Erosion of Ejecta at Meteor Crater, Arizona

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New methods for estimating erosion at Meteor Crater, Arizona, indicate that continuous ejecta deposits beyond 1/4–1/2 crater radii from the rim (0.25R–0.5R) have been lowered less than 1 m on the average. This conclusion is based on the results of two approaches: coarsening of unweathered ejecta into surface lag deposits and calculation of the sediment budget within a drainage basin on the ejecta. Preserved ejecta morphologies beneath thin alluvium revealed by ground-penetrating radar provide qualitative support for the derived estimates. Although slightly greater erosion (2–3 m) of less resistant ejecta locally has occurred, such deposits were limited in extent, particularly beyond 0.25R–0.5R from the present rim. Subtle but preserved primary ejecta features (e.g., distal ejecta lobes and blocks) further support our estimate of minimal erosion of ejecta since the crater formed ~50,000 years ago. Unconsolidated deposits formed during other sudden extreme events (e.g., landslides) exhibit similarly low erosion over the same time frame; the common factor is the presence of large fragments or large fragments in a matrix of finer debris. At Meteor Crater, fluvial and eolian processes remove surrounding fines leaving behind a surface lag of coarse-grained ejecta fragments that armor surfaces and slow vertical lowering.

INTRODUCTION

Because impact craters on the Earth, Mars, and Venus are instantaneously created with common initial morphologies, their degradation can be used to infer the intensity and style of erosional processes through time. Here we develop geological methods for estimating average vertical erosion over most of the continuous ejecta across one of the largest and youngest terrestrial craters, Meteor Crater, Arizona. These methods assess the differential transport of ejecta fragments and the sediment budget within a local drainage basin on the ejecta blanket to describe erosion of the continuous ejecta located beyond 1/4–1/2 crater radius (>0.25R–0.5R) from the present rim. By contrast, prior studies concerning erosion of other constructional landforms (lava flows) emphasized analyses of changing surface relief, amount of local eolian deposition, and soil maturity [e.g., Wells et al., 1985, 1987; Dohrenwend et al., 1986; McFadden et al., 1986, 1989]. Our methods can be applied to the study of other impact craters that are in a variety of geologic, climatic, and planetary settings in order to assess quantitatively the amount and styles of degradation.

Meteor Crater (35°1'30''N; 111°01'15''W) was formed ~50,000 years ago [Sutton, 1985; Nishizumi et al., 1991; Zreda et al., 1991] on the southern Colorado Plateau, 2.5 km east of Canyon Diablo. The crater is nearly 1200 m across, 180 m deep, and has a 30–60–m-high raised–rim (Figure 1). Previous studies of Meteor Crater provided fundamental data regarding the mechanics of crater formation and ejecta emplacement [e.g., Barringer, 1905, 1910, 1914; Tilghman, 1905; Nininger, 1956; Shoemaker, 1960; Shoemaker and Kieffer, 1974; Roddy et al., 1975; Roddy, 1978]. Conclusions regarding the degradational state of the ejecta, however, vary. Several workers [Shoemaker and Kieffer, 1974; Nishizumi et al., 1991] infer considerable erosion of ejecta based mostly on examination of steep near–rim areas. Others [Phillips et al., 1991] estimated only minor denudation of ejecta after examining large ejecta blocks farther from the rim to about ~1.0R. Such disparate estimates for erosion, however, are not necessarily contradictory but simply reflect rates and styles that depend on slope and lithology [Grant and Schultz, 1990]. The following systematic assessment of reworked, transported, and redeposited ejecta tests the hypothesis that local slopes and ejecta lithology has controlled erosion from the steep inner rim area to the lower relief outer–continuous ejecta.

