The Role of Rim Slumping in the Modification of Lunar Impact Craters

Mark Settle and James W. Head III

Department of Geological Sciences, Brown University, Providence, Rhode Island 02912

Wall failure has significantly altered the structure of virtually all large, fresh-appearing lunar craters. Wall blocks exposed on a crater's interior walls are interpreted to be sections of the transient cavity rim that slumped into the cavity during the terminal stages of crater formation. Impact excavation cavities have been reconstructed by depositing the innermost terrace block exposed within a crater to its inferred original position at the cavity rim and accounting for the volume of material that slumped into the cavity. Critical model assumptions include (1) the radial variation of topography near the initial cavity rim crest, (2) the structure of the failure surface along which wall blocks slumped into the cavity, and (3) the geometric shape of the initial cavity. The terrace restoration model has been applied to 12 fresh lunar craters with observed rim crest diameters Dc ranging from 19 to 137 km. Up to an initial cavity diameter Dc of 30 km, reconstructed cavity depths are comparable to or greater than cavity depths extrapolated from nonterraced craters of less than 15 km in diameter. For a wide range of model parameters the reconstructed depths of impact cavities 15-30 km in diameter are significantly greater than depths predicted by small-crater morphometry, implying that cavity depths inferred from depth/diameter ratios observed for small craters may substantially underestimate the depth of impact cratering events in this size class. Reconstructed cavity depths for Dc > 70 km, however, are consistently less than cavity depths extrapolated from smaller craters. This indicates that the morphometric transition from small, relatively unmodified, bowl-shaped craters (Dc < 15 km) to large, terraced, saucer-shaped craters (Dc > 80-90 km) cannot be solely attributed to rim-slumping modification. Ejecta fallback and basement rebound also play a role in modifying impact crater cavities, however, the manner in which the volume of fallback ejecta and basement rebound material varies with increasing crater size is unknown. The discrepancy between cavity depths extrapolated from small craters and those obtained from the terrace restoration model suggests that impact excavation cavities become relatively shallower at larger diameters. However, this cannot be conclusively demonstrated until the effects of rebound and ejecta fallback are quantitatively accounted for.

INTRODUCTION

The shape of lunar impact craters varies significantly with increasing crater size. Craters with rim diameters Dc less than 12-15 km are characterized by an average ratio of depth/diameter of 1:5. The depth/diameter ratios of larger craters consistently decrease with increasing crater size, ranging from 1:8 for craters 20 km in diameter to 1:30 for craters with diameters of 140 km [Pike, 1977a]. This morphometric transition is accompanied by a distinctive variation in crater morphology. Large craters exhibit complex terraced walls, floor hummocks, central peaks, and flat floors [Smith and Sanchez, 1973; Howard, 1974; M. Cintala and J. W. Head, manuscript in preparation, 1979] which are inferred to have formed during the terminal stages of crater formation [Gault et al., 1968; Dence, 1968; Quaide et al., 1965]. The frequency with which terraced, central peaks, and flat floors occur in fresh lunar craters increases with increasing crater size [Cintala et al., 1977], suggesting that modification phenomena such as rim slumping, floor rebound, and ejecta fallback become increasingly pervasive in larger craters.

Wall terraces are prominent features in large lunar craters. The mechanism of terrace formation is qualitatively understood to be a slumping process in which segments of the rim of the initial crater cavity are translated downward and inward [e.g., Shoemaker, 1962; Guest and Murray, 1969; Mackin, 1969]. Rim slumping increases the rim crest diameter of a crater and decreases its depth, thereby reducing the depth/diameter ratio. Although rebound and fallback may play important roles in cavity modification, several investigators have proposed that rim slumping may be primarily responsible for the transition in lunar crater morphometry that occurs at diameters of 10-20 km [Quaide et al., 1965; Gault et al., 1975; Malin and Dzurisin, 1978]. The purposes of this study are to analyze the process of rim slumping and to measure the effect of terrace formation on the shape of large lunar craters. Preliminary results have been presented previously [Settle and Head, 1976, 1978].

Knowledge of the depth of impact excavation cavities would provide important information on the maximum depth of material exposed within a crater's ejecta deposit (termed 'swirl texture' by Smith and Sanchez [1973]). The initial geometry of very large craters and basins. Present estimates of the maximum depth of ejecta excavated by basin-sized impacts such as Imbrium range from 30 km to 200 km [Head et al., 1975; Dence et al., 1974].

RIM SLUMPING MECHANISM: MORPHOLOGICAL EVIDENCE

Variations of Slumping Mechanism With Crater Size

Differences in the observed morphology of crater walls suggest that the mechanism and the scale of wall failure vary with crater size and substrate [Cintala et al., 1977]. Many craters 15-20 km in diameter are characterized by cuspate rims and contain so-called 'scallopl features at the base of their exposed interior walls (Figure 1a). Scallopl deposits are characterized by a distinctive surface texture consisting of a series of closely spaced, crescent-shaped ridges of low topographic relief (termed 'swirl texture' by Smith and Sanchez [1973]). The arcuate outline of the head scarp associated with each scallop deposit is responsible for the cuspate appearance of the crater rim (Figure 1a). The arcuate, ridged appearance of scallop deposits suggests that the initial cavity rim slumped as a series of sheets of material that each maintained some coherence and moved in relation to one another during their descent en masse into the cavity [Smith and Sanchez, 1973; Cintala et al., 1977].
Wall terraces initially appear in fresh lunar craters 20–30 km in diameter and occur with increasing frequency in larger-sized craters. All fresh lunar craters greater than 70 km in diameter contain distinctive terraced walls [Cintala et al., 1977]. Craters with terraced walls generally exhibit polygonal rim outlines [Quaide et al., 1965]. Terraces are characterized by scarps facing the center of a crater and by relatively flat tops (ledges) arranged in a stair-step manner from floor to rim crest (Figure 1b). The gross morphology of wall terraces indicates that individual terrace blocks possessed considerable coherence during the slumping event. In any particular sector of a crater wall, contacts between terrace ledges and adjacent head scarps are generally subparallel, indicating that individual terrace blocks slumped along a series of imbricate failure surfaces. However, the location and morphology of the leading edges (toes) of terrace blocks near the crater centers are obscured by fallback and impact melt deposits (Figure 1b). The frontal edges of terrace blocks may have been partially destroyed owing to convergence at the crater center and/or central rebound of the crater floor.

