W.I.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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

INTERAGENCY REPORT: ASTROGEOLOGY 13

LUNAR CRATER MORPHOLOGY AND RELATIVE AGE DETERMINATION OF LUNAR GEOLOGIC UNITS

Part 1: Classification, by H. A. Pohn and T. W. Offield

Part 2: Applications, by T. W. Offield and H. A. Pohn

January 1969

Prepared under NASA Contract No. R-66

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LUNAR CRATER MORPHOLOGY AND RELATIVE AGE DETERMINATION OF LUNAR GEOLOGIC UNITS

Part 1: Classification

By

H. A. Pohn and T. W. Offield

INTRODUCTION

If certain assumptions, discussed below, are granted, relative ages of lunar craters can be determined by the degree of freshness of their major topographic components such as the rim crests, walls, and surrounding rim deposits. An early, very generalized correlation of age with four or five morphologic classes of craters was proposed by Baldwin (1949, p. 128; 1963, p. 188-195). Crater morphologic classes somewhat more closely defined from telescopic observations and believed to represent age classes have been recognized from the outset of the U.S. Geological Survey's lunar mapping program (Hackman, 1961; Wilhelms, 1966). N. J. Trask (unpub. rept.) proposed that numbers be used to express the dependence of morphology on age in young craters smaller than 3 km within Apollo landing sites.

The system described here represents a refinement of these earlier basic approaches, made possible mostly by the Moon-wide coverage of Orbiter IV photographs. A morphologic continuum from the most subdued to the sharpest lunar craters is defined, and this sequence is interpreted to reflect the relative ages of the craters. Evidence for correlation of age with progressive morphologic change has already been presented for small craters (Trask and Rowan, 1967). Most craters larger than about 1 km, anywhere on the Moon, can be assigned relative ages by means of the system described here, if adequate photographs are available.

We subscribe to the hypothesis that most lunar craters formed by impact and assume, therefore, a common initial form for most craters in a given size category. The assumption that departures from this initial form reflect real age differences is borne out by observable superposition relations. For example, where two craters are superposed, the younger crater appears fresher: it has a sharper rim, more widely distributed and less subdued ejecta (relative to crater size), less subdued terraces, and fewer superposed craters. It is also assumed that a relatively regular progression of morphologic changes occurs as a crater "ages." This "aging" may result from mass wasting, mantling and structural modifications effected by micrometeorite and meteorite bombardment, volcanic processes, and crustal vibrations.

CRATER-AGE CLASSIFICATION

In examining more than 1,000 young lunar craters, we have found that with few exceptions they can be ordered into three classes, on the basis of the planimetric shape of their rim crests. The actual size classes exhibit some overlap, as follows: <20 km crater diameter (round), 16-48 km (polygonal), >45 km (round, with distinct rim crenulations). For simplicity, in this paper the overlap is ignored, and class size limits are taken at 20 and 45 km; thus, Class I, >45 km; Class II, 20-45 km; and Class III, 8*-20 km. Because of differences in the initial shape of craters, a slightly different morphologic continuum can be defined for each of the three classes. Within each class, numbers can be assigned to any morphologic stage as an index of apparent age. As an arbitrary convention, to permit generally similar craters to be compared as closely as possible, we have chosen for each size class a decimalized sequence of morphologic stages or apparent ages from 0.0 (oldest) to 7.0 (youngest). Some of the age criteria in any crater may be slightly equivocal, but a crater's place on the decimal scale can generally be expressed within specified limits. The error increases with increasing age and

*Class III can be extended to include craters as small as 1 km but assignment of ages to craters smaller than 8 km poses particular problems, discussed in part 2 of this paper.

is represented typically by ±0.1 in craters of age 6.0 and by about ±0.4 in craters of age 1.0. No relation of absolute time and the numbers chosen for our scale is implied.

The apparent ages are determined by evaluation of a number of morphologic components (fig. 1). All components must be considered in arriving at a relative-age determination, but the most important single criterion is rim-crest sharpness. Other diagnostic features are the freshness of textural detail of ejected materials, morphology of terraces, and size-frequency distribution of superposed craters. Figure 2 shows craters believed to represent different points in the general aging sequence in each of the three size classes, and the caption describes their diagnostic features.

Progressive change of several crater features as a function of inferred age is shown in figure 3. The figure demonstrates the observed points in the inferred apparent-age sequences of the three crater classes at which various features appear, attain maximum development, and disappear. For rays, the points are defined from Earth-based full-Moon observations and for other features from Orbiter IV photographs with 70- to 100-meter resolution. Specific features are:

Rays.--The preservation of bright rays, best for all craters at age 7.0, is dependent on crater size as crater-age increases.

Radial ejecta.--The continuous blanket of material surrounding a crater beyond 1/4-1/3 crater diameter from the rim crest, characterized by ridges and grooves radial to the crater, is termed "radial ejecta." Radial ejecta is best developed and most easily distinguished on planar surfaces but can generally be discerned on rougher terrain by careful examination.

Satellitic craters.--Satellitic craters are generally arranged in subradial strings, in loops and arcs, or in clusters around fresh craters. Their size is dependent