PHYSICAL SETTING

Flat–lying sedimentary rocks generally comprise the low–relief plains surrounding Meteor Crater (Figure 1) [Moore et al., 1960]. Fragments ejected from the fine–grained Permian Coconino sandstone mark the deepest rocks excavated by the impact [Shoemaker, 1960]. The Coconino is conformably overlain by 2.7 m of the Permian Toroweap sandstone and 80 m of the mostly limestone/dolomite Permian Kaibab Formation [Shoemaker, 1960]. Approximately 9 m of the lithologically diverse Triassic Moenkopi Formation unconformably caps the sequence (Figure 1) [Shoemaker, 1960]. More detailed descriptions of these rocks are found in McKee [1934, 1938, 1945, 1954], Shoemaker and Kieffer [1974], Roddy et al. [1975], and Roddy [1978]. Estimated volumes of Coconino/Toroweap, Kaibab, and Moenkopi excavated during crater formation vary [Roddy et al., 1975; Croft, 1980] (Table 1). For brevity, fragments from the Coconino/Toroweap, Kaibab, and Moenkopi are referred to as Coconino, Kaibab, and Moenkopi ejecta, respectively.

A continuous ejecta blanket derived from all excavated lithologies surrounds the crater out to ~1 km from the rim crest and was capped by a thin layer of fallback ejecta (Figure 1) [Shoemaker, 1960, 1987; Shoemaker and Kieffer, 1974; Roddy et al., 1975]. Ejecta near the rim rapidly thin outward following a steep power–law decay [Garvin et al., 1989] with radial to subradial troughs and ridges similar to the hummocky ejecta around simple pristine craters on the Moon and Mars [Schultz, 1976; Much et al., 1976; Carr, 1981]. Exposed outer–continuous ejecta can extend from ~0.5R–2.0R and are mostly comprised of Kaibab. Primary or reworked Coconino ejecta are rare beyond ~0.5R, even in long–term depositional traps.

Soils on the ejecta possess a carbonate Bk horizon between stage II and stage IV of development [Gile et al., 1966; Machette, 1985]. Such a range of features (e.g., carbonate laminae 0.1–1.0 cm thick, thick coatings on clasts that sometimes coalesce into massive and cemented accumulations) probably reflects the carbonate–rich nature of the parent ejecta and complicates age determination. Most alluvium at the crater, however, is mantled by soils correlating with the
late Pleistocene Jeddito Formation and the Holocene Tsegi and Naha Formations in the Hopi Buttes region ~80 km to the northeast [Shoemaker, 1960; Shoemaker and Kieffer, 1974].

Radial gullies incise near-rim and upper flank portions of the continuous ejecta and deposit thin alluvial fans and diffuse drainages beyond ~0.6R [Shoemaker, 1960; Shoemaker and Kieffer, 1974; Roddy et al., 1975] that locally bury outer-continuous ejecta (Figures 2 and 3). Confined fluvial activity is limited to erosion of gully floors and deposition in small, distal fans. On a broader scale, Canyon Diablo and circumcrater drainages are separated by a low divide ~1.5 km west of the crater (Figure 2).

The presently arid climate at Meteor Crater is characterized by strong (>30 m/s), southwesterly winds [Green and Sellers, 1964; U.S. Department of Commerce, 1968] that formed a patchy wind streak extending northeast of the crater (Figure 1). This prevailing wind may have persisted since crater formation [Breed et al., 1984]. Biostratigraphic correlations between crater-floor lake sediments and other southwestern lakes [Forester, 1987], however, suggest that other aspects of climate varied considerably over the crater's 50,000-year history. Wetter-than-present conditions existed during the late Wisconsin pluvial from 25-20 to 15-12 ka (thousands of years before present [e.g., Morrison and Frye, 1965; Mifflin and Wheat, 1979; Smith, 1979]). Although there is a dearth of postpluvial crater lakebeds (R. Forester, personal communication, 1983) increased monsoonal precipitation may have occurred during the late Pleistocene/early Holocene [e.g., Van Devender, 1990; Spaulding and Graumlich, 1986; Betancourt, 1987]. Conditions since the early Holocene, however, averaged drier than present [e.g., Van Devender et al., 1987; Wells et al., 1985; Forester, 1987].