Dence [1968] has suggested that the slip surfaces involved in terrace slumping extend to the center of the crater and that central peaks develop as part of the collapse process. However, central peaks can be found in craters that do not possess terraced walls (for example, Diophantus, 27.8°N, 34.3°W). In addition, theoretical calculations by Ullrich [1976] indicate that upward movement beneath the base of a crater cavity may occur completely independently of rim collapse phenomena as the result of stress-wave interaction. Unfortunately, there is very little morphological or theoretical evidence that can be used to determine the subsurface configuration or inward extent of terrace block failure surfaces.

The transition from one style of rim slumping to another is gradational and occurs over a range of crater sizes. Several craters contain some combination of scallops and terraces, indicating that more than one type of failure mechanism operated within a single crater (for example, note the structural contrast between the northeast and southwest walls of Lalande, 4.5°S, 8.7°W). Comparison of the style of slumping within craters 15–50 km in diameter generally indicates that with increasing crater size the failure surface migrates outward beyond the cavity rim crest, engulfing increasingly larger portions of the initial cavity rim.

**Nature of Terrace Failure Surfaces**

If individual terraces behaved as perfectly coherent blocks during a rim-slumping event and if subsequent degradation of the crater wall was insignificant, the observed structure of terraces would represent the actual configuration of the terrace blocks at the conclusion of the slumping event. However,
In contrast to the crater Dawes (Figure 1a), the crater Timocharis ($D_o = 34$ km) is characterized by a polygonal rim outline and terraced crater walls. Terrace ledges are interpreted to be sections of the rim and walls of a crater’s initial excavation cavity that slumped into the cavity during the terminal stages of crater formation. The structure and morphology of wall terraces indicate that terrace blocks maintained considerable coherence during the rim slumping event.

Terrace blocks consist of fractured and brecciated crustal material, and it is unlikely that these blocks would slump as perfectly coherent masses in the absence of a lubricating agent such as groundwater [Sharpe, 1938]. Consequently, talus movement along head scarps during and after slumping may modify the original configuration. In many fresh craters the boundary between the head scarp above a terrace and the actual ledge forming the top of the terrace block is sharply delineated and locally linear. Furthermore, in certain fresh craters such as Aristarchus, terrace ledges exhibit a concentric surface texture similar to ejecta deposits beyond the crater’s rim crest. If extensive mass wasting had occurred, then the contacts between terrace ledges and head scarps would be irregular, and primary ejecta textures on terrace ledges should have been destroyed. On the basis of this morphological evidence we conclude that modification of the terraced walls of fresh craters has been relatively limited and that the observed configuration of terraces within fresh craters is representative of the wall structure at the end of the main slumping event. This conclusion is supported by the unmodified nature of impact melt deposits found on crater walls and floors [Hawke and Head, 1977].

Morphometric evidence also indicates that the structure of terraced walls within fresh craters has not been severely altered by talus movement. In general, the inclination of the face scarps of individual terrace blocks increases with increasing radial range from a crater’s center. For example, Figure 2 displays the variation of wall slope along the east wall of the crater Timocharis ($D_o = 34$ km) as a function of normalized radial range. The position of terrace scarps is indicated by vertical arrows in Figure 2; terrace ledges are areas of relatively low inclination. The maximum slope of terrace face scarps on the east wall of Timocharis varies from $24^\circ$ to $32^\circ$ with increasing range. If mass-wasting processes had extensively modified the terraced walls of Timocharis, it is unlikely that the inclination of terrace scarps would vary in this manner, but rather terrace scarp slopes would all be approximately constant and equal to the angle of repose of fragmental crustal material. Similar variations in terrace scarp slope are observed in other fresh craters (Figure 5; $R_o$ is crater rim crest radius). If the face scarps of individual terrace blocks have not been severely deformed in the latter stages of a slumping event, as argued above, then the head scarp above a particular terrace ledge represents a vestige of the terrace failure surface. The
Terrace blocks are inferred to be segments of the rim and walls of the initial crater cavity that slumped along a series of imbricate, curved failure surfaces during the latter stages of crater formation. The subsurface extent and configuration of terrace failure surfaces are unknown. Terrace scarps observed within fresh craters are represented by areas of high inclination to the left of vertical arrows denoting scarp crests. Note that wall slope decreases near the crater’s rim crest.

The maximum slope observed along a head scarp should thus be approximately equivalent to the inclination of a planar surface locally tangent to the original failure surface. If the imbricate failure surfaces separating individual terrace blocks can be considered approximately parallel in the vicinity of the initial cavity rim (see Figure 3), then the inclinations of head scarps situated at progressively lower elevations should reflect the manner in which the shape of the slumping failure surface varied with depth. The fact that the slope of terrace scarps increases as a function of radial range (as shown in Figure 2) implies that terrace blocks have slumped along curved failure surfaces which are highly inclined near the original ground surface and less steeply inclined at greater depths.

Timing of the Event

Various features on terraced walls are interpreted to be impact melt deposits emplaced during the cratering event [Howard and Wilshire, 1975; Hawke and Head, 1977], including (1) smooth dark pools of material perched on terrace ledges and (2) lavalike flows with and without well-drained channels and levees. Flow features and cracks associated with these melt deposits indicate that the material was molten and behaved in a fluid manner at the time of emplacement. Superposition of melt deposits on terraced walls indicates that the main slumping event must have occurred during the latter stages of the cratering event. Gault et al. [1968] used the term modification stage to describe short-term and long-term crater modification processes. However, we use the term in a more restricted sense, as the modification stage of the cratering event, to refer to those processes operating in the terminal stages of the event which modify the shape of the transient crater cavity.

