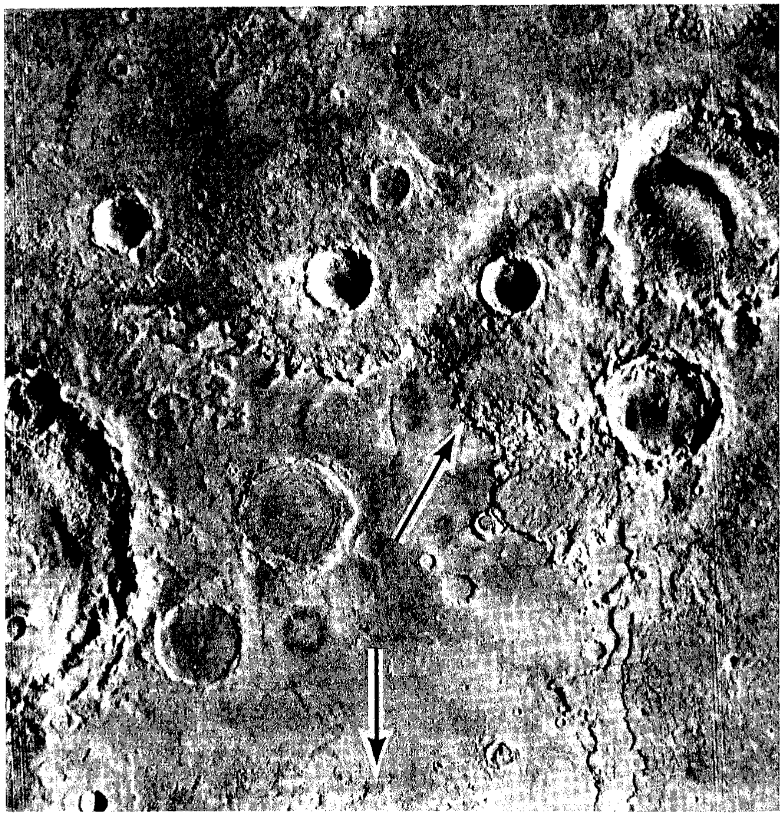


Figure 7.12
Irregular scarp on Mars (arrows). Material between arrows exposed by erosion of overlying layers. Viking orbiter frame 369S32, 259 km high, 249 km wide, centered at 6.3° N, 8.0° W.

mand much attention during early studies. Mapping requires attention to the full geologic scene and not merely to special features that may give a partial or false picture.

The second interpretive step is to infer more precisely what the process was (primary or secondary impact cratering, pyroclastic volcanism, lava extrusion, aeolian deposition or erosion, etc.). This refinement usually requires that the clues to emplacement processes discovered during mapping be supported by theory, experiment, field study of analogous terrestrial features, or actual samples of the unit or a similar unit. The history of the interpretation of lunar craters and of the peripheries of ringed impact basins is recounted here in some detail to illustrate this interaction between mapping and other studies.

A major contribution of geologic mapping is to show whether all parts of a given terrain formed simultaneously. Shoemaker (1962b) interpreted the crowding of satellitic craters around the crater Copernicus as a sign that they formed simultaneously with Copernicus (Figure 7.3A). He also analyzed their pattern in detail on the basis of ballistic theory and his field study of Meteor Crater, Arizona. He found that all observed features are consistent with origin of Copernicus by a primary impact of a cosmic body followed by secondary impacts of the ejected material onto the surrounding surface.

Next, Shoemaker and Hackman (1962) showed that secondary-crater swarms of Eratosthenes and Archimedes are similar to those of Copernicus, even though they are more subdued and rayless and those of Archimedes are, furthermore, cut off in some sectors by mare materials (Figure 7.4). Certain features of other complex craters, however, seemed to be inconsistent with the proposed simultaneous origin of all crater parts by impact. Some craters' central peaks seemed to have summit craters like those of volcanoes, thus to differ in origin and age from the rest of the crater. Superposition of smooth pools on some craters suggested, similarly, that the pools' material was post-impact and volcanic. The satellitic pits of Copernicus that compose the Stadius rilles (Rimae Stadius) seemed to be volcanic craters that were unrelated to Copernicus because of their nonradial alignment (Figure 7.3A, letter *S*).

These findings required either the development of endogenic (internal origin) hypotheses or refinements of the impact model. Some investigators concluded from these anomalies that the entire primary crater and its satellitic craters are endogenic. In the 1960s, however, hybrid theories were in greater favor; volcanism was thought to modify impact craters in diverse ways and to produce a wide variety of other lunar landforms as well.

Better data enabled the competing hypotheses to be tested. Lunar Orbiter images (1966–7) resolved the "volcanic pits" of central peaks into irregular depressions amid jagged parts of the peaks, like the depression in a molar tooth. Thus, these are typical lunar central peaks. Studies of terrestrial meteorite craters were concurrently demonstrating that central peaks originate by the immediate rebound of impact-crater floors. The Orbiter images also revealed that the Stadius chains, although not radial to Copernicus in overall map plan, have ejected material that *is* radially disposed. This observation removed the main argument against secondary-impact origin. In a classic case of laboratory support of an observation-based hypothesis, impact origin was conclusively demonstrated when experiments at the NASA Ames Research Center, California, reproduced the configuration of the craters and their ejecta down to the last detail by near-simultaneous impacts at different timings and spacings. The smooth pools were the last "postimpact, volcanic" part of craters to be reinterpreted in impact terms. Superior images of fresh lunar craters revealed flow textures between the pools and adjacent gradational veneers that indicate an extensive coating by some material. The material was identified as impact-melt rock by analogy with the melt rock that overlies large areas of some terrestrial impact craters.

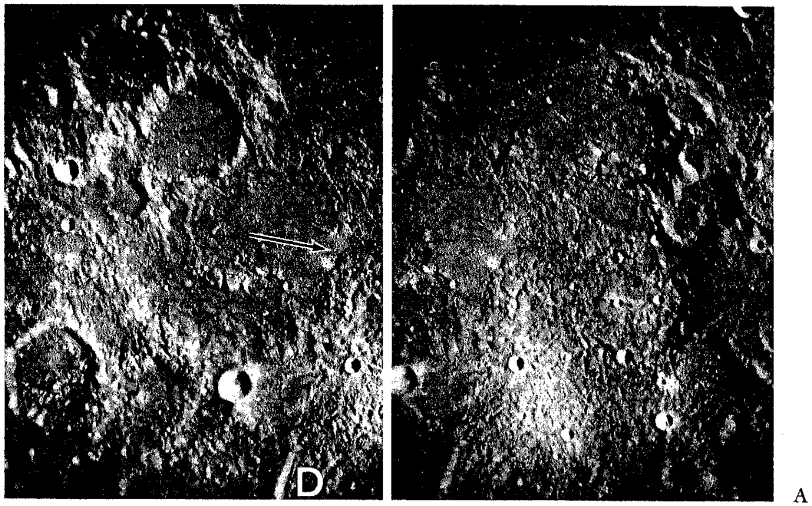
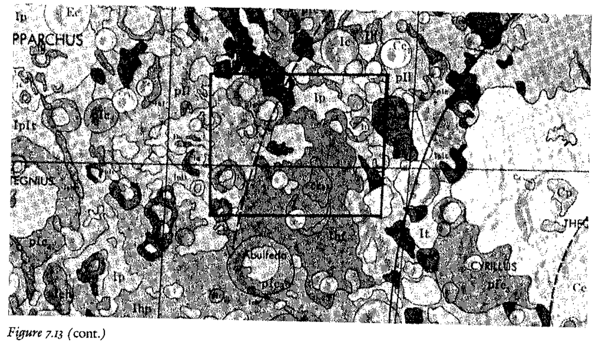


Figure 7.13
Region of Apollo 16 landing site showing changes of mapping caused by changes of interpretation. A. Stereoscopic photographs (see Figure 7.16). Arrow, landing site (9.0° S, 15.5° E); D, *crater Descartes (48-km diameter). Apollo 16 frames 974 (right) and 976 (left).* (Continued)

These sophisticated interpretations were substantiated by samples of lunar material and, reciprocally, helped to explain the samples. Complex, multiply reworked impact breccias were found at every terra site visited by Apollo and the Soviet Luna unmanned samplers, including the Apollo 16 site, where volcanic rock had been predicted and sought (Figure 7.13).