PREVIOUS ESTIMATES OF EROSION

Previous conclusions regarding the preservation state of ejecta vary (Table 2). For example, Nishiizumi et al. [1991] estimated considerable erosion of primarily Coconino and fallback ejecta with missing thicknesses decreasing from 12–20 m near the rim to 3–5 m at 1.0R [Shoemaker and Kieffer, 1974]. Their estimates are based largely on observations of the steep near-rim and the assumption that uniform exposure ages of large, more-distal ejecta blocks reflected rapid exhumation during early crater history. Similarly, Roddy et al. [1975] and Roddy [1978] estimated that 20–25% of the original ejecta volume was eroded based on the difference between predicted "preerosion" crater profiles and present thicknesses established by extensive drilling around the crater. They estimated that erosion had widened the rim by 30 m while lowering it by 20 m; farther out, erosion decreased to ~2–3 m.

In contrast, Phillips et al. [1991] found that ejecta blocks between the rim and ~1.0R possessed exposure ages matching the crater age and concluded that these blocks had never been buried. Relief of
AMOUNTS OF EJECTA EROSION

Approach of Current Study

Quantitative estimates of the amount of ejecta eroded (beyond 0.25R-0.5R) in this study are based, first, on coarsening of surface lag deposits on the ejecta and, second, on the sediment budget in a drainage basin on the western crater flank. The first approach compares the coarse-grained ejecta lag deposits with those of underlying in situ ejecta. Ejecta lags are defined as surface accumulations of coarse, angular to slightly rounded fragments averaging ~2-3 cm thick (excluding large blocks) that directly overlay their parent material. Such lags do not exhibit the underlying silty, vesicular, class-poor horizon typical of most stone pavements in the arid southwest [McFadden et al., 1987]. Lags can be used to accurately estimate erosion if (1) unweathered ejecta grain size properties are fairly uniform; (2) lag formation reflects predominantly vertical erosion; and (3) in situ weathering is accounted for. When these conditions apply, the eroded ejecta thickness ($D_0$, in cm), is approximated by

$$D_0 = \frac{C_1}{C_0} D_1$$

where $C_1$ is the maximum possible concentration of coarse fragments in lag deposits relative to unweathered ejecta, $C_0$ (based on a normalized sample percentage determined from the standard deviation of grain size distributions), and $D_1$ is the average thickness (in cm) of the lag-layer being considered (Figure 4). The second approach assesses the sediment budget of alluvial/colluvial deposits in a largely enclosed drainage basin west of the crater. This method yields values for average vertical erosion when the total volume of missing sediment is divided by the area of the drainage basin. Additional corrections are required, however, in order to account for sediment transport from the basin through minor divide breaches, eolian deflation, and vertical dissolution.

TABLE 1. Estimated Volumes of Rocks Excavated During Crater Formation

<table>
<thead>
<tr>
<th>Formation</th>
<th>Minimum, m³</th>
<th>Maximum, m³</th>
</tr>
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<tbody>
<tr>
<td>Moenkopi</td>
<td>0.5 X 10⁶ *</td>
<td>6.4 X 10⁶ +</td>
</tr>
<tr>
<td>Kaibab</td>
<td>45.6 X 10⁶ +</td>
<td>49.5 X 10⁶ *</td>
</tr>
<tr>
<td>Coconino/Toroweap</td>
<td>11.0 X 10⁶ +</td>
<td>26.0 X 10⁶ *</td>
</tr>
</tbody>
</table>

*From Roddy et al. [1975].
+From Croft [1980].

