PROCESSES OF LUNAR CRATER DEGRADATION: 
CHANGES IN STYLE WITH GEOLOGIC TIME

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(Received 2 January, 1975)

Abstract. Lunar crater degradation can be divided into two time periods based on differing styles and rates of crater degradation processes. Comparison of lunar radiometric age scales and the relative degradation of crater morphologic features for craters larger than about 5 km diam shows that Period I, prior to about 3.85–3.95 b.y. ago, is characterized by a high influx rate and by formation of large, multi-ringed basins. Period II, from about 3.85–3.95 b.y. to present, is characterized by a much lower influx rate and lack of large multi-ringed basins. Craters formed throughout Period II show generally constant morphologic characteristics. Craters formed in Period I show markedly different characteristics although their residence time could not have increased more than 15% over the total time of Period II. The vast majority of crater degradation of Period I craters took place nearly coincident with their time of formation.

Elements of crater degradation and modification during Period I include destruction of crater exterior, rim, and wall facies and structures, decrease in crater depth, and increase in crater floor width. Examination of fresh crater geometry reveals that major changes in crater depth and floor width parameters can occur with the addition of only minor volumes of material as crater fill. Volumes sufficient to produce these characteristic changes are readily available in the surrounding crater wall and rim deposits and can be derived by erosion associated with the observed morphologic changes. Depositional mechanisms associated with lunar landslides are capable of moving material across the crater floor-wall boundary while maintaining and propagating the characteristic break in slope. A prime source of crater degradation during Period I is related to the formation of multi-ringed basins. The widespread ballistic sedimentation associated with the formation of these basins produces a near-saturation bombardment which excavates and mobilizes large volumes of local material and preferentially moves it into nearby low regions. Seismic effects contribute to degradation by enhancing slope instability and by mobilizing material for downslope movement. The net effect for a crater influenced by multi-ringed basin formation is a tendency toward destruction of crater facies and structure by near-saturation bombardment and seismic effects, the erosion and mobilization of crater material, and the redepition of this material in nearby low regions, primarily on the crater floor. This process appears to be of major importance in the degradation and modification of craters, in generation of interior crater fill, and in the formation and propagation of Cayley-type plains surfaces.

1. Introduction

Craters and their associated deposits are the most abundant landforms on the lunar surface and exist in an overwhelming variety of states of preservation. Their abundance, variety, and formation throughout lunar history suggests that these landforms contain a record of the types of lunar processes acting to modify the lunar surface and any variations in the rates and styles of these processes during geologic time. Studies of lunar crater morphologic degradation processes may therefore yield important information about lunar history.

Morphologic classification of lunar craters and correlation with relative age has been carried out at several levels of detail and from several points of view (Baldwin, 1949, 1963; Wilhelms, 1970; Arthur et al., 1963, 1964, 1965, 1966; Pike, 1968; Ronca
and Green, 1970; Pohn and Offield, 1970). Baldwin (1963) described a five-fold classification scheme which relied primarily on number of superposed craters to differentiate classes. Arthur et al. (1963) outlined a similar classification. In another approach, Pohn and Offield (1970) suggested that relative ages of lunar craters could be determined by the degree of freshness of the major topographic components of the crater. These studies have identified several processes which were important in crater degradation, have outlined several crater morphologic components which were changing with time, and have then used these two factors to arrange lunar craters in a relative age classification. The relative age classifications are based on fundamental assumptions, supported by stratigraphic relationships, that (1) craters and their morphologic components are crisp and sharp at the time of their formation (e.g., Tycho), that (2) the majority of lunar craters share generally similar initial morphologies, and that (3) degradation is largely due to the continuous operation of degradation processes proceeding at an unknown but probably non-linear rate. The relative age classifications were occasionally used to correlate geologic events (Offield and Pohn, 1970), and to study possible styles of crater degradation with relative age (Ronca and Green, 1970). Degradation of small craters (generally less than 2 km diam) has been studied by Ross (1968), Soderblom (1970), Chapman et al. (1970), and Soderblom and Lebofsky (1972). This study concentrates on craters larger than about 5 km in diam.

The purpose of this paper is to calibrate crater degradation relative age schemes to radiometric dates obtained from lunar samples, to analyze changes in morphologic features and causal factors as related to the time scale, and to model the style and rate of lunar surface degradation processes as related to lunar geologic time.

2. Changes in Crater Morphologic Features with Geologic Time

The relative age scheme of Pohn and Offield (1970) represents the most detailed analysis of variations in crater morphologic factors. Using rim crests, walls, and surrounding rim deposits (Figure 1), Pohn and Offield outlined a morphologic continuum from sharpest to most subdued lunar craters and interpreted the position in this sequence to reflect the relative ages of the respective craters (Figure 2). Pohn and Offield (1970) emphasized that the crater number intervals do not represent equal time spans because of the probable non-linear nature of lunar processes of erosional modification of landforms. Offield and Pohn (1970; ms.) have utilized this scheme to obtain relative ages for a number of events in lunar history. Radiometric dating of returned lunar samples has provided ages for several events dated relatively in the Pohn and Offield scheme. Figure 3 compares the relative historical framework of the Pohn and Offield scheme with radiometric ages for certain lunar events. Although boundaries of Eratosthenian and Copernican periods are still not precisely defined, the radiometric dates provide a significant calibration of the relative crater age scheme. The formation of the Imbrium basin (4.2 on the Pohn and Offield scale) is closely followed in time by Orientale, the youngest multi-ringed basin (4.8 on the
Fig. 1. (a) Morphologic components of young lunar craters as exemplified by Copernicus (~ 93 km diam). (b) Morphometric parameters shown in crater cross-section; $D_f =$ floor diam; $D_r =$ rim crest diam; $R_i =$ interior relief; $R_e =$ exterior relief; after Pike (1968).
Pohn and Offield scale). A comparison of the calibrated age scheme and crater density with time is shown in Figure 4. Two different periods of lunar history are readily apparent. Period I, prior to about 3.85–3.95 b.y. is characterized by a high influx rate (and higher crater density per unit time) and the formation of large, multi-ringed basins. Period II, from 3.85–3.95 to present, is characterized by a much lower influx rate (and much lower crater density per unit time) and lack of large multi-ringed basins. Period II begins after the formation of Orientale, 4.8 on the Pohn and Offield scale. Figure 4 represents crater density which in turn represents the accumulation of cratering events with time. Changes in influx rate are represented by changes in the slope of this curve. Therefore, the boundary between Periods I and II would appear even more pronounced on a plot of flux rate with time.