As a result of these new data, geologists no longer had to equally weigh endogenic and impact hypotheses for the origins of geologic units and could reassess the features that had stumped them. Their mapping of the peripheries of impact basins had revealed diverse crater chains and clusters, grooves, ridges, and even domelike forms that seemed superposed on some of the craters (Figure 7.13B). All of these could be explained by diverse volcanic processes.



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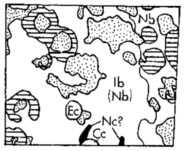

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Figure 7.13 (cont.)

B. Geologic map prepared before the landing (Wilhelms and McCauley, 1971). Area of 7.13A outlined. Apollo 16 sampled units Ihf and Ip. C. Geologic sketch map of area of 7.12A incorporating post-Apollo results that indicate all units are of impact origin.

Previous (7.13B) and current (7.13C) mapping conventions and interpretations differ as follows. Units Cc_1, pIc_3, and pIc_2 (lower Copernican, upper pre-Imbrian, and middle pre-Imbrian crater materials, respectively) were and are interpreted as impact deposits and are not remapped. Units CEhf (Copernican or Eratosthenian hilly and furrowed material) and Cp (Copernican plains material) were believed volcanic; they are deleted because CEhf is reinterpreted as superficial ray material superposed on older hilly and pitted terrain, and Cp (outside remapped area) is probably impact-melt rock contemporaneous with unit Cc_1. Morphologically diverse units Ich (Imbrian crater chain and cluster material), Ici (Imbrian irregular-crater material), and pIci (pre-Imbrian irregular-crater material) were considered either secondaries of basins or volcanic; secondary origin is now favored (Sec. 7.2.7) for them and for some Ic and pIc, and all are combined in 7.13C as one unit (horizontal line pattern). Imbrian units Id, Ih, Ihf, Ihp, and Ip (dome, hilly, hilly and furrowed, hilly and pitted material, and plains materials, respectively) were interpreted as volcanic; unit Ip is retained (stipples) but is reinterpreted as impact-generated; the other units and unit pIl (thought to be pre-Imbrian material pervasively faulted during Imbrium impact) are combined as Imbrium-basin material (unit Ib). Unit It (undivided Imbrian terra material) was considered of uncertain origin; it is now considered a minor surficial cover and is deleted. Unit IpIt (undivided Imbrian or pre-Imbrian terra material) was considered to be basically of basin origin, and unit pIr (pre-Imbrian rugged material) to be pre-basin rock uplifted by impact; both units are now combined as Nectarian basin material (unit Nb). Crater Descartes (former unit pIc, of uncertain origin) is given the equivalent current designation Nc?

However, reexamination revealed previously unsuspected similarities in morphology, map pattern, distance from the source, and secondary-to-primary size ratio between these large features and secondary craters of Copernicus and the laboratory models. Therefore, the circumbasin craters and related landforms were probably created by secondary impacts of basin ejecta. Because all impact structures follow the same general plan, even subtle, isolated landforms could now be traced to their source basins and used to date the units that they touch (Figure 7.13C).

This new knowledge was especially useful in the interpretation of nondistinctive units that had been set aside during early mapping as "undivided terra material" (units It and IpIt, Figure 7.13B). These rocks could now be reinterpreted by an application of the principle of uniformity. One can tentatively assume that the nondistinctive terrain formed in the same way as the better-expressed terrain of a younger analog. For example, the lunar crater Tycho possesses, but nearby craters lack, the diagnostic indicators of impact origin (Figure 7.14). Because of the proven dominance of impact on the Moon, one can reasonably assume that older craters also once had distinctive radial ejecta and secondary craters like those of Tycho, but that the old craters have been eroded by the ubiquitous rain of smaller impacts that has always attacked the Moon at all scales (Section 7.2.3). Degraded basins, similarly, once resembled fresh-appearing basins like Orientale.

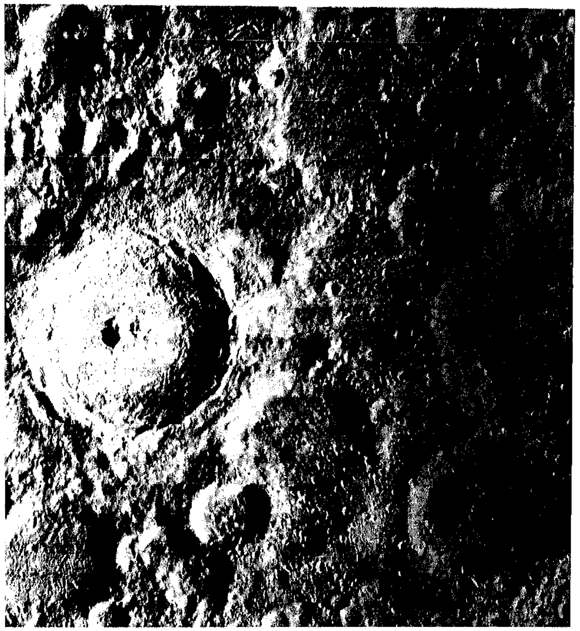


Figure 7.14
Lunar crater Tycho (85-km diameter; 43.3° S, 11.2° W), surrounded by finely textured ejecta and secondary craters (compare Figure 7.2). Other craters in view lack such sharp detail. Lunar Orbiter 4 frame H-119.

The new understanding of the Moon has greatly simplified lunar geologic mapping and models of lunar evolution. When every peculiar landform was thought possibly to be a volcanic extrusion of different composition or age and when each crater might have a different origin, mappers did not know what was significant and what could be omitted. As a result, geologic maps were complex. Now, a geologic map of the lunar terrae can consist, essentially, of the overlapping deposits of some forty basins.

In summary, the steps toward the current understanding of the Moon included (1) observations based on images (satellitic craters of Copernicus), (2) theory (ballistics), (3) multiplication of hypotheses to cover apparent anomalies (the "postcrater" features), (4) acquisition of new data (images and samples obtained by spacecraft), (5) laboratory testing (simultaneous impacts) and geologic field study of analogs (terrestrial impact melts), and (6) testing and application of the new paradigm by renewed geologic mapping. In my opinion, the new impact paradigm has not been found faulty, but it is subject to further testing and revision with new data.

Martian studies cannot yet be generalized in this way because many endogenic features are present, a variety of partially understood erosional and depositional processes have operated, and the uniformitarian principle has more limited validity on complex planets than on airless, waterless, relatively simple planets. Martian geologic mapping, therefore, is still relatively complex. Nevertheless understanding of Martian geology is advancing rapidly because of the good coverage by images and maps (see Section 7.3) and because Mars can be compared to and contrasted with both the Earth and the Moon.

This account has shown that neither geologic mapping nor any other kind of study is sufficient by itself. As the literature clearly shows, theory that is not based on examination of actual planetary surfaces is as unrealistic as it is in terrestrial geoscience. Similarly, mappers require nonmapping data to confirm that their genetic interpretations are physically possible and to help them choose between multiple working hypotheses.

7.3. DEALING WITH PLANETARY IMAGES

Although a complete job of planetary geologic mapping requires nonvisual "remote sensing" data of several types (see Section 7.4.1; Basaltic Volcanism Study Project, 1981, Chap. 2) and, eventually, samples collected from the surface, the richest data sources for the mapping are images. Experience has revealed several difficulties in viewing images that are encountered by every beginner.