TABLE 2. Previous Estimates of Erosion of Ejecta at Meteor Crater

<table>
<thead>
<tr>
<th>Study</th>
<th>NR, m +</th>
<th>OC, m +</th>
</tr>
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<tbody>
<tr>
<td>Nishiizumi et al. [1991] and Shoemaker and Kieffer [1974]</td>
<td>12-20 m</td>
<td>-3-5 m*</td>
</tr>
<tr>
<td>Roddy [1978] and Roddy et al. [1975]</td>
<td>up to 20 m</td>
<td>-2-3 m*</td>
</tr>
<tr>
<td>Grant and Schultz [1989, 1990]</td>
<td></td>
<td>-0.5-0.6</td>
</tr>
<tr>
<td>Phillips et al. [1991]</td>
<td></td>
<td>&lt;1-2 *</td>
</tr>
<tr>
<td>Pilon et al. [1991]</td>
<td></td>
<td>&lt;2-3 *</td>
</tr>
</tbody>
</table>

+NR=Near Rim (≤0.5R).
+OC=Outer-Continuous (>0.5R).
*Inferred from data presented in published results.

these blocks limited erosion of surrounding ejecta to only 1-2 m (Table 2). Phillips et al. [1991] felt that it was unlikely that: (1) all blocks were uniformly buried during impact but then exhumed by identical erosion rates; or (2) the blocks were variably buried but then simultaneously exposed by different erosion rates. Their lower estimate of erosion is similar to that reported by Grant and Schultz [1989, 1990] and Pilon et al. [1991], where variations in outer-continuous-ejecta thickness detected by ground penetrating radar were ascribed to superposition on preimpact surface topography, rather than erosion from an assumed preerosion profile (Table 2).
SELECTED CROSS-SECTIONS FROM WEST OF CRATER

Fig. 3. Selected cross sections through diffuse drainage deposits, distal alluvial fans, and thin colluvium inside the semienclosed basin. The location of each cross section is indicated in Figure 9. Fans and diffuse drainages are typically 1.0–1.5 m and 0.3–0.7 m thick, respectively (Figure 2). Locally thicker fans (up to 3 m thick) and diffuse drainages (up to 1.5 m thick) occur, but the lesser accumulations are much more common. In general, the thicknesses of fans and diffuse drainages decrease distally. Unit thicknesses were initially constrained using pits excavated through to the underlying ejecta. Buried colluvium beneath the diffuse drainage (generally not shown) is less than ~20 cm thick.

Equation Used For Erosion Estimates Based On Grain Size Comparisons

Vertical Erosion (Do) = \( \frac{C_v}{C_o} \times D_i \)

Eroded Ejecta Thickness (Do)

Lag Deposit

Coarse Fragment Concentration (C)

Initial Ejecta Thickness

Present Ejecta Thickness

Time = 0

Time = 1

Fig. 4. Idealized block diagram identifying terms used in calculation of vertical erosion from surface lag deposits versus subsurface ejecta grain size comparisons. The equation does not include corrections for losses owing to lateral transport or other lag evolution processes that are discussed in the text. Block diagrams are not to scale, and lag deposit thickness is exaggerated.

The following discussion details these two methods. Resultant erosion estimates are then compared with data from ground penetrating radar transects through alluvium on the ejecta, the scale of preserved primary–ejecta features, and erosion of other catastrophic, unconsolidated landforms.

Surface Versus Subsurface Grain Sizes

A total of 110 samples (Figure 5) of subsurface ejecta, ejecta-lag deposits, alluvium, colluvium, and windstreak sediments were sieved using standard methods [Folk, 1980] and screen-mesh sizes of 16 mm (~4.0 phi) to 0.03 mm (5.0 phi). Subsurface samples (28) generally from below 30 cm depths were used to characterize the unweathered ejecta grain size distribution and then compared with ejecta lags from the surface in the same locations (Figure 5). Ejecta fragments coarser than ~3 cm required in–field sieving of ejecta excavated from pits (Figure 5). Still larger blocks (>20 cm) involved measuring the block number/area in the walls of large pits and the block number/area observed along a gully incising the crater flank (Figure 5). The measured number/area clearly reflects in situ accumulation following fluvial erosion of fines because fans downstream of this and other gullies are devoid of blocks >15–20 cm in diameter (Figure 6).
Sieve analyses. Grain sizes of the unweathered, subsurface Kaibab (Figures 7a and 7b) and Coconino (Figure 7c) ejecta show modes at 0.074 mm (3.75 phi) and 0.21 mm (2.25 phi), respectively. All ejecta samples also exhibit modes (Figure 7c) at the smallest 0.031 mm (<5.0 phi) and largest sizes >4 mm (>2.0 phi) that are probably artifacts of cutoff sieve diameters. The total Kaibab ejecta mass in each grain size bin is fairly uniform and has a standard deviation of 30–55%. The resulting contrast between subsurface ejecta samples and ejecta lags (e.g., Figure 7d) indicates that surface grains larger than 4 mm (~2 phi) are concentrated by a factor up to 6X. In situ field sieving of larger clasts reveals, however, that ejecta lag surfaces contain a 3X concentration of coarse fragments (Figure 5) with the largest blocks (>20 cm) concentrated by only ~2X (Figure 6).