Fig. 2. Changes in diagnostic crater features with age. The numerical values denote seven morphologic stages and relative ages ranging from 0.0 (most degraded; greatest relative age) to 7.0 (least degraded; least relative age). From Pohn and Offield (1970).
In constructing their scale of crater relative ages, Pohn and Offield (1970) divided lunar craters into three size classes: Class I (>45 km diam; round with distinct rim crenulations); Class II (20–45 km; polygonal); and Class III (8–20 km; round). Lunar multiringed basins were not considered in this classification. Since each size class has a slightly different initial shape, the morphologic continuum defined for each varies slightly. Relative ages are determined for craters within a given size class by evaluating the characteristics or condition of a series of morphologic components (Figures 1, 2).

Crater rays – Crater rays are the first diagnostic feature to disappear after the formation of a fresh crater (Figure 2). Oberbeck (1971) presents evidence that the high albedo associated with rays from the crater Copernicus is due to excavation of underlying material by small secondary impacts in the ray region. Adams and McCord (1971, 1972a, 1973) have shown that bright rays expose material which is more crystalline than the dark-glass rich background material and that bright ray material darkens with time by impact induced vitrification and mixing with background material. Albedo patterns of rays formed in Eratosthenian time (Figures 2–3) are no longer readily distinguishable from background material.

Satellitic Craters – These features are found arrayed around a primary crater in clusters and chains and their size increases with the size of the primary crater. As shown in Figure 2, satellitic craters associated with smaller craters disappear faster than larger ones (Pohn and Offield, 1970) due to micrometeorite bombardment and formation of abundant primary craters of similar size. In the larger craters, however, the general style and intensity of weathering dominating Period II of lunar history has not been sufficient to obliterate all satellitic craters. Distinctive satellitic crater fields are associated with three post-Imbrium basin, pre-latest mare craters (Iridium,
Fig. 4. Total accumulation of impact craters on lunar surfaces as a function of age (from Soderblom et al., 1974). Crater degradation periods are added. The ages of various lunar volcanic and impact units are shown and are plotted against the total amount of cratering developed on those surfaces. Isotopic age analyses are taken from references in Figure 3. The integrated impact flux measurements are those of Soderblom and Lebofsky (1972) and Soderblom and Boyce (1972). The approximately linear increase in degree of cratering from the present back to about 3.5 b.y. implies a fairly constant flux for that period. Before about 3.5 b.y. the fluxes were dominated by a torrential but rapidly declining flux probably generated as the last remnants of the accretional debris distributions were swept up (Soderblom et al., 1974).
Plato, and Archimedes). These range in age between 4.6 and 5.3 on the Pohn and Offield scale and at least Iridium appears to pre-date the formation of the Orientale basin. Although the satellitic craters are distinctive in these ancient examples, immediately older craters do not show this same development. Offield and Pohn (1970) date the Orientale ejecta blanket (associated with the youngest lunar multi-ringed basin) at \( \sim 4.8 \) (Figures 2, 3), which places the last major event of this type at the time of formation of the oldest craters which have not lost their satellitic craters. Surface modification processes characteristic of Period I appear to obliterate or mask satellitic craters at a much more rapid rate than in the later period.

Multi-ringed basins characteristically have much larger satellitic craters (5–25 km) which can be readily identified around the younger basins, such as Orientale and Imbrium. However, these too soon become difficult to differentiate from other craters of similar size in older basins.

**Radial facies** – The radial facies (ridges and grooves developed on parts of the ejecta blanket surrounding the crater; Pohn and Offield (1970)) while not as prominent as other major components, appear to persist slightly longer than satellitic craters. They do not, however, range appreciably into Period I, the age dominated by higher flux rates and multi-ringed basin formation.

Radial facies surrounding multi-ringed basins occur on a considerably larger scale than in craters considered by Pohn and Offield (1970). Even these are highly degraded after a short period of time during Period I (compare Orientale, Hevelius Formation, and Imbrium, Fra Mauro Formation).

**Rim Crest Sharpness** – Sharpness decreases with time (Figure 2) and appears to be related to increasing impact crater density which tends to give the crater rim crest a crenulated appearance. Crater rim crests of Period I often appear rounded and grooved in nature.

**Polygonality** – Class I (>45 km) and II (20–45 km) craters tend to become slightly more polygonal with time; Class III (1–20 km) craters have an initial circular shape which changes to polygonal at about 4.5 (Pohn and Offield, 1970). Thus, Class III craters which form during Period I are generally more polygonal. Causes of increased polygonality are uncertain, but slumping of crater walls and rim crests along pre-existing fracture systems may be an important factor. Adler and Salisbury (1969, Figure 2) have shown that variations of polygonality and circularity with age are small.

**Wall Terraces** – As shown by Pohn and Offield (1970) large terraces tend to break up so that with time, a decrease in size and sharpness and an increase in number is seen (Figure 2). For craters forming during Period I (Figure 4), a process of subduing and coalescing has progressively destroyed terraces. Interior radial channels appear in craters formed prior to about 4.3 and begin to dominate crater walls (Figure 2). The beginning of the disappearance of terraces and the initiation of radial wall channels occurs between 4 and 5 on the Pohn and Offield relative age scheme (Figure 2). This is coincident with the transition between Periods I and II (Figures 3, 4).

**Interior Radial Channels** – The appearance of these features is related in time to
the disappearance of wall terraces in the interval 4.5–4.3 approximately at the boundary between Periods I and II. Radial channels are not always uniformly displayed in older craters. Some craters formed late in Period II show only several radial channels which frequently appear to be impact craters elongated on the wall slope. Older craters often show well developed radial channels on one or two walls.