The first is seeing the relief reversed – depressions as elevations and elevations as depressions. Illumination from the upper left of a scene apparently causes the fewest problems, but this orientation is not always achievable. I prefer always to keep north at the top, to memorize best the appearance of scenes. The reversed-relief annoyance can be overcome by training one's perceptions to react to certain clues. For example, the most abundant circular forms on impact-dominated surfaces are craters, that is, depressions. Martian surfaces often present greater difficulties, and even experienced observers have trouble with this morphologically diverse planet. Here, too, impact craters can be found and imprinted on the mind as negative. Other landforms will then seem to fall into their correct relief.

Rational analysis of sun-illumination direction is often needed in addition. Slopes facing the sun appear to be much brighter than those facing away from it, and those facing away may be in shadow (Figure 7.2A). This analysis may have to continue throughout a study of Mars, because the Mariner and Viking orbiter images are more diverse in sun illumination than are Lunar Orbiter images (most of which were taken at rising-sun illumination on the nearside and at setting-sun illumination on the farside). The need for caution is illustrated by the fact that some Martian mosaics include frames with opposite illuminations; what appears to be a trough or crater on one frame may appear to change into a ridge or dome on the next. The flyby missions that imaged the other planets produced more uniform illumination directions.

The angle between the sun's rays and the surface is another variable. The same feature looks very different at low and high solar illuminations (Figures 7.3, 7.15). Low-angle illumination emphasizes topography, and high-angle illumination emphasizes brightness differences of features like crater rays and lunar maria. An area of lunar mare may look so rough at grazing illumination near the terminator (the boundary between shadowed and illuminated terrain) that it does not look planar (Figure 7.15B). Differences may be evident on the same or different images. In a common example, the sun-facing slope of a given crater is so bright as to appear washed out, whereas the opposite slope of the same crater, on the same image, shows considerable topographic texture because of grazing sun illumination. Although the long shadows on low-sun images usefully bring out subtle topographic features, the shadows may completely obscure the insides of craters (Figures 7.2A, 7.15B). Images taken at two or more illuminations are therefore needed to fully interpret most geologic units. In comparing units, the observer must either compare images taken at about the same illumination angle or compensate mentally for the differences. Unawareness of the effects of lighting once led naive observers to interpret long shadows cast by boulders as missiles or spirelike monuments. For lunar photogeology, sun-elevation angles of about 1 to 20 degrees for smooth surfaces and 10 to 45 degrees for rugged surfaces have been found to be optimal. The availability of controlled stereoscopy for some images (Figures 7.13, 7.16) has not diminished the importance of sun angle.

Another problem is adjustment to varying resolution of the images. Resolution is defined as the size of an object that can be identified (identification resolution) or detected (detection resolution). Planetary images vary widely in resolution, and the different resolutions have different uses. Large-scale, detailed images are usually necessary to show the textures and contact relations upon which most interpretations of origin are based. Small-scale, regional images are useful for mapping the distributions and associations of units, which are also valuable in interpretations, as discussed in the previous section. For the Moon and similar planets, the large-scale images show details of the

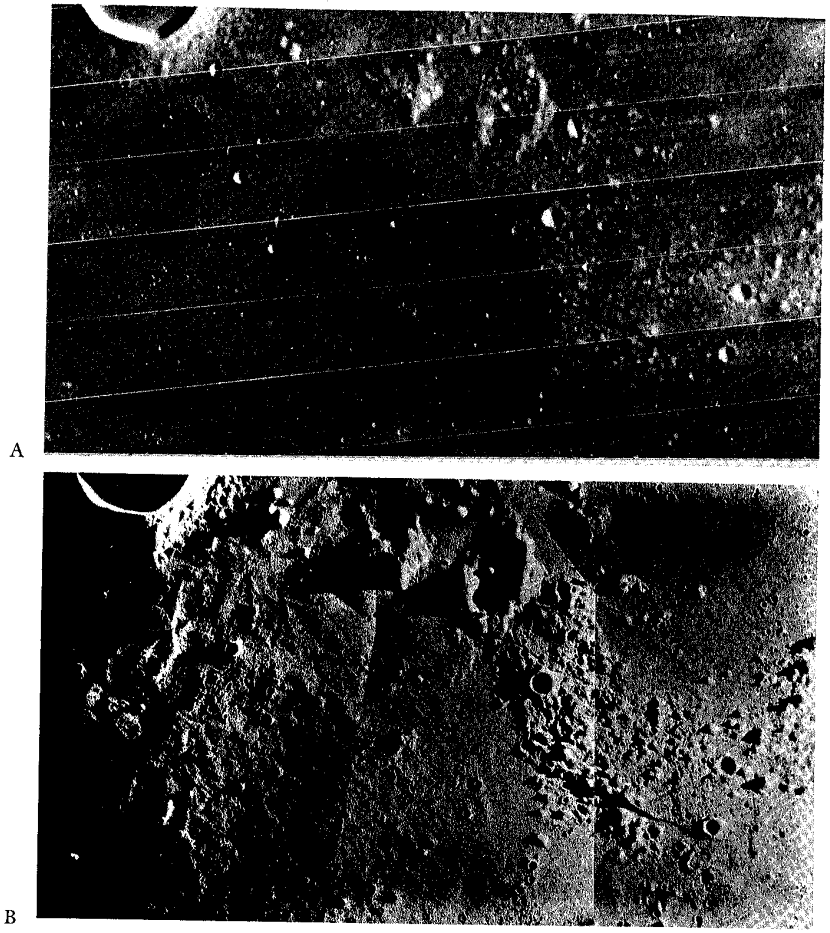


Figure 7.15
A lunar area under different sun illuminations. Large crater at top is Kunowsky (18-km diameter; 3.2° N, 32.5° W). A. Sun angle averages 18.5 degrees above horizontal. Lunar Orbiter 4 frame H-133. B. Sun angle from 3 degrees above horizontal at right to grazing at left. Apollo 14 frames 10375-10377 (right to left).

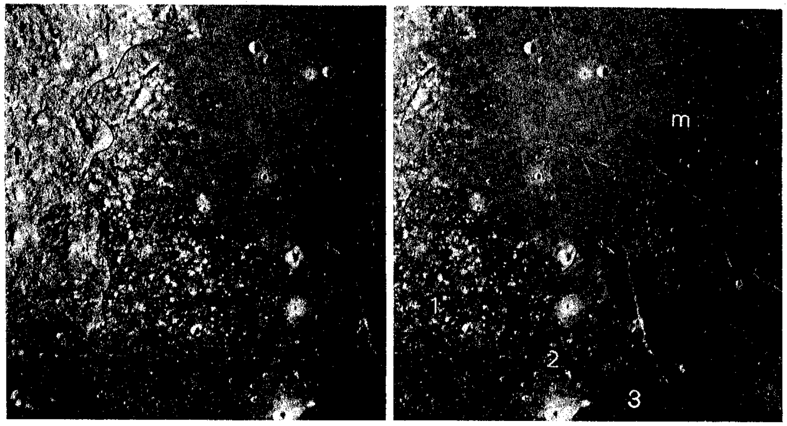


Figure 7.16
Stereoscopic pair of photographs of region along the contact between Mare Serenitatis (m) and Montes Haemus (compare Figure 7.4). For a three-dimensional view without a stereoscope, look at a point on the left photograph with your left eye and at the same point on the right photograph with your right eye, let your eyes unfocus, cross them until the points converge, and then refocus. Dark lunar blanketing material of variable thickness may be mapped, alternatively, everywhere it is visible (are as 1–3), only where it is most conspicuous (areas 2 and 3), only where it completely covers the terra (area 3), or not at all. t, terra material that is probably exposed (left frame). Apollo 17 mapping-camera frames 2102 (right) and 2103 (left); each frame covers an area 300 km high.

regolith that covers most of the surface, whereas the small-scale images show the configurations of the basic bedrock units – those of impact basins and maria. For Mars, images that cover very large areas are of little value for geologic purposes. Medium-resolution views (taken at ranges of about 6000 to 10,000 km above the surface) show the major geologic units. Higher-resolution Martian views potentially can reveal details of stratigraphic relations and textures that are diagnostic of the units' emplacement and modification processes. In particular, such views may reveal geologic units of the same sizes as terrestrial geologic units, which are not resolved at the regional scales.