The coarsening of fragments in the ejecta lags indicates only minor vertical erosion. Removal of fines from only ~20 cm of ejecta could produce the observed 6X concentration of coarse fragments in the surface lag measured by sieve analyses (Table 3a). Slightly greater erosion (30 cm) is necessary to account for the 3X concentration noted during field sieving. The 2X concentration of blocks >20 cm requires 40 cm erosion in addition to that required for incision of the associated gully (Table 3a). Hence the three size ranges yield generally comparable values of erosion; however, they do not include adjustments for processes of lag evolution that might influence clast concentrations, thereby masking more significant erosion.

Evolution of coarse-grained surface lags. The evolution of most lag surfaces leading to stone pavements reflect a variety of processes including (1) deflation, (2) surface wash, (3) colluviation, (4) physical/chemical weathering, (5) eolian deposition, (6) soil creep, and (7) upward clast migration. At Meteor Crater, comparison between surface lags and subsurface ejecta properties allows assessing the relative importance of each of these processes in ejecta–lag evolution.

Strong southwesterly winds at Meteor Crater deflate fine-grained ejecta and form the windstreak, thereby contributing to lag evolution as in other areas of the desert southwest [Cooke and Warren, 1973; Ritter, 1986; Dohrenwend, 1987]. Grain sizes within the windstreak are smaller than 0.35 mm (<1.5 phi), but are large enough to reflect saltation transport (Figure 8a). Because Canyon Diablo is upwind, it intercepts saltating sediments from distant sources; hence, the windstreak must be largely created by deflation of ejecta around Meteor Crater.

Surface wash on the ejecta (i.e., unconcentrated surface runoff) also selectively removes fine fragments and could contribute locally to lag evolution [Cooke and Warren, 1973; Ritter, 1986; Dohrenwend, 1987]. The presence of thin alluvial and colluvial deposits around the crater most likely reflects the consequences of surface wash. Equations given in Emmett [1970, 1978] yield surface wash velocities on the outer-continuous ejecta of ~10 cm/s (based on flow depths of 1–2 cm and gradients of 0.1–0.01) and indicate that fragments larger than 1–2 mm accumulate in situ. Fluvial transport of larger blocks is confined only within gullies.

Colluviation (i.e., combined effects of surface wash and local mass movement) also causes some lateral transport of surface fragments [McFadden et al., 1986, 1987]. At Meteor Crater this process creates colluvium deposits up to 40 cm thick that bury outer–continuous ejecta in certain locations. Although constituent grain size distributions (Figure 8b) generally resemble unweathered Kaibab ejecta, larger and smaller sizes are notably depleted (Figures 7a and 7b). Based on the maximum 40-cm thickness of the colluvium, lateral
transport of fragments by colluviation correspond to vertical lowering of up to that value (40 cm).