Crater Floor Roughness – Large (> 20 km; Class I and II) fresh lunar craters have a very distinctive floor texture which can be characterized as rough at large scales. Central peaks contribute to this appearance but the overall roughness is caused by abundant domes sometimes reaching several hundred meters in elevation and often covering major portions of the crater floor (Figure 1). Floor roughness of this type is primary and is distinct from hummocky floors caused by abundant subsequent impact craters. The primary domical roughness associated with the floors of relatively young impact craters such as Tycho, Aristarchus, and Copernicus, seems to persist back into geologic time until about the boundary between Period I and Period II because highland craters such as Arzachel (4.8) and Piccolomini (4.3) have a somewhat subdued, but still distinctly rough, crater floor. Craters immediately older than this (Period I), however, quite often show a distinctly smoother floor in which few, if any, domes are present.

Central Peaks – Coincident with the smoothing of the crater floor is a decrease in the size and often the disappearance of central peaks. The central peaks of Albategnius and Alphonsus are only a fraction of the size of those seen in younger craters of comparable size (Theophilus, Langrenus) and in others (Ptolemaeus, Stofer, Aliacensis, etc.) central peaks are not visible.

Wood (1969) has shown that the ratio of weak (subdued, covering small area) to strong (sharp, covering larger area) central peaks increases considerably in older lunar craters (Figure 5a). For the Arthur scale of crater classes, the boundary between Period I and Period II (Figure 4) occurs between crater categories 2 and 3. Wood (1969) has also shown that the percentage of craters with central peaks in a given crater size range decreases dramatically with age (Figure 5b). Again, the most marked change occurs between Arthur crater categories 2 and 3. In summary, central peaks show evidence of modification and disappearance with time. The most distinct changes correspond approximately to the boundary between Periods I and II (Figure 4).

Crater Shallowing – Baldwin (1963), Pike (1968, 1971) and others have noted the tendency of the interior relief ($R_i$; measured vertically from floor to rim crest) of non-mare flooded craters of similar sizes to decrease with increasing age. Pike (1968) has developed a shallowing parameter, $\phi$, which is defined by crater position on a plot of $R_i/D_r$ vs $D_r$ (where $D_r$ is the rim crest diam). Although there is a slight increase in the shallowing parameter (decrease in crater depth) with time from Copernican to Imbian, the dramatic change occurs with craters of pre-Imbian age. Over one half of the craters which formed in pre-Imbian time (Period I) have $\phi$ values greater than 60 (Figure 6a), while no craters formed subsequently (Period II) have $\phi$ values in this range. The depth-diam fields for these $\phi$ values are shown in Figure 6b.
These relationships imply that the most pronounced crater shallowing occurred during Period I and that craters which formed as long ago as early Period II, have not undergone similarly pronounced shallowing.

**Crater Floor Widening** — Baldwin (1963), Pike (1968; 1971) and others have also noted that non-mare flooded crater floors of a given size range tend to broaden with time (the wall width decreases). Pike (1968) has developed a crater floor spreading parameter, $\psi$ which is defined by crater position in a plot of floor diam ($D_f$)/rim crest diam ($D_c$) vs $D_r$. Values show good correlation with the corresponding shallowing factor ($\phi$) for the same crater, suggesting that $\phi$ and $\psi$ both describe similar degrees of crater modification (Pike, 1968, p. 202). Pike (1968) combined these two values into a relative age index (Figure 7) which emphasizes that in addition to shallowing,
Fig. 6. Relationship of lunar crater interior relief ($R_i$) and crater age. (a) Relationship between shallowing parameter $\phi$ (defined by position on a plot of $R_i/D_r$ and $D_r$) and lunar crater stratigraphic position. Larger values of $\phi$ are shallower craters. Total number of craters = 253. From Pike (1968). (b) Logarithmic depth-diameter fields for over 300 flat floored lunar craters (> 20 km diam) grouped by relative stratigraphic ages. Fields enclose all craters within each age group. From Pike (1971).

Fig. 7. Relationship between crater age index $\omega$ and lunar crater stratigraphic positions. $\omega$ is a combination of $\phi$, the crater shallowing parameter, and $\psi$, the crater floor-spreading parameter ($\omega = \phi + \psi/2$). Higher values of $\omega$ indicate shallower craters and wider crater floors. From Pike (1968).
crater floor spreading shows dramatic variations between Period I and Period II of lunar history.

Summary – Several key crater morphologic characteristics show distribution and degradation patterns which are distinctly related to the two major periods of geologic time (Figure 4). In particular, larger craters (primarily Class I and II, >20 km) which formed during Period II show little evidence of distinctive modification even though they may have been present on the lunar surface for over 80% of lunar history. Most craters formed early in Period II show the same morphologic characteristics as younger craters (satellitic craters; radial facies; distinct rim crest, terraces, and central peaks; primary crater floor roughness; lack of distinctive radial channels) and also show crater depths and floor widths similar to younger craters of the same size. However, craters formed immediately prior to this in Period I show markedly different characteristics, even though their residence time on the lunar surface can only increase by a maximum of about 15% over the total time of Period II.

In particular, craters formed even in the later stages of Period I have lost their satellitic craters, radial facies, and primary crater floor roughness, and their rim crests, terraces, and central peaks are highly modified or absent. Radial channels become distinct in the crater walls and crater floors become shallower and wider.

3. Processes of Modification of Crater Morphologic Features

What are the significant factors and processes which modify crater morphologic features and result in such distinctive characteristics for Periods I and II? Two important features characterize Period I:

(1) a high frequency and broad size variation of infalling material (Hartmann, 1969, 1972; Soderblom et al., 1974) (Figure 4) and

(2) the formation of basins, a family of large lunar craters (usually >200 km and forming multiple rings) which distribute large volumes of ejecta over wide areas of the lunar surface.