Ideally, low- and high-resolution images are available of the same area and are used in tandem. Information from small points viewed at high resolutions can then be extrapolated to the larger areas. Subtle properties visible on the small-scale images often assume new significance after being seen in the magnified views. Section 7.4.1 shows how geologic mapping can be used to keep track of the different kinds of information obtainable from different kinds of images.

Stereoscopic images are of great value but are rare. The value of Lunar Orbiter stereoscopy is limited by the construction of each image out of narrow parallel strips ("framelets"), producing a stairstep effect when seen stereoscopically (Mutch, 1970). Most Apollo orbital images (true photographs taken by "mapping" or "metric" and "panoramic" cameras) provide excellent stereoscopy (Figures 7.13, 7.16) but cover only 20 percent of the Moon – and less than 20 percent at favorable sun illuminations (Masursky et al., 1978). The Mariner and Viking orbiters of Mars and the flybys of the other planets flew too high to routinely provide the base–height ratio necessary for good stereoscopy, although a few pairs do provide stereoscopic views. Direct views of the third dimension are at least as valuable for geologic purposes as high resolutions (Figure 7.16).

Discussion of the radar images of Venus is beyond the scope of this chapter. Suffice it to say that what appear to be shadows and bright slopes do not necessarily have the same significance as those visible on images taken in visual wavelengths.

The problems of viewing images can be overcome with experience, but even the most experienced observer may be troubled by the great diversity of the accumulated data bank. This is especially true for the Moon, which was never imaged systematically on both hemispheres. Lunar images are diverse in resolution, viewing angle (obliquity), format, and contrast (Mutch, 1970). The best Martian dataset, the Viking orbiter images, was acquired more systematically than the lunar images (Carr, 1981). Also, Mars is uniformly covered by excellent maps and photomosaics, particularly the very useful mosaics at a scale of 1:2,000,000 (see Chapter 3). The images of the other planets also vary in illumination, obliquity, and resolution but were acquired relatively systematically and are being mosaicked, catalogued, and rendered into maps so well that adjustment to their vagaries is not difficult.

7.4. MAP CONVENTIONS, FORMAT, AND PRODUCTION MECHANICS

7.4.1. *General mapping procedure*

The first step in examining a new planet or region is a general reconnaissance. The mapper scans the images and base map to gain a general idea of what kinds of units and structures are present, that is, the geologic style. This reconnaissance may take the form of a sketch map on a paper copy of the base map. A rapidly drawn sketch will focus the mapper's attention right from the beginning on the "big picture" – the geologic context and mutual relations of the most important units. Detailed examination of small areas and final interpretation of peculiar-appearing features can come later, after their possible significance has been assessed.

Planetary geologic mapping, like all science, progresses by building on previous work (see Section 7.2.7). It proceeds best by testing some working hypothesis or multiple working hypotheses, no matter how wrong they may later prove to be; purely inductive mapping is seldom productive. A mapper's success in this first reconnaissance will therefore depend on experience. The nongeologist will have no idea what to look for. The expert in the planet under study will look for familiar features and contact relations and also for those that appear new. The expert in another planet will have an advantage if the old and new planets have some common features and, furthermore, will have polished many mechanical mapping techniques that apply to all planets.

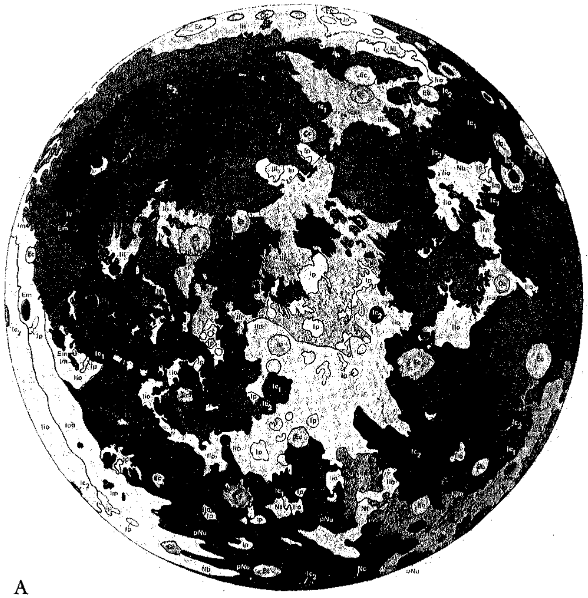
The purpose of the map should be decided early, because maps for different purposes are constructed differently. The most important decisions are scale and level of detail. There may be no choice about the scale if only one scale of base map is available, but a wide choice of level of detail is open even in this case. Some maps show the maximum detail that can be drawn and portray each contact faithfully (e.g., Figure 7.11B). At the opposite extreme are "cartoons" that show only the general relations among the most significant units or groups of units (e.g., Figure 7.17). Typically, a region is mapped in detail at large scales if it is poorly understood and is cartooned at small scales if it is well understood. In making the decision about degree of fidelity or cartooning, remember that a detailed map can be converted into a cartoon but not the reverse.

Whereas most geologic maps portray geology as it is today, special ***paleogeologic*** maps are sometimes constructed. Some paleogeologic maps portray only the geologic units that formed during some specific period or epoch. Others portray the cumulative record through that specific time (Figure 7.17B). Paleogeologic maps are usually derived from maps that show the present geology (Figure 7.17A).

Although most maps are constructed for eventual publication, some are constructed for personal purposes because of mapping's power as a learning tool. A mapper benefits from having to examine an entire area closely and from constant testing of hypotheses about unit origin and age against map relations and distribution. Although "learning maps" can bypass some of the guidelines described in the rest of this chapter, completion of a map through to publication is good training for all mapping.

I suggest that the best first step in actual mapping is to start in an area where familiar units are clearly expressed and to map their limits and relations. This process might be repeated in several parts of a large area or a whole planet. Temporary blank spaces are left in the less-well-understood intervening terrain.

A corollary of this progress from the known to the unknown is to start with the youngest unit in a region. Young units are usually the best expressed and most easily interpreted, and their contacts are the most complete and easiest to map. Terrestrial geologists commonly map the Quaternary alluvium first in order to focus on the diminished remaining area that contains the more significant and difficult problems. Similarly, planetary geologists com-



A

Figure 7.17
Simplified geologic maps of the lunar nearside (in Carr, 1984, pp. 197–205). A. Present Moon. Time-rock units (capitals): C, *Copernican;* E, *Eratosthenian;* I, *Imbrian;* N, *Nectarian;* pN, *pre-Nectarian. Rock units (lowercase letters):* b, *basin material;* c, *crater material;* d, *dark-mantling material;* i *(second letter), Imbrium-basin material;* i *(third letter), inner deposits;* m, *mare material;* n, *Nectaris-basin material;* o *(second letter), Orientale-basin material;* o *(third letter), outer deposits;* p, *plains material;* t, *terra-mantling material;* u, *undivided material;* v, *volcanic-dome complexes.* (Continued)

monly first map the young craters and well-defined patches of young plains. The contacts of young units truncate older contacts.

On Earth, units are often mapped by "walking" their contacts. One does the same, figuratively, in planetary mapping. Each unit is scanned until its end; then a contact is drawn. The contact is then traced until the two units it delimits no longer meet, whereupon it either terminates or continues as the contact between the first unit and a different second unit. If each unit with distinct contacts has properties indicating a common age and formative process over its whole area, and if its contact geometry and crater densities both

B

Figure 7.17 (cont.)
B. Paleogeologic map based on 7.17A, showing units that formed before and during the Lower Imbrian Epoch.

indicate the same age relations with adjacent units, all is well. Inconsistencies are noted if they appear. The process of transferring complex information from an image to the map in the form of contact lines becomes increasingly automatic with increasing experience.