**Idealized Terrace-Slumping Process**

In order to develop a method for restoring terraces to their preslump positions it is necessary to formulate a conceptual model of the terrace-slumping process. On the basis of the observations cited above we envision that a major section of the cavity rim slid down into the cavity as a collection of discrete blocks separated by a series of failure surfaces in the terminal stages of the cratering event (Figure 3). These failure surfaces were curved zones of rupture that were approximately parallel in the vicinity of the initial cavity rim; their location and structure in the vicinity of the cavity floor are unknown. Failure may have occurred as the result of (1) mechanical instability of the cavity walls under the influence of gravity [Quaide et al., 1965; Gault et al., 1975; Melosh, 1977], (2) late-stage reorientation of the flow field within the target material, resulting in vortical downward and inward motions in the vicinity of the cavity rim [Maxwell and Moises, 1971; Ullrich, 1976], or (3) some combination of these two mechanisms [Ullrich et al., 1977]. Although the actual manner in which failure occurs is unknown, material along the failure surfaces was probably deformed extensively in an irreversible nonelastic fashion. We assume a plastic mode of failure during the slumping process [see Melosh, 1977], implying that the terrace blocks possessed some combination of cohesive and frictional shear strength. Analytical solutions to slope stability equations were initially developed by Sokolowski [1965] for plastic failure by ignoring the weight of the slope material [see Harr, 1966; Scott, 1963]. These solutions indicate that (1) failure occurs along a logarithmic spiral slip surface if the material possesses frictional strength and (2) failure occurs along a circular arc slip surface in purely cohesive materials. Civil engineering techniques for determining slope stability, such as the Swedish circular arc method and the method of slices, also employ circular arcs and logarithmic spirals to represent slump failure surfaces [Wu, 1976]. It seems likely that terrace blocks were translated along a failure surface that could be approximated by one of these geometric shapes.

---

**Fig. 2.** Variation of wall slope along the eastern interior wall of Timocharis as a function of normalized radial range. Timocharis possesses a flat floor that extends to a range of 0.34 crater radius. Wall scarps are represented by areas of high inclination to the left of vertical arrows denoting scarp crests.

**Fig. 3.** Schematic diagram of idealized terrace-slumping event described in the text. Terrace blocks are inferred to be segments of the rim and walls of the initial crater cavity that slumped along a series of imbricate, curved failure surfaces during the latter stages of crater formation. The subsurface extent and configuration of terrace failure surfaces are unknown. Terrace scarps observed within fresh craters are interpreted to be vestigial remnants of terrace block failure surfaces.
Reconstruction of the initial crater cavity is accomplished by a two-step method. In the first step the radius of the initial cavity is inferred by determining the point of intersection between (1) a polynomial equation representing the craterward extension of observed rim topography and (2) a model failure surface which is tangent to the face scarp of the innermost exposed terrace (Figure 4). The face scarp of the innermost terrace block is assumed to be a remnant of the rim wall of the initial cavity. The model failure surface conforms to a specific geometric shape and represents the hypothetical path along which the initial cavity rim wall slumped. Strictly speaking, the translation path of the cavity rim wall is not a ‘failure surface,’ since the wall of the initial cavity is an unbounded (free) surface during a slumping event. However, owing to the imbricate nature of the terrace failure surfaces and the assumption that deformation principally occurred along failure surfaces, this translation path should have paralleled the innermost failure surface (Figure 3). If this failure surface can be represented by a particular geometric curve, such as a logarithmic spiral or a circular arc, then the translation path of the cavity rim wall should be represented by a similarly shaped curve. The model failure surface is constrained to be inclined at a particular angle θ at the rim of the initial cavity. In the second step of the reconstruction method a geometric shape such as a cone or paraboloid is assumed for the failure surface. The depth of the cavity is inferred by determining a specific geometric surface for which the volume of material forming the rim and upper wall of the initial cavity (vertically hatched area in Figure 4) is equal to the volume of material presently situated between the crater floor and the bottom of the initial cavity (crosshatched area in Figure 4). This model assumes no net bulking (i.e., density change) of material involved in the slumping process.

We now examine the assumptions involved in defining the terrace restoration technique:

1. **Cavity rim topography.** A crater’s presently observed rim crest and exterior deposits represent the unslumped portion of its initial cavity rim. It is assumed that the topographic structure of the initial cavity rim can be approximated by extrapolating presently observed radial topographic trends inward toward a crater’s center. Preslump rim topography is specified by a polynomial equation fit by the method of least squares to the presently observed exterior topography. In relatively flat regions this polynomial fitting procedure is applied between 1.0 and 2.5Ro. However, in areas of highly variable preexisting topography (for example, highland terrain) the fitting procedure is applied between 1.0 and a minimum range of 1.5Ro. The purpose of this polynomial equation is to describe major topographic trends. Therefore the equation was constrained to be the lowest-order polynomial expression that achieved a correlation coefficient of 0.90 or better with the observed exterior crater topography (a sampling of graphical results is presented in Figure 10). It was found that polynomials of third degree and lower order were able to satisfy this criterion for all craters occurring on mare surfaces or at mare/highland boundaries. Highland craters characterized by exteriors which could not be represented by a third-degree or lower-order polynomial expression (with correlation c > 0.9) were not considered for further analysis.

2. **Initial cavity rim wall.** The face scarp and ledge of the innermost terrace are assumed to correspond to the rim wall and rim crest of the initial crater cavity (Figure 3). The structure and morphological characteristics of wall terraces within fresh craters indicate that individual terrace blocks maintained considerable coherence during the slumping event, implying that deformation principally occurred along failure surfaces. If the upper portion of the innermost terrace block was not extensively deformed during the slumping event, the slump path of the cavity rim wall should parallel the innermost terrace failure surface. Under these circumstances the inclination of the rim wall slump path at the cavity rim crest (angle θ in Figure 4a) is approximately equivalent to the inclination of the innermost terrace failure surface near the initial cavity rim (angle θ in Figure 3). The model failure surface corresponding to the translation path of the cavity rim wall is therefore constrained to be tangent to the face scarp of the innermost terrace and to be inclined at a specific angle θ at the cavity rim (Figure 4).

Measurements of rim scarp slopes within terraced craters can be used to estimate the inclination of terrace block failure surfaces near the initial cavity rim. The maximum slope observed on scarps beneath a crater’s rim crest should approximate the inclination of the outermost failure surface at the ground surface. Crater wall slope is measured as a function of normalized radial range in Figure 5 for the 12 large terraced craters selected for analysis (Table 1). Wall slope was measured over horizontal distances of several kilometers using topographic contour data from Lunar Topographic Orthophotomaps. Maximum values of wall scarp slope occur near the observed crater rim at ranges of 0.8–1.0Ro and generally range from 25° to 45°.

Localized mass-wasting processes would tend to reduce the
initial slope of a crater’s rim scarp. Furthermore, failure surfaces nearer a crater’s center most likely intersected the exterior ground surface at slightly higher angles than the outermost failure surface owing to the curved nature of the failure surfaces and the general increase in elevation towards the rim crest. Therefore innermost terrace failure surfaces may have intersected the cavity rim at an angle somewhat greater than 45°. An angle of 60° is considered to be a reasonable estimate of the inclination of the model failure surface at the rim crest of the initial cavity (angle θ in Figure 4). However, cavity reconstruction results will also be presented for θ = 45°.

3. Initial cavity shape. The shape of the initial cavity can be approximated from the characteristics of small, fresh, non-terraced lunar craters (1 km < Do < 15 km). The structure of these small craters provides the best approximation of transient cavity shape presently available, although some wall failure has occurred [Wood and Andersson, 1978]. In high-resolution photographs the flanks and toes of individual rock slides can be identified on small crater walls [Howard, 1973]. Downslope talus movement will reduce the curvature of the initial cavity walls and decrease the depth of the initial cavity. However, in comparison to larger craters in which the initial cavity has been completely destroyed, we will consider small fresh craters to be relatively unmodified.

The radial variation of interior crater topography can be described by the equation

\[ y = \left( \frac{r}{R_0} \right)^a \]

where \( y \) is the elevation above a crater’s floor, \( d_o \) is the observed rim crest-to-floor crater depth, \( r \) is radial range from a crater’s center, and \( R_0 \) is the observed rim crest radius of a crater, all in meters. A conical crater shape would be represented by \( a = 1 \) in (1), whereas a parabolic crater shape would be represented by \( a = 2 \). The observed variation of interior elevation as a function of radial range within five morphologically fresh craters with \( D_o < 15 \) km is shown in Figure 6 (see Table 2). The shape of these craters is intermediate between a conical (\( a = 1 \)) and parabolic (\( a = 2 \)) geometry. Localized wall failure has probably reduced the initial curvature of the walls, and it is likely that the initial cavities correspond more closely to a parabolic shape than to a conical geometry. However, results will be presented for different cavity shapes. We note that Dence [1973] has suggested that the initial cavities of impact craters possess parabolic shapes on the basis of field studies of terrestrial impact structures.

4. Angle of friction during terrace slumping. To determine the logarithmic spiral failure surface appropriate to plastic failure in frictional materials, it is necessary to specify the angle of friction \( φ \) of material involved in the slumping process [Sokolovski, 1965; Scott, 1963]. Soil mechanics experiments conducted at the Apollo landing sites indicate that the lunar regolith possesses an average angle of friction ranging from 38° to 42° [Mitchell et al., 1973, Table 8-V]. Analysis of boulder tracks at the Apollo 17 landing site suggests a wider range of 28°–50° ([Mitchell et al., 1973, Table 8-III]; see also results of the Apollo 16 penetrometer experiments [Mitchell et al., 1972, Table 8-VIII]). Melosh [1977] has argued that the strength of lunar crustal materials should decrease significantly during a large-scale cratering event, and thus the effect

<table>
<thead>
<tr>
<th>Crater</th>
<th>Average Diameter, km</th>
<th>Age</th>
<th>Substrate</th>
<th>Location</th>
<th>Data Source</th>
<th>Cross-Section Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delisle</td>
<td>26</td>
<td>E</td>
<td>mare</td>
<td>30°N, 35°W</td>
<td>LTO39B1, B2</td>
<td>N23°E, S23°E, W12°N</td>
</tr>
<tr>
<td>King</td>
<td>75</td>
<td>C</td>
<td>mare</td>
<td>5°N, 121°E</td>
<td>LTO65C1, C4, D2, D3</td>
<td>S16°W, S41°W</td>
</tr>
<tr>
<td>Lambert</td>
<td>30</td>
<td>E</td>
<td>mare</td>
<td>26°N, 21°W</td>
<td>LTO40A3, B4</td>
<td>N39°E, E30°S, S47°W, N56°W</td>
</tr>
<tr>
<td>Langrenus</td>
<td>135</td>
<td>C</td>
<td>mare/highland border</td>
<td>9°S, 61°E</td>
<td>LTO80B4, C1, D2</td>
<td>N2°E, S29°E, W19°S, N17°W</td>
</tr>
<tr>
<td>La Perouse</td>
<td>80</td>
<td>IC9</td>
<td>highland</td>
<td>11°S, 76°E</td>
<td>LTO81D2</td>
<td>N0°E, N54°E, E5°S</td>
</tr>
<tr>
<td>Madler</td>
<td>27</td>
<td>C</td>
<td>mare/highland border</td>
<td>11°S, 30°E</td>
<td>LTO78C2, 79D1</td>
<td>E23°N, W28°N</td>
</tr>
<tr>
<td>Peirce</td>
<td>19</td>
<td>E</td>
<td>mare</td>
<td>18°N, 53°E</td>
<td>LTO44D4</td>
<td>N25°E, W33°S, N43°W</td>
</tr>
<tr>
<td>Picard</td>
<td>24</td>
<td>E</td>
<td>mare</td>
<td>15°N, 55°E</td>
<td>LTO62A1, A2</td>
<td>E9°S, S20°E, W33°S, N19°W</td>
</tr>
<tr>
<td>Plinius</td>
<td>43</td>
<td>E</td>
<td>mare</td>
<td>15°N, 24°E</td>
<td>LTO60B1, B2, 42C4</td>
<td>N4°E, E41°S, W35°S</td>
</tr>
<tr>
<td>Sklodowska</td>
<td>116</td>
<td>IC9</td>
<td>highland</td>
<td>18°S, 96°E</td>
<td>LTO100A1, A2</td>
<td>W27°S</td>
</tr>
<tr>
<td>Theophilus</td>
<td>95</td>
<td>C</td>
<td>mare/highland border</td>
<td>11°S, 26°E</td>
<td>LTO78C2</td>
<td>N26°E, N13°W</td>
</tr>
<tr>
<td>Timocharis</td>
<td>34</td>
<td>C</td>
<td>mare</td>
<td>27°N, 13°W</td>
<td>LTO40B2, B3</td>
<td>N49°E, N90°E, W25°S, W39°N</td>
</tr>
</tbody>
</table>

Crater selection criteria are discussed in the text. Structural data for individual craters were compiled from Lunar Topographic Orthophotos (LTO’s) along a variety of crater cross sections. Crater ages as given by Wilhelms and McCauley [1971] and Wilhelms and El-Baz [1977].
tive angle of friction of crustal material during terrace slumping may be much less than values determined by static measurements. It is assumed here that values of 5° and 50° bracket the range of friction angles characterizing lunar crustal materials during terrace slumping. Both angles have been employed in restoring terrace blocks along logarithmic spiral failure surfaces.

Data Sample

The cavity reconstruction model was applied to 12 fresh craters 19–137 km in diameter. Crater morphometric data were compiled from Lunar Topographic Orthophotomaps (LTO, prepared by NASA and the Defense Mapping Agency; 1:250,000 scale with a nominal 100-m contour interval) using an electronic digitizing board (accuracy, ±0.25 mm) and a Hewlett-Packard 9830A minicomputer for data storage. The size, age, and background terrain of craters within the data set are documented in Table 1. Craters were selected for analysis on the basis of (1) fresh morphological appearance (i.e., pristine ejecta textures and well-defined terraced walls characterized by steep rim scarps and nondissected terrace ledges [see Pohn and Offield, 1970; Head, 1975]), (2) craters possessing depth/diameter ratios and rim height/diameter ratios representative of other fresh craters of similar size [see Pike, 1977a], (3) the availability of topographic data (topographic maps presently exist only for areas on or adjacent to the ground tracks of the Apollo 15, 16, and 17 missions [Kinsler, 1975]).

Craters with diameters smaller than 70 km in Table 1 were formed in Copernican or Eratosthenian times (all less than ~3 b.y. old). Owing to the scarcity of young craters greater than 70 km in diameter, a few Imbrian-aged craters inferred to be younger than or contemporaneous with the Orientale cratering event are included in the data sample (Table 1).

Positive Bouguer gravity anomalies interpreted to result from isostatic structural adjustments are exclusively associated with larger (D ≥ 200 km) and older craters [Phillips et al., 1976]. Craters within the data sample are consistently smaller and younger than craters characterized by such positive gravity anomalies, implying that the craters analyzed here have not experienced major structural modifications due to long-term isostatic compensation.

<table>
<thead>
<tr>
<th>Crater</th>
<th>Rim Crest Diameter D₀, km</th>
<th>Rim-to-Floor Depth dₒ, km</th>
<th>dₒ/Do</th>
<th>Age</th>
<th>Location (Data Source)</th>
<th>Cross-Section Directions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borel</td>
<td>4.9</td>
<td>1.10</td>
<td>0.22</td>
<td>E</td>
<td>22.4°N, 26.4°E (LTO42C2)</td>
<td>N8°W, S41°W</td>
</tr>
<tr>
<td>Cauchy</td>
<td>12.2</td>
<td>2.69</td>
<td>0.22</td>
<td>C</td>
<td>9.6°N, 38.7°E (LTO61A3)</td>
<td>N47°W, E5°N</td>
</tr>
<tr>
<td>Deseilligny</td>
<td>6.2</td>
<td>1.28</td>
<td>0.21</td>
<td>E</td>
<td>21.1°N, 20.6°E (LTO42C1)</td>
<td>N25°W, S41°E</td>
</tr>
<tr>
<td>Kuiper</td>
<td>6.8</td>
<td>1.64</td>
<td>0.24</td>
<td>C</td>
<td>9.8°S, 22.7°E (LTO76D2)</td>
<td>N40°E, W2°N</td>
</tr>
<tr>
<td>Sarabhai</td>
<td>7.5</td>
<td>1.80</td>
<td>0.24</td>
<td>E</td>
<td>24.8°N, 21.0°E (LTO42B4)</td>
<td>N14°W, W6°S</td>
</tr>
</tbody>
</table>

Crater ages have been determined from the 1:1,000,000 scale U.S. Geological Survey map series for the lunar nearside. These craters possess circular rim outlines, concave interior walls, small flat floors, and depth/diameter ratios characteristic of small fresh lunar craters [Pike, 1975a,b]. Rim-to-floor depth has been measured between a crater's maximum rim crest elevation and minimum floor elevation. Morphological and morphometric evidence indicates that rim-slumping modification of these small craters is relatively limited in comparison to larger terraced craters. The interior structure of these craters, measured along cross-sections specified in the table, is displayed in Figure 6.
Slumping is then equivalent to the depth of a paraboloid for a parabola (a = 2 in (1)). Cavity depth prior to slumping is calculated through an iteration process by assuming a generalized geometric shape for the initial cavity. This terrace is restored by the method illustrated in Figure 7 with an initial diameter of 23,640 m. Thus for the set of model parameters employed in Figure 7 the cavity reconstruction method produces an estimate of Timocharis cavity depth that is significantly greater than the depth predicted by extrapolating small-cavity depth/diameter ratios to crater cavities greater than 15 km in diameter.

Results for Entire Data Sample

Inspection of the interior structure of large craters reveals that the position of terrace ledges, the number of terraces exposed, and the inclination of terrace scarps may be quite different in different sectors of a single crater. In addition, the radial variation of exterior topography may vary significantly in different directions [Settle and Head, 1977]. Average cavity dimensions can be determined by applying the terrace restoration technique to several cross-sectional profiles at individual craters. In some cases, such as Theophilus and Sklodowska, topographic data are only available for certain crater sectors; in other cases, such as King, preexisting topography is extremely variable, and no low-order, monotonically decreasing polynomial expression can be fit to the topography lying beyond certain sections of the crater rim. These considerations restricted the number of cross-sectional profiles that could be examined at certain craters.

Estimates of initial cavity rim diameter \( D_0 \) and cavity depth below the original ground surface, \( d_{int} \), for the entire data sample (Table 1) are presented in Figures 8 and 9 for a circular arc and logarithmic spiral failure surface, respectively. Both hypothetical failure surfaces were constrained to be inclined at an angle of 60° at the cavity rim (angle \( \theta \) in Figure 4); a parabolic initial cavity was employed in determining cavity depth in both Figures 8 and 9. An angle of friction \( \phi \) of 30° was used in determining the logarithmic spiral failure surfaces. Examples of reconstructed (prespum) cavities determined by restoring terraces along circular arc failure surfaces are illustrated in Figure 10 for specific cross sections within the craters Delisle (\( D_0 = 26 \) km), King (\( D_0 = 75 \) km), and Langrenus (\( D_0 = 137 \) km).

In both Figures 8 and 9 the order of the polynomial expression used to represent the radial variation of exterior topography in different directions is designated by different symbols: circles signify first-order polynomials, diamonds signify second-order polynomials, and triangles signify third-order polynomials. Higher-order polynomials indicate that rim elevation increases at a greater rate with decreasing radial range. Therefore if the interior structure of each crater was reasonably uniform, then, in general, greater volumes of slumped rim material would be estimated by the higher-order polynomial equations, and larger estimates of initial cavity depth would be preferentially associated with higher-order polynomial expressions. However, the data in Figures 8 and 9 indicate that there is no consistent relationship between cavity depth estimates and the order of the polynomial representing failure surface along which the innermost terrace block slumped into the initial crater cavity. This circular arc is constrained to be tangent to the face of the innermost terrace block and to be inclined at a predetermined angle (\( \theta = 60° \)) at the rim of the initial cavity. The model circular arc failure surface (dotted line, Figure 7a) is extrapolated upward, and the polynomial equation representing exterior crater topography is extrapolated inward to a point of intersection which is taken to be the radius of the preslump cavity. Along the northeast Timocharis cross section the observed crater rim crest (5840 m elevation) occurs at a range of 16,770 m (1.03\( R_c \)) from the center of the crater and the ledge of the innermost terrace is situated at a range of \( \sim 10,000 \) m (0.60\( R_c \)) and 4100-m elevation. This terrace is restored by the method illustrated in Figure 7a to an initial position at a range of 11,820 m (0.70\( R_c \)) and an elevation of 6915 m.

Once the initial radius of Timocharis is specified, cavity depth prior to slumping can be determined by accounting for the volume of wall and rim material that slumped into the cavity. Cavity depth is calculated through an iteration process by assuming a generalized geometric shape for the initial cavity such as a parabola (\( a = 2 \) in (1)). Cavity depth prior to slumping is then equivalent to the depth of a paraboloid for which the volume of material initially situated above the terraced wall of the observed crater (vertically hatched region in Figure 7b) exactly equals the volume of material presently situated above the model cavity and below the floor of the observed crater (crosshatched region in Figure 7b). The rim-to-floor depth observed along the northeast cross section of Timocharis is 9350 m. In comparison, a depth/diameter relationship describing the average shape of small (\( D_0 < 15 \) km) fresh lunar craters (\( d_0 = 0.196D_0^{1.05} \) [Pike, 1977a]) predicts a rim-to-floor depth of 4780 m for a crater cavity with an initial diameter of 23,640 m. Thus for the set of model parameters employed in Figure 7 the cavity reconstruction method produces an estimate of Timocharis cavity depth that is significantly greater than the depth predicted by extrapolating small-cavity depth/diameter ratios to crater cavities greater than 15 km in diameter.

Fig. 7. Type case example of the cavity reconstruction method schematically illustrated in Figure 4 as applied to a northeast cross-sectional profile of the crater Timocharis. (a) The position of the cavity rim prior to slumping is determined as the point of intersection between a model failure surface which is tangent to the face scarp of the innermost terrace (dotted line corresponding to a circular arc with \( \theta = 60° \)) and a second-degree polynomial equation which describes radial topographic trends beyond the presently observed rim crest of Timocharis (dashed line). For this set of model parameters the terrace restoration method indicates that rim slumping enlarged the Timocharis crater cavity by 40%. (b) Cavity depth is determined as the rim-to-floor depth of a parabolic cavity for which the volume of material initially forming the cavity rim and walls (vertically hatched area) equals the volume of material presently located above the base of the cavity and below the observed crater floor (crosshatched area).
Fig. 8. Cavity dimensions prior to slumping determined by the cavity reconstruction technique employing a circular arc model failure surface with $\theta = 60^\circ$ and a parabolic cavity shape. For the purposes of data presentation the abcissa scale is discontinuous at a cavity diameter of 40 km. Solid symbols denote the order of the polynomial expression fit by the method of least squares to exterior crater topography along specific crater cross sections (circles, first-order polynomial; diamonds, second-order polynomial; triangles, third-order polynomial). The data scatter for individual craters principally results from azimuthal variations in interior wall structure and exterior crater topography (see Figure 10 for examples). Solid reference lines represent the average observed dimensions of fresh lunar craters [Pike, 1977a, b]. The dashed reference line is an extrapolation of the depth/diameter relationship observed for small craters ($D_0 < 15$ km). Note that the average depths of reconstructed cavities with $D_i < 40$ km are situated above the dashed line representing small-crater morphometry, whereas the average depths of reconstructed cavities with $D_i > 70$ km are less than cavity depths predicted by the small-crater depth/diameter relationship.

The sensitivity of the terrace restoration model to certain critical assumptions can be examined by varying the values of key parameters and comparing resulting estimates of initial cavity diameter and depth with cavity dimensions displayed in Figures 8 and 9. Parameter testing results are presented in Figures 11, 12, and 13.

Parameter Tests

The sensitivity of the terrace restoration model to certain critical assumptions can be examined by varying the values of key parameters and comparing resulting estimates of initial cavity diameter and depth with cavity dimensions displayed in Figures 8 and 9. Parameter testing results are presented in Figures 11, 12, and 13.
Initial cavity dimensions for terrace restoration along logarithmic spiral failure surfaces using a 5° angle of friction are presented in Figure 11. Such low friction angles may more accurately characterize the dynamic strength of geological materials during a large-scale impact cratering event [Melosh, 1977]. Other model parameters (θ = 60°, parabolic cavity geometry) have been left unchanged. Figure 11 shows that this set of model assumptions produces reconstructed cavities with depth/diameter ratios that are comparable to ratios observed for small (Dc < 15 km) fresh craters within the 15- to 30-km range of cavity diameter. Cavities larger than 30 km fall below the dashed reference line. The difference between reconstructed cavity depth and cavity depth predicted by small-crater morphometry increases with increasing cavity size. The average depth of the restored Theophilus (Di = 83 km) and Langrenus (Di = 105 km) cavities is ~50% of the cavity depth predicted by the extrapolated depth/diameter relationship for small nonterraced craters.

Another critical parameter in the terrace restoration model is the assumed inclination of the model failure surface at the rim of the initial cavity (angle θ in Figure 4a). In Figure 12, reconstructed cavity dimensions are presented for terrace restoration along circular arc failure surfaces which intersect the initial cavity rim at an angle of 45° (all other parameters remain as described in Figure 8). The value of 45° is an average estimate of maximum rim scarp slope presently observed within large lunar craters and probably represents a minimum estimate of the inclination of the model failure surface at the initial cavity rim. The average depths of restored cavities are 1.4–1.2 times greater than cavity depths predicted by small-crater morphometry over a range of cavity diameters from 17 to 26 km in Figure 12. Restored cavities greater than 40 km in diameter again plot below the reference line. Average cavity depths for Theophilus (Di = 81 km) and Langrenus (Di = 101 km) are approximately 60% of cavity depths predicted by the small-crater morphometric relationships for equivalent cavity diameters. Similar results were obtained by restoring terraces along logarithmic spiral surfaces with θ = 45° for φ = 50° and a parabolic cavity geometry (data not shown). Therefore decreasing θ to 45° has the effect of reducing restored cavity depths (compare Figures 8 and 12).

In order to evaluate the degree to which model results were influenced by the assumed shape of the initial (preslump) cavity, terraces were restored along circular arc failure surfaces with θ = 60° (as in Figure 8 results), and initial cavity depth was determined using a cavity geometry intermediate between a cone and a paraboloid. This cavity shape is explicitly described by a radial variation of interior cavity elevation proportional to r^-a (equivalent to a = 1.5 in (1)). This cavity geometry closely corresponds to the observed shape of small fresh craters at ranges of 0.0–0.6Rc (see Figure 6). As shown in Figure 13, this intermediate cavity geometry produces cavity depth estimates that are 2.3–1.8 times greater than cavity depths predicted by small-crater morphometry over a range of cavity diameters from 15 to 30 km. As observed in the previous cases, the ratio of restored cavity depths to cavity depth esti-
Fig. 10. Comparison of preslump cavity structure inferred by the cavity reconstruction method (dashed cross-section lines) with observed crater structure (solid cross-section lines) for three different-sized craters. Terraces have been restored along circular arc failure surfaces ($\theta = 60^\circ$), and a parabolic cavity shape has been assumed (same model parameters as employed in Figure 8). Discrepancies in cavity radius and depth determinations for different crater cross sections principally result from azimuthal variations in wall structure and exterior crater topography.

mates based upon small-crater morphometry decreases with increasing cavity diameter. Restored cavity depths for Theophilus ($D_t = 78$ km) and Langrenus ($D_t = 100$ km) range from 80% to 75% of the cavity depths predicted by small-crater morphometric relationships for equivalent cavity diameters.

In summary, greater estimates of initial cavity depth are produced by (1) larger values for the angle of friction of lunar crustal material during a slumping event ($\phi$), (2) larger values for the inclination of the model failure surface at the initial cavity rim ($\theta$), and (3) a more conical geometry for the initial excavation cavity. However, model estimates of initial cavity dimensions do not vary in a linear fashion with changes in these parameters. The greatest variation in model results was produced by an order of magnitude reduction in the assumed value of the angle of friction during a slumping event (compare Figures 11 and 9); the smallest variation in model results was produced by a 25% decrease in the assumed inclination of the model failure surface at the initial cavity rim (compare Figures 12 and 8).

Discussion and Conclusions

The depth of excavation of an impact cratering event is the maximum depth below the original ground surface at which the target material is forcibly dissociated and laterally displaced during the excavation stage of crater formation. A zone of plastic deformation extends beyond the maximum depth of excavation in which material is permanently displaced but individual particles have maintained their relative positions. Rock samples representing the maximum depth excavated will most likely fail to be ejected beyond the crater rim and will probably be mixed into the breccia deposit filling the excavation cavity. The maximum depth of material actually ejected from the initial cavity (i.e., ejecta sampling depth; see Head et al. [1975]) may be significantly less than the maximum depth of excavation of the cratering event owing to the excavation of large volumes of material which are not transported beyond the cavity rim. In small-scale laboratory impacts into sand targets a significant fraction of crater depth is produced by
compression of substrate material [Stöffler et al., 1975] such that the depth of excavation of the crater, as defined above, is actually less than the observed crater depth. However, since the density and strength of lunar crustal materials should increase with crustal depth [Tóksoz et al., 1974; Talwani et al., 1974; Todd et al., 1973], compression will probably account for only a small portion of the total volume of the excavation cavities formed by large-scale lunar impacts [Head et al., 1975]. At this scale the depth of excavation of the cratering event should be approximately equal to the depth of the initial crater cavity.

If rim slumping is the primary mechanism of cavity modification, initial cavity depths inferred by restoring slump terraces to their original positions and reconstructing the excavation cavity prior to slumping should serve as approximate estimates of the depth of excavation of individual cratering events. Initial cavity dimensions determined by the terrace restoration technique developed in this study are model dependent, in that different combinations of assumed parameters produce varying estimates of initial cavity diameter and depth. The exact structure of terrace failure surfaces and the exact shape of large-scale excavation cavities prior to slumping are not known, and therefore it is presently impossible to specify a set of boundary conditions that will uniquely constrain the terrace restoration model. Nevertheless, cavity restoration results presented in Figures 8, 9, 11, 12, and 13 for various combinations of model parameters have several common features (summarized in Figure 14). In all cases, reconstructed cavity depth is approximately equal to or somewhat greater than cavity depth predicted by small-crater morphometry over the 15- to 30-km range of cavity diameters. Over the 30- to 70-km range of cavity diameters the difference between reconstructed cavity depth and cavity depth based upon the extrapolated depth/diameter relationship for small lunar craters decreases to a point at which the inferred depths of restored cavities fall below the reference line representing small-crater morphometry (Figures 8, 9, 11, 12, and 13). Finally, the depths of reconstructed cavities greater than 70 km in diameter are consistently less than cavity depths predicted by small-crater morphometric relations (Figure 14).

Although small ($D_c < 15$ km), fresh-appearing lunar craters do not appear to have experienced wholesale rim collapse, localized wall failure processes have undoubtedly modified their initial morphometry to some degree. Therefore the initial depth of excavation of small nonterraced craters should be somewhat greater than the presently observed depth of these craters. If the depth/diameter ratio of impact excavation cavities is constant over a wide range of cavity sizes (for example, 1 km $< D_i$ 1000 km) and if rim slumping is the principal mechanism of cavity modification in craters with $D_i > 15$ km, then it is reasonable to expect that reconstructed cavity depths should be situated above the reference line representing the
observed depth/diameter relations of small craters [see Hörz et al., 1976]. This in fact is the case over a range of cavity diameters from 15 km to at least 30 km for a wide variety of model parameters. On the basis of these model results we conclude that (1) initial cavities excavated by impact cratering events in the 1 km < D_e < 30 km size range are morphometrically similar and (2) the observed shallow morphometry of terraced craters with rim crest diameters D_o of less than ~40 km can be accounted for by rim-slumping modification of their initial excavation cavities.

For impact crater cavities greater than 70 km in diameter (equivalent to D_e = 80–90 km), however, the average depth of restored initial cavities is significantly less than cavity depth estimates extrapolated from small-crater morphometry. This discrepancy may in part be due to (1) an inability to recognize innermost terrace blocks which were destroyed as they slumped, (2) partial settling of exterior topography around the crater rim as it reached its present configuration, or (3) assumed values of model parameters as discussed in the previous section. There is little morphological evidence within the domical and hummocky terrain forming the flat floors of large craters which suggests that additional terrace blocks were initially situated at ranges less than the presently exposed innermost block. Furthermore, there is no consistent relationship between crater size and the order of the polynomial expression representing exterior crater topography which might indicate that the rim topography of larger craters is partially 'deflated' [Settle and Head, 1977]. Rather, the discrepancy between reconstructed cavity depth and cavity depths predicted by small-crater morphometry observed for D_e > 70 km is interpreted to be the result of a change in the depth/diameter ratio of initial excavation cavities formed by such large impact events and/or a change in the relative importance of rim slumping in modifying initial cavities greater than 70 km in diameter. In either case we conclude that rim slumping cannot solely account for the difference between depth/diameter ratios characterizing small, relatively unmodified lunar craters and the observed depth/diameter ratios of craters with rim crest diameters of greater than 80–90 km.

Two other factors may contribute to the modification of impact excavation cavities: (1) fallback of crater ejecta and (2) rebound of basement material. At terrestrial impact craters such as Brent and Meteor Crater, Arizona, lenses of highly shocked breccia containing clasts from all target formations overlie the allochthonous breccia deposit filling the crater cavity and have been interpreted as fallback [Dence, 1968; Sho-
In the past, depth/diameter ratios characterizing small fresh lunar craters have been employed to estimate the depth of excavation of large lunar craters and basins [e.g., Dence et al., 1974; Moore et al., 1974; Hörz et al., 1976]. This method of estimating impact excavation depth assumes that the depth/diameter ratios of excavation cavities produced by lunar impacts are essentially constant for all craters larger than several kilometers in diameter. It further assumes that the observed discontinuity in crater depth/diameter ratios at \( D_o \approx 15 \) km is the result of a significant increase in the ability of modification processes to reshape the initial cavities of larger craters. This study has demonstrated that rim slumping cannot solely account for a transition from an excavation cavity possessing a characteristic small crater depth/diameter ratio to the observed morphometry of lunar impact craters greater than 80 km in diameter. Additional investigation of the volumetric significance of basement rebound and ejecta fallback in reshaping the initial crater cavity is required in order to determine the actual variation of initial cavity depth with increasing cavity size. However, in the absence of quantitative studies of the effects of these factors we note that the difference between initial cavity depths predicted by small-cradter depth/diameter
SETTLE AND HEAD: RIM SLUMPING AND LUNAR IMPACT CRATERS

MODIFICATION OF INITIAL CAVITY SHAPE PRODUCED BY RIM SLUMPING

FIG. 14. Summary of terrace restoration model results. Data bars represent the range of average values of cavity depth and diameter obtained for individual craters employing the various model parameter combinations presented in Figures 8, 9, 11, 12, and 13. Results for Sklodowska are based upon analysis of a single crater cross section and should be treated circumspectly. The general variation of preslump cavity depth with increasing cavity diameter is represented by the dashed line, which is an approximate best fit to reconstructed cavity dimensions determined for a wide range of model conditions. Data for restored cavities of less than 50 km in diameter are too densely concentrated to be presented individually. See text for interpretation of model results.

An approximate linear fit to the average dimensions of reconstructed cavities with \( D_l > 50 \text{ km} \) (dash–question mark line in Figure 14) would imply that basin impact events on the scale of Orientale (inferred \( D_l \approx 620 \text{ km} \)) and Imbrium (inferred \( D_l \approx 970 \text{ km} \)) excavated of the order of 35–50 km below the lunar surface, respectively. In a previous study, Head et al. [1975] evaluated various estimates of the interior volume of the Imbrium basin and the volume of its exterior ejecta deposits in order to determine the amount of primary ejecta excavated by the Imbrium event. On the basis of these volume estimates, Head et al. [1975] concluded that the maximum depth of excavation of Imbrium ejecta is of the order of 27–40 km, in general agreement with a cavity depth estimate of 50 km inferred by extrapolating the results of the terrace restoration model to an Imbrium-sized cavity. In comparison, cavity excavation depths estimated by extrapolating small-crater depth/diameter relations to cavities 620–970 km in diameter are more than a factor of 2 greater, of the order of 80–120 km (e.g., Moore et al. [1974]; see also Dence et al. [1974]). The results of this study imply that basin-forming impact events did not excavate lunar mantle material at depths greater than 60 km. However, it is necessary to note that the cavity reconstruction models appropriate to very large lunar craters may differ significantly from the terrace restoration method presented here, owing to scale-dependent variations in cavity modification processes.

Acknowledgments. The authors wish to thank Mike Dence, Don Gault, Jay Melosh, Dick Pike, Keith Howard, and Clark Chapman for thoughtful and constructive reviews of an earlier version of this paper. The patience and diligence of Nancy Christy, Laurie Raymond, and Judy Botelho in preparing the manuscript for publication is sincerely appreciated. A portion of this study was conducted while the senior author was at the Air Force Geophysics Laboratory. We gratefully acknowledge the support of the laboratory and the support of NASA under grant NGR-40-002-116.

REFERENCES

Allen, C. C., Central peaks in lunar craters, Moon, 12, 463–474, 1975.