Potential factors in crater modification during Period I include primary impacts, which increase manifold and would tend to speed up the modification of most crater morphologic parameters. The increased flux (Figure 4) would also increase the role of lateral sedimentation at all scales since each additional primary crater produces thousands of secondary and tertiary craters which in turn will mix and modify materials. Proximity weathering would have a marked effect in short time periods because large craters would not be as widely separated in time and space as they are in Period II. Equally significant during this early period of increased flux is the greater size range of impacting bodies, resulting in the formation of major lunar multi-ringed basins and the vast increase in scale of proximity weathering associated with a single event of this type. If the edge of the Imbrium crater clusters (mapped at a scale of 1:5 million; Wilhelms and McCauley, 1971) are taken as an approximate edge of significant modification from the Imbrium event, then the radius from the point of impact indicates that the Imbrium event significantly modified ~ 19 million km² or 50% of
the lunar surface. Between forty and fifty of these basins have been recognized on the Moon (Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971; Howard et al., 1974) and their distribution and the approximate edge of their textured ejecta blankets is shown in Figure 8. In summary, proximity weathering should be accelerated in Period I in two ways: (1) the increased rate of cratering events causes local proximity weathering to be much more important, and (2) the area of multi-ringed basin lateral sedimentation for each event is so great (Figure 8) that the scale of proximity weathering for single events is increased considerably over the same process in the post 3.8 b.y. Period II.

![Figure 8. Distribution of lunar basins. Topographic boundary of basin is shown in solid line. Approximate edge of textured ejecta blanket is shown by dotted line. Dotted line is placed at one basin radius from basin rim and is estimated based on position of this boundary at younger basins such as Imbrium and Orientale. Basin location from Howard et al. (1974).](image)

*Landslides* would also be a more significant factor during Period I because of the increased role of primary and secondary cratering which would tend to initiate movement on unstable slopes (a process discussed by Oberbeck et al. (1973) and Howard (1973)). *Seismic effects* associated with increased impacts and with large craters the size of multi-ringed basins are difficult to assess since the partitioning of energy of the impacting projectile is not well understood. Titley (1966) has reviewed the potential of seismic energy as an agent of terrain modification on the Moon and concluded that seismic energy associated with impacts would be an important factor in erosion. Others have attempted to determine the amount of seismic energy released in large impacts (Van Dorn, 1968, 1969; Ronca and Green, 1970) but calculations have often been uncertain because of the difficulty in determining the actual crater of excavation. Titley (1966) cited nuclear explosion data which suggested that the percentage of total energy expended seismically ranged from about 0.02–0.3%. However,
Mickey (1964) has shown that larger yields produce over 6% seismic energy. An effect such as this would certainly degrade the morphology of large craters by initiating landslides and would also cause smoothing of surfaces of older plains units by a seismic shaking type of modification of small craters. The seismic shaking associated with events such as these would agitate and partly mobilize loose surficial material out to significant distances from the basin rim.

It is difficult to assess the potential role of volcanism as a crater modifier in Period I since most of the features associated with volcanic deposits (domes, cones) are small enough to have been destroyed by the high flux during this period. Baldwin (1963) and Pike (1968, 1971) have demonstrated that old lunar craters show a marked degree of shallowing in comparison to similar diameter craters of younger age (Figures 6a, b). Pike (1968, 1971) interprets this shallowing to be due in part to volcanic flooding. Because of the distinctive albedo and geochemical characteristics of Period II mare lavas, it is much more apparent that this process has operated as a crater modifying process on a selective basis subsequent to Period I. Earth-based spectral studies (Adams and McCord, 1972b; McCord et al., 1972), orbital geochemical surveys (Metzger et al., 1973; Adler et al., 1973), and other remote sensing data (Oberbeck et al., 1973) reveal a regionally homogeneous highland surface at the scale of craters considered here. Lack of geochemical distinctiveness of Period I crater floor surfaces from background material suggests that floor material may be derived from surrounding upland sources rather than from distinct volcanic floor filling.

Other than local, mare-associated pyroclastic deposits (Heiken et al., 1974; Lucchitta, 1974; Head, 1974a; McGetchin and Head, 1973), Apollo sample results suggest that blanketing by pyroclastic volcanism is not a significant lunar process at this scale.

Tectonism may have played a role in the modification of craters in early lunar history but specific examples are difficult to identify. Other than faulting associated with the formation and modification of craters and basins there is little evidence for extensive internally-generated tectonic processes. Although evidence for local strike-slip movement has been noted (Fielder, 1965), the majority of effects on craters seem to be related to slump preferentially occurring along old structural lineaments and weaknesses.

Isostatic rebound is another potential factor in crater modification. It may have played an important role in the early history of the moon due to the presence of a thinner crust and different crustal thermal conditions. Variations in crater depth with time have been cited as evidence for extensive isostatic rebound early in lunar history (Baldwin, 1963; Pike, 1968; 1971). Crater floor deformation and isolated shallow craters also suggest that isostatic rebound occurred locally during Period II (Schultz, 1974).

Which of the potential factors and processes outlined are responsible for the distinctive crater modification style of Period I? Consideration of the cross-sectional geometry of large lunar craters (>20 km) illustrates some important points in reference to crater modification processes (Figure 9). The crater Copernicus (~93 km diam; Figure 1) is generally typical of large craters in that it has a central peaked,
rough-textured, crater floor which shows little evidence of isostatic rebound. Its flat floor takes up $\sim 59\%$ of the crater diam and the average crater wall slope is $\sim 12^\circ$. Vertical viewing of photographs of large craters apparently tends to overemphasize crater depth and interior slopes so that the saucer-shaped geometry of large lunar craters is not always appreciated. Not readily appreciated is the fact that a small volume of crater fill has a dramatic effect on crater shallowing and crater floor broadening early in the crater filling history. For the Copernicus case (Figure 9),

![Graph showing relationship between crater interior relief ($R_i$) and crater floor diameter ($D_f$) with progressive filling of the crater for the example of the crater Copernicus (Figure 1). Because of the saucer-shaped geometry of fresh large craters, a small percentage of the crater volume added in early stages of crater fill has a larger effect on $R_i$ and $D_f$ than the same volume added in later stages of crater fill. Approximately 2% of the total volume would cover the primary crater floor roughness (Figure 1) while approximately 16% would cover the central peaks.]

about 2% of the total volume of the crater deposited on the crater floor would cover the primary crater floor roughness (domes and mounds up to 200 m in height). If approximately 16% of the crater volume ($\sim 2800$ km$^3$) were deposited on the crater floor, the central peaks would no longer be visible. Both of these estimates neglect the dome and peak volumes and thus tend toward overestimates of the volume needed. Even with the addition of this small volume, the floor diameter ($D_f$) would have increased 18% (Figure 9). Because of the geometry of the crater about 25% of the crater volume added as fill would reduce crater depth ($R_i$) $\sim 40\%$. Therefore it
seems quite possible that the dramatic changes in crater parameters could be brought about by small amounts of crater fill relative to total crater volume.