Weathering (e.g., vertical dissolution, frost wedging) should systematically reduce large ejecta fragments to sizes transportable by surface wash and deflation [Cooke and Warren, 1973; Ritter, 1986; Dohrenwend, 1987]. Several observations, however, limit the effectiveness of this process at Meteor Crater. First, dissolution of large Kaibab blocks can be constrained to less than 5 cm since their surfaces preserve exposure ages matching that of the crater [Phillips et al., 1991]. Second, small (~15-25 cm) unfragmented, distal ejecta blocks are preserved beyond the outer-continuous ejecta. Impact and survival at this range (up to 5.3R) require an original block size within a factor of ~2X that observed [see Schultz and Gault, 1979] and limits combined physical and dissolution weathering to ~20 cm. Third, observations of weathered fragments (~0.1-0.5 m) around very large ejecta blocks (~1-3 m) reveal that they can still be easily traced to their pre-weathered position. The large size of the weathered fragments precludes significant lateral transport by surface wash and is a more qualitative indicator of only minor weathering. Based on these observations, contributions to lag evolution by weathering processes corresponds to ~20 cm.

The remaining processes of eolian deposition, soil creep, and upward clast migration make negligible contributions to lag formation at Meteor Crater in the areas sampled. First, the underlying silty zone signifying eolian deposition in other settings [Wells et al., 1985; McFadden et al., 1986, 1987] is not present under the ejecta lag outside the windstreak. Second, not only are contributions to stone pavement formation by soil creep questionable [Selby, 1982; Wells et al., 1990], but features (e.g., surface terracettes) thought to be diagnostic of the process [Denny, 1965; Hooke, 1972, 1990; Cooke and

Fig. 6. Comparison between (a) the block densities per m² exposed in the walls of pits and mines dug into the pristine ejecta and (b) the block density exposed on the floor of a gully on the northwest-crater flank. Block numbers derived from Figure 6b required measure of the fairly uniform density of blocks in 1 m wide cross sections (normalized to cross-sectional area) along the gully. The bottom portion of Figure 6b depicts the in situ accumulation of blocks that are too large to be transported as surrounding finer-grained material is removed. The number of blocks exposed across segments of the gully floor is only slightly larger than expected from gully incision; hence, little erosion has occurred in addition to that required for gully incision.
Fig. 7. Histogram plots of the average percent ejecta mass versus grain size for unweathered Kaibab ejecta samples from (a) less than 0.5R and (b) greater than 0.5R. All plots present grain size in phi units (grain diameter in mm to the -log2). Modes occur at <5.0, 3.75, and >-2.0 phi in both plots. The standard deviation of the mass within any grain size interval is generally 30–50% of the average interval mass. (c) Histogram plot of unweathered Coconino ejecta with modes at 5.0, 2.25, and -2.0 phi. Closer examination reveals the 2.25 phi mode reflects the breakdown of the Coconino ejecta into constituent grains. The standard deviations of mass/grain size interval are similar to those in the Kaibab ejecta. (d) A typical comparison plot of the surface-lag versus unweathered subsurface grain size distributions from the Kaibab ejecta. Fragments in the surface lag material that are coarser than -2.0 phi are concentrated 2X relative to the unweathered subsurface ejecta. (e) Grain size distribution of in situ-weathered Moenkopi Formation from beyond the limit of the continuous ejecta. Note the distinct differences between the ejecta grain size (Figures 7a, 7b and 7c) and the Moenkopi Formation grain size distributions.

[Warren, 1973] are also not found on the ejecta. And third, the fairly uniform grain size with depth indicates minimal upward clast migration [Cooke and Warren, 1973; Ritter, 1986; Dohrenwend, 1987] through the ejecta.

**Modified erosion estimates.** Ejecta lags at Meteor Crater principally reflect 20–40 cm vertical lowering and in situ accumulation of coarse fragments following selective removal of fines by colluvial and fluvial (surface wash) processes. Colluvial and weathering processes further contribute to ejecta removal and account for an equivalent lowering of at most 40 and 20 cm, respectively. When erosion estimates from sieve analyses (20 cm), field sieving (30 cm), and block comparisons (40 cm) also include the effects of colluvial and weathering processes, the total erosion of the outer-continuous ejecta is now modified to at most ~1 m (Table 3a).
Fans bury ejecta and thin