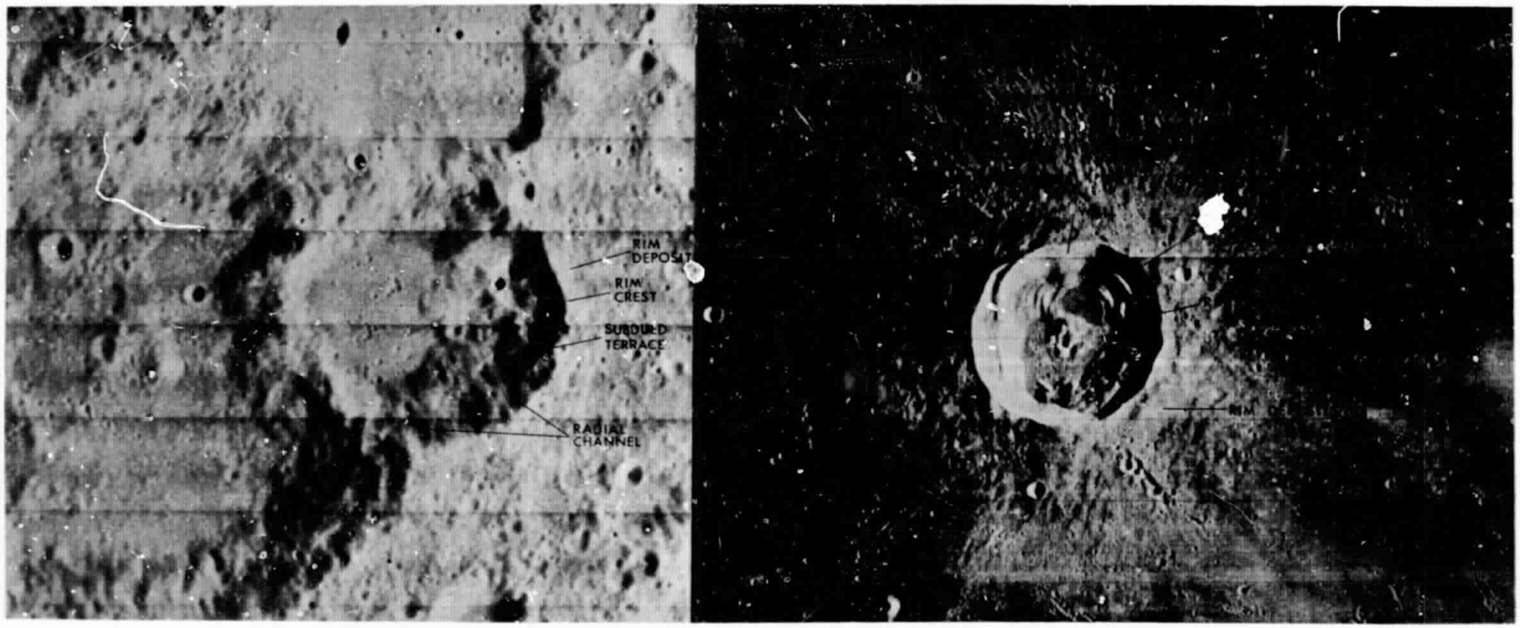


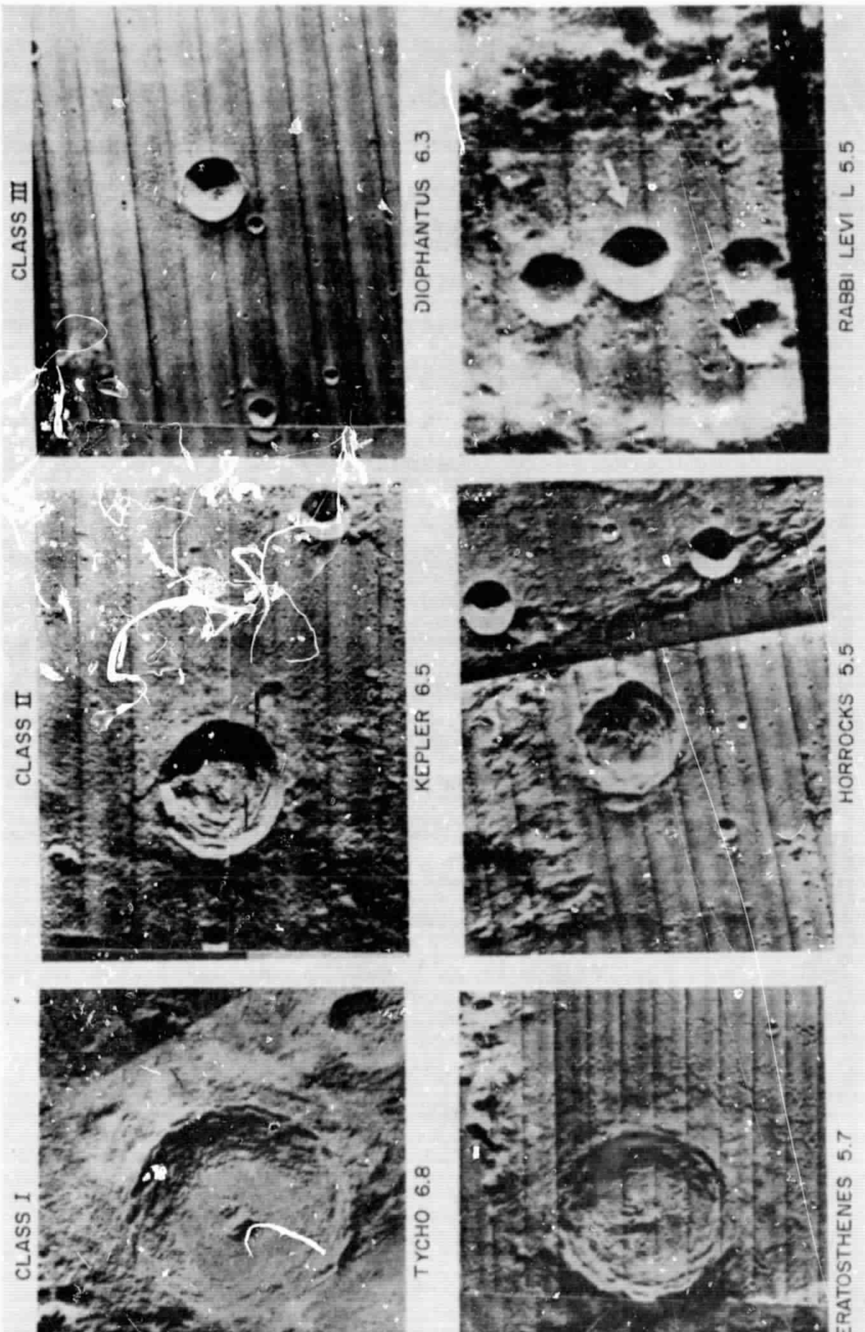
Figure 1.--Morphologic components of young and old craters used in relative age determinations.

on the size of the primary crater, and small craters may not exhibit satellitic fields at Orbiter IV resolution. The ages shown in figure 3 for disappearance of satellitic craters are for mare or plains surfaces and may be displaced upward 0.1-0.3 in uplands because of poorer preservation of small craters in rough terrain.

Rim-crest sharpness.--Crater rim crests are considered sharp if they do not exhibit minute crenulations or rounding indicative of modification by small cratering events or mass wasting. Thus example III-6.3 (fig. 2) would be considered sharp, whereas III-4.8 would be considered subdued.

Terracing and interior radial channels.--These two features are closely associated and are not generally size dependent, except that Class III craters lack terraces. Terraces in the freshest large craters form as many as seven large sharp-edged tiers on the crater walls. From that initial configuration, the large terraces appear to break up by slumping, so that more and smaller terraces with somewhat rounded edges are characteristic of the fairly fresh to intermediate geomorphic stages. This phenomenon is at a maximum at age 4.5-4.8. In craters older than this, the terraces are progressively more subdued and appear to coalesce, so that fewer discrete terraces are present. By age 4.3, the first interior radial channels are observed on the crater walls in all three classes. These channels dissect the terraces and become more abundant and deeper toward a maximum at age 2.5. In craters older than this, the channels progressively disappear, concomitant with destruction of the terraces, to form massive hummocky deposits along the lower walls of the craters.

Polygonality.--Class I craters are generally circular when formed and become slightly to markedly polygonal after


CLASS I
CLASS II
CLASS III
TYCHO 6.8
KEPLER 6.5
DIOPHANTUS 6.3
ERATOSTHENES 5.7
HORROCKS 5.5
RABBI LEVI L 5.5

Class I
(>45 km)

Example: Tycho--6.8

Rim crest--Round outline with numerous crenulations.
Walls--Terraced; uppermost terrace never as deep as 1/3 crater depth and generally 1/5-1/6 crater depth. Terraces usually discontinuous; no single terrace occupies more than 1/10 of the crater circumference. Slump features often angular and blocky appearing.
Rim--Sharp, gently concave upward but irregularly terraced. Hummocky from rim crest outward, grades rapidly outward into radial "braided" texture, which in turn grades into secondary crater field. Conspicuous ray pattern.

Example: Eratosthenes--5.7

Rim crest--Very slightly subdued but mostly sharp.
Walls--Terraces slightly subdued.
Rim--No rays; well-developed radial facies. Exterior terraces subdued more than wall terraces; low crater frequency on rim.

Class II
(20-45 km)

Example: Kepler--6.5

Rim crest--Polygonal outline, most commonly hexagonal.
Walls--Terraced, uppermost terrace commonly occurs at 1/4-1/3 crater depth but may occur just below the rim crest. Terraces angular but may have a "soft" texture. Terraces almost always continuous over 1/4 of the crater circumference.
Rim--Gently concave upward but irregularly terraced; moderately hummocky from rim crest outward. Grades rapidly into braided pattern which in turn grades into grooved secondary facies. Has rays.

Example: Horrocks--5.5

Rim crest--Very slightly subdued.
Walls--Terraces slightly subdued.
Rim--Near radial facies quite subdued, extreme radial facies and secondaries absent.

Class III
(8-20 km)

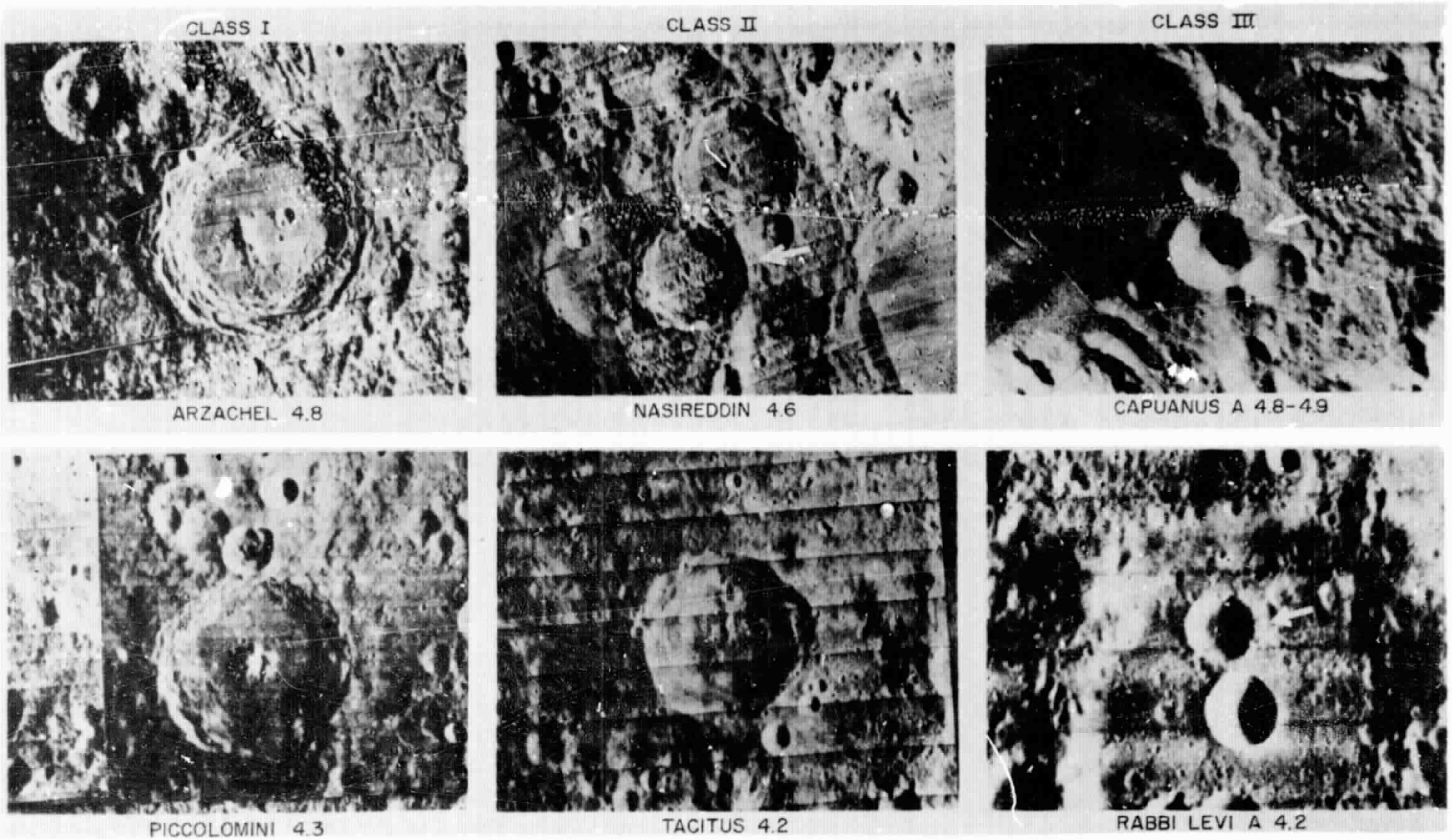
Example: Diophantus--6.3

Rim crest--Round in outline.
Walls--Smooth, no terracing; possibly a slight break in slope just below the rim crest.
Rim--Continuously concave upward, smooth to slightly undulating from the rim crest outward. Pronounced break in slope (rampart) just outside rim crest. At 1/5-2/5 crater diameter materials grade rapidly into discontinuous "dune" texture which in turn grades into radially grooved facies at approximately one crater diameter. No rays.

Example: Rabbi Levi L--5.5

Rim crest--Round in outline, slightly subdued.
Walls--Smooth.
Rim--Appearance of slight exterior radial channeling in rampart. No radial facies past one diameter. Slight remnants of "dunes."

Figure 2.--Examples of craters in the three size classes in progressively greater stages of erosional modification. The differences are interpreted to indicate difference in relative age. Framelet strips are approximately 10 km wide.


CLASS I
CLASS II
CLASS III
ARZACHEL 4.8
NASIREDDIN 4.6
CAPUANUS A 4.8-4.9
PICCOLOMINI 4.3
TACITUS 4.2
RABBI LEVI A 4.2

Example: Arzachel--4.8

Rim crest--Ranges from sharp to subdued. Only discrete segments of rim crest are subdued.
Walls--Terraces subdued, but not coalesced.
Rim--Exterior terraces quite subdued and highly cratered although superposed craters are small (>3 km). Radial facies barely discernible.

Example: Nasireddin--4.6

Rim crest--Partly subdued.
Walls--Maximum development of terraces, which are more subdued than in craters of age 5.5. Bases of individual terraces subdued.
Rim--Cratering apparent on rim. No radial facies.

Example: Capuanus A--4.8-4.9

Rim crest--Round in outline, subdued; rampart has disappeared; slightly cratered.
Walls--Smooth.
Rim--Marked crater frequency on rim. No "dunes."

Example: Piccolomini--4.3

Rim crest--Entire rim crest somewhat subdued.
Walls--Terraces exhibit considerable subduing and coalescing but are distinct.
Rim--Generally at least one large crater superposed on the rim. No radial facies.

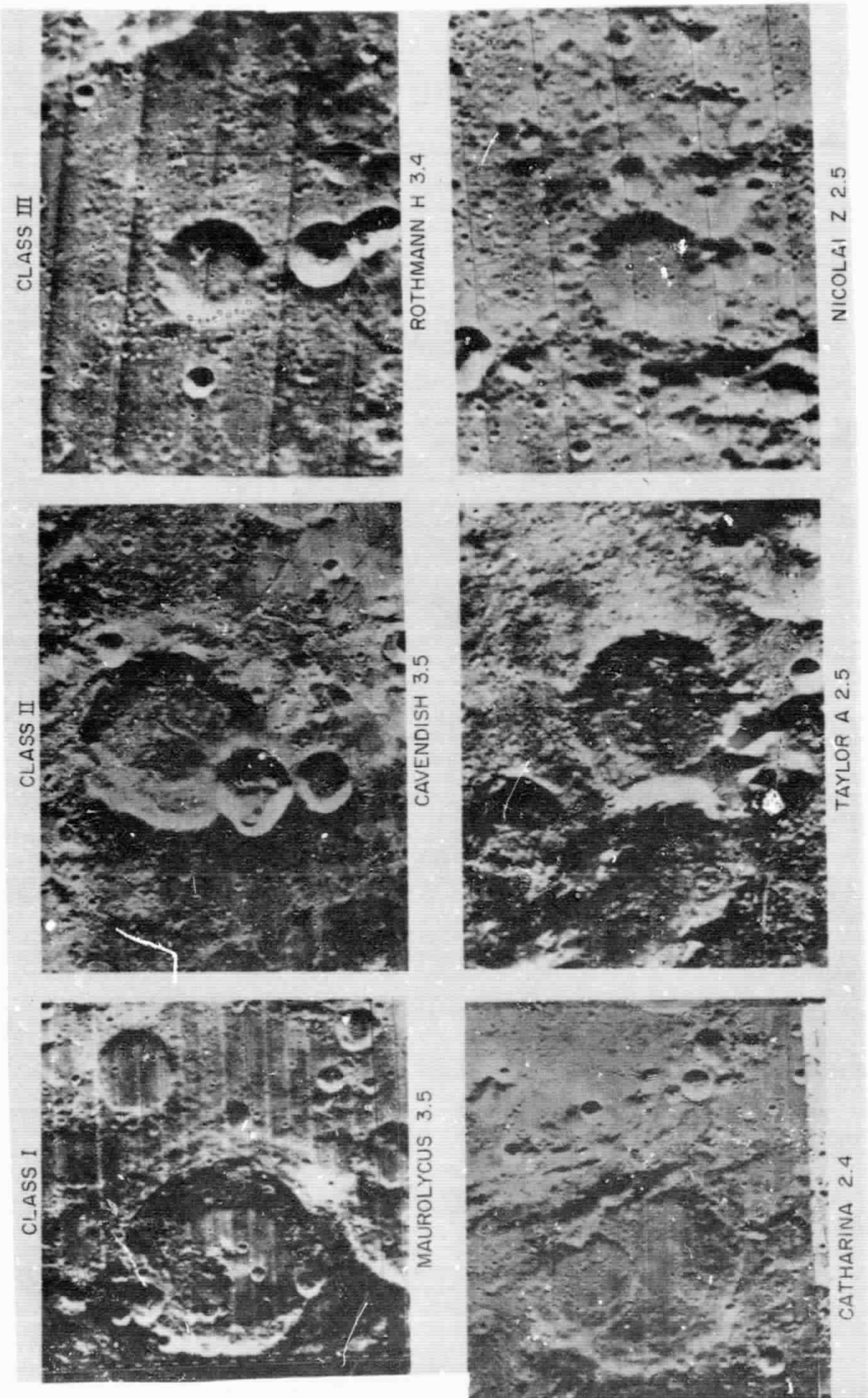
Example: Tacitus--4.2

Rim crest--Heavily subdued but relatively unaffected by resolvable craters.
Walls--Terraces subdued.
Rim--Moderately high crater frequency on the rim.

Example: Rabbi Levi A--4.2

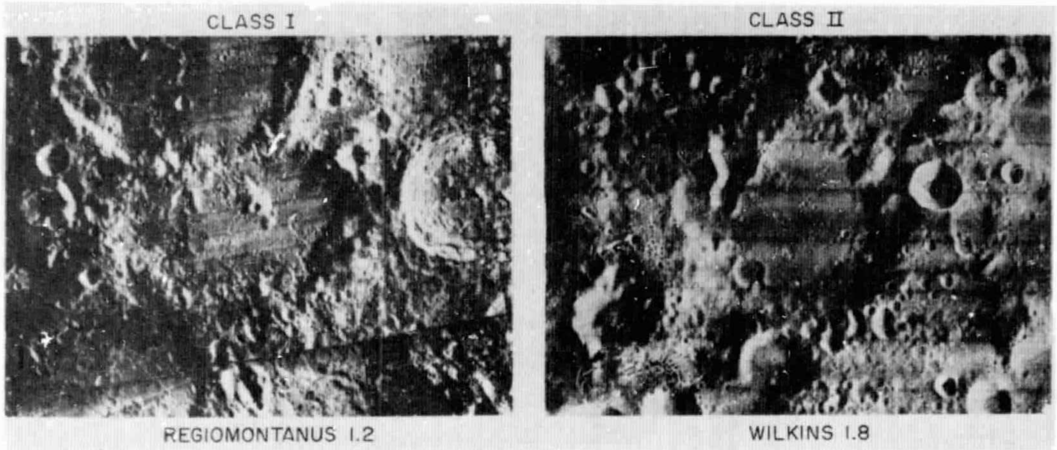
Rim crest--Outline subrounded, subdued; distinct small crenulations due to coalescing craters.
Walls--Radial channeling present; crater filling is evident.
Rim--Larger craters on rim (1/20-1/10 crater diameter).

Figure 2.--Examples of craters in the three size classes in progressively greater stages of erosional modification. The differences are interpreted to indicate difference in relative age. Framelet strips are approximately 10 km wide--Continued.


CLASS I
CLASS II
CLASS III
MAUROLYCUS 3.5
CAVENDISH 3.5
ROTHMANN H 3.4
CATHARINA 2.4
TAYLOR A 2.5
NICOLAI Z 2.5

Class I (>45 km)	Class II (20-45 km)	Class III (8-20 km)
Example: Maurolycus--3.5	Example: Cavendish--3.5	Example: Rothmann H--3.4
Rim crest--Almost totally subdued; numerous small craters on the rim crest. Walls--Terraces coalesced, edges smoothed; radial channels present. Terraces are moderately cratered and highly subdued. Rim--Distinguishable but very cratered, commonly interrupted by relatively large craters.	Rim crest--Subdued, but exhibits hummocks formed by coalescing craters. Walls--Terraces very subdued and coalesced, and in many craters absent; radial channels apparent. Rim--Highly cratered, broken by some large craters.	Rim crest--Outline more polygonal than round; subdued and breached. Walls--Radial channeling conspicuous; breaching common. Rim--Hummocky, heavily cratered.
Example: Catherina--2.4	Example: Taylor A--2.5	Example: Nicolai Z--2.5
Rim crest--Wholly subdued; commonly disrupted by one or more craters whose sizes are a large fraction (1/4) of the crater diameter; crest line apparent. Walls--Radial channels well developed; terraces occupy only a small part of the crater circumference and are very subdued and form broad hummocks rather than stepped terraces. Rim--Barely discernible; high density of craters on rim.	Rim crest--Completely subdued. Walls--Terraces barely discernible; radial channels are at a maximum. Hummocks apparently due to a combination of terracing and radial channel development. Rim--Highly cratered, intersected by craters of sizes a large fraction of the primary crater.	Rim crest--Polygonal outline; highly crenulated and subdued. Walls--Well-developed radial channels. Rim--Many large craters on rim; extent of rim barely discernible.

Figure 2.--Examples of craters in the three size classes in progressively greater stages of erosional modification. The differences are interpreted to indicate difference in relative age. Framelet strips are approximately 10 km wide--Continued.



Example: Regiomontanus--1.2

Rim crest--Discontinuous and broadly rounded; no distinct crest line.
Walls--No significant terraces; radial channels barely discernible; hummocky texture.
Rim--Heavily cratered, dissected and hummocky.

Example: Wilkins--1.8

Rim crest--Completely subdued; crest line not discernible.
Walls--Terraces replaced by large hummocks.
Rim--Not mappable as a unit distinct from wall, intersected by numerous craters whose sizes are a large fraction of the primary crater.

Figure 2.--Examples of craters in the three size classes in progressively greater stages of erosional modification. The differences are interpreted to indicate difference in relative age. Framelet strips are approximately 10 km wide--Continued.

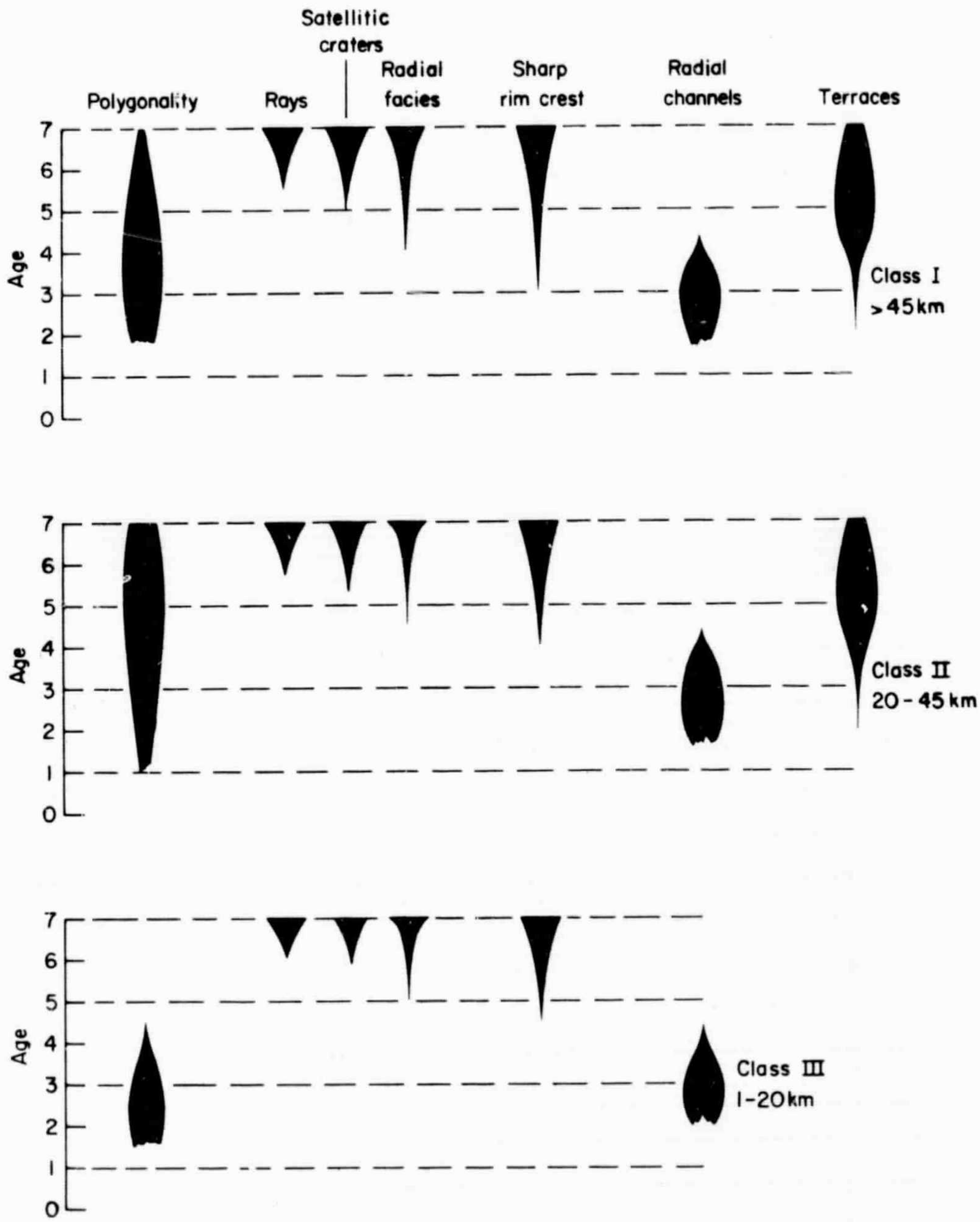


Figure 3.--Change in diagnostic crater features with age.

age 4.0, depending on influences such as local fracture pattern and superposed cratering events. Class II craters form with polygonal outlines and remain obviously polygonal throughout all stages of modification. Class III craters form with circular outline; polygonality appears by age 4.4 and reaches a maximum at age 2.5.

Rim texture.--Rim materials of fresh craters are irregularly hummocky and are broken by short, curved terraces which are convex outward. As craters approach age 2.5, the hummocks and terraces are progressively smoothed. In craters older than age 2.5, the frequency of superposed craters approaches saturation, resulting in an increase of rim roughness.

For craters in Class III, an additional age criterion not seen in the larger classes is variation in the geometry of the interior shadow and of the associated photometric darkening pattern (subresolution shadow effects in microtextured slope material). This criterion is best applied at sun angles of 15° to 30°, the illumination of most Orbiter photographs. Figure 4 shows idealized drawings of six small craters in order of age. (The shadow geometry and photometric darkening depend partly on sun angle, exposure, print contrast, and other variables of the Orbiter photographs). In craters of age 6.0 and 6.5 the shadow impinges on a slightly raised floor and is therefore convex toward the sun; photometric darkening is present only as a small flare on each side of the shadow in the upper part of the sunward wall. By age 5.5 and 5.0, craters may or may not have small areas of flat floor which slightly affect the shadow geometry; by age 4.5 no floor remains. With progressive aging, the shadows curve more broadly and become irregular as they reflect increasing jaggedness in the rim crests; the photometric darkening extends as cusps which enlarge to cover the whole nonshadowed wall by age 4.2. In craters of age 4.0, reappearance of flat floors is common and therefore shadows are again convex

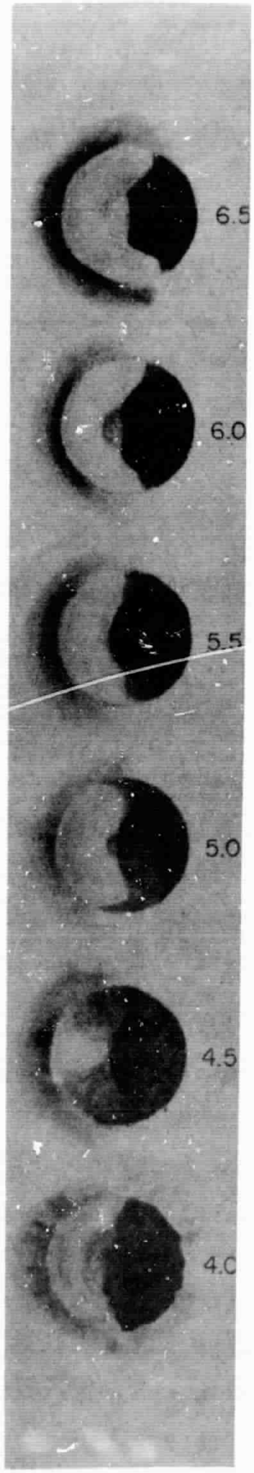


Figure 4.--Idealized age sequence of small craters showing diagnostic shadow shapes.

sunward; photometric darkening is irregularly distributed.

TIME SIGNIFICANCE OF THE RELATIVE-AGE SCALE

The chosen crater-number intervals probably do not represent equal spans of time because erosional modification of lunar landforms is almost certainly a nonlinear process. This nonlinearity stems from sequential erosion in which material eroded from the uppermost meter in height of a crater rim or terrace is redeposited downslope and must be removed over and over as the overall crater form is degraded. The erosion rate therefore probably is approximately exponential, but the exact function cannot be determined from present data.

If craters are eroded mainly by micrometeorite bombardment, then the rate of erosion is dependent on the flux rate of infalling particles. Any variations in size and frequency of these particles which may have occurred throughout lunar geologic time will have added to the departure from linearity of the proposed numbering scale with respect to time.

Absolute ages and particle flux rates can be determined only by radiometric dating of lunar materials. When this is done, it should be possible, by means of relative age criteria, to extrapolate the absolute-age data over much of the lunar surface.

VARIABLES AFFECTING THE CRATER-NUMBERING SYSTEM

Factors that may contribute to an erroneous assessment of crater ages are:

Rock strength.--Lunar materials probably vary considerably in their response to the stresses produced by impact and generated during subsequent crater modification. A crater on a contact between different geologic units might therefore be expected to show differences in internal morphology. Although such differences may be present in very small craters, they have not been observed in craters larger then 1 km, even where the craters (e.g., Menelaus and Eratosthenes) cross contacts between presumably very different geologic materials such as those which form mare and terra.

Volcanic materials.--Although most craters described in the age sequence are presumed to be of impact origin and, in a given size class, have similar initial forms, it is quite likely that endogenetic (volcanic or tectonic) craters with variable initial forms also occur on the Moon (McCauley, 1967b). Such craters may not only be different initially but may also be modified at a different rate, resulting in an incorrect appraisal of age under the proposed crater-numbering system. The effect of these factors on the numbering system cannot be assessed at this time because the range in form and the abundance of endogenetic craters are not known.

Fill and mantling units with hummocky, undulating, and planar topographic expression are common in the uplands and appear to mantle many craters. A result of this mantling is that crater features are subdued even more than they would be by erosion alone. Thus, such craters appear to be older than they actually are.

Proximity aging.--A crater within range of ejecta from an impact event will be mantled, as well as subdued, by secondary impacts. A crater thus modified will appear older than it really is. Modification of this sort results in what we have termed "proximity aging" and presents one of the most difficult problems in assigning relative ages to craters. In youthful craters, proximity aging appears to result more from secondary impacts than from ballistic deposition. However, the distribution of impacting secondary particles typically is nonuniform; thus, only part of the rim crest of a crater may be subdued. The unaffected part reveals the true geomorphic stage of the crater. Proximity aging by a single event will have contributed little to the present form of older craters (0.0-4.0). The apparent age of most older craters thus reflects proximity aging by many events as well as the more continuous processes of meteorite bombardment and seismic vibrations, so that proximity aging, not specifically identifiable, is intrinsic in the geomorphic development of old craters and therefore need not receive special attention in assigning age numbers to these craters.

It is concluded that by careful consideration of detailed morphology and crater size and shape, lunar craters can be assembled in an orderly age sequence from the youngest to the oldest. The crater numbering system described here has several applications in the analysis of craters and other surfaces (discussed in part 2).

LOCATION OF CRATER EXAMPLES SHOWN IN FIGURE 2. (-, S lat or W long; +, N lat or E long.)

	LONG	LAT
Tycho	-11.2	-43.2
Eratosthenes	-11.3	+14.5
Arzachel	- 1.9	-18.2
Piccolomini	+32.3	-29.8
Maurolycus	+14.0	-41.8
Catharina	+23.6	-18.1
Regiomontanus	- 1.0	-28.5
Kepler	-38.0	+ 8.1
Horrocks	+ 5.9	- 4.0
Miller	+ 0.7	-39.3
Tacitus	+19.0	-16.2
Cavendish	-53.8	-24.6
Taylor A	+15.5	- 4.2
Wilkins	+19.7	-29.5
Diophantus	-34.3	+27.6
Rabbi Levi L	+23.1	-34.7
Capuanus A	-25.7	-34.7
Rabbi Levi A	+22.7	-34.3
Rothmann H	+25.5	-29.1
Nicolai Z	+21.5	-40.9

Part 2: Applications

By

T. W. Offield and H. A. Pohn

INTRODUCTION

An inferred continuum of morphologic stages observed in lunar craters was described in part 1, and a numbering system to express these differences in form was proposed. Because superposition relations nearly everywhere on the Moon show that craters with subdued morphologic features are older than craters with sharper, apparently fresher, features, numbers assigned to craters according to the aforementioned system are believed to correlate generally with crater age. If such a correlation does, in fact, exist, regional geologic units and lunar events can be assigned relative ages independently of inferred superposition or intersection relations or other less direct methods such as crater size-frequency counts (Shoemaker and Hackman, 1962; Shoemaker, Hackman, and Eggleton, 1962; McCauley, 1967a). Any unit extensive enough to contain a large population of craters can be dated as slightly older than the oldest crater superposed on it. The circular multi-ringed mare basins can be dated by determining the age of the oldest craters which cut structures related to the formation of the basin or are superposed on the circum-basin deposits construed to be basin ejecta blankets.

SIZE-DEPENDENCE OF CRATER-AGE CHARACTERISTICS

The effect of size on the apparent age of craters must be considered if crater age is to be used in dating geologic units that the craters are superposed on. At the outset, we supposed intuitively that where two craters differed in size, the smaller would be degraded more rapidly than the larger crater and that this would be true throughout the complete spectrum of sizes.

To determine the relation between crater size and morphologic modification (apparent aging), we used identical morphologic criteria to assign age numbers to the most subdued craters of several sizes superposed on four regional geologic units, each of which has been interpreted as essentially isochronous (Eggleton, 1964; Shoemaker and Hackman, 1962; McCauley, 1967b). The curve connecting apparent ages of these oldest superposed craters of different sizes on each surface is nearly flat for craters larger than 8 km (fig. 1). This shows that craters larger than 8 km do not change markedly in apparent age assignable on the basis of geomorphic characteristics.

Craters smaller than 8 km, however, are affected by modifying processes in such a way that they are subdued more rapidly than larger craters, resulting in an offset in the changes of morphologic detail in the former relative to the latter. For example, if a surface is dated as age 4.5 on the basis of craters larger than 8 km, then by using the same morphologic characteristics, a crater 3 km in diameter will show an apparent age as much as 1 1/2 numbers lower (fig. 1). Still smaller craters will show greater apparent ages on the same surface. However, the numbering system proposed in part 1 for Class III craters can be used for craters smaller than 8 km if a crater-number offset curve (like those in fig. 1) is made for each unit being dated. Interpolation from figure 1 may make construction of a new offset curve unnecessary in many instances. On most extensive geologic units older than age 5.5, the population of craters 8-15 km in diameter generally is large enough to assure the presence of the oldest possible superposed crater for determining the age of the unit. Craters in this size range should be used for dating such units, because smaller craters will appear to be older than they actually are and larger craters may not be numerous enough to provide the oldest possible example on any given unit. For dating younger units, it generally will be necessary to use smaller craters and to deduce the age by means of individual offset curves or interpolation from figure 1.

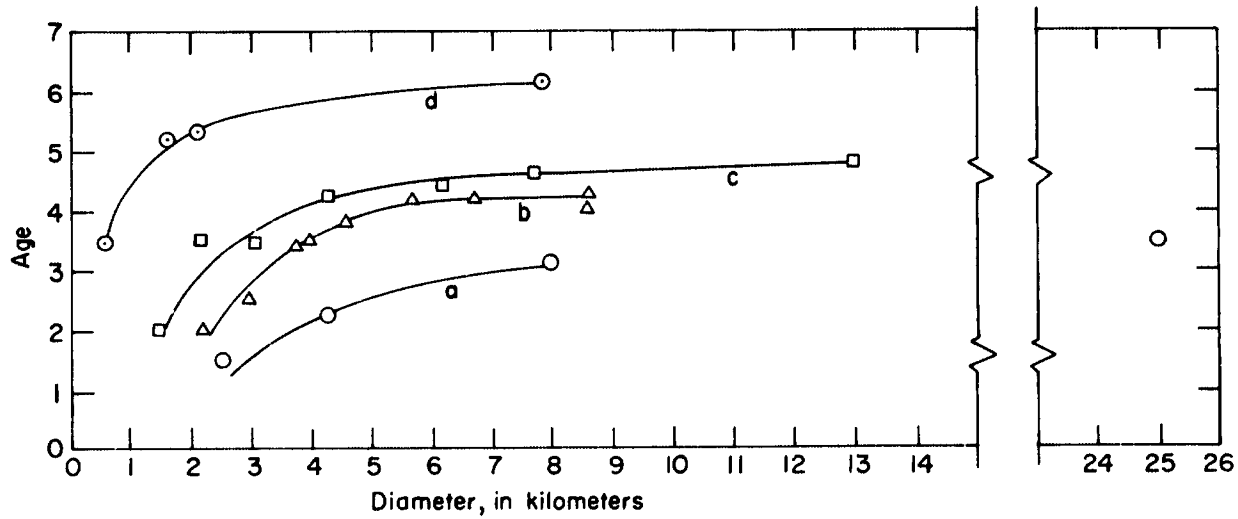


Figure 1.--Change in apparent age as a function of size for craters on isochronous surfaces: a. Crisium rim; b. Imbrium blanket; c. Orientale blanket; d. Copernicus ejecta.

DATING OF SURFACES AND EVENTS

The numbering system was tested by dating the oldest craters on three regional lunar geologic units. Each of these units is believed to be isochronous. In addition, the sequence of relative ages of these units is indicated by superposition relations, superposed-crater abundance, and freshness of detail. These units were the hummocky materials surrounding the Imbrium basin and inferred to be its ejecta blanket (oldest), the Orientale basin ejecta blanket, and the western Oceanus Procellarum mare material (youngest). The test results agreed with the established relative-age sequence of the three isochronous units. Other similar tests (for example, Sinus Iridum crater ejecta blanket relative to the inferred Imbrium ejecta blanket; Serenitatis basin relative to the inferred Imbrium ejecta blanket; the relative ages of many crater pairs such as Copernicus-Eratosthenes, Aristoteles-Eudoxus, and Aristoteles-Plato) also showed agreement between ages assigned by the numbering system and ages determined from clear-cut superposition relations.

Figures 2 and 3 give the results of crater-age determinations for several mare basins and regional geologic units on the Earthward face of the Moon, and for a few features on the farside. Table 1 shows the basis for the ages in figures 2 and 3; data for farside features are not given because of difficulty in citing precise locations.

The oldest reasonably well preserved basin dated thus far (fig. 2) is the double-ring Schiller basin. Other basins apparently formed in the following order: Nectaris, Serenitatis, Muscoviense, Humorum, Crisium, Imbrium, and Orientale. Tsiolkovsky, perhaps a large crater and not a multi-ring basin, is slightly younger than Orientale. The above age sequence differs somewhat from Hartmann's (1964, p. 184), who estimated that the Nectaris basin is relatively young (between Crisium and Imbrium in age).

Each basin may have been partly filled shortly after it formed, but the present major surface units in the maria are much younger

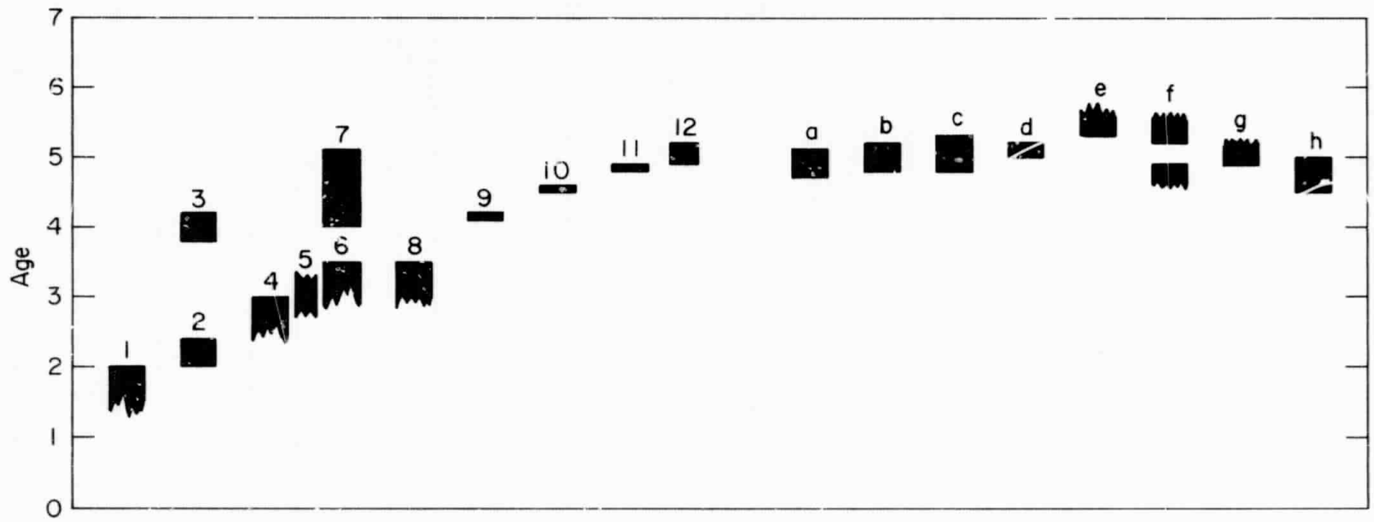


Figure 2.--Crater-age determinations of lunar basins and associated units and of plains units. Boxes span uncertainty in age determination. Basins: 1. Schiller; 2. Nectaris; 3. Nectaris "blanket"; 4. Serenitatis; 5. Muscoviense; 6. Humorum; 7. Humorum "blanket"; 8. Crisium; 9. Imbrium "blanket"; 10. Iridum; 11. Orientale; 12. Tsiolkovsky. Plains: a. Southern crater-fill plains; b. Northern plains; c. Central plains; d. Orientale inner-ring fill; e. Southwest of Mare Smythii; f. Tsiolkovsky region; g. Eastern far-side plains; h. Central far-side plains.

than the basins they occupy. The ages given in figure 3 are upper and lower limits generalized for very large mare areas. On a more local scale, especially in the western maria, superposition relations of individual fresh craters and mare materials typically reveal the presence of several local geologic units of different ages within the limits shown. The oldest mare surface units dated so far (fig. 3) are little older than the Orientale basin, and most are decidedly younger.

In high-resolution Orbiter II and III photographs, the eastern maria in the equatorial region appear to have more highly battered small craters than the western maria; thus, the former may be older (U.S. Geol. Survey Apollo site maps, open-filed in 1968). This suggested age relation is confirmed by our crater-age numbers which show that, although relatively young units are present in places, generally the Fecunditatis and Tranquillitatis mare units are older than those of the western maria. Crisium mare material is, however, as young as some of the western mare material. Its relative youthfulness was suggested earlier as one explanation of its low crater frequency at telescopic resolution (Shoemaker, Hackman, and Eggleton, 1962). Also, lunar night thermal infrared observations (R. L. Wildey, personal commun.) show that Crisium is relatively warm among maria, presumably an indication that the insulating regolith material is thinner than in other maria and, thus, that Crisium mare material has been subjected to erosion for a shorter time.

The mare material in Tsiolkovsky is about the same age as the surface units in eastern Oceanus Procellarum, and the mare filling of the Muscoviense basin is slightly younger, perhaps correlative with the units of western Procellarum.

Surface units of the light terra plains all appear to have formed in the relative-age interval 4.5-5.6 (fig. 2); most units which can be dated satisfactorily are younger than the Orientale basin. Light plains units near Tsiolkovsky are in part younger and in part older than that crater. None of the extensive light plains units are as young as the youngest mare units.

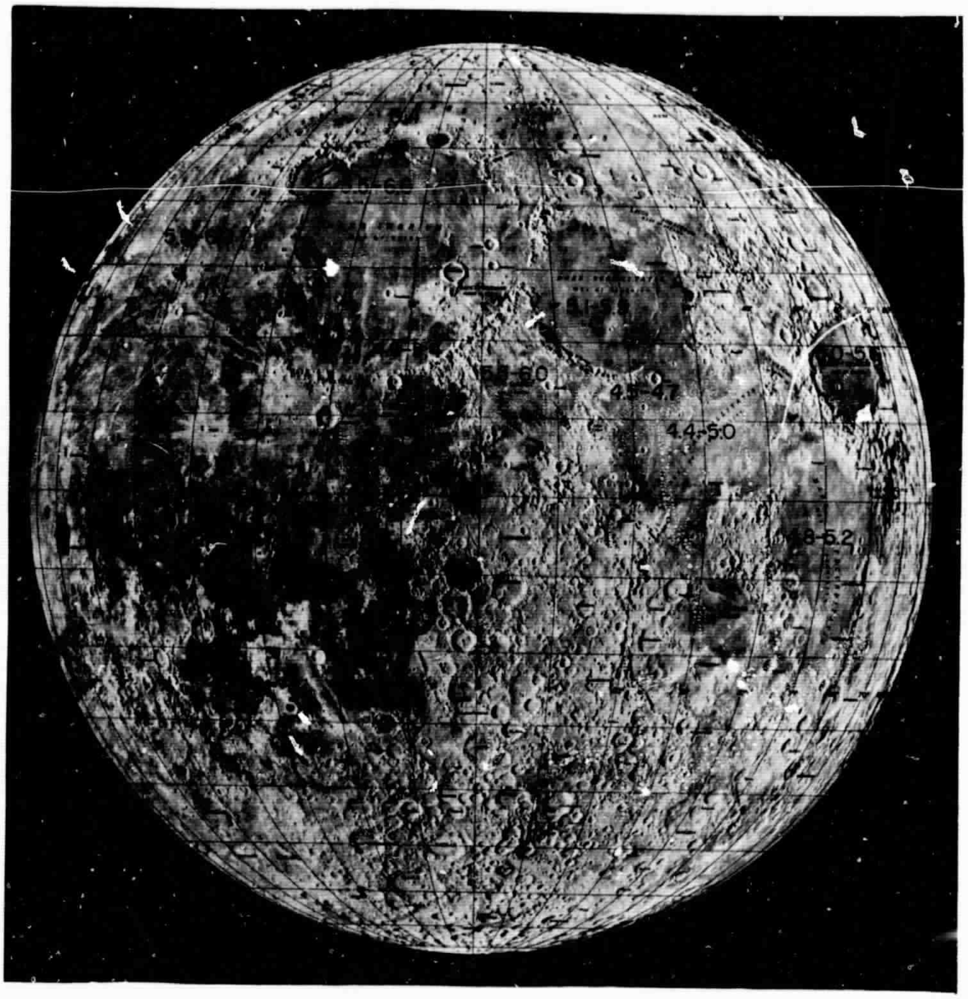


Figure 3.--Relative ages of regional mare surfaces. (Base map is USAF Lunar Reference Mosaic.)

RAMIFICATIONS OF THE CRATER-NUMBERING SYSTEM

A number of observations and conclusions about local and Moon-wide geologic correlations have already resulted from use of the crater-numbering system, and others will be made possible by it. Some of the age determinations bear out earlier geologic inferences from telescopic data; in general, there is good correspondence between the ages determined by this system and those arrived at by systematic geologic mapping. Other age determinations refute or cast doubt on older interpretations, and open the way to new and more precise interpretations. Some important points are discussed briefly below.

1. A marked discrepancy is found in dating the Humorum basin and the hummocky, partially blanketing materials around it. On the basis of telescopic observations, these hummocky materials had been thought to be basin ejecta (Titley and Eggleton, 1964; Titley, 1967), but crater-age determinations show them to be approximately a whole integer younger than the basin on our proposed number scale (fig. 2; table 1). This age difference seems to be confirmed qualitatively by a paucity of 1-10 km craters superposed on the hummocky materials as compared with the abundance of such craters on large areas which appear to be original basin rim and not covered by the hummocky materials. Because of the age difference, and other considerations, such as the fresh appearance and patchy distribution of the hummocky materials, we suspect that they are relatively young volcanic blanketing units not directly related to the formation of the Humorum basin. Figure 2 shows a similar discrepancy between the age of the Nectaris basin and the age of widespread hummocky blanketing materials around it, which supports the conclusion by Milton (1968) that the hummocky materials are volcanic.

2. The identification of basin ejecta blankets has rested hitherto on distinctive morphology of the deposits and their distribution around a basin. It now should be possible to determine the presence and extent of basin ejecta blankets too old to have

Table 1.--Representative supporting data for age determinations shown in figures 2 and 3

Unit	Crater used for dating	Age	Superposition relationships*
Schiller basin	Segni	2.0	A
Nectaris basin	Catharina	2.4	A
	Rothmann G	2.0	D
Nectaris blanket	Tacitus	4.2	A
	Pons	3.8-3.9	C
Serenitatis basin	Littrow	3.0	A
Humorum blanket	Fontana G	4.2	D
	Fontana C	3.8	D
	Lepaute	3.6-3.8	D
	Hainzel L	4.1-4.2	D
	Ramsden H	4.0-4.2	D
	Vitello	4.8-4.9	A
	Hansteen	4.9-5.1	A
	Western plains	4.8-5.1	A
Crisium basin	Proclus P	3.2-3.5	A
	Proclus S	3.4-3.6	A
	Tisserand A	3.4-3.6	A
	Picard G	3.5	A
	Cleomedes	3.5	A
Imbrium blanket	Arata A	4.2	A
Iridum	Iridum	4.6	E
Orientale basin and blanket	Schlüter	5.0-5.1	A
	Eichstadt	5.0	A
	Shaler	4.8	Syn-basin?
	Rocca	4.2	C
	Crüger	4.8	A

Table 1.--Representative supporting data for age determinations shown in figures 2 and 3--Continued

Unit	Crater used for dating	Age	Superposition relationships*
Southern and western plains	Orientale blanket	4.8	D
	Zagut	4.9-5.1	A
	Lilius B	4.7-4.9	B, C
	Deluc C	4.8-4.9	B
Northern plains	Timaeus	5.2-5.3	A
	3 craters 126 km north of Pascal	4.8-5.0	B, C
Central plains	Cayley	5.5	A
	Whewell	4.9	C
	Arzachel	4.8	C
	Thebit	5.1-5.2	A
Frigoris mare	Protagoras	5.1-5.3	C
	Timaeus	5.2-5.3	C
	Aristoteles	5.5	A
	Archytus	5.5-5.6	A
	Pythagoras	5.4	A
	J. Herschel F	5.0	B, C
Tranquillitatis mare	Ross D	4.7	A, C**
	Sinas E	5.0	A
	Maraldi B	5.0	A
	Cauchy A	4.4	B, C
	Römer J	5.1	A
NW Tranquillitatis mare	DeSeilligny A	4.5	B, C
	Ross P	4.7	A
Serenitatis mare	Posidonius P	5.5	A
	Bessel E	5.1	C
	Eudoxus	5.6	A
	Posidonius N	5.3	A, C

Vaporum mare	Manilius	5.5	C
	Manilius D	6.0-6.1	A
East Imbrium mare	Archimedes	4.9-5.3	B, C
	Feuillée	5.1	C
	Eratosthenes	5.7	A
	Eratosthenes B	5.4	A
Mare south of Copernicus	Lansberg	5.1-5.3	C
	Lansberg D	6.0	A
	Bonpland E	5.7	A
Southern Procellarum mare	Flamsteed A	5.5-5.6	C
	Flamsteed	5.8	A, C
	Herigonius	5.5-5.6	A, C
	Euclides B	6.0	A
	Bullialdus	5.7	A, C
NW Imbrium mare	Helicon	5.1-5.4	C
	Carlini	5.6-5.8	C
	Heis	5.9-6.1	A
	Leverrier	5.9-6.0	A
	Leverrier D	5.5	A
	Kirch	5.6	A
N Procellarum mare	Dechen	5.5	C
	Lavoisier	5.1-5.4	C
	Harding	6.0-6.1	A
	Markov	5.3	C
	Naumann	5.8-5.9	A

Table 1.--Representative supporting data for age determinations shown in figures 2 and 3--Continued

Unit	Crater used for dating	Age	Superposition relationships*
W Procellarum mare	Cavalerius	5.9-6.0	A, C
	Lohrmann BA	6.0	A
	Lohrmann A	6.0	A
	Reiner	5.9	A, C
	Kraftt E	5.7-5.8	A
	Galilaei	5.8-5.9	A
	Schiaparelli	5.3-5.5	C
	Marius D	5.3-5.4	C
Humorum mare	Vitello	4.8-4.9	C
	Liebig F	5.6	A
Crisium mare	Cleomedes G	4.5	B, C
	Cleomedes FA	5.6	A
	Messala	5.7-5.8	A
	Eimmart C†	5.0	C
Fecunditatis mare	Petavius	4.5	C
	Messier G	5.2	A
	Goclenius A	4.8	C

*Superposition relations: A, named crater superposed on unit or structure; B, materials of unit found in crater interior; C, materials of unit inundate crater rim; D, materials of unit superposed on crater; E, crater appearance (see part 1).

**A, C indicates partial embayment of rim materials.

†Determination from Orbiter IV front side apolune photograph with poorer resolution and lower lighting than usual photographs.

a distinctive morphology. Small pre-blanket craters (1-8 km) will be absent or indistinct (mantled) and larger pre-blanket craters, particularly those close to the basin, will be subdued to the extent that they appear older than they actually are. Post-basin craters should have normal age characteristics. Thus a noticeable break in the crater-age/frequency data will occur at the age just before the oldest post-basin crater and will mark the presence and age of a suspected ejecta blanket. The extent of the blanket will be indicated by a line or zone around the basin where the crater-age distribution becomes continuous. Such determinations, however, may be ambiguous where extensive blankets of volcanic materials are present.

3. Superposition relations of craters so consistently confirm the relative age numbers assigned that any anomaly seems to require a special explanation. One such anomaly, noted by D. E. Wilhelms, is provided by the craters Isidorus and Capella, northeast of Mare Nectaris (fig. 4). The apparent age of Capella is greater than that of Isidorus by 1.5 on the number scale, yet Capella is clearly superposed on Isidorus. Capella and Isidorus apparently had different initial morphologies, and we believe that Capella is a volcanic crater. It is one of a few craters which have "overfit" central peaks and unusually irregular rim morphology. These unusual craters generally occur in groups and most are located in areas of complex structure.

4. Use of the crater-numbering system also offers a possibility of identifying secondary craters associated with some of the younger lunar basins, that is, those craters produced by impact of fragments ejected from the basins or from volcanic vents along basin-radial fractures. Strings or clusters of craters radial to the Orientale basin are dated as the same age (4.8) as the basin. In addition to these, individual 5- to 15-km craters of this age are uncommonly abundant in a belt around Orientale and almost certainly are secondary craters formed by impact of material ejected from the basin. By applying the numbering system

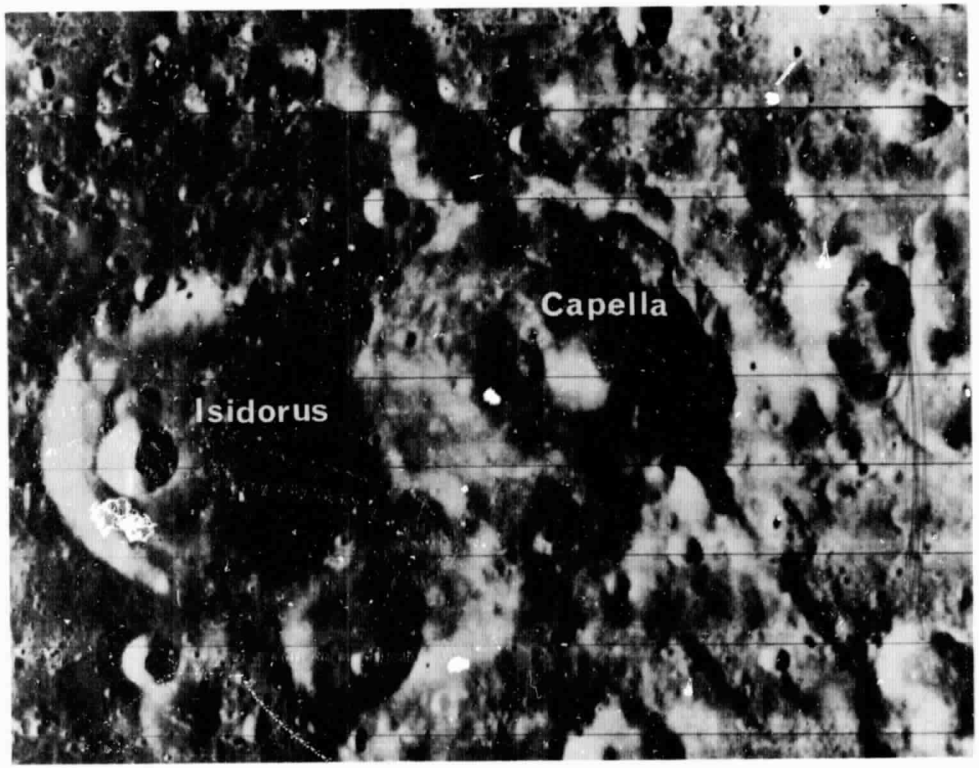


Figure 4.--Anomalous crater-age and superposition relationship of Isidorus and Capella. Framelet strip about 10 km wide.

to craters in the central and southern uplands, clusters of 10- to 20-km craters of the same age as the Imbrium basin have been identified; these may well be Imbrium secondary craters.

5. If craters everywhere on the Moon are degraded at about the same rate, then assignment of age numbers on the basis of geomorphic stage permits Moon-wide stratigraphic correlations. This will facilitate refinement of the present Moon-wide time-stratigraphic sequence.

6. Light (relatively high albedo) terra plains are difficult to date precisely because they typically occur in small areas such as in crater floors: the dates given in figure 2 are generalized to show probable age limits for numerous separate plains areas within broad regions of the Moon. Nevertheless, the data (table 1) suggest that terra plains, believed to be generally of volcanic origin, formed all over the Moon in a relatively brief period of time; they formed in age interval 4.5 to 5.6, and most are in the age range 4.7-5.2. This period coincides with the emplacement of mare surface units in many areas, although the mare units are mostly younger. It is interesting to compare small-crater frequencies on various light plains and mare surfaces of similar ages. Craters on light plains (4.8-5.1) north of Mare Frigoris are an order of magnitude more abundant than on light plains (4.9-5.1) in the southern terra or on mare materials of Tranquillitatis (4.4-5.0) and Fecunditatis (4.8-5.2). That these age differences are too small to explain such crater-abundance variations in terms of impact frequency is indicated by the fact that ejecta blankets around craters of ages 4.2 and 4.8 or 4.8 and 5.2 do not show nearly the disparity in crater abundances seen in the compared mare and plains surfaces. From these observations, we believe that most of the craters on the highly cratered plains are probably of endogenetic origin. In addition, comparison of albedos for mare and light plains units of similar ages suggests that the relatively greater brightness of plains is an intrinsic property and that the plains are formed of different materials than the mare units. Although

the time involved is not known, the emplacement of so many light plains and mare units in a small interval on the crater evolution scale suggests that this was a relatively short period of widespread volcanic activity on the Moon.

The ramifications described above can be tested only be detailed application of the proposed system to many different areas of the lunar surface. It is believed that the proposed system will serve as a relatively precise means of deciphering local geologic relationships and correlating the geology of widespread areas on the Moon.

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