A preliminary stratigraphic column should also be devised early in the project and updated throughout the study. Waiting until the end of a study to construct the column and the box explanation (see Section 7.4.6) inevitably causes unnecessary reworking of the geology.

Mappers initially will probably refer to the best images of large regions, but eventually they will examine all the available images. This may involve considerable struggle with the coverage. No planet and very few large areas of planets are favored by continuous good images (see Section 7.3). While poring through the image collection, the mapper can record whatever units or structures are seen clearly on each image by drawing a piece of a contact or a structure, coloring a small area, or making a verbal note. Appropriate symbols can be devised to keep track of the information that is gleaned from each type of image of an area – perhaps a series of letters that, with modification, will become geologic unit symbols (see Section 7.4.4). Part of the value of geologic mapping is its power to integrate all the diverse data from the different images.

Even if the mapper is temporarily ignorant of the geologic context of a feature glimpsed on an image, all the pieces of the puzzle should eventually come together. The overall geologic picture that emerges from this mapping and note-taking will probably be one that would not have been grasped by scanning the diverse available images without mapping.

Remote sensing data on albedo (Figure 7.3B), color spectra, radar, etc. are integrated where possible with the information obtained from low-sun-illumination images. The most easily used remote sensing data are in an imaged format (Basaltic Volcanism Study Project, 1981, Ch. 2). The imaged patterns can often be matched directly with already mapped geologic units. Remote-sensing data sometimes suggest the presence of units that were missed in the geologic mapping. "Color" (spectral reflectance) patterns of the lunar maria, for example, have suggested the presence of units that were later found to differ in density of superposed craters (e.g., Wilhelms, 1980). Where rock units and remote-sensing patterns coincide, the remote-sensing properties probably pertain to chemical composition or some other intrinsic property of the rock unit. In other cases, the remote-sensing data apply to a surficial modification that crosses unit boundaries (e.g., dust layers on Mars). Nonimaged remote-sensing data from a dense array of points can also be related to rock units. The geologic significance of scattered or low-resolution data may remain ambiguous. The most easily measured properties are not necessarily the most significant (Mutch, 1970, p. 58).

7.4.2. *Separation of interpretation from observation*

Each stage of mapping requires some interpretation. The act of drawing contacts involves the interpretation that three-dimensional geologic units are present. The criteria for defining the units usually have to be selected from among many possible sets of attributes. The significance, origin, and age of geologic units are inferred at several levels of precision, and these hypotheses may change during or after the mapping (Section 7.4.7). For the map to be credible and useful to the reader, therefore, the basis for all unit assignments and genetic interpretations must be made clear. In particular, the role of interpretation must be specified and distinguished from the objective data on which it is based. Several conventions for conveying this distinction have been developed.

One fundamental requirement in planetary mapping is the clear separation, in the explanation and text (Section 7.4.6), of the interpretation(s) of each unit from the list of objective physical characteristics by which the unit was identified by the mapper and can be reproducibly mapped. For example, one could distinguish the following:

Characteristics: Forms dark, extensive, level, mostly smooth surfaces having sharp contacts with adjacent terrain.

Interpretation: Basaltic lava

Second, units are given objective, not interpretive, names: crater rim materials or mare materials, not impact ejecta or basalt. During early lunar studies, when the origin of most craters was uncertain, the rim material might be interpreted alternatively as debris ejected from an impact crater, lava ejected from a volcanic crater, or the precollapse edifice of a caldera. Nevertheless, the unit could be mapped geologically and ranked stratigraphically, to a first approximation, on the basis of observational criteria. Even when the impact origin of most lunar craters was well established, the term "ejecta" was avoided because the radial deposits might contain more material dislodged by secondary impacts than primary ejecta from the crater itself. "Rim material" or "radial rim material" thus remained preferable to "ejecta" as descriptive terms. Similarly, an undistinctive planar deposit could equally well have been emplaced by volcanism, impact, or fluidlike sedimentation of debris, and each material can vary greatly in such properties as composition, viscosity, and grain size. In fact, the origin of some well-mapped and -dated lunar plains materials is still uncertain. The undecided mapper should state the uncertainties and give some alternative interpretations that are consistent with observation.

Placement of contacts should also be reproducible. A user of the map should be able to locate a contact on an image after having read the description of the adjacent units. However, the portrayal of units may differ among mappers who agree about interpretations. A thin surficial unit or a buried but still detectable bedrock unit may be mapped, depending on the map's purpose (see the following section). The exact placement of contacts may differ even among mappers who agree about which layer to map (Guest and Greeley, 1977, p. 17). In general, these differences are unimportant so long as the mapping is reproducible. Attempts to eliminate personal bias by quantifying mapping have proved unsuccessful because of the complexity of geologic terrains.

Each unit should be mapped in such a way that only its interpretation and not its contacts or status as a unit will have to be revised significantly when new data are obtained. When Apollo photography showed that the Serenitatis border unit in Figure 7.5 is older than the central unit, the symbols Em and Im could simply be replaced by appropriate new symbols without remapping or redefining any units. The finding by Apollo 16 that the plains in the Descartes region are of impact and not volcanic origin required changing only the interpretation and not the contacts, unit name, or time-rock assignment of the plains unit (Figure 7.13, unit Ip). Changes of name, age, and interpretation, but not of contacts, were required when three units of crater material and parts of two more were reinterpreted as secondary craters of the Imbrium basin (Figure 7.13C, horizontal line pattern).

Sometimes, however, new data may require more fundamental changes. The hilly and furrowed Descartes Mountains were mapped as the rock unit Descartes Formation on the assumption that the distinctive furrows were intrinsic to the deposition of the unit (Figure 7.13). Extensive adjacent tracts were mapped as hilly and pitted material, and both units were interpreted as volcanic (Wilhelms and McCauley, 1971). When the Apollo 16 samples showed that the Descartes Formation consists of impact breccia, the furrows and pits were reinterpreted as secondary-impact craters superposed on earlier impact deposits. In this still-tentative interpretation, the craters are a modification and not part of the true depositional units. The secondary-crater deposit could now be shown to overlie Nectaris-basin material, Nectarian crater materials, or other underlying units (Figure 7.13C). Many of these new contacts do not completely coincide with those of the previously mapped units. Other interpretations might alter the contacts in other ways.

Many pitfalls have been avoided by sharply distinguishing interpretation from observation on planetary geologic maps. Nevertheless, the distinction has been weakened in recent years. Lunar mare material is now commonly called "mare basalt" – a reasonable change in view of the results of the lunar sampling. However, many mappers, especially novices, tend to weaken the observation–interpretation distinction for less securely interpretable units such as those of plains or small hills on Mars that seem more easily explained by volcanism than by less familiar processes. Unsuspected novelties may appear even in seemingly secure cases. Although the observation of currently active volcanism on Io, for instance, would seem to establish the origin of Io's units beyond all doubt, it does not demonstrate whether the present form of many units is depositional or erosional in origin or whether inactive depressions are vents or are calderas that never vented any material. Even when sampling or other on-site exploration establishes the origin of a unit, the findings might not apply to apparently similar units elsewhere. Readers of geologic maps with unsupported or unqualified genetic statements will be unaware that doubt exists. The mapper should state the basis for various possibilities as well as the reasons for favoring one.

7.4.3. *Map units*

At some phase of the mapping, preferably early on, the observed rock units are converted by some convention into map units – the units that are actually shown on the map and given a specific symbol, color, and position in the columnar map explanation. This conversion commonly involves recasting the observed units to make the map simpler or more readable or to remove some fallacy, such as confusion of rock and time concepts. Map units may be rock or time-rock units, of any rank, depending on the scale and purpose of the map.

As in all geologic mapping, planetary geologists must decide whether to lump or split when devising map units. Lumping is more common because more individual units are usually mapped in the early stages of a study than when the mapped area becomes better understood (Shoemaker, 1962a, p. 123). Splitting at late stages usually requires some remapping.

One extreme form of lumping is to show only the time-rock units. Another is to devise *"provinces"* that include diverse though related units. The main lunar provinces are the maria and the regions covered by basin materials of a given age. Martian provinces might be the Tharsis bulge, northern lowlands, cratered southern uplands, and channel-and-valley province (Carr, 1984, p. 211). These kinds of lumping are appropriate for small-scale synoptic maps, such as figures in books.

Some generalized map units combine diverse rock units whose age and origin are poorly known. An example is undivided terra material, which was called pre-Imbrian or Imbrian terra material (symbol, IpIt) on many lunar maps (Sections 7.2.2, 7.2.4, 7.2.7; Figure 7.13B). Devising one or two such "wastebasket" map units is a means of delineating unsolved problems. Unit IpIt proved to consist mostly of impact-basin deposits, which are now explicitly identified by the map units (Figure 7.13C, unit Nb).

A common type of lumping on planetary maps at all scales is to combine into generalized map units all the individual deposits that are physically similar and that are of about the same age (e.g., Copernican crater materials, Eratosthenian mare materials, or Imbrian plains materials). The materials may belong to the same time-rock system or series or, in favorable circumstances, can be stratigraphically bracketed more closely. The individual occurrences may differ in age within these limits, as do those of craters, or they may be contemporaneous, as are many separated patches of circumbasin lunar plains. Contrary to terrestrial practice, individual adjacent patches of the same map unit may be separated by contacts, the younger shown overlapping the older (e.g., Figure 7.5A, Aristillus and Autolycus).

Whether multiply occurring rock units are lumped or separately portrayed depends largely on their number relative to the map scale and on the availability of color for the final publication. Extensive rock units such as those of large impact basins may correspond directly with the map units. This treatment more nearly approaches terrestrial usage than does the lumping of many isolated crater or plains deposits into a single unit. Small-scale maps, however, may include the deposits of so many basins that lumping of all those of a certain age is desirable (Figure 7.17).

Fine distinctions made during mapping are sometimes retained. Crater-material subunits, for instance, once played a large role on lunar geologic maps (Wilhelms, 1970, pp. 40–2; Mutch, 1970, pp. 165–74). When little was known about lunar craters, objectivity required that rim, wall, peak, and floor materials be subdivided because they differ morphologically. Each could be interpreted according to the current state of the mapper's knowledge. Mappers could separate the parts of the crater they believed to be endogenic – as many parts were thought to be (Section 7.2.7) – from the parts they believed were of impact origin. The colored boxes for the units representing these parts in the map explanation (see Section 7.4.6) could show a substantial difference in age when arranged vertically and a slight difference when placed side by side. Because almost all parts of impact craters now appear to have been formed essentially simultaneously by the original impact, the age differences are considered minor and the parts ordinarily are not distinguished on maps. Remaining exceptions requiring separate map units might include unusual craters, craters mapped to investigate the cratering process, and floor-filling materials or other units that are still considered to postdate the rest of the crater.

Two or more superposed units are commonly recognized in the same area (see Section 7.2.2). The mapper then decides whether to show the surficial deposit, the underlying deposit that can be seen through the surficial cover, or both (Figures 7.13, 7.16, 7.18).A rule of thumb is to show the deposit that is topographically most conspicuous at the scale of the mapping. This unit will be the colored map unit. That is, the most conspicuous unit is shown by the most conspicuous convention. However, a map emphasizing basins will omit surficial units such as pyroclastic dark-mantling material (Figure 7.16) and a map emphasizing dark-mantling materials will probably omit the basins.

Conventions have been developed to show more than one superposed unit if desirable. Buried units whose textures are still visible may be shown by dotted contacts and symbols in parentheses (Figure 7.18B). Examples include basin materials buried by dark-mantling materials, plains contacts beneath crater deposits, and buried basin massifs. Where possible, buried contacts are drawn at the limit of their observed topographic expression rather than at the inferred or projected limits. An alternative is to show the underlying unit in color and the overlying unit by an overprint pattern, such as stipples or hachures (Figure 7.18B). This convention is useful for thin parts of dark-mantling materials or for rays of young craters. A third convention employed on some maps is to define a colored map unit as including underlying and overlying units. For example, the lunar map unit Imbrian and pre-Imbrian terra material commonly designated a pre-Imbrian crater or basin unit that was inferred to be overlain by a thin cover of Imbrian material. This designation differs from the already discussed map unit called Imbrian *or* pre-Imbrian terra material, whose age is not known more exactly.

7.4.4. *Unit names, letter symbols, and colors*

Each map unit is given a distinctive name, letter symbol, and color or pattern. Names may be formal or informal, as convenient. The U.S. Geological Survey developed many new formal names for lunar geologic units during the 1960s, but current practice favors informal names (crater material, mare material, ridged plains material, etc.). Formal names are still bestowed on rock units that are stratigraphically distinctive, laterally continuous, frequently discussed, or difficult to describe briefly. For example, the name "Medusae Fossae Formation" concisely and objectively describes an enigmatic, stratigraphically complex, morphologically diverse set of Martian deposits whose properties could not be expressed by a simple descriptive name.

Introduction of a new formal stratigraphic name requires a formal definition. Each definition includes a statement of intention to define a new name, the coordinates of the unit's type area, the feature after which the unit is

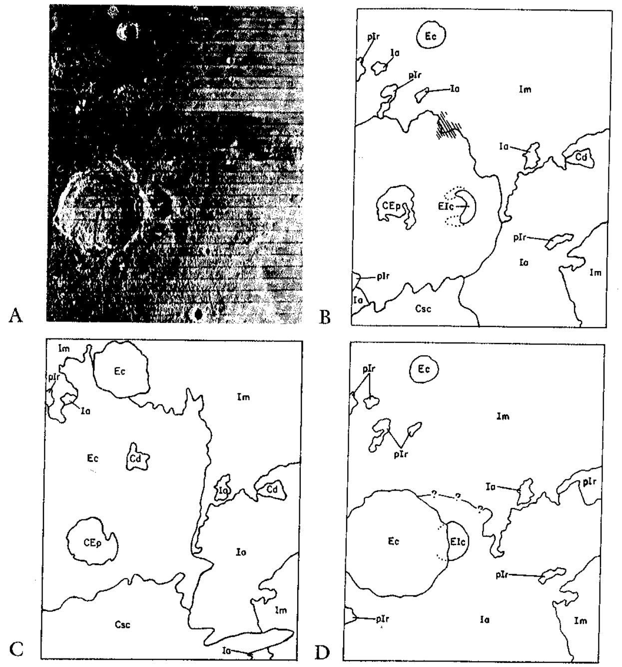


Figure 7.18
Different, equally valid methods of mapping an area. A. Photograph of Aristoteles region (crater 87 km in diameter; 50.2° N, 17.4° E). Lunar Orbiter 4 frame H-98. B. Most conspicuous units stressed. C. Surficial units stressed. D. Deep-lying units stressed.

named, the relation to overlying and underlying units, and, preferably, the number of the image showing the type area. The North American Commission on Stratigraphic Nomenclature (1983) provides guidelines for defining new names that apply to planetary mapping, except that such matters as a unit's lithology and thickness in the type area (type section) may be less well known than they are on Earth.

Each unit name, if not already a formal name including a term like "formation," should include a term like "material" or "deposits" to show that the unit is a material unit and not a physiographic form. As discussed, interpretive names like "basalt" or "ejecta" should be used very rarely and cautiously.