There are several potential sources of material for non-volcanic crater fill. Material derived from the adjacent crater walls is the source in closest proximity. If crater walls are eroded to provide material for crater floor fill, they may either erode back at a constant slope or show a decrease in wall slope. Figure 10 illustrates the hypothetical evolution of the interior wall slope of Copernicus (about 12° slope at present and little modified since its formation) for the case of decreasing slope. A decrease in slope of less than 1.5° would provide the volume necessary to cover the primary crater floor roughness. A decrease in slope of about 2° would provide the necessary volume of material to cover the central peaks (~2800 km³), while increasing the crater diameter by only about 12%.

Is slope recession a contributing factor in the degradation of crater walls and a source for crater fill? Data from Baldwin (1949) and Pike (1968, Table IV) indicate that the mean slope of crater walls decreases with increasing crater size and that for 27 craters, all in the 50–100 km diam range, the maximum slope was 14.8° and the mean was 7.2°. For a given crater size the average wall slope of older craters is less than that for younger craters. For instance, Copernicus (~12°) (~93 km diam) has a steeper wall slope than Alphonsus (~7°), an older (pre-Imbrian) crater (~110 km diam). There is similar evidence for changes in crater diam. Comparison of progressively older craters shows that rim crests become increasingly subdued (Pohn and Offield, 1970) usually due to erosion and rounding. In a crater such as Alphonsus
Fig. 11. Period I craters Flammarion (top, 75 km), Ptolemaeus (middle, 153 km), and Alphonsus (bottom, 118 km) in the lunar central highlands, south of the Imbrium basin. The 41 km Period II crater Herschel is seen just north of Ptolemaeus. Wall channels in the three Period I craters are developed preferentially in a NNW-SSE direction, radial to the Imbrium basin and parallel to grooves and furrows in the intercrater areas. Portion of Lunar Orbiter IV, 96M.
(Figure 11) there is uncertainty in the location of the rim crest, particularly in a north-south direction where erosion from Imbrium has been greater. This suggests that the original sharp rim crest has been eroded back. The uncertainty is of the order of 5–7 km for many areas along the rim. Thus the rim crest of Alphonsus may have migrated back as much as 10–15% of the crater diameter, which implies the erosion of a significant amount of wall material (∼3000 km³) for a crater of this size (Figure 10). Problems of rim crest location are even more acute with older craters such as Ptolemaeus (Figure 11). The cases of wall slope and rim crest migration illustrated in Figure 10 are simplifications. In the crater Alphonsus and Ptolemaeus, the development of radial wall channels is an additional important part of crater

Fig. 12. Development of channels in crater walls. Oblique view looking southwest along northern part of crater containing Mare Ingenii. Width of field in center of photo is approximately 75 km. Craters forming on a slope tend to be elongated in a down-slope direction (see pair of 5–10 km diam craters on wall and rim in foreground). Continued erosion and regional impact events tend to enhance the development of wall channels (AS15-91-12374).
wall degradation and migration (Figure 11). It is clear that although the slope is migrating, it is not an even, continuous process as illustrated in Figure 10. Crater wall channels are an important element in this migration and appear to form in at least two ways. Many channels originate from primary impacts since impacts forming on the interior wall slope tend to be slightly elliptical with the long axis parallel to the downslope direction. Repeated impacts and downslope movement of material tend to enhance this development (Figure 12) so that wall channels are built up by the same process which is degrading and destroying the terraces. An additional mode of

Fig. 13b.

Fig. 13a–b. Development of wall channels in Alphonsus and Ptolemaeus and relation to Imbrium basin crater chains. (a) Oblique view of the 153 km diam crater Ptolemaeus. Approximately one half of the crater Alphonsus is seen in the lower left. Wall channels in both these craters tend to be preferentially developed in a NNW direction (towards the upper left of the figure) in a direction radial to the Imbrium basin. (Portion of Apollo 16 Metric Frame 578). (b) Vertical view of the western half of Ptolemaeus. Wall channels in Ptolemaeus are seen to be continuous with extensive crater chains in intercrater areas, particularly to the west and north of Ptolemaeus. (Apollo 16 Metric Frame 991).
formation (Head, 1972) is illustrated by Alphonsus and Ptolemaeus where deeply furrowed wall channels are preferentially developed in a NNW-SSE direction, along a radial from the Imbrium basin (Figures 11, 13). This series of distinct radial channels parallels and is continuous with widespread secondary crater chains from the formation of the Imbrium basin (Head, 1974b). These craters and chains have reached down below the average slope and have excavated a considerable amount of local wall material, which was predominantly redeposited downslope and downrange on the crater floor. In conclusion, degradation of crater walls by wall slope migration and development of wall channels is a significant process in the modification of older craters. It provides a significant amount of locally derived material (Figure 10), the majority of which is deposited on the crater floor. This process provides material which is also important in modifying other crater characteristics such as crater floor morphology (disappearance of primary floor roughness and central peaks) and morphometric parameters (decrease in interior relief, \( R_i \), and increase in crater floor diam, \( D_f \)).

Is the process of secondary crater erosion and deposition effective in areas other than crater walls, and if so, does it contribute to crater modification? Reexamination of Figures 11 and 13 shows that the linear chains forming radial channels in Alphonsus and Ptolemaeus continue up onto crater rims and out into intercrater areas. In fact, the whole region (except for crater floors) is heavily lineated by secondary chains radial to Imbrium which originated from that event (Head, 1972, 1974b; Oberbeck et al., 1974). Oberbeck et al. (1973, 1974) have shown that secondary cratering events excavate many times the volume of the incoming material which forms the crater. For discrete secondary events and chains, Oberbeck and Morrison (1973a, b) and Head (1972) show how material is deposited downrange and that in a crater chain, the downrange craters are highly modified by ejecta from uprange craters. If these characteristics are now considered for a multi-ringed basin event, the effects are even more dramatic. Instead of single discrete chains of secondaries, a multiplicity of chains and clusters are forming in an extremely short period of time over a very broad area surrounding a multi-ringed basin. This implies that considerable volumes of local material are being excavated over a wide area at a given time and that the excavated material shows a net movement downrange. In the case of the Flammarion-Ptolemaeus-Alphonsus region (Figures 11, 13) secondary crater structures are primarily preserved on higher terrain such as crater walls, rims, and rough intercrater areas. Smooth plains materials are found in local lows at all elevations (Eggleton and Schaber, 1972), and in large regional lows such as crater floors and intercrater areas. These observations and associations strongly suggest that the intense secondary crater near-saturation bombardment of the regions surrounding a multi-ringed basin has mobilized vast quantities of local material and moved it preferentially into local and regional low areas. Since most of these low areas are craters (Figures 11, 13), this process is responsible for major crater degradation and filling.

In summary, this process (1) destroys crater floor, wall, and rim structure with secondary chains and clusters, (2) mobilizes material from these events, and (3)
Fig. 14. Avalanche deposit at the Apollo 17 Taurus-Littrow site. Top: topographic relationships shown in center photo. The bright deposit overlies dark material on the valley floor and appears to be an avalanche from the massif to the south (bottom). Contours are in meters; $A-A'$ is line of profile shown. Note lack of pile-up of debris at base of slope and preservation of sharp slope-valley floor interface. Modified from Howard (1973).
moves the material across the surface, depositing it in local and regional lows such as craters and intercrater areas. This process provides an additional large source of material outside the crater for transport into the crater and modification of crater floors, possibly decreasing $R_i$, and increasing $D_f$.

What are the characteristics of the process of secondary crater-induced slope erosion and deposition? A specific example of slope erosion is seen at the Apollo 17 site (Howard, 1973). There, secondaries impacted the top of the 2 km high South Massif and initiated an avalanche of debris down off the massif slope and out onto the flat floor of the valley for a distance of more than 4 km (Figure 14). This example is particularly significant for the following reasons:

1) mode of deposition – Howard (1973) has shown that this avalanche was as ‘efficient’ as terrestrial avalanches attributed to air-cushion sliding in spite of the lack of atmospheric lubrication or cushioning fluids on the Moon.

2) style of deposition – a very striking characteristic of the Apollo 17 avalanche is that it did not pile debris preferentially at the base of the slope, but instead spread it remarkably evenly over a large area (21 km$^2$) of the valley floor. Not only is it rather evenly dispersed, but the sharp nick point between the massif slope and the valley floor is distinctly preserved in the area of the avalanche deposit (Figure 14). This has two implications for crater degradation – (a) material shed off crater walls in a similar mode would not be deposited as a talus pile emplaced along the base of the crater wall, but instead would move out onto the crater floor for considerable distances to form a regionally smooth deposit; (b) the distinct break in slope characteristic of the intersection of the crater floor and wall would tend to be maintained and propagated in spite of mass movement of material across this boundary. Therefore this process, if recurrent, would tend to fill a crater floor (decreasing $R_i$), increase the diameter of the floor (increasing $D_f$), while preserving the relatively sharp boundary at the floor/wall interface. The characteristics of deposits of this process are very similar to crater flooding by lava fill, except that lavas do not usually modify the surface above their level of flooding.

3) Rate of process – Howard (1973) noted several avalanches on the Moon which had been initiated by secondary cratering but these features do not appear abundant enough to have been a major factor during the time of decreased flux (Period II). However, the characteristics of Period I suggest that this process would be extremely significant because of the higher flux rate, the proportionally similar increase in the rate of secondary cratering, and the increased maximum crater size (multi-ringed basins). This major difference in rates may help to explain why craters which have formed as long ago as 3.7 b.y. (early in Period II) still do not show signs of major morphologic change while those forming just prior to this in late Period I are greatly modified.

It is concluded that secondary-induced avalanches and their deposits represent an important process in crater morphologic degradation in terms of rates of modification, and degradation style (e.g., preservation of the sharp boundary between crater floor and wall) with time.
What role do multi-ringed basins play in crater modification? The nearside central highlands region provides an example of the effects of a single multi-ringed basin (Imbrium) on surrounding terrain (Figure 15). The Apennine Front is approximately 150–200 km from the rim of the Imbrium crater. From the Imbrium crater rim \( r = 485 \text{ km} \) outward (Figure 15b) to about 1.8 crater radii there is a distinct lack of pre-Imbrian craters at this scale. The continuous blanket, made up primarily of the Fra Mauro Formation (Figure 15c), has eroded, filled or blanketed most of the pre-existing craters. Farther out, pre-Imbrian craters become visible, and large linear chains radial to Imbrium have been mapped (Figures 15b, d). Abundant smaller chains also exist in this region (Figures 11, 13) but are not seen on this map scale. Imbrian plains units begin abruptly in this area of high density of crater chains and are most widespread there (Figure 15e). This appears to be an example of near-saturation bombardment by chain-forming secondary projectiles and the erosion of large amounts of material which move off highs into local and regional lows, such as crater floors (Figures 11, 13). Farther out \( \sim 4.5 \text{ crater radii} \) crater chains give way to distinct and separated crater clusters (Figures 15d, e). There is an accompanying marked decrease in the density of plains units. If the plains units are predominantly formed by mobilization and downslope movement of material by saturation cratering, then the patchiness of plains units at greater distances from the crater rim appears to be related to the decrease in density of secondary impacts and their formation in clusters rather than as a dense series of chains.

It is significant that the effects of a multi-ringed basin event (as outlined above) modify pre-existing craters to different degrees, as a function of range. If a series of fresh craters had formed on a radial to Imbrium just prior to the Imbrium event, they would show radically different morphologic age parameters just after the event even though they were all the same age (Figure 15f). Proximal craters would be destroyed or blanketed. Intermediate range craters would show degradation of virtually all parameters, increase in radial channels, decrease in \( R_i \), and increase in \( D_f \). They would go from \( \sim 7 \) on the Pohn and Offield scale (Figure 2) to somewhere in the range below \( 4 \). Distal craters would also be significantly modified, but to a lesser degree than more proximal craters.

In summary, multi-ringed basin erosion and deposition is an extremely significant modifier of crater morphologic parameters. This modification is achieved through depositional blanketing, secondary bombardment, and mobilization of material and deposition as flat plains in lows in a manner similar to the Apollo 17 avalanche deposit. The significant variations in the levels of crater modification from a single multi-ringed basin event indicate that the Pohn and Offield (1970) numbering system must be applied with extreme caution for craters formed during Period I \( (<4.5 \text{ on their scale, Figures 2, 3, 4}) \).

In conclusion, crater morphologic characteristics show dramatically different patterns in the two periods of lunar history (Figures 2, 3, 4). The different patterns are directly related to the distinctly different flux rates and size range of craters characteristic of the two periods. Elements of crater degradation and modification
Fig. 15a–f. Effect of multi-ringed basins in crater modification: the Imbrium basin-central highlands example. (a) Location map of Figure 15b–e. Apennine Mountain Front is about 150–200 km from the rim of the Imbrium crater. All geologic units and features are taken from Geologic Map of the Near Side of the Moon at a scale of 1:5 million (Wilhelms and McCauley, 1971). (b) All Pre-Imbrian craters > 25 km. (c) Craters formed subsequent to the Imbrium event and their ejecta blankets; dark area is maria deposited after Imbrium event. Majority of non-mare material north of 0° is Imbrium ejecta blanket, including Fra Mauro Formation. (d) Large linear crater chains (black) radial to Imbrium and of Imbrian age; Imbrian crater clusters are also mapped (enclosed by lines). (e) Imbrian plains (black). Maps 15b–e are plotted on a Lambert azimuthal equal area projection (Rükl, 1972). (f) Idealized cross-sectional model of Period I crater erosion showing the effects of a multi-ringed basin event and some specific examples for the Imbrium basin. Cross-section covers approximately the area in Figure 15a–e, extending north-south (not to scale).
during Period I include destruction of crater exterior, rim, and wall facies and structures, decrease in crater depth, and increase in crater floor width. Examination of fresh crater geometry reveals that major changes in crater depth and floor width parameters can occur with the addition of only minor volumes of material as crater fill. Volumes sufficient to produce these characteristic changes are readily available in the surrounding crater wall and rim deposits and can be derived by erosion associated with the observed morphologic changes. Depositional mechanisms associated with lunar landslides are capable of moving material across the crater floor-wall boundary while preserving the characteristic break in slope. In addition to the increased flux characteristic of Period I, crater degradation during this time is accelerated by the formation of multi-ringed basins. The widespread ballistic sedimentation associated with the formation of these basins (Figure 15f) produces a near-saturation bombardment which excavates and mobilizes large volumes of local material and preferentially moves it into nearby low regions. Seismic effects contribute to degradation by enhancing slope instability and by mobilizing material for downslope movement. The net effect for a crater influenced by multi-ringed basin formation is a tendency toward destruction of crater facies and structure by near-saturation bombardment and seismic effects, the erosion and mobilization of crater material, and the redeposition of the material in nearby low regions, primarily on the crater floor. This process appears to be of major importance in the degradation and modification of crater characteristics during Period I and is an important mechanism in the formation and propagation of Cayley-type plains surfaces. The role of volcanism in the modification of craters during Period I is still not well understood but appears subordinate to impact-related processes. Modification of craters formed during Period II is due primarily to the vertical influx of meteoritic material which is much reduced during this period (Figure 16).

Fig. 16. Schematic model of crater erosion for craters formed during Period II
(\(\sim 3.85-3.95\) b.y. to present).
4. Discussion and Implications of Models of Crater Degradation Processes

4.1. Morphologic Comparisons of Period I Craters

Concepts of crater degradation are based primarily on craters which formed during Period II. The steady and slow rate of change and style of degradation characteristic of these craters and this period differs substantially from that of Period I. The rapid and uneven weathering of craters by multi-ringed basins in the early part of lunar history (Figure 15f), illustrates the difficulty in trying to assign relative ages to Period I craters in different areas of the Moon on the basis of morphologic parameters.

4.2. Origin of Cayley-Type Plains

The association of smooth plains material with secondary crater clusters and chains from multi-ringed basins (Figure 15) suggests that Cayley-type smooth plains units primarily originate from a mode of deposition where near-saturation or heavy bombardment of secondaries mobilizes material and moves it into adjacent lows creating or enhancing smooth upland surfaces (Head, 1972; Oberbeck et al., 1974; Head, 1974b). Processes of crater degradation are closely associated with the source and mode of deposition of additions to plains surfaces.

4.3. Use of Period I Crater Depths to Detect Isostatic Readjustments

Baldwin (1963, 1968, 1970, 1971), Pike (1968, 1971), and others have cited decreases in crater rim height and floor depth from fresh craters to degraded craters as evidence for extensive isostatic readjustment for older lunar craters, and Baldwin has used variations in these relationships to predict the viscosity of the Moon's outer layers. The processes of degradation of these craters were thought not to be related to infilling by rim material because of volume considerations (Baldwin, 1963, p. 193) and not to be related to debris infilling or complete isostatic uplift because of smooth floors and the fluid-type flooding effect implied by the preserved nick point at the edge of the crater floor (Pike, 1971, pp. 388–390). However, the time scale supplied by subsequent dating of lunar samples indicates that although there is some overlap (Figure 6) the change in crater depth and floor width parameters is abrupt at the boundary between Periods I and II. This indicates that major changes were associated with the earlier period rather than proceeding at an even rate throughout geologic time. In addition, it has been shown (Howard, 1973) that the avalanche process is extremely efficient in moving material on the moon and that the process has the property of preserving the nick point at the base of slopes. Also, the effects of multi-ringed basin-induced erosion and redeposition, as outlined above, are volumetrically significant enough to provide considerably more fill than that considered by Baldwin (1963). The increased rate of fill would tend to decrease the mass anomaly and probably decrease the tendency toward isostatic uplift. Based on these considerations, it is concluded that the style and intensity of erosional and depositional crater modification processes in Period I are primarily responsible for the decrease in rim height and floor depth parameters during that period.
For this reason, further investigation of rheological properties of lunar crustal material using crater morphology should concentrate on the examination of specific craters showing evidence of movement and modification of crater rims and floors (e.g., Gassendi, Tauruntius).

4.4. IMPACT PIERCING OF THE LUNAR CRUST

Beals (1971) used the shallow, relatively smooth, flat floored appearance of many older lunar craters to hypothesize that they formed in an early thin-crust stage of lunar history by impact piercing and flooding of the crater floor. Although this hypothesis cannot be ruled out as a contributing factor in early lunar history, the lateral sedimentation outlined here is believed to be primarily responsible for the smoothed flat floors of these ancient craters.

4.5. USE OF PRE-EJECTA BLANKET CRATER GEOMETRY TO ESTIMATE THICKNESS OF EJECTA

Oberbeck et al. (1973, 1974) have shown that a secondary projectile excavates considerably greater than its own mass when forming a secondary crater. The important role of near-saturation bombardment by secondaries and lateral sedimentation in multi-ringed basin events (Figure 15) implies that a volume of material considerably greater than that ejected from the primary crater is excavated by secondaries. Therefore, approximations of the volume of material excavated from multi-ringed basin primary craters which are based on ejecta blanket thickness estimates would tend to be overestimates because of the volume of locally derived material added to the ejecta blanket. In addition, material excavated by secondary crater bombardment tends to be eroded off highs and deposited preferentially in lows. Therefore, basin ejecta thickness estimates derived from estimates of amount of material surrounding or filling pre-ejecta blanket craters are potentially affected by two factors: (1) the craters used in these estimates all formed in the intense period of weathering characteristic of Period I; therefore, they would probably not be morphologically fresh just prior to the event; (2) the process of multi-ringed basin ejecta deposition is largely an erosional process (Figure 15); therefore, pre-existing features with significant topographic relief such as craters will be even more degraded by the early stages of the ejecta event. These two factors suggest that use of depth/diameter and rim height relationships for fresh craters in estimating thickness of ejecta fill will tend to overestimate this thickness.

4.6. RESIDENCE TIME OF PERIOD I CRATERS

The high rate of modification of craters in Period I suggests that the residence time of a crater on the lunar surface during this period may be relatively short. Even though absolute rates are at present unknown, it seems unlikely that lunar highland craters dating from the period of earliest post-crustal formation could have survived throughout Period I as proposed by Baldwin (1970) and Hartmann (1971). It seems more likely that the vast majority of Period I lunar surface craters seen today formed in the terminal phases of Period I, although a few of the larger remnant multi-ringed
structures may be older. There is also evidence for an increased period of flux (terminal lunar cataclysm) late in Period I (Tera et al., 1974). The existence of such a period would further reduce the possibility of preservation of craters formed early in Period I.

4.7. Crater degradation and the Apollo 16 site

The geology of the Apollo 16 site illustrates several aspects of crater degradation processes. A degraded 60 km diam crater (unnamed crater B) centered about 25 km west of the Apollo 16 site (Head, 1974c) has been interpreted to be important in the history of the region. The flat Cayley plains are interpreted to be floored by shock-melted fallback and floor breccias while Stone and Smoky Mountains are composed of wall and rim deposits, all formed by the unnamed B crating event (Head, 1974c). Two 30–35 km diam craters (Dollond B, C) subsequently formed just to the northwest of unnamed B, eroding a portion of its rim and depositing some material on its floor. The Imbrium cratering event then heavily bombarded the region with secondaries and produced a dense northwest-trending series of grooves and furrows from these secondary chains. Material excavated by these crater chains was redeposited in low regions, obscuring the crater chains in these lows and adding locally excavated material to the originally smooth-surfaced crater floor, preserving its plains-like nature. The sequence at the Apollo 16 landing site thus appears to contain an upper layer of breccias which were derived from local material excavated from surrounding terrain by intense bombardment by Imbrium secondaries. This unit overlies breccias which represent the floor deposits of the unnamed B crating event (Head, 1974c). The plains units within most highland craters appear to result from the addition of erosional products to originally flat crater floors.

4.8. Crater degradation on Mars

The association of major crater degradation with the period and process of early intense lunar cratering suggests that a similar high rate of degradation may be associated with the period and process of formation of early craters on Mars. Chapman et al. (1969) have proposed that such a period existed based on the intensity of cratering. The lunar analogy suggests that the fundamental degradation of early Martian craters may be associated with erosional and depositional processes related to the intense bombardment characteristic of this early period. As outlined by Soderblom et al. (1974), and Pike (1971) other processes (aeolian, volcanic, fluvial) continue to modify craters during subsequent Martian history.

Acknowledgements

This work was performed under National Aeronautics and Space Administration grant NGR-40-002-116 which is gratefully acknowledged. Thanks are extended to the National Space Science Data Center for providing many of the photographs used in this study. The help of Ross Stein, Ken Jones, T. A. Mutch, Mark Settle, Ray
Arvidson, Andrew Miller, and Bruce Wilks in discussion and review of the manuscript and the help of Dan Dickinson, John Ladd, Sven Grenander and Jacqueline Taylor in the preparation of the manuscript is gratefully acknowledged.

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