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INTERAGENCY REPORT: ASTROGEOLOGY 55

GEOLOGIC MAPPING OF THE SECOND PLANET

by

Don E. Wilhelms

Part 1: Rationale and General Methods of Lunar Geologic Mapping

Part 2: Technicalities of Map Conventions, Format, Production Mechanics, and Reviewing

Part 3: History of the U.S. Geological Survey Lunar Geologic Mapping Program

October, 1972

Prepared under NASA Contract W-13,204

Prepared by the Geological Survey for the National Aeronautics and Space Administration

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ILLUSTRATIONS

Introduction

This paper attempts to convey the experience accumulated in the 11 years of the U.S. Geological Survey's lunar geologic mapping program[1/] to geologists who contemplate mapping the Moon, Mars, or any other planetary body with a visible solid surface. This is done in general terms in Part I, where I stress that lunar geologic mapping is similar in philosophy and principle, as well as in many details of method, to terrestrial geologic mapping. We have transferred what we learned on the first planet mapped geologically, the Earth, to the second, the Moon. Since this transfer has been successful in advancing lunar science, we can extend the same methods to other planets without changing our approach or methods, just as we have not changed the name of our science from geology to "selenology"(see for example, Ronca, 1965). In Part II, I give detailed guidelines for constructing maps, with the intention not of dictating procedures but of avoiding re-inventions of techniques already proven to be successful or unsuccessful. The same intention led to the inclusion of Part III, a history of the Survey's lunar mapping program, which although generally successful and a worthy model for future programs, included a number of mistakes that should not be repeated.

Why do we attempt geological mapping of other planets when photographs--often very poor ones--are the only data available? Presumably we wish to learn the planet's three-dimensional make-up, its formative and modifying processes, and its history, including origin and subsequent evolution. Some kinds of data, such as chemical composition and absolute ages, have to be collected on the planet itself. But many things cannot be learned on the ground, given any less than an extravagant expense of resources and time, but they can be learned from photographs to a considerable extent. These include the structure of the whole planet and the geometric relations, areal distribution, and sequence of formation of its crustal elements. Besides being important in its own right, this knowledge of the planet-wide framework is essential for determining the setting of the tiny spot samples examined or collected on the surface (Carr, 1970, p. 5). This progression from gross- to fine-scale analyses is actually more desirable and efficient than the opposite one used on Earth.

Requisites for Planetary Mapping

Geologic mapping is a difficult, time-consuming exercise for which some geologists are better suited than others. The answer to the question of who will be an effective planetary mapper has become increasingly clear to me in the eight years I have been examining lunar geologic maps. The best maps have been produced by experienced field geologists who understand the purpose, strengths, and limitations of geologic maps; who see their utility in lunar and planetary studies

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1/ The great bulk of this program was conducted as supporting research for the National Aeronautics and Space Administration's lunar exploration program under Contract Nos. R-66 and W-13,130. The present report was prepared for the Planetology Programs Office under NASA Contract No. W-13,204.

even in the absence of final data; who are willing to apply their research methods and understanding of terrestrial geologic relations and processes to other planets; who are patient and careful; and who have no hangups about extra-terrestrial bodies. There is a close empirical correlation in quality between a geologist's lunar and terrestrial maps. Geologists who have made at least one complete and good terrestrial map from field studies generally have been able to make good lunar geologic maps, if they wanted to. Some good geologists have made inferior lunar maps because they just couldn't see the point of it or were unable to transfer what they learned on Earth to the Moon. So far, lunar mapping has been primarily inductive in its approach and based on the principles of stratigraphy, and dependent for unit definition on geometric relations and topographic properties. Fancy quantitative "remote sensing" analyses have not played an important role in the work. Planetary mapping, then, is not for non-geologists or for geologists who have rejected the traditions of their science, and expect to get real results quickly by machines and numbers; a planet is too complex to be studied exclusively by quantitative analyses, though these are of course essential for many purposes.1/ One must expect primarily to gather facts, and to advance slowly to understanding, not to suddenly comprehend the origin of the subject planet or the Solar System. If one is suited to this discipline and sufficiently patient, he can garner substantial satisfaction from his labors as order emerges and the planet at last becomes comprehensible.

Acknowledgements

For completeness, this paper has incorporated considerable material, including verbatim quotations from: 1) a summary of the telescopic phase (1960-1967) of the lunar program (Wilhelms, 1970), 2) a pamphlet that accompanies a synoptic map of the near side based both on telescopic and Lunar Orbiter data (Wilhelms and McCauley, 1971), and 3) a book which perceptively evaluates the stratigraphic approach to lunar mapping (Mutch, 1970). Much other material, especially in Parts II and III, has not been set down before and is drawn from my six-year experience as coordinator of the Survey's lunar geologic mapping program. The discussion of map explanations was prepared with the help of Rudolph W. Kopf, representative, U.S.G.S. Geologic Names Committee. Two lunar mapping stalwarts contributed valuable suggestions: John F. McCauley, currently Chief, Branch of Astrogeologic Studies, and from the start of the intensive mapping program (1963) deeply involved in its development, and David H. Scott, who, although relatively new (1969) to the program, has bypassed many of the earlier workers in mapping proficiency and productivity because of his concentrated approach, insight, and long previous experience in solving problems by geological methods. Others who contributed the valuable suggestions are G. E. McGill,

1/ All geologists can benefit from reading or re-reading the excellent collection of articles in the book, "Fabric of Geology" (Albritton, 1963), for reinforcement of their appreciation for the philosophy and methodology of the historical, primarily qualitative science of geology.

University of Massachusetts, and G. W. Colton, U.S.G.S.

Suggestions from users are welcomed and will be incorporated in a second edition of this paper should one become desirable.

PART I

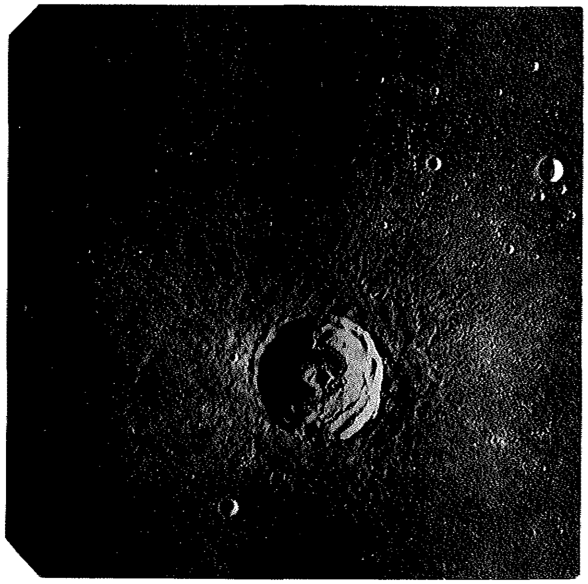
RATIONALE AND GENERAL METHODS OF LUNAR GEOLOGIC MAPPING

Geologic Units and the Principles of Sequence

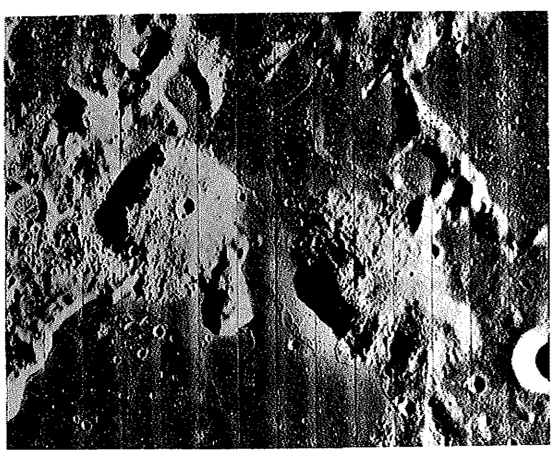
Lunar mapping as practiced by the Survey depends on a vital concept derived from terrestrial stratigraphic practice: That the crust is composed of discrete, three-dimensional bodies of rock called geologic units, each having limited vertical and horizontal extent. The geometric relations among units record their sequence of formation: younger rocks are deposited upon, or intrude, older rocks. Most non-geologists and even many geologists seem surprised at first that planets can be studied productively from so simple a perspective. We know, however, that no planet made of solid material can be totally homogeneous or randomly heterogeneous. Recorded on its surface in the form of discrete rock masses arranged in complex overlapping sequences are the events which have shaped that surface--impacts that throw out blankets of bedded ejecta upon older terrain, and, for large planets, the volcanism that builds stratified flows, cones, domes and the like. This concept of discrete mappable units occupying specific stratigraphic positions is an essential research tool; it reduces the enormous complexity of a planetary crust to comprehensible proportions, and allows without field examination much to be learned about the structure, history, and formative processes of a planet's surface.

The process of recognizing the geologic units which compose a planet is straightforward in principle. One tries to block out units each of which formed, relative to its neighboring units, (a) by a discrete process, and (b) in a discrete time interval. Unity of formative process is inferred from a distinctive texture--ridges, hillocks, lobes, pits, complete smoothness, etc.--that occurs uniformly over an extensive area, or varies regularly, as in a symmetrical array about a negative or positive landform. A uniform or regularly varying albedo pattern commonly accompanies the topographic pattern. For example, crater rim material, with its concentric arcuate hummocks close to the crater and radial ridges farther out, probably was formed by a single event, ejection from the crater (fig. 1a). Other types of units include a patch of mare or light plains with a smooth surface and uniform albedo, a dome with uniform ridged texture (fig. 1b), a cluster of hills and furrow-like craters having a distinctive, uniform, and repetitive pattern (fig. 1c), and a mantle of uniform albedo superposed on diverse underlying terrain (fig. 1d). The uniform or regularly varying pattern may be broken up by younger units or structures, so that the complete distribution of the unit must be mapped to identify it as a unit. One tests the likelihood of unity of formation by asking, "Can what I see be explained by laterally continuous rock bodies?"

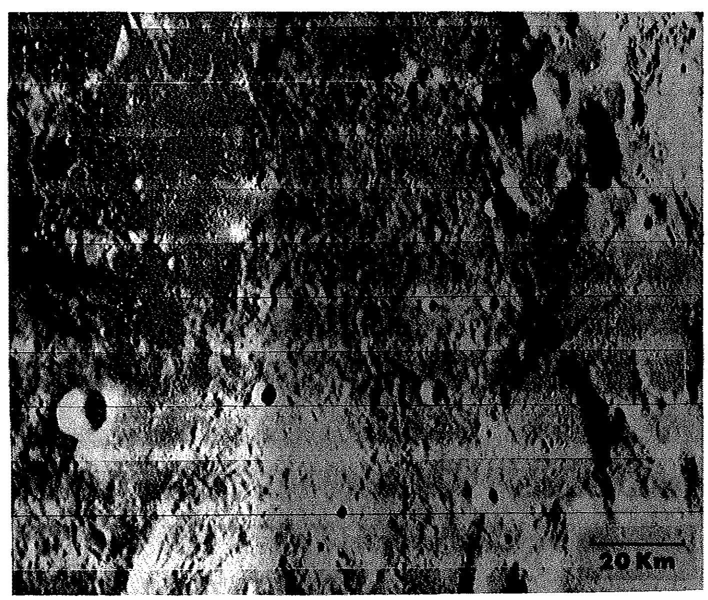
Once units are recognized, the procedure of determining their age relative to their neighboring units is even simpler, although it is at the heart of the geologic approach, which is essentially historical and distinct from the approach of many other sciences. This procedure relies on the principles of sequence. Because temporal relations are expressed as three-dimensional spatial relations, these can commonly



a. Crater Timocharis (34 km diam.). The rim material has regular properties in concentric bands and was undoubtedly produced by a single process, ejection from the crater, so is a geologic unit. Apollo 15 metric-camera frame 1147.

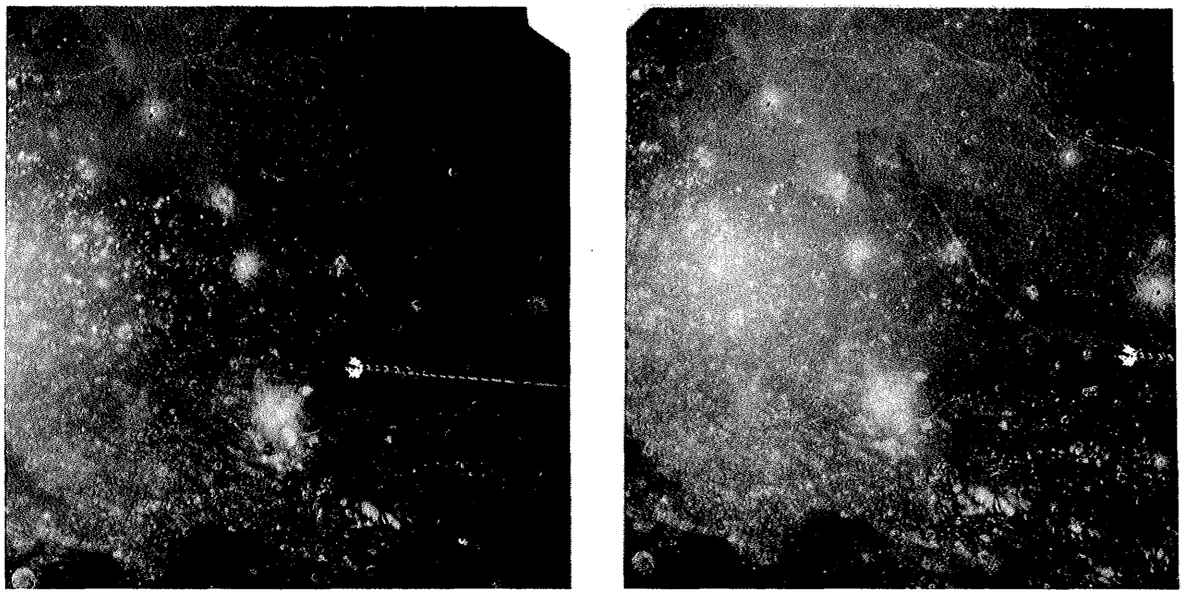


b. Possible extrusive domes, Gruithuisen γ (left, 18 km diameter) and δ (right). The complex, uniform texture of shallow overlapping pits is probably primary. Lunar Orbiter V frame M-184.



c. Descartes-type material, with repetitive pattern of furrows and hills. Mantles crater Descartes at bottom of picture. Part of Lunar Orbiter IV frame H-89.

Fig. 1.—Examples of lunar geologic units.



d. Dark mantle on terra, increasing in thickness to upper right (northeast). Sulpicius Gallus region, southwestern Mare Serenitatis. Parts of 2155 and 2156 Apollo 15 metric-camera frames (stereo pair). Long dimension of photos approximately 150 km.

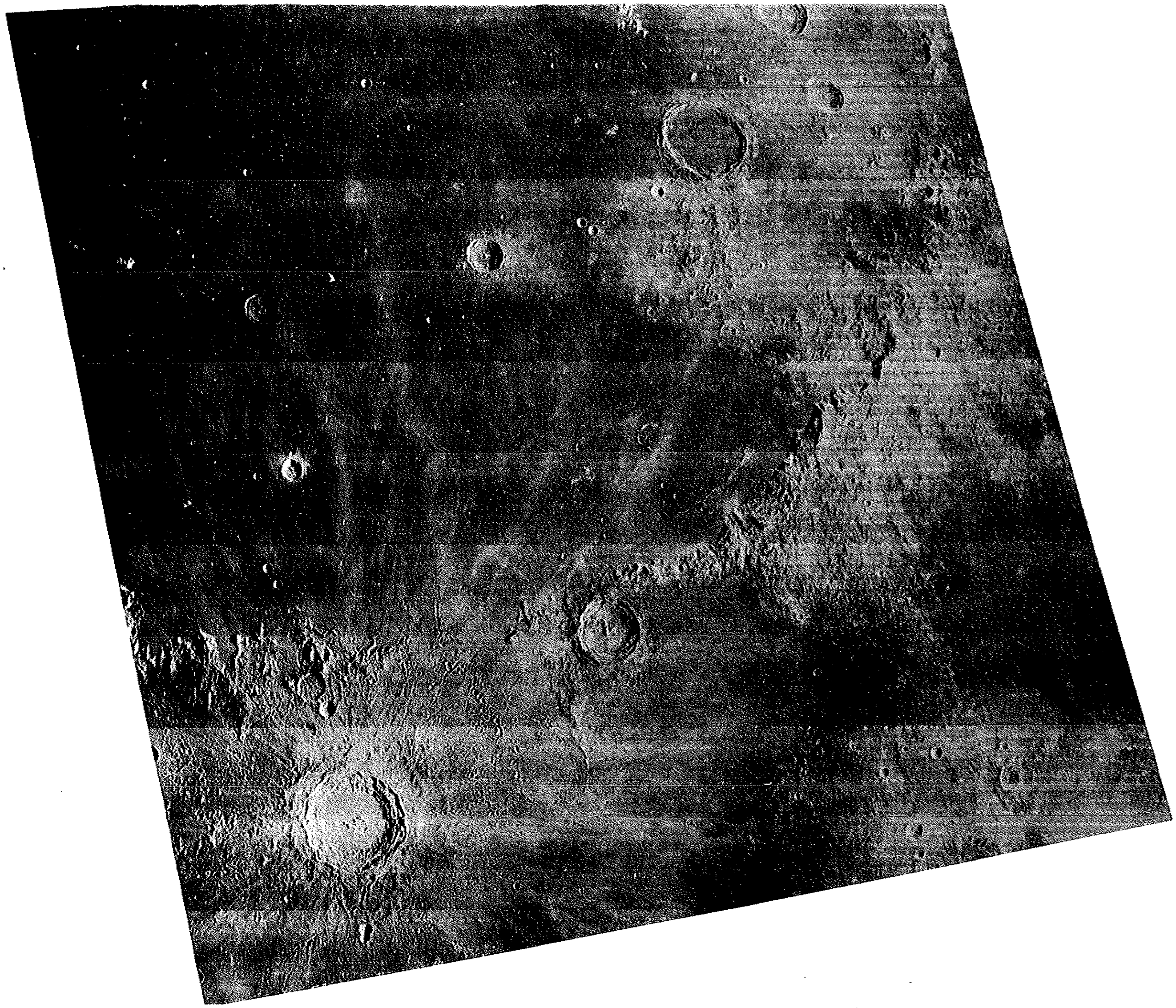
be seen in the areal pattern of the units and their surface contact relations: a younger unit overlaps or embays an older unit; the contact of a younger unit cuts across the contact between two older units. In a commonly cited example that clearly demonstrates lunar stratigraphic methods (fig. 2) (Wilhelms, 1970, p. F7-F10): Copernicus obviously is younger than the mare material around it because its rim material, secondary craters, and rays cross the mare material in an unbroken pattern; on the other hand, mare material fills and embays Archimedes, and truncates the contact between its ejecta and the underlying plains, so is younger than Archimedes.

It is important to note that the concept that parts of a unit formed in "about the same way," is meant in very general terms: origin by ejection of material from a central source; or by emplacement as fluid flows or by viscous extrusion. One may not know whether ejection or emplacement occurred by an impact or volcanic mechanism. Details of origin and composition must await direct exploration, or sophisticated and cautious comparison of lunar features with terrestrial analogs and laboratory models (Mutch, 1970, p. 59-62 gives a list of warnings about use of analogs). Therefore units should always be mapped as objectively as possible on the basis of reproducible physical criteria. But each unit is mapped as such on the basis of a geologic judgement that it has unity of origin and age.

It should also be emphasized at this point that, although we use topographic characteristics more than any other property to define units (Wilhelms, 1970, p. F6), we attempt to map materials, not physiographic forms; the crater rim material, not the crater, which is just a hole. And similarly for plains; on Earth plains may be formed by erosion or by sedimentation but on the Moon they are probably formed by deposition of materials (lava or rock fragments) whose intrinsic mobility caused them to assume flat surfaces. So lunar mapping is not geomorphology, but rather an attempt at stratigraphy, even by its strict definition as the study of layered rocks, although few cross sections through layers can be observed (Mutch, 1970, p. 259-261) because of the nature of the Moon itself.

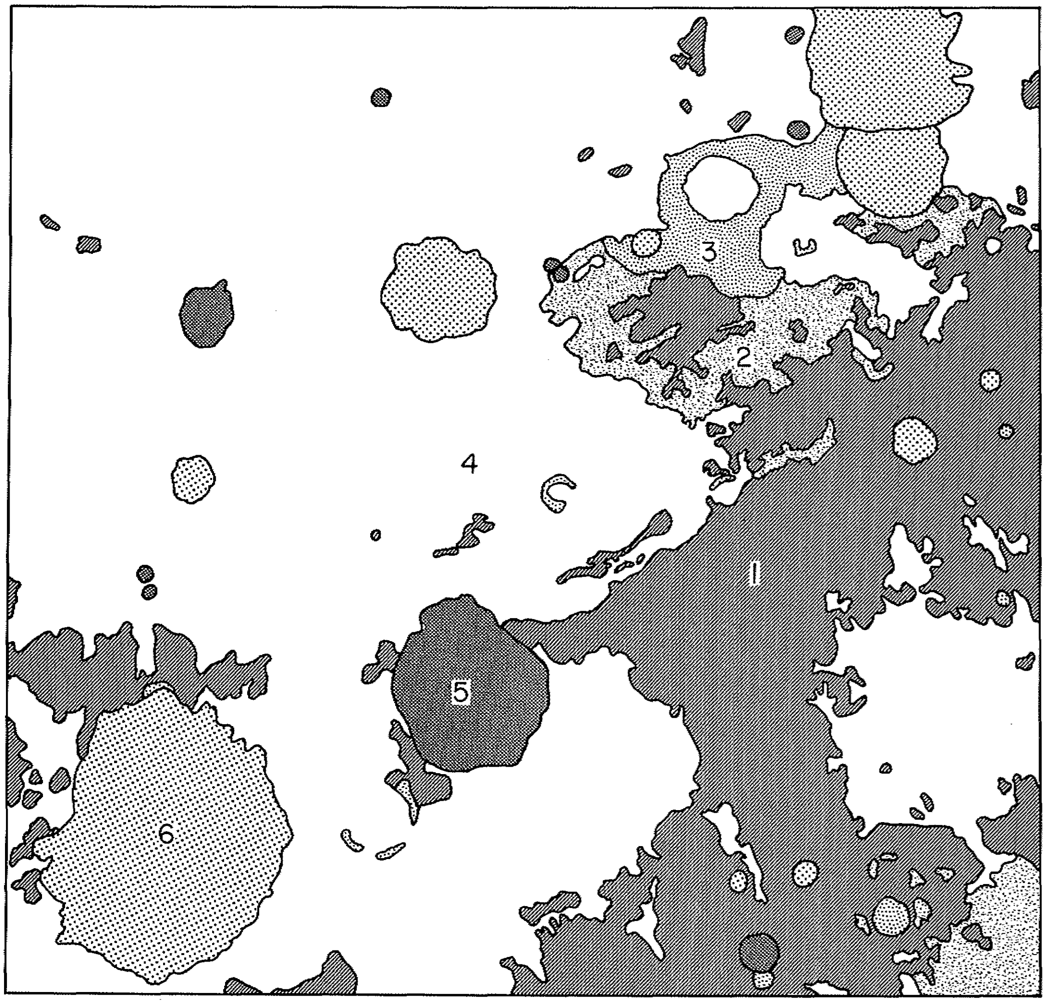
The degree of exactness achieved in identifying units--how "discrete" the process and time interval of formation--will vary widely with the character of units and quality of available data. The foregoing guidelines to lunar mapping can probably be applied readily by most students in well photographed, relatively fresh terranes--about late Imbrian and younger--where true stratigraphic units can be recognized from their primary characteristics such as crater rim hummocks, ridges, or mare flow lobes. It is in older, subdued-appearing terranes where this approach encounters harder going. In such terranes, primary textures and surfaces are not always visible, and we may have to be content with defining units by superposed crater populations, erosional morphology, or other secondary characteristics--a practice which is justifiably frowned on in terrestrial stratigraphy. Secondary characteristics, unfortunately, might be equally developed on quite different units, which remain undetected; that is, we might recognize and map in these situations only physiographic, not rock-stratigraphic, units.[1/] Nevertheless, partial strat-

1/ Note added in proof: Preliminary Apollo 16 rock analyses suggest that this happened at the Descartes site (fig. 1c). The distinctive pits that characterize the "Descartes-type" unit may be superposed on unrelated, older, possibly polygenetic, terrane.



a. Photograph of Copernicus-Archimedes region.
Lunar Orbiter IV moderate-resolution frame 126.

Fig. 2.--Principles of sequence.



b. Geologic map of same area (after Wilhelms and McCauley, 1971). Units are numbered from oldest (1) to youngest (6). The contacts of each successively younger unit cut across those of older units. Unit 6 is known to be younger than unit 5 because its radial rays are superposed on unit 5.

igraphic sequences can usually be worked out in old terranes by overlap and transection relations, mainly among crater rims and plains. This is possible if one makes the reasonable assumption that in a general sense uniformitarianism is applicable to the Moon--that older terranes are likely to be degraded equivalents of younger, demonstrably bedded ones (fig. 3). Lunar stratigraphers will not object if the mental process that imagines the conversion of young forms to old is considered geomorphology, so long as one keeps in mind the probable bedded nature of even the oldest terrane and thinks stratigraphically.

Correlations

To build a geologic picture on a planet-wide basis, the individual, local units must be correlated and related to the total stratigraphic record. The most rigorous method in lunar stratigraphy, as in terrestrial, is use of extensive and synchronous datum planes. The best ones on the Moon are the ejecta blankets and secondary impact craters of the Imbrium, Orientale, and Nectaris basins. The mare material is also useful though not quite so synchronous. Synchronous materials of large young craters, including their secondary impact craters, are also useful over smaller but still considerable regions.[1/] Many lunar units have been dated as younger or older than these units, and the following four principal subdivisions of lunar stratigraphy, first worked out in the Copernicus-Archimedes region (Shoemaker and Hackman, 1962) and somewhat modified later (McCauley, 1967; Wilhelms, 1970), have been established: Copernican System, ray-crater material and contemporaneous materials; Eratosthenian System, materials older than ray-crater material but younger than the bulk of the mare material; Imbrian System, everything from the bulk of the mare material down through the Imbrium basin ejecta blanket (a considerable volume of material); pre-Imbrian, everything older than the Imbrium basin ejecta blanket. A move is now afoot to subdivide the pre-Imbrian on the basis of the ejecta and materials of the Nectaris basin.

Extrapolations necessary in the absence of these regional units are made by: (1) density of superposed craters, and (2) correlations of morphology with age. Relative (and absolute) age determination by means of crater population is a favorite topic in the literature (for example see Mutch, 1970, p. 263-270) and will not be discussed further here, except to caution against misleading conclusions resulting from the very large percentage of lunar craters that are secondary impact craters. Morphology of craters has come into wide use in extrapolation since the advent of Lunar Orbiter photographs (Pohn and Offield, 1970; Trask, 1970; Soderblom and Lebofsky, 1972). Age correlations are made by comparing morphology of isolated craters with morphology of craters previously dated relative to one of the regional datum planes, under the assumption that morphology partly indicates state of preservation. As noted above, a fundamental observation of lunar stratigraphy is that a kind of uniformitarianism applies: that craters and other landforms are fresh

1/ The utility of crater materials as stratigraphic datum planes is reduced by the fact that their lower and upper surfaces are randomly placed unconformities. In particular, the most extensive and easily dated crater materials, the young ones, usually have a free surface that is of little stratigraphic use (Mutch, 1970, p. 164-165).

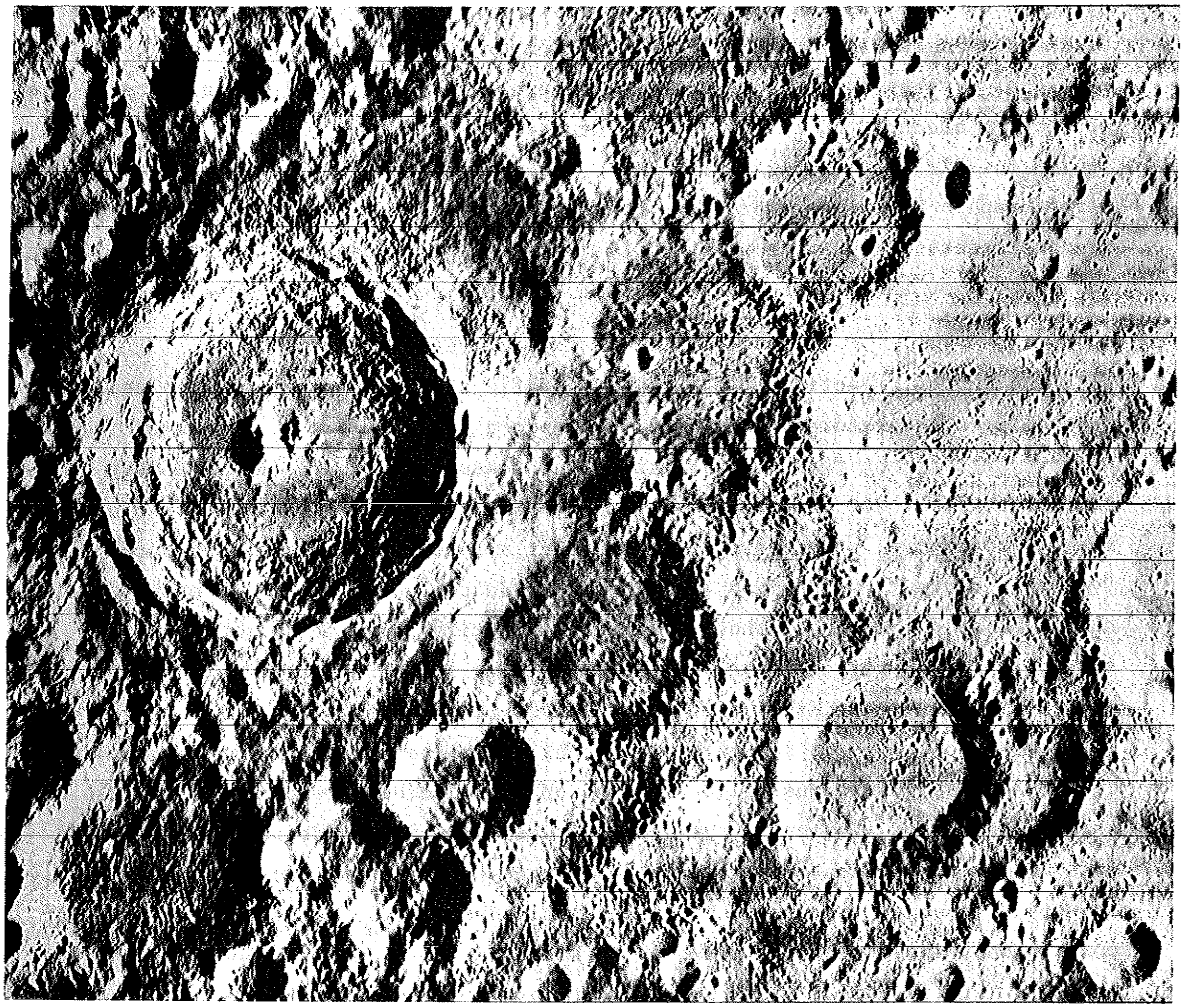


Figure 3.--Comparison of old and young terranes. The crater Tycho, left, (85 km diameter) is surrounded by a sharply hummocky rim, finely-textured radial ejecta, and swarms of secondary impact craters. These have greatly affected the topography of the nearby crater rims and of their planar floor material. Lunar uniformitarianism suggests that the Tycho-size crater on the right (Orontius) and the medium-sized craters were once surrounded by similar sharply textured materials that similarly affected their neighborhoods, but these effects have vanished. Presumably, however, the crater materials and old plains are still present but have been complexly degraded and mixed into their present characterless shape by repetitive cratering. So old terranes are composed of sequences just as complex as in young terranes, but the nature of the components must be inferred by analogy. Lunar Orbiter IV frame H-119, framelets 003-022.

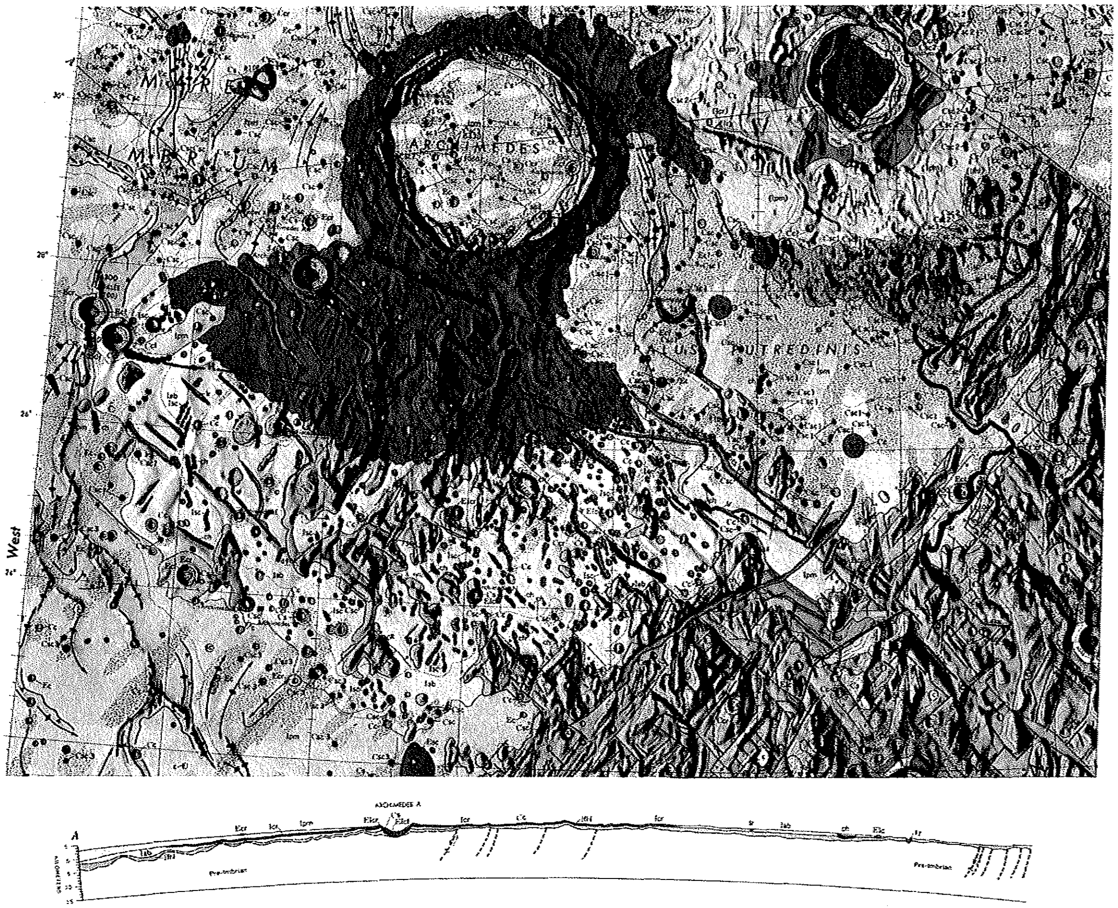
when young, and become degraded with time (Wilhelms and McCauley, 1971, pamphlet). Although less desirable than more direct stratigraphic methods (using regional blankets as marker horizons or superposition and intersection relations), the dating of craters by their physiographic appearance works well in practice if age categories are not too finely drawn. Craters used this way are, in a sense, the "guide fossils" of lunar stratigraphy. The results are consistent with established stratigraphic relations where they can be tested. For example, no severely degraded craters of the type assigned to the pre-Imbrian can be identified on either the Imbrium or the Orientale circumbasin blankets, both of Imbrian age.

Avoiding the Interpretive Bias

The Survey, reacting to the sub-scientific state of much lunar geologic and parageologic literature before 1960, has made a great effort to map objectively. We have insisted on reproducible lines; the reason for their placement must be fairly obvious to other workers viewing the same photographic data. Unit names must be objective, not interpretive--"crater material," not "impact ejecta" or "volcanic rocks." Units must be objectively described on the basis of physical characteristics, so that other workers can identify them; definitions must be straightforward, not contrived to fit a tortuous interpretive maze. The description of defining characteristics must be separated clearly from discussion of genetic interpretations, in two separate paragraphs under the unit's box in the explanation. Age assignment must also be based on reproducible criteria, which must be stated. Rock and time units must be separated. Entire quadrangles or regions must be mapped, so that everything present has to be taken into account, not only objects of special interest (odd craters, sinuous rilles, lineaments, etc.) that contain only those elements which nourish special prejudices. (The Earth-analog game has very frequently been played this way, by very sloppy rules.) Cross sections, though highly interpretive, should be drawn, as on Earth, if for no other reason than to test the map relations.

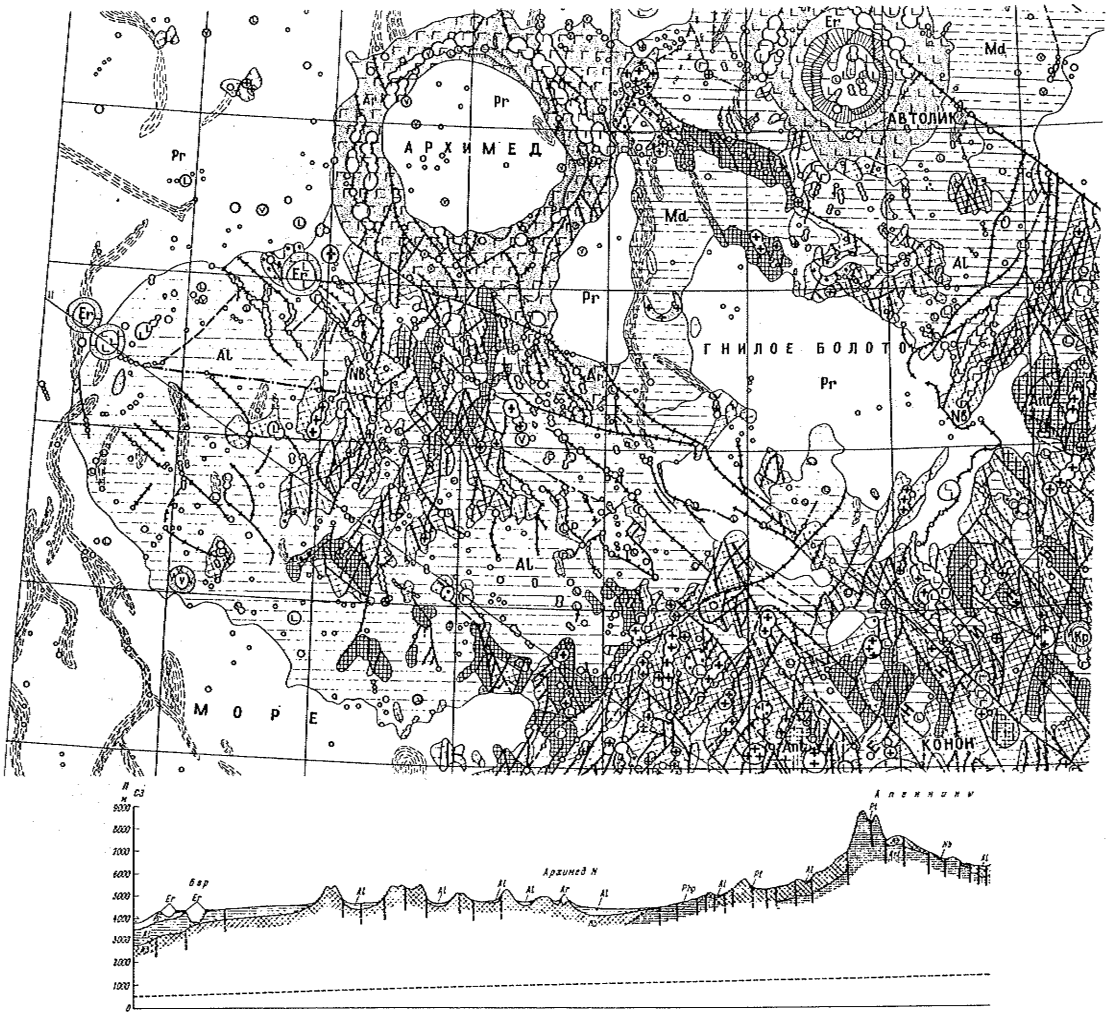
To be sure, there is considerable latitude for differences of opinion even within these tight guidelines and within the constraint of mapping material units ranked stratigraphically. In fact, no two people are going to draw lines exactly the same way--though it is remarkable, perhaps, how closely similar the lines of two experienced mappers usually are (compare, even, figs. 4a and 4b). Lines might be drawn in several equally reproducible ways, because of differing opinions about which units are stratigraphically significant--for example, a thin overlying mantle or a buried, but still strongly expressed, crater rim; in this case two workers may agree exactly on the observation, but not on the map portrayal. There is, of course, some difference of opinion about relative age of units, even among people applying the same criteria. There is difference in artistic style--smooth or jagged lines--and in "lumping" versus "splitting." But all of these differences also occur in terrestrial geology. Lunar mapping has strayed unacceptably far from Survey guidelines only when a strong interpretive bias has made maps unreadable by a mapper's colleagues; two maps have been candidates for rejection for this reason.[1/]

1/ Footnote--see next page.



a. Geologic map and section of the Montes Apenninus region of the Moon, by R. J. Hackman (1966).

Fig. 4.--Alternative U.S. (a) and U.S.S.R. (b) maps of the same region. For (b),turn page.



b. Geologic-morphologic map and profile of the region of the cirque Archimedes and the mountainous Apennine massif, by A. C. Sukhanov and V. G. Trifonov (in Peive, ed., 1969). Profile extends beyond map area and is at a somewhat smaller scale.

To eliminate all interpretive bias, there has been a continuing attempt to quantitize lunar properties for use in hard, reproducible unit descriptions. The most useful easily measurable property has been albedo. Pohn and Wildey (1970) photometrically distinguish 20 normal albedo steps. From 5 to 10 have been used on lunar maps. But on the 1:5,000,000-scale near-side map (Wilhelms and McCauley, 1971) only two--dark and light--were used. This dichotomy could indicate a basic two-fold compositional dichotomy--mafic and felsic. Other albedo steps may represent additional compositional variations or degree of exposure of fresh rock. In any case, albedo variations, whether fully understood or not, can be used to help characterize units.

Besides albedo, possible defining properties include thermal (infrared) anomaly at eclipse, color, polarization, slope characteristics derived by photogrammetry or photoclinometry, and microwave and radar response at various wavelengths (both Earth-Moon and bistatic). Some of these--especially infrared and color--have proved informative, and others--radar--are beginning to appear interesting. But possibly we never will be able to improve much on qualitative, commonly laborious geologic mapping based on topographic properties and geometric relations. There are too many data to treat quantitatively; machines can never define units. The author's opinion of the stratigraphic utility of these properties is very well expressed by Mutch (1970, p. 58).

In all science, one is most apt to find what he is looking for; that is, his view of his subject matter is colored by the spectacles he wears. I have been describing the spectacles that the Geological Survey wears during its lunar mapping program; they have filters that pass material-geologic units, and polarizers that stack the units in stratigraphic sequence where possible. We believe that results have shown these spectacles to be better than others yet tried on the Moon, because they pass information that corresponds with the true nature of the Moon. Other spectacle prescriptions are of course possible but of such low transmissivity as not to be efficient in advancing geological knowledge in an orderly and economical way.

A Soviet group under Sukhanov (1967), partly following guidelines established by Khabakov (1962), also maps with historical spectacles, but thinks less in terms of material units and more in terms of structures. As I understand it, the Soviets recognize two kinds of lunar units, craters and maria, and believe that nearly everything now seen on the Moon is one of these, modified by structural patterns to a greater or lesser degree. For example, they, like us, recognize the maria to be younger than the Apennine Mountains, but they believe the Apennines to be old mare material that has undergone long, protracted deformation by internal forces (fig. 4b). Their "structure" spectacles predestine this different conclusion.

Another productive lunar student who wears both historical and endogenetic

1/ (From preceding page.) The main reason for outright rejection, so far, has been failure, caused by poor spatial perception or sloppiness, to transfer shapes that are clearly visible on photographs to a map. One could set up a quick semi-quantitative test for the quality of a lunar map: the amount of time it takes someone, while looking at the photographs, to locate a feature on the map.

filters on his spectacles is the English astronomer-geologist Gilbert Fielder (1965). His fundamental uniformitarian postulate is the diametrical opposite of ours: he believes that topographically sharp features are old, and subdued features, young (1965, p. 146-153). He believes, for example, that Stadius and Archimedes are young craters beginning to grow up through the surface, eventually to look like their richly detailed (but, paradoxically, relatively uncratered) neighbor Copernicus.

To reiterate the thesis of the present paper in this context: use of the concept of material stratigraphic units has led the Survey in a different direction from the Soviets and Fielder, and before them, Shaler, Spurr, and von Bülow. The internal-structural model allows each small feature such as a hillock or ridge to be interpreted <u>ad hoc</u>, whereas our model unifies many small adjacent features as look alike, then seeks the explanation of this unity in layered units. The result is a mixed endogenetic and exogenetic interpretation. Contrary to a widespread calumny, the Survey's ruling model is not impact--as should be obvious from the many volcanic interpretations that appear on our maps. Impact as an explanation for multi-ring basins and many craters is arrived at only when a reasonable mechanism is sought for the emplacement of the extensive materials around them that appear to be layered.

Purpose of Geologic Maps

At this point, after generalizing about the lunar and planetary mapping approach and before detailing the methods of constructing a map, we should pause to consider the purpose of geologic maps. As has been stressed, planetary geological mapping is the offspring of terrestrial geological mapping. So we will know how to map a planet if we remember how we map the Earth; and if we momentarily forget why we are mapping a planet, we should recall why we map the Earth. We map to learn and to communicate. For full understanding, we must study an entire area, not selected features of interest, so we make maps to keep track of our observations economically and record them in their proper geometric relations. By mapping, we continually organize and classify the data, formulate and test multiple working hypotheses, and finally, generalize nature's complexities into a portrayal that seems consistent with available data and our accumulated knowledge.

A map must filter observations, not record all of them; otherwise it is not useful to anyone but its author. But it must also show the basis for the author's generalizations, so that other workers can test them against the facts, and either confirm them or modify them in the light of new theory. A terrestrial map made ten years ago should not be superseded by global plate tectonic theory, but rather, should be the basis for testing the theory; and a lunar map should do the same for, say, impact and volcanic theories. So in effect geologic maps are the objective, testable records and models of geology and correspond to the graphs and equations of the experimental sciences.

PART II

TECHNICALITIES OF MAP CONVENTIONS, FORMAT, PRODUCTION MECHANICS, AND REVIEWING

Map Units

A mapper usually finds that the units he has recognized and outlined require some recasting when being expressed as map units, to improve cartographic clarity or scientific rigor. This section gives some rules to be followed in setting up map units.

We should first recall the different conceptual types of units now recognized by American stratigraphers (American Commission on Stratigraphic Nomenclature, 1970). The distinctions are important in separating interpretation from observation and in keeping one's logic straight; continuing confusion of these types by European stratigraphers may impede their objective evaluation of the Moon. The Code of Stratigraphic Nomenclature distinguishes between rock-stratigraphic units--material subdivisions of the crust that are distinguished solely on the basis of lithologic properties, and time-stratigraphic units--material units which include all rocks formed in a specific interval of time. Rock-stratigraphic units are the practical mapping units and are the basis for defining time-stratigraphic units. A third unit is a nonmaterial subdivision--the geologic-time unit, which is defined in terms of time-stratigraphic units. The basic rock-stratigraphic unit is the formation; these are divided into members, and combined into groups. The basic time-stratigraphic unit is the system; these are divided into series, and combined into the era or erathem. Geologic-time units that correspond to systems are periods; to series, epochs. "Upper" and "lower" are physical terms so are applied to rock-stratigraphic and time-stratigraphic units; "late" and "early" are time terms.

Another type of unit that now might be needed on the Moon is the soil-stratigraphic unit, which might advantageously be used to codify regolith units (Mutch, 1970, p. 174-195). Other types and ranks of Earth units have no present lunar application.

The term "lunar material unit" has been proposed as the lunar parallel to the terrestrial rock-stratigraphic unit (Wilhelms, 1970, p. F11). It was defined as "a subdivision of the materials in the Moon's crust exposed or expressed at the surface and distinguished and delimited on the basis of physical characteristics." The purpose of distinguishing lunar material units from rock-stratigraphic units was to emphasize the fact that mapped lunar units, though defined by physical characteristics like Earth rock units, are not always nicely discrete, tabular, internally uniform bodies defined by true primary lithologic characteristics. That is, lunar material units may be either true rock-stratigraphic units or "terrain units." Also, the word "material" was preferred over "rock" because of a vague uneasiness at calling terrain "rock" and because we knew that most lunar units would turn out to be debris, breccias, and other crumbly stuff. But all of this is still rock and not some exotic extraterrestrial compound, so the word "rock" should perhaps come into greater use even for photogeologic units.

Another term that should be clearly understood is "map unit" itself. This is the unit that is shown on a map with its own symbol, color, and position in the box explanation. Map units may be rock-stratigraphic units (lunar material units) of any rank, or time-stratigraphic units of any rank, depending on the purpose and scale of the map.

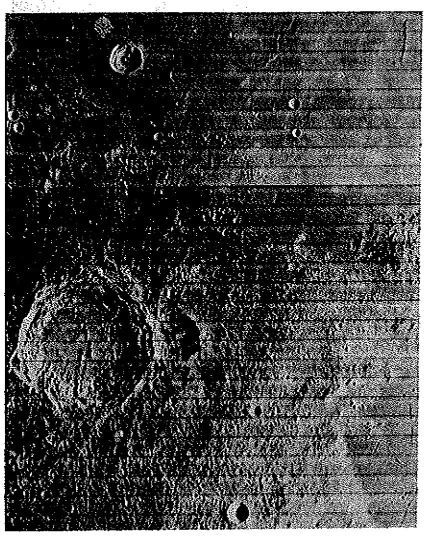
Each limited body of material that the geologist has outlined as a unit by the principles set forth in the previous sections cannot be a map unit. Some laterally continuous formations, such as basin ejecta blankets, are sometimes used individually as map units, as is the most common practice on Earth. Very commonly, however, formations of indistinguishable appearance occur in many separated localities, and it is convenient to combine all of these as a single map unit. The individual occurrences of such a map unit have the same general age range--that is, are assigned to the same time-stratigraphic unit--but may vary in age within this range. Examples of such map units are "Imbrian plains material," which consists of thousands of separate pools of light plains material, possibly ranging in age from early to late Imbrian,[1/] and "ray-crater material," consisting of materials of a great number of individual young rayed craters, assigned to the Copernican System. These Copernican rayed craters are superposed on nearly all other materials, and may have been formed over the last half of lunar history. So a map unit can include an extensive sequence. Poorly defined lunar material units that no one would call rock-stratigraphic units are treated similarly. Thus we may have "terra material, undivided" appearing every place on a map where we don't understand the geology. (This unit may also, of course, be used on small-scale or special-purpose maps that lump well understood units.)

Two occurrences of the same map unit may be separated by a contact, with the younger shown overlapping the older (for example where materials of one Copernican crater overlap those of another); this is not done on terrestrial maps.

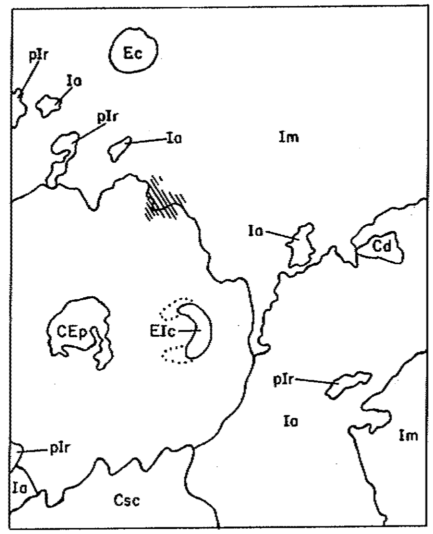
Two or more completely superposed units are commonly recognized (fig. 5). A thin dark or light unit may give an area its characteristic albedo, while an underlying unit may contribute the dominant topography. Or two superposed units, such as materials of two craters, may both be expressed topographically. The unit that is stressed, by being mapped in color, should be the unit that is most conspicuous at the scale of mapping being used. Ordinarily this is the youngest unit that contributes conspicuous topographic expression; but it may be the thin dark or light unit without topographic expression of its own. At low resolution, the rim material of an old crater in the southern highlands is prominent, and on maps at the 1:5,000,000-scale it is the unit mapped in color. But if high-resolution photographs show that the rim has a mantled appearance, then various mantling materials may be the units mapped in color on larger-scale maps based on these photographs. Map most conspicuously what you see most clearly.

Buried units whose textures can still be seen commonly are shown by dotted

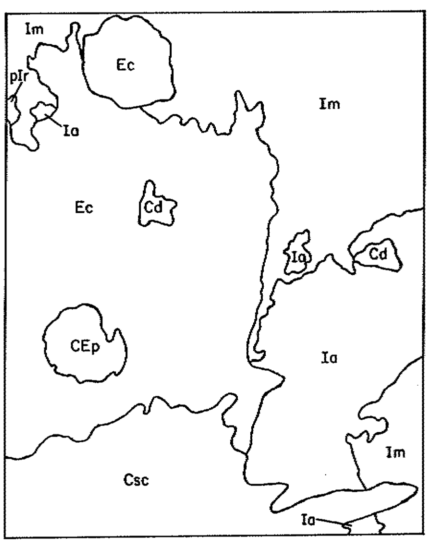
1/ One group of the plains "formations" has been called Cayley Formation, and another, Apennine Bench Formation, but this use of formational names is disappearing.



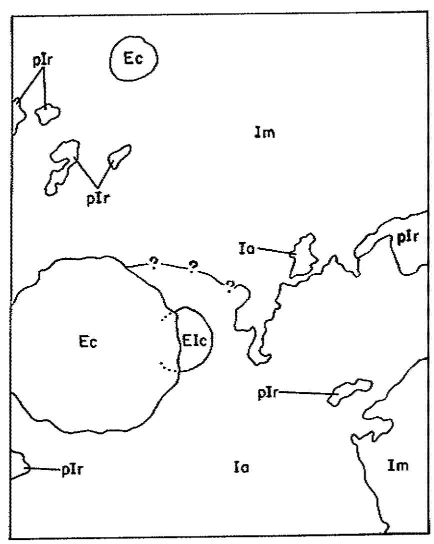
a. Photograph of area. Crater Aristoteles, 85 km diameter. Lunar Orbiter IV frame H-98, framelets 218-247.



b. Most conspicuous units stressed.



c. Surficial units stressed.



d. Deep-lying units stressed.

Fig. 5.--Alternative methods of portraying a terrane. Portrayal of (b) is ordinarily preferred. Csc--Copernican satellitic crater material; Cd--Copernican dark mantling material; diagonal line pattern--dark material; CEp--Eratosthenian or Copernican plains material; Ec--Eratosthenian crater material; EIc--Imbrian or Eratosthenian crater material; Im--Imbrian mare material; Ia--Imbrian Alpes Formation (Imbrium basin ejecta?); pIr--pre-Imbrian material of rugged terra.

contacts and symbols in parentheses; alternatively, an overprint pattern may be used for the overlying unit. Special dash-dot symbols are used for buried crater rim crests where subunits are indistinct. Buried contacts are drawn at the limit of observed topographic expression, not at the inferred or projected limits. Some units are defined to represent both the underlying and overlying layers (Milton, 1968; Wilhelms, 1970, p. F12). Provinces of quite diverse constitution can be mapped as units, provided their compound nature is explained fully and no pretense is made that they are true rock-stratigraphic units (McCauley and Wilhelms, 1972).

Crater material subunits have always played a large role on lunar geologic maps (Wilhelms, 1970, p. F40-F42; Mutch, 1970, p. 165-174). Crater materials--of rim, wall, floor, peak, etc.--were extensively subdivided, for objectivity, because they look so different. This subdivision has proved, however, to be excessively demanding on mapping time and available colors. There is sentiment now, therefore, to lump all materials of a crater. Or a more interpretive two-fold system could be used: (1) materials completely disaggregated and redistributed by crater formation (ballistic and base-surge ejecta); (2) materials structurally highly deformed but not disaggregated (inner "Schuppen" rim material, wall material, central peak material, and some hilly floor material). Materials believed formed after the crater (smooth floor materials and planar pools in rim and wall depressions) are usually mapped as separate, non-crater units, although formerly some of these were included as crater materials.

Names, Letter Symbols, and Colors

Each map unit is given a distinctive name, letter symbol, and color. Names may be formal or informal, as convenient. Formal names are given to some laterally continuous units, such as the Fra Mauro Formation, that are almost certainly true rock-stratigraphic units. Formal names may also be given to units of unwieldy description that are of special stratigraphic significance, even though the geology of the unit is not completely understood; an example is the Alpes Formation, which otherwise might be called "material forming equidimensional or slightly elongate hummocks of light albedo." Most units, well or poorly understood, are now given short descriptive informal names, followed by the word material(s); examples are crater materials, mare material, hilly and furrowed material, and dome material. All names are objective, not interpretive--"crater rim material," not "impact ejecta" or "volcanic rocks."

The symbol for a lunar map unit, like its terrestrial counterpart, consists of an abbreviation of the system to which the unit is assigned (capital letter) and an abbreviation of the formal or informal name (lowercase letters). Units that may belong with equal likelihood to either of two systems or any of three are given two capital letters representing the possible range (youngest first). If the age of a unit is unknown or only approximately known, capital letters may be omitted. The order of lower-case letters, where possible, should be: noun or formation first, adjective or member second, submember third. Ic, <u>c</u>rater material (formation); Icr, <u>c</u>rater <u>r</u>im material (member); Icrh, <u>c</u>rater <u>r</u>im material, hummocky (sub-member). Where the modifier is an integral part of the name, it may come first, especially to avoid ambiguity: pIst, structured terra material. The reason for each letter in the symbol must be apparent from the name; you cannot label "hilly material" Er because it happens to be rough. But all words of the name need not be abbreviated in the symbol; hilly and pitted material (of Imbrian age) can be abbreviated Ih if there is no ambiguity with other "h" units; but if you also have the Hevelius Formation, you must label the Hevelius Ihe; or label it Ih and label the hilly and pitted material Ihp. In other words, symbols should have the minimum number of letters to be unambiguous. A maximum of four letters may be in the symbol; pI counts as one; all other combinations count as two (CE, EI, etc.).

Use letters in preference to numbers where possible. When units are numbered, higher numbers refer to younger units (Im_2 is younger than Im_1). Numbers follow all letters, because they refer to the whole unit, not the basic formational unit ($pIcr_2$, not pIc_2r).

In all text material, the Survey prefers to refer to units by name, not symbol--"mare material," not "Im." If you must use symbols in text, say "unit Im." Symbols are newly defined on each map's explanation; symbols for the same unit may therefore vary from map to map, but we have tried to keep them as uniform as possible.

Symbols which are queried on the map should always be explained explicitly. "Queried where doubtful" is not good enough; say, "queried where could be Erathosthenian" or "queried where could be unit x." Be sparing in the use of queries; each one must be drafted on a final map. Convey only important doubts--probable departures from the defined meaning of the symbol, not just slight uncertainty as to whether you have mapped correctly.

Colors are assigned to associate like units and disassociate unlike units. Intense colors are used for small patches, weaker colors for large. The practice of using strongly contrasting colors for adjacent beds, which seems to be prevalent in terrestrial maps of the Survey, has not been followed on lunar maps in deference to the association principle. The attempt is made to express both rock-stratigraphic and time-stratigraphic relations. Age is usually shown more or less spectrally, colors toward the red for young units, toward the violet for older; oldest (pre-Imbrian) units are brown. Variations of a type of unit are shown by variations of the basic colors--muddy or mixed versus pure.

Line Symbols

A mapper should separate materials and structures clearly in his mind. Materials are mapped in color, structures with black lines. Exceptions, where structures are shown in color for one purpose or another, should be clearly labelled for what they are. (We went through an early trauma in deciding whether rilles should be shown as structures or geologic units; consensus was soon reached that linear rilles are structures (graben), and that rilles with chain craters are materials; but sinuous rilles continue to be shown both ways.)

Line symbols used on lunar maps follow terrestrial precedent as far as possible, with some additional special ones for the Moon. In explanations, all line symbols except completely closed ones, such as those for crater rim crests, are drawn straight; appurtenances, such as barbs, are drawn on top of the line. There is general consistency in style of symbol and wording of the explanation from map to map, but not slavish uniformity. One must always use symbols appropriate to his purpose and describe them in accord with his geology and his interpretations. The only unchanging requirements are clarity and appropriateness; the idea is to describe what you did.

Contacts are the thinnest lines on a map. Draw all other symbols with heavier line weights.

Structures.--The use of fault symbols should be kept to a minimum; many straight features that looked like faults on telescopic photographs are seen on better photographs to be coincidental linear--and even quite non-linear--arrangements of other features. "Inferred" fault is usually better--though unnecessary for a sharp graben. In the absence of removal or stripping of material by erosion, faults do not ordinarily form contacts between units. However, fault scarps, retreated to an unknown degree, may form some contacts by restricting the lateral extent of post-faulting material, so the fault symbol on maps includes such scarps. Faults should be drawn where the projection of the fault intersects the land surface.

A lineament is a negative feature, not an alinement of separated features (to avoid unwarranted connection of unrelated objects). Long, narrow positive features are shown by a dash-cross-dash symbol.

Dashes.--Dashed contacts are commonly overused. Dashes are expensive to draft and leave unattractive white spaces. They should be used only to convey something of interest to the reader, not to express the personality of the mapper; that is, they should express a degree of doubt, not laziness or the fact that the mapper doubts everything. If all contacts are gradational, this fact should be expressed by a blanket note, not dashes. When a mapper draws a line, he is not saying that everything within it is exactly the same, but only different from what is outside, to a degree of accuracy called for by the scale and purpose of the map. Dashes should be used primarily where the photography is exceptionally poor or the contacts especially indistinct or especially gradational. So try to use solid lines, even where you are not completely sure of location within a couple of millimeters (1 mm = 1 km at 1:1,000,000 scale). 1/

Both lunar and terrestrial maps of the Survey have distinguished different kinds of doubt by different dash lengths--long for approximately located, short for inferred or gradational, etc. We have found this tiresome and most authors of lunar maps now use only long dashes.

A reasonable practice on cross sections is: solid contacts where only thickness or position, not presence, of a unit is in doubt; dashed contacts where the

1/ Note added in proof: New Survey policy, probably based on considerations like these, is that dashes will be drafted by BTI only when absolutely necessary.

presence of a unit at that location is inferred. Where hardly anything is known, or where a unit grades with the basement, a scratch boundary is used; that is, a color boundary without a black line (indicate your desire for this type of contact by writing the word "scratch" on your manuscript).

Format

The best way to learn the format that has been used for lunar geologic maps is to study some of the maps, but some salient points should be mentioned first. The format is based on long-standing U.S. Geological Survey practice.

Items on the map sheet (fig. 6) are (1) the map, (2) unit explanation (to right of map), (3) structure-symbol and undated-unit explanation (below unit explanation or map), (4) scale (below map), (5) cross section (below scale), (6) title, author and date (below everything), (7) organization note (upper left corner of map), (8) cooperation note (above map and centered on sheet), (9) credit note and data sources (lower right corner of map), (10) notes on base (lower left corner of map; or left side of map if extensive, as on all 1:1,000,000-series maps), (11) text (left of map unless an extensive base note is there), (12) location of map area (anywhere), and (13) photographic index map (anywhere).

As discussed in the following section, details of this format will be changed for maps submitted for publication from now on. The geologist need concern himself only with the new format for the box explanation.

Explanation

Layout.--A geologic map explanation should show the age relations among the geologic units on the accompanying map, and should describe the units or refer to descriptions available elsewhere in the map package (margins or pamphlet) or in other literature. Each map unit is represented by a box, usually colored, containing its map symbol. To show age relations, these boxes are arranged in chronologic order, the youngest at the top. To show some broad descriptive classification or geographic subdivision, there may be more than one vertical column of boxes, for example, separate columns for crater materials, mare materials, and terra materials, or for a mare province and a terra province.

The Survey is currently (mid-1972) changing the format for map explanations. Formerly, on nearly all lunar maps, age relations and descriptions were shown by a single array of boxes (fig. 6). Unit titles appeared beneath the boxes, and text descriptions beneath the titles. Overlapping or uncertain age relations were shown by braces. On present Survey maps, age relations and descriptions are shown separately (fig. 7). In the upper part of the sheet, the age relations are shown by the arrangement of colored boxes, each containing a map symbol as usual, but without a title or other words outside the box. Age relations are shown partly by braces and partly by vertical overlap of rectangular boxes. Boxes that designate discrete map units should not touch; those that designate subdivisions of a map unit may touch. System and series names are written horizontally and their braces are to the right of all boxes (series braces formerly were on the left); these names should read

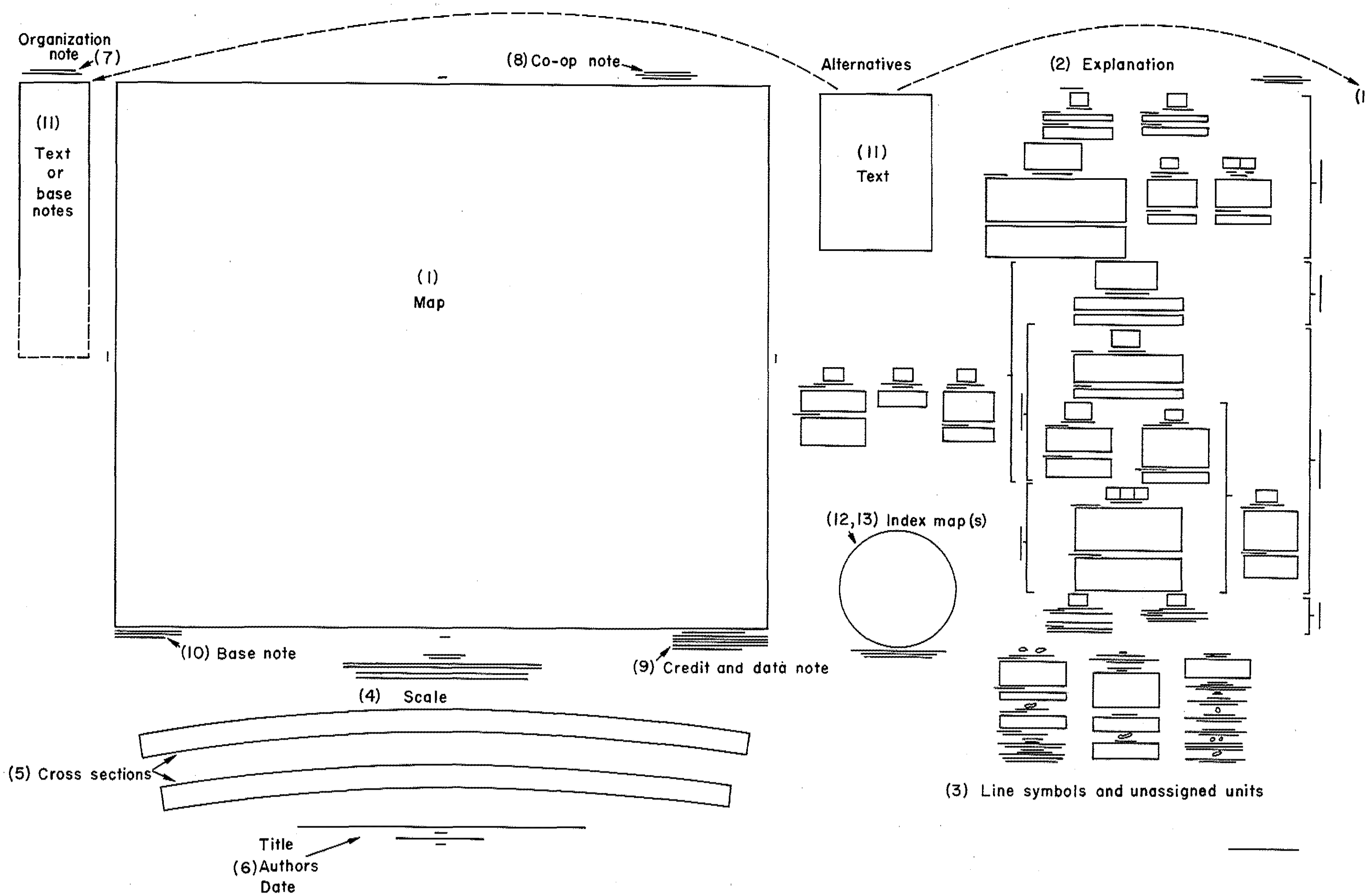
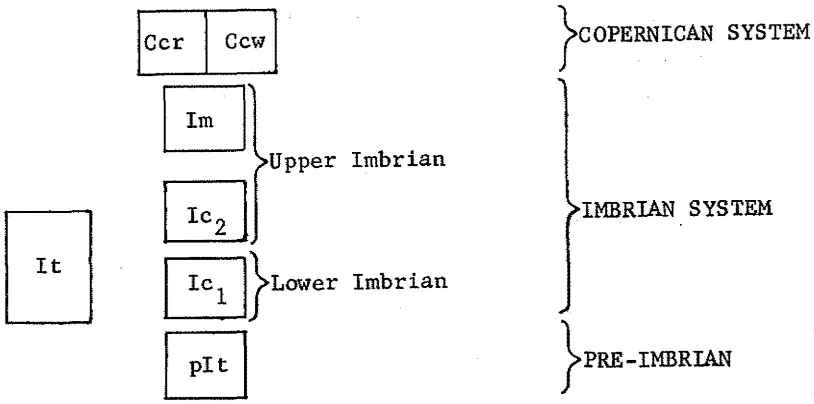


Fig. 6.--Format of typical lunar geologic map sheet.

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

MATERIAL OF RAY CRATERS
Comments as required

Ccr — RIM MATERIAL
Characteristics
Interpretation

Ccw — WALL MATERIAL
Characteristics
Interpretation

Im — MARE MATERIAL
Characteristics
Interpretation

Ic_2 — CRATER MATERIAL
Characteristics
Interpretation

Ic_1 — CRATER MATERIAL
Characteristics
Interpretation

It — TERRA MATERIAL
Characteristics
Interpretation

pIt — TERRA MATERIAL
Characteristics
Interpretation

Figure 7.--New U.S. Geological Survey map-explanation format.

from youngest to oldest (ages formerly read from oldest to youngest, opposite from the order of letters in the map symbol). Entirely below this array is a second array for the unit names and descriptions. The colored boxes with the map symbol are repeated, but all are placed in a single vertical column. Box titles are to the right of these boxes, and descriptive material starts to the right of the titles and continues indented below. In both the correlation array and the description array, colored boxes should be placed as close to the map as possible, in order to utilize new electronic color-scanning devices that have a limited reach. Because details of the new format are still being worked out, it will not be described in detail here; a supplement will be sent later to recipients of this manual.

Unit descriptions.--After the box title is a paragraph on physical characteristics, followed by one on genetic interpretations, which must be clearly separated from the characteristics, though of course based on them. ("Characteristics" has come to mean "description," not the strict list of defining properties implied by the word "characteristics.")

For each major and new map unit, a type area, in which the unit is most distinctive, and if possible, where contact relations are clearest, should be given in the "characteristics" paragraph; for newly named formal units, the "should" becomes a "must." To be correlated with this occurrence, other occurrences must possess most of the characteristics of the type area. Definitions of new units should follow the Code of Stratigraphic Nomenclature, with allowances for lunar differences, and must include announcement of intent to establish a new name, bounding coordinates and description of type area, specification of the name-giving geographic feature, and relation to subjacent and superjacent units. (Defining a new formal unit is a weighty matter that should be undertaken only when a widespread stratigraphically important unit requires a name for convenient reference.)

In the explanatory material, use a telegraphic style, and particularly avoid articles and forms of the verb "to be": not, "The unit is of high albedo and has a rugged or partly smooth topographic expression," but "High albedo; rugged or partly smooth." In long descriptions, group similar characteristics in sentences--albedo in one, topography in another, distribution in another, etc. Elements of these sentences can be separated by semicolons. For some reason, the Survey does not put a period or any other punctuation at the end of an explanation paragraph, even if the paragraph includes sentences that do have periods.

Keep the explanation as short as possible, and shoot for a 3,000-word limit on text material (complete-sentence prose). The stick-up type used on maps is fantastically expensive.

Material to Submit

The following materials are required from an author when he submits a map to the Survey:

1. Stable-base copy of original drafting in ink. The base must be translucent; it is normally a plastic such as cronaflex or mylar, preferably about .004" thick (thicker sheets produce poor copies, thinner ones are insufficiently scale-stable). The relief base (imprinted photomechanically on the plastic) must not be in black, or it will interfere with the black geology lines when the two together are copied photomechanically onto the scribecoat to be scribed; we have always used brown. The best strategy is to imprint the base on the back of a double-frosted sheet ("left reading") and draft on the front, so that erasures do not affect the base.
2. A separate sheet for overlays such as ray pattern and dark mantling material. (Note: some authors, if they anticipate numerous changes, compile letter symbols and lines on separate sheets; but this makes ozaliding difficult, so combine symbols and lines before submission.)
3. A completely accurate colored ozalid of the map. This is called the "mill copy" and, after approval by the Director, is used by the Branch of Technical Illustrations (BTI) as their drafting guide; it even supersedes the author's original stable-base inked copy.
4. Text: double-spaced typed copy, preferably on 25-line manuscript paper obtainable from the Survey (ultimately the General Services Administration).
5. Explanation: two possible formats:
   a. Double-spaced typed copy like the text.
   b. Single-spaced copy on a single large sheet of paper, layed out in correct format. (I prefer this style because format and inconsistencies among unit descriptions are clarified; but it is more difficult to construct this large sheet than the page-sized package.)
6. Colored explanation layout, if not in the form of 5b.
7. Marginal notes, index maps, etc. (see section on format).
8. Cross section (optional)--stable base.
9. Cross section (optional)--colored ozalid mill copy.[1/]
10. Duplicate uncolored copies of map, cross section, text, and explanation.
11. And of course, save a copy of everything yourself. You will need these for reference in telephone discussions with reviewers; and the mails do lose things.

Note: On all material the author submits, he must label every patch of every unit. In drafting, BTI will label only as many patches as it believes necessary, because the color of a published map carries most of the story. This point is commonly not understood by authors when they check color proofs; they waste a lot of time pointing out missing labels.

Do's and Don't's

Following is a list of guidelines that will help you prepare better maps. You should consider this list and the ones that follow in all stages of your

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1/ Although not always included with the final map package, cross sections (Survey editors call them "geologic sections") should always be drawn, as in terrestrial geology, to test the map relations.

mapping--before, during, and after. The listed items are not supposed to be cliches, but are derived from observations made repeatedly in the course of reviewing and editing lunar maps.

1. Make a reconnaissance of the whole area before starting, and decide tentatively on units; I do this by making a nearly complete map in pencil on a paper copy of the base, before committing ink to a stable-scale copy of the base. This reconnaissance is necessary for internal consistency.
2. Lay out and write the explanation while mapping--not after.
3. Watch embayment relations; at a triple point, the contact of the youngest unit is the continuous one; that is, the contact between the two older units must terminate abruptly at the young one.
4. Remember that you are mapping materials, not topographic forms. This means, for example, that the contact bounding materials of a crater must be drawn not at the rim crest, but at the outer limit of deposits thought to be associated with the crater; these will commonly be expressed only as a slope having no distinctive topographic texture. (if in doubt what to map in an old crater, look at a young crater.)
5. In drafting, remember that you are communicating both to other geologists and to draftsmen who know no geology.
6. You must color out your own map after you think you are finished; you will catch dozens or hundreds of errors.
7. Compare and discuss the geology on your map with authors of adjoining maps; resolve all major conflicts. This will both clarify your mapping and bring the compromise that is essential for consistent portrayal.

Or to put it negatively, following is a partial list of errors that keep cropping up on lunar maps.

1. Inconsistency between map and explanation in the following respects:
    a. Units shown on one but not the other.
    b. Different unit and structure symbols (commonly caused by a change of mind during mapping that is not completely incorporated).
    c. Age relations as shown in explanation differing from those shown on map by the overlap and embayment relations.
2. Units not fully or accurately described in explanation (usually because of being copied from other maps or written after completion of the mapping).
3. Conclusion drawn in interpretation paragraph from relations not mentioned in characteristics; or significance of a characteristic not stated in interpretation paragraph.
4. Reason for age assignment not stated.
5. Inconsistency between map and cross section.
6. Uneven portrayal in different parts of the map (commonly caused by trying to map too much detail early in a project, then giving up).
7. Too much attention to circular craters and their subdivisions, and too little to irregular craters and non-crater units.

8. Incompleteness ("leave it to the reviewer to fix").
9. Ambiguous layout of units in the explanation (very common).
10. Confusion between contacts and structural symbols, especially between dashed contacts and lineaments, and where fault and scarp symbols are at contacts.
11. Lines not closed off.
12. Joins between lines made in the space between dashes rather than on a dash (how can the draftsman tell where to close the line?).
13. Units without symbols.
14. Overprints of symbols and lines.
15. Indistinct leaders (short lines from letter symbol to unit), including confusion with contacts and structures.
16. Ambiguous dash length.
17. Queried units on the map that are not explained in the explanation (always must say "queried where could be younger" or some other <u>specific</u> reason for querying--not just, "queried where doubtful"--though you may say this for structures and contacts).

And as another way of describing errors, I list below two, equally wrong, extremes--because we seek happy mediums.

<u>ONE EXTREME</u>	<u>THE OTHER</u>
Excessive splitting of units that obscures the big picture.	Excessive lumping that ignores significant differences.
Excessively contorted line drawing that (while accurate) crowds the map and obscures the overall relations.	Excessive "cartooning" that ignores significant detail.
Too-careful, time-consuming line drawing.	Sloppy line drawing.
Excessive expression of doubt and qualification; for example, ignoring the great likelihood that craters like Tycho are of impact origin.	Insufficient expression of doubt and qualification; for example, assuming that all craters are of impact origin.
Too detailed or too far-out new ideas--more a portrayal of the mind than the Moon.	Too few new ideas--just another map sheet like all others.
Overinterpretation that causes contacts to cross objective boundaries or to be drawn where no differences occur.	Underinterpretation that results in an "objective" terrain map.
Leroy or other time-consuming template lettering.	Unreadable symbols (too faint, too nonstandard, or too sloppy).
Recalculating positions and ignoring the base.	Attempts to match base where the base is very inaccurate.
Copying other maps.	Complete re-invention of the wheel (resulting from poor scholarship).

ONE EXTREME	THE OTHER
Not thinking of implications of the symbols and conventions for units and structures.	Developing own set of completely new conventions.
Repeating all material between text and explanation (the text should summarize and hit the highlights; the explanation is a dictionary).	No tie, or inconsistencies between text and explanation
Going back to first principles (needed once, but no longer).	Addressing work only to other lunar geologists.
Extensive list of characteristics that conveys no mental picture (especially, a list contrived to fit a tortuous interpretive maze).	Brief list of unit characteristics that conveys no mental picture.

Reviewing and Editing

The Survey has a long tradition of thorough reviewing, editing, and reworking of manuscripts.1/ This process necessarily delays the publication of manuscripts, but usually improves them. Lunar maps, in particular, have gone through an agonizingly long period of examination and reworking--particularly the bad ones, but also the good ones, for we have tried hard to maintain consistency and achieve clarity in the face of continuing scepticism about the validity of our product. Although the job has not been pleasant for reviewers or mapping coordinators, I believe it had to be done. When you have finished a job, all the time you have spent on it is largely forgotten; but the map remains there forever with your name on it, and the name of your organization.

For lunar maps, the Survey review and edit process is as follows: (1) Branch Chief's approval of authorship, title, and scope; (2) coordinator's check of units and format; (3) at least two technical reviews, preferably sequential with author's alterations in between, but sometimes necessarily simultaneous; (4) coordinator's and Lunar Geologic Names (Standards) Committee final check; (5) Branch Chief's review; (6) Technical Reports Unit (TRU) edit of map and (usually) edit of text; (7) Survey Geologic Names Committee's check; (8) Director's approval (seldom any changes; sometimes deletion of excess material); (9) transmittal to Branch of Technical Illustrations (BTI), at which time all changes must cease or be charged monetarily against the author's project. For book reports (professional papers, bulletins, and outside publications), an additional exasperating step comes after approval: Branch of Texts edit and preparation for the printer. Book reports thus go through two independent mills--TRU (Geologic Division) and Branch of Texts (Publications Division). The Survey (Branch of Map Reproduction--BMR) prints maps; the Government Printing Office (GPO) prints book reports.2/

1/ Reviewing means technical reviewing for content and organization by a colleague; editing means checking for mechanical defects, spelling, grammar, format, and departure from standards.

2/ Additional information on Survey practice and standards is contained in the manual "Suggestions to Authors of the Reports of the United States Geological Survey" (U.S. Geol. Survey, 1958).

Technical reviewing is probably the most important step in this mill. Not even the best author can communicate perfectly to a reader, because he can never put himself completely in the reader's place; there is always something the author knows that he subconsciously assumes the reader knows, but doesn't. Also, authors are seldom consistent throughout the whole map, text, and explanation. For bad mappers or writers, of course, the review process will illuminate even worse shortcomings. So I cannot emphasize strongly enough the importance of thorough reviews. A review of a map is a major job; it should take several days. A review will not be complete unless the reviewer colors out the map himself while examining the photographs upon which the map was based. He must constantly go back and forth between photos, map, and explanation. So if you are going to undertake a planetary (or any) map, you must be prepared to review heavily and be reviewed heavily. Dividends are improvement of your own map by colleagues' reviews, and improvement of your own mapping by your review of other maps; you learn both the geology of other areas and the techniques of other workers.

Review comments should be helpful, not consist of query marks or sarcastic comments. If the author thought he was wrong or was not communicating, presumably he would have expressed himself differently; so tell him your objection specifically.

Comments on maps, including color proofs, are to be written in the margins, with leaders into the body of the map pointing clearly to the place in question.

All comments by reviewers must be responded to, either by accepting them or rejecting them in writing, usually in notes next to the original comment.

And finally, the faster you turn to the review job when it is given you, the faster the map will be published. Slow reviews are the biggest reason for the Survey's reputation for delayed publication. Because of this, it is now a general Survey rule that when one receives a review job, he drops all other work.

PART III

HISTORY OF THE U.S. GEOLOGICAL SURVEY LUNAR GEOLOGIC MAPPING PROGRAM

Before the space age began in 1957, most investigators concentrated on topical studies of selected lunar features (craters, lineament patterns, etc.) for the purpose of deducing their origin, or confirming a prejudice for either exclusive impact or exclusive volcanic origin of lunar features. Some whole-Moon studies were performed, including extensive ones by people with a bias for internal origin (Shaler, Spurr, von Bülow, Khabakov), and less elaborate ones by those favoring impact or mixed origins (Gilbert, Baldwin, Kuiper).1/ Few lunar students looked systematically for stratigraphic sequences in lunar rocks, and almost all thought in terms of physiographic forms (craters) not materials (crater rim materials). What was lacking was a systematic, stratigraphically-based geologic mapping effort that incorporated as strict a separation of interpretation and observation as possible; this combination has been the charter of the Survey's program.

Two principal Survey products stimulated by the dawning space age preceded the main mapping program. In the first, for the Army Corps of Engineers, photogeologist Robert J. Hackman drew a map at a scale of 1:3,800,000 showing three stratigraphic units--pre-mare, mare, and post-mare (Hackman and Mason, 1961). This map was accompanied by maps showing rayed craters and physiographic provinces (chiefly Hackman) and by rather bold terrain evaluations and geologic interpretations (chiefly Mason). In the course of this work Hackman suspected the time lag between the formation of the Imbrium basin and its filling by mare material, because of the excess of fairly fresh (so presumably post-basin) craters on the terra (Hackman, oral communication, 1971). In a concurrent and independent effort, Shoemaker was systematically mapping the Copernicus region in greater stratigraphic detail, at the scale of 1:1,000,000. Except in its use of interpretive unit names, this map was to become the prototype for the 44 lunar quadrangles of the main Survey systematic effort. A small experimental edition was printed in color, but not released to the public, by the U.S. Air Force Aeronautical Chart and Information Center (ACIC). The base was a prototype shaded relief chart made by ACIC.2/

1/ In all European lunar geological publications I have seen, an internal origin is favored for all or nearly all lunar features, and the same was true in America before the space age; exceptions were the works of Gilbert, Barrell, and Dietz. It was the astronomers who favored the impact hypothesis, and they were scorned as "catastrophists" by the geologists, probably still defending themselves against bible-based pre-geology. The current acceptance among American geologists of impact as a major--but, emphatically not sole--lunar process is probably due to Shoemaker, who saw the validity of the arguments of Gilbert and Baldwin, and who helped discover new terrestrial impact craters. The Soviet and other European geologists apparently still prefer to explain nearly all lunar phenomena by analogy with terrestrial phenomena familiar to them.

2/ See next page.

(The map also appeared in color in the November 1963 edition of "Fortune.") While mapping, Shoemaker recognized the fundamental stratigraphic succession: Imbrium basin - mare material - Eratosthenes - Copernicus. This map demonstrated, against considerable skepticism and opposition, the validity of the geologic mapping approach to lunar studies. As a result of this demonstration and the active support of John O'Keefe (NASA Headquarters), Manfred Eimer (JPL), Robert Carder (ACIC), and Lorin Stieff (USGS), the systematic mapping program began under NASA sponsorship.

The stratigraphy that Shoemaker had worked out, a statement of stratigraphic principles that underlie lunar geologic mapping, and a black-and-white version of the Copernicus prototype map were published in a joint paper by the two pioneers (Shoemaker and Hackman, 1962) and in a paper on interpretation of craters by Shoemaker (1962).

The first three maps published in the systematic program--Kepler, Letronne, and Riphaeus Mountains--showed essentially three types of units--crater materials, mare materials, and terra materials; only the crater materials were extensively subdivided by age and facies. On one of the maps in an early violation of the principle of separation of interpretation and observation, smooth plains and hummocky materials were both assigned to a unit which was believed to be the ejecta blanket of the Imbrium basin.[1/] Such distinct units should always be distinguished in mapping even if they ultimately prove to have similar origins. The maps, like the early stratigraphic system of Shoemaker and Hackman (1962), also failed to separate clearly rock-stratigraphic and time-stratigraphic units, such as the rock unit "mare material" and the time-stratigraphic unit "Procellarian System." An important advance was recognition of the presence of Imbrian-age craters, those that are younger than the Imbrium basin but older than the mare material.

In late 1962 and early 1963 a group of new mappers was recruited by Shoemaker to augment and partly replace the quartet of himself, Hackman, Marshall, and Eggleton; a year later the newcomers were ready to pressure the establishment to make certain changes. (These young Turks are now, of course, the establishment.) Good agreement was reached at a stratigraphic conference of all mappers in November 1963. Rock-stratigraphic and time-stratigraphic units were firmly separated

1/ For a discussion of this unit's nomenclature history, see Wilhelms, 1970, p. F23-F27).

2/ (From preceding page). The Copernicus base chart by ACIC was the prototype of their highly useful and well executed series of 44 Lunar Astronautical Charts (LAC) which are the bases for all the Survey 1:1,000,000 geologic maps and which give their names to the maps. The airbrush technique proposed by ACIC, like our geologic mapping technique, was at first regarded as unscientific, old-fashioned, and impossible to do systematically. However, the technique was successfully demonstrated on the prototype, and ACIC began its systematic production of the maps under Robert Carder in St. Louis and William Cannell at Lowell Observatory in Flagstaff. This very productive and at times brilliantly effective effort was concluded in early 1969. The cooperation between ACIC has continued, and all Survey lunar maps have been printed on ACIC bases except a few large-scale maps of potential Apollo landing sites, printed on Army Map Service (Topocom) photomosaics.

(McCauley, 1967, p. 437; Wilhelms, 1970, p. F11, F23, F30-F32); formational names were introduced, and the splitting of units was accelerated. The basic time-stratigraphic units and the general mapping philosophy agreed on at this meeting have proved adequate for completion of the rest of the 1:1,000,000-scale program and the recent compilation of the whole area of 44 quadrangles at a scale of 1:5,000,000 (Wilhelms and McCauley, 1971). Subsequent changes in conventions became increasingly minor as the mapping progressed. Two additional meetings of all mappers were necessary to adjust some of the mapping conventions. Now, changes are handled by filtering them through the mapping coordinator, who listens to ideas and then passes them around to the other mappers for approval or rejection.

The conventions adopted at the 1963 meeting have proved flexible enough to permit a slight apparent retrogression; formational names have been down-played on recent maps and informal designations substituted. For example, the Cayley Formation and Apennine Bench Formation are now usually called "light plains material," and the Gassendi Group of crater materials, younger than the Humorum basin but older than the mare material, is now called "crater materials." This is done because it is each individual occurrence of a type of material, not the aggregate, that is equivalent to a terrestrial formation, but each cannot be given a name. So all plains patches or craters in a given time-stratigraphic system are grouped together and designated informally.

The downplaying of formational names became particularly necessary when the mapping moved from the mare and circumbasin regions, with their laterally extensive marker units useful in regional correlations, to the southern cratered highlands, which seemed to offer no such clearcut stratigraphy. Early examination, based on telescopic photography and visual observations, revealed essentially three types of topography: craters, plains, and hilly intervening terrain ("moonite"). Most authors saw no good laterally continuous units in the hilly terrain, which showed a more patchwork texture than the circumbasin units, although some (Cummings, Offield) believed it to be mantled by extensive beds of volcanic material. Plains units were segregated according to crater density, but only three distinct classes of completely flat plains were recognized. An early attempt was made to set up discrete, alternating rock-stratigraphic groups of crater materials and plains materials (Cozad and Titley, unpublished), but the stratigraphy proved too complicated for this. Highland geologic studies did not progress much until Lunar Orbiter photographs became available (1967). Textures of the hilly units could then be better evaluated, and as a result, several units of possible terra volcanics and one additional distinct basin ejecta blanket (Nectaris) were distinguished; but some hilly terrain has not been separated into consistently recognizable units, and may never be (still "moonite"). One of the previously recognized plains units was found to be pre-Imbrian in age, and most other plains were seen to form a fairly uniform Imbrian assemblage. Craters came to be ranked stratigraphically according to their morphology and to serve as "guide fossils" (Pohn and Offield, 1970; Wilhelms and McCauley, 1971). A fairly good understanding of the highlands is now in hand; although indeed without many laterally continuous units, their geology is explainable in terms of basins or absence of basins, accumulations of plains materials wherever there are depressions, and possibly, local superposition of positive volcanic landforms.

A word in retrospect about the utility of visual telescopic observations. ACIC used them to great advantage, overcoming the initial scepticism mentioned earlier, and improved greatly on the photographic data. Some geologic mappers also used them successfully to "field check" relations that appeared ambiguous on photographs, for example, the age of a crater relative to the adjacent mare material (determined from the presence or absence of secondary impact craters, which are commonly very small). And all mappers saw much more detail at the telescope than on the early primitive telescopic photographs--though not always more than on the excellent series taken by G. H. Herbig at the Lick Observatory 120-inch reflector--and got a good impression of the important effect on feature detectability of changing illumination. But as work progressed we began to realize that we were spending too much time to gain too little information. Only a few critical relations were ever tested at the telescope, and most geological insights were gained from protracted studies of large regions on photographs. And later when we compared our telescopic notes with Orbiter photographs, most of us realized that we had not seen things accurately enough for good geologic interpretation; lines of "volcanic craters" became miscellaneous semi-alined depressions or spaces between hills; "faults" became ragged scarps. Much of this was due to the rarity of good seeing. But in any case, visual observations are seldom testable; even valid observations are not scientifically acceptable unless others can confirm them.

Mapping at scales larger than 1:1,000,000 began in 1964 on the basis of Ranger photographs (Trask, in press). Four black-and-white maps were incorporated in another report, seven black-and-white ozalid preliminary maps were made, and six maps were published in color, the last in late 1971. The long time lag between the flights of the Ranger spacecraft and the publication of the last Ranger maps is due to the low priority given these maps when better data from Lunar Orbiter were acquired.[1/]

Maps based on photographs from Lunar Orbiters I, II, III, and V in support of Apollo landings were produced starting in 1966. A great many (27) were produced quickly for screening reports printed by the Langley Research Center, where the (highly competent) Lunar Orbiter Project Office was located. Seven of the areas were remapped for the Manned Spacecraft Center at two scales, 1:25,000 and 1:100,000, and in several versions each, for use in planning Apollo missions to the maria; five of these maps at 1:25,000 and seven at 1:100,000 have been

1/ Hansen (1970) and McGill and Chizook (1971) have prepared user's guides to Orbiter photographs, and Bowker and Hughes (1971) have compiled a complete atlas that includes a user's guide.

printed in color. (Two of the areas became landing sites.) The 1:100,000-scale maps have the greater scientific interest, largely because they show more stratigraphic variety and place the geology of the sites in a broader context.

Currently, maps at large scale have been or are being prepared for landings starting with Apollo 14, the (predominantly) non-mare missions. These maps are more interesting to make and read than those of the mare sites because they cover geologically more diverse terrain, and, significantly, because most of them include relatively fresh features. At large scales, most of the Moon is quite uniform and subdued-appearing and becomes diverse only in young features, whose distinctive textures have not yet become degraded.

Another way of seeing a diverse Moon is to look at it from a distance. The mapping based on Lunar Orbiter IV photographs (starting May 1967) has probably been the most interesting and productive of all. These photographs have been used to modify 20 of the 36 1:1,000,000-scale quadrangles partly mapped at the telescope and to map 8 more quadrangles in their entirety. The 1:5,000,000-scale near-side map (Wilhelms and McCauley, 1971) was satisfying to make and is a good medium of communication for the important things, though it is a little crowded. The time, money, and base maps that are available coincide with this preference, and mapping of the two-thirds of the Moon not covered by the near-side map is being done at the 1:5,000,000-scale.[1/]

A short account of the effectiveness of the early quick-look work versus the later, drawn-out, inductive mapping will be of interest to mappers attacking a new planet. Some of the basic facts about the Moon's structure and evolution were thought out early in the game by Gilbert (1893), Hackman and Mason (1961), Shoemaker (1962), Baldwin (1949, 1963), and Kuiper (1959). They saw that most craters and the basins were of impact origin, but that the basins were filled in a relatively brief time by volcanic mare material. Also, quite early, Baldwin (1949), Shoemaker,and Hackman (see above) perceived the important fact that a time gap intervened between basin formation and filling. Important contributions of the later mapping were the recognition of the light terra plains as a major unit that apparently belonged neither to the basins or the maria, and the tentative recognition, on Lunar Orbiter photographs, of terra volcanics (bright, positive relief). The impact origin of the basins was clinched by studies of the Orientale basin and the discovery, through systematic mapping, of the Orientale, Imbrium, and Nectaris secondary craters. Moreover, the fundamental role played by the basins in nearly every way became clearer, including their influence on volcanism and the major contributions by buried and degraded basin ejecta to the total volume of lunar surface materials. Apollo radiometric dates have shown that the "relatively brief time" of mare formation is brief if the total number of lunar feature-forming events is taken as the scale, but that substantial mare formation actually occupies a con-

1/ Given the best possible photography, I believe that a scale of 1:2,500,000 would be optimum for mapping the Moon. Smaller scales are crowded and do lose some data of interest, such as small fresh features, whereas the information that can be shown at larger scales is not very significant in most regions, because of the smooth appearance of most terrain.

siderable portion (half a billion years) of the total most active part of lunar history (the first 1 1/2 billion years). The impact-volcanic controversy for crater origin has shifted in favor of impact, but some craters are certainly of volcanic origin.

In summary, the early work deduced some origins, and the later work documented these origins, charted the extent of the various units, deduced the three-dimensional structure over much of the crust, and discovered new fundamental units. This has resulted in a good model of the structure and evolution of the Moon that puts each crustal component in perspective of the whole. The problem with emphasizing origins is that nearly everyone plays with only certain ones. Several people that did this may have been right, but many others were wrong for one reason or another--including selection of analogs that contain only those elements that nourish special prejudices. So insight can establish working hypotheses, but these must be tested, modified, and amplified by systematic study, which forces examination of the geometric relations, areal distribution, and sequence of formation of all crustal elements.

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