Like its terrestrial counterpart, the symbol for a planetary map unit consists of an abbreviation of the system to which the unit is assigned, in capitals, and an abbreviation of its formal or informal rock-unit name, in lowercase letters. Units that are equally likely to belong to two or three systems are given two capital letters representing the possible range, the youngest being placed first (e.g., units CEhf and IpIt, Figure 7.13B). The capital letters may be omitted if the age is unknown or only very approximately known or if time-rock schemes have not been devised for the planet (Figure 7.9). The order of the lowercase letters symbolizing the rock-unit name generally proceeds from the basic formational name to modifiers, which may be members and submembers of the formation (e.g., crh for "crater, rim, hummocky"). However, the modifier may come first if it is an integral part of the name (e.g., tp for "textured-plains" material). The letters correspond to the name and not to an additional characteristic the author wishes to illuminate; the textured-plains material is not symbolized, for example, by "hp" to show that the texture referred to is hummocky. For readability and avoidance of excessively subtle distinctions, the total number of letters and numbers in a symbol should not exceed four (counting pI, pN, and other "pre-" forms as one symbol). Symbols should have the minimum number of letters compatible with unambiguity. For example, the symbol Ih could be used for Imbrian hilly and furrowed material as well as for the Hevelius Formation; but a third letter must be added to one of the symbols if both units appear on the same map.

Where units are numbered, the oldest unit of a class is designated 1 (on line or subscript), and higher numbers refer to younger units (Figures 7.9, 7.13). Numbers follow all the letters, because they refer to the whole unit symbol (e.g., Icr_1, not $\mathrm{Ic}_1\mathrm{r}$). Numbers are undesirable as unit designators except for age distinctions because names and the corresponding letter symbols provide more direct clues to the units' properties.

In texts, a unit is referred to by its name or by the term "unit" plus the letter symbol, rather than by the letter symbol alone (e.g., "younger mare material" or "unit Im_2," rather than simply "Im_2").

The reason for querying a symbol on a map should always be given. A symbol like "Ec?" obviously means that there is some doubt about the assignment; the explanation should state whether the doubt is that the crater

is younger, older, or a crater after all. Queries should be used sparingly because each one must be drafted on the final map.

Colors are chosen to associate like units and disassociate unlike units. Intense colors are used for small patches, weaker colors for extensive units. The best color schemes convey both rock-unit and time-rock associations. The readability of a map depends strongly on the choice of colors. Ideally, all maps of a given map series have similar schemes.

7.4.5. Line symbols

Line symbols on planetary maps follow terrestrial precedent as far as possible. The narrowest line is the contact between units.

Dashes are useful to indicate special kinds of contacts or structures or very doubtful position, but not to indicate routine doubt. Their drafting adds to the expense and delay in the final map preparation. A line can be mapped solid if it can be correctly positioned to within a few millimeters. Dotted lines, however, are valuable for delimiting buried features. A "scratch" boundary (a contact without an accompanying black line) may separate colored units from blank areas where data are entirely absent.

On cross sections, dashed lines are more useful for indicating doubts about the existence of a unit than about its thickness, which is almost always uncertain. Dashed lines, queried lines, or scratch boundaries may be used, however, where thicknesses are totally speculative or where no further useful inferences can be made.

Lines that are coarser than contacts, usually distinguished by special symbols, are used for structures and for physiographic features, such as crater rim crests. Faults are usually mapped on geologic maps. On maps of some planets, especially those that are not fully understood, the list of line symbols might be quite long. Ganymede, for instance, is mapped with a wide variety of structural symbols representing various furrows, grooves, troughs, rimmed troughs, ridges, and the like (Figure 7.7). In the present stage of mapping these are distinguished, even though future work may show that several are minor variants of a basic type. Each symbol should be fully explained on each map, because symbols may vary among maps.

Like stratigraphic units, structures should be given objective names and their interpretations should be separated from their descriptions in the explanation (e.g., "Scarp: *Interpreted as* fault, locally modified by erosion"). This lesson was learned when better data showed that many lunar "faults" that had been mapped from telescopic photographs and visual observations were, in fact, rather crude alignments of unrelated features. "Lineation" would have been a preferable term. Even "lineations," however, seldom turned out to be significant on the Moon.

Although line symbols are usually in black, they may be colored on special-purpose maps. Features such as rilles (long linear or sinuous depressions) that are considered especially significant may be bounded by contacts and colored as are material units, provided their structural or erosional origin is made clear. They may even be considered as material units. For example, a "rille material" unit may be mapped if it is meant to represent either talus or the exposed, truncated edges of units inferred to be exposed on the rille walls. This was common practice on early lunar geologic maps. Both talus and an exposed section were, in fact, found by the Apollo 15 astronauts in the sinuous rille Rima Hadley. Conventions may be used flexibly to suit special purposes if they are explained and if the distinction between materials and structures is remembered and stated.

A further departure from the Stratigraphic Code may be required by the map scale. As explained in Section 7.2.5, structures may be so dense as to be individually unmappable (e.g., fractured plains material or chaotic material on Mars, grooved material on Ganymede, many units on Venus). The structural characteristic of these units is more apparent than the primary depositional characteristics. In such cases, the unit is mapped on the basis of the structural modification (possibly of more than one true material unit) and this departure is explained verbally.

7.4.6. *Explanation*

Every geologic map is accompanied by a set of boxes that represent the color and symbol of each map unit and a set of examples of each line symbol. These keys to the map are referred to as the explanation, legend, or key.

The explanation indicates the stratigraphic relations of map units. The most straightforward explanation arranges the boxes in a vertical column, with the box for the youngest unit at the top and the oldest at the bottom. The map units in each system or series are enclosed by brackets labeled with the time-rock names. Boxes of units whose ages are overlapping or uncertain are also shown by brackets, by horizontal positioning, or by diagonal dividing lines if the boxes touch. Boxes for members of a formation or other closely related units touch without a separating space. They may touch at the top and bottom if the relation is one of age. Ends of boxes representing laterally gradational facies touch laterally, commonly with sawtooth boundaries.

Since the early 1970s, terrestrial and planetary geologic maps of the U.S. Geological Survey have employed a more complicated explanation that includes two arrays of colored boxes, each containing the map symbol. One is a vertical array, the "description of map units," which does not necessarily strictly follow stratigraphic order, although it generally has the youngest units or groups of units at the top. The names, characteristics, and interpretations of the units and definitions of new names are written, in telegraphic style, next to each box. The other array, the "correlation of map units," shows all that is known about the stratigraphic relations of the units (Figure 7.9C). The dimensions of this array depend on the number of stratigraphically distinct map units and lateral facies. Related rock units or provinces are commonly

grouped in one or both arrays. One Martian geologic map introduced the useful innovation of parallel explanations for depositional and erosional units (Milton, 1975).

The map may be accompanied by a text giving the overall picture of the mapped geology. The text can include such items as geologic setting, provinces, amplifications of the unit interpretations, overall structure, and geologic history.

7.4.7. *Mechanics of map assembly*

When the mapper is confident of his or her general understanding of an area, mapping can begin on a stable base that will be used for the final map production. I start this process fairly early, because many changes can be made without damaging a properly constructed base map. Such a base is made of transparent plastic (Mylar, Cronaflex, etc.) that is scale-stable (resistant to shrinkage and expansion) and on which the shaded relief or other terrain portrayal is printed on the back – the so-called left reading. Geologic lines are drawn on the front and can be erased without erasing the base even if the lines are drawn in ink. Symbols are placed on the same map and can be pencilled in preliminary stages of mapping. The base portrayal is in brown or some other nonblack color that will not be confused with the geology and that will not reproduce as strongly as the geology when copied by Ozalid, Xerox, or other processes.

The author must label every patch of a unit, even if the final published version will "carry" the identity of some patches only by the color. Most drafters are not geologists and should not have to guess the author's intention about any matter.

At several stages in the mapping, the plastic map is copied onto paper and the paper copy is colored out. Coloring is an essential test of how well the map units and stratigraphic column have been selected and portrayed. This coloring usually results in updating the original stratigraphic and genetic hypotheses. The new viewpoints are incorporated during further mapping. Coloring also always uncovers innumerable inconsistencies and other technical errors that escape even the most careful examination of the uncolored original.

A common error in geologic mapping is to draw junctures of three units incorrectly (Figure 7.19). For readability, the youngest unit should be shown to cut off the contact between the other two on the map as it does in nature. This relation will automatically be drawn correctly if the youngest unit is mapped first. Contacts created by erosion will show the reverse relations: The contacts that bound an old unit exhumed from beneath younger units will cut off the contacts between the younger units. Coloring will help the author identify incorrect truncation relations, which may otherwise escape even the most experienced mapper.

Separate scale-stable manuscript sheets can include additional information

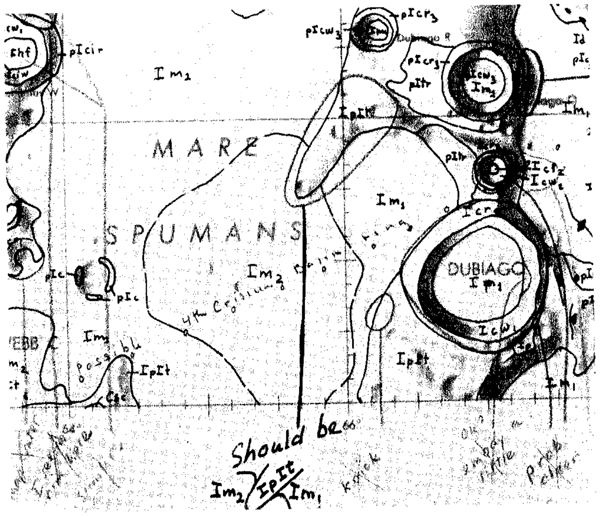


Figure 7.19
Example of map review. Contact-truncation relations and other matters are shown incorrectly on map and are corrected by reviewer in margin. As mapped, unit IpIt (undivided terra material) looks like the youngest unit because it truncates the contact between units Im_1 (older mare) and unit Im_2 (younger mare). The contact should be drawn to suggest diagrammatically a flooding by Im_2 of the two preexisting units.

such as overlay patterns and structures that are to be shown by colored or other special lines. These are registered to the shaded-relief base by registration studs, as are all other stable materials that combine to produce the final map (several parts of the base map, the drafter's scribesheet of the author's linework, "peelcoats" for the colors, etc.). Final maps can be constructed on unstable material such as paper only if they are to be reproduced entirely by photographic or color-scanning processes.

The last colored-out paper copy becomes the "mill copy," which is the guide for drafting and is also used by the author and editors to indicate changes. Authors should color out the mill copy because they will almost always find errors even at this late stage. There is also a colored mill copy of the explanation, including the verbal material, and of a cross section, if one has been constructed. Hand coloring of the explanation boxes and cross section by the author will probably uncover discrepancies between them and the map that have persisted until the end (usually because each change introduces inconsistencies that are not incorporated in all the ancillary working materials). Special supplements to the mill copy may be desirable to provide instructions to the drafter. These might include a sheet to designate line weights clearly and another to clarify a complicated area.

7.4.8. *Consultation and review*

Like all other scientific work, geologic mapping requires more than one person's input. Even experienced mappers consult with others who are working on adjacent areas, comparable areas, or similar problems.

More particularly, maps require reviews by peers. Experience has shown that at least two colleagues should thoroughly examine a map or other publication and frankly express both general and detailed criticisms. A good review requires that the reviewer color out an uncolored copy of the map while examining the data on which it is based. The reviewer should constantly cross-check between map, explanation, and text. Although this task is onerous and time consuming, it always improves a map if done well. The most useful review comments consist of specific criticisms or questions, not a question mark or other vague sign of confusion that will leave the author wondering what is not clear. Comments written in the margins of a map or text, with leaders to the point of difficulty in the body of the map or text, are easier to read and check off than are comments written on the map itself (Figure 7.19). It is in an author's best interest to respond to each comment. Reviewing is also educational to the reviewer and is part of the job of mapping.

Reviews are exploited most productively if the author answers the first before obtaining a second. That is, the author finishes the map three times: once before review, again amid the review process, and again after the last review. This enables two reviewers to view a map as if it were final, not having to go over another reviewer's work. When the reviewers disagree with each other, the author decides which version, if either, to accept.

After review and revision, maps ordinarily undergo a different level of examination, the edit. Editing is the search for mechanical defects in cartographic matters, language, use of geologic nomenclature, and matches with adjacent maps. Much editing is merely the imposition of standards from a style manual. More useful practice is for the editor, normally a nongeologist, to put himself in the place of a naive user of the map and point out things that seem wrong.

Both the reviews and the edits usually uncover matters so familiar to authors that they do not realize the need to state them explicitly. Also, few mappers maintain consistency of presentation over the whole map area and explanation. Different levels of detail or use of different conventions, which may have changed during the course of the mapping, are normally clearer to a reviewer or editor than to the author.

7.4.9. *General guidelines*

The mapper and the reviewer should seek a happy medium between fussiness and carelessness:

1. Small features or fine details should not obscure the big picture, but neither should excessive lumping or "cartooning" gloss over significant differences; worse still, one part of a map should not be constructed in intricate detail while another part is "cartooned."
2. Interpretations should neither uncritically favor a ruling hypothesis nor discuss each conceivable alternative in great detail.
3. Maps should neither uncritically copy others nor strive for originality to the extent of losing sight of the obvious.
4. The list of the defining characteristics of units in the explanation should neither be too brief or otherwise inadequate to allow reproducible mapping nor so excessively complete as to obscure the salient points.
5. The explanation (which is a dictionary) and the prose text should be neither redundant nor inconsistent.

The following additional problems appear repeatedly on manuscripts of geologic maps:

1. Contact lines and structural symbols that are confused because of ambiguous line weight
2. Contacts, especially dashed contacts, that are not connected clearly
3. Unreadable letter symbols
4. Unlabeled patches of units
5. Overprints of symbols and lines
6. Indistinct leaders (the short lines from the letter symbol to a patch of a unit)
7. Inconsistency of symbols between map and explanation
8. Unexplained queries
9. Interpretations based on properties not mentioned among the list of characteristics
10. The reason for age assignments unstated
11. Ambiguous layout of the explanation
12. Incomplete marginal information (scale, credits, source of base, source of data, etc.)
13. Failure to explain the geology for the novice reader
14. Incompleteness (in the hope the reviewer will find the problems)
15. Inconsistencies between the map and the cross section.

These long lists should not inhibit a novice mapper. Their precepts will become automatic with time. However, their observance from the early stages of mapping will help assure a smooth flow of the manuscript map through the review and editing mill. They can be used as checklists. Their purposes are to facilitate map production and to maximize the value of the map both for the mapper and for the user.

7.5. POSTSCRIPT

Geologic mapping can reap considerable rewards. With a relatively minor expenditure of time, effort, and funds, it provided the stratigraphic framework for selection of optimum sites for the Apollo landings and, later, for extrapolation of the findings from these spots to the rest of the Moon. Both the predicted and unexpected results illuminated a range of previously mysterious phenomena and led to new ways of looking at the Moon and other planets and to new paradigms to be tested. I am sure that if geologic methodology had not been available, Apollo exploration would have been content with learning "the" composition and age of the Moon from one or two points. The other planets would have merited only flyby reconnaissance for obtaining astronomical and geophysical data. Imaging of the planets would have been considered scientifically useless. Fortunately, a brilliant technology has been dedicated to the acquisition of spectacular and informative images from as far away as Uranus and Neptune. Geologic mapping is determining the basic architecture and history of planets from Mercury to the far reaches of the solar system and preparing the way for visits to their surfaces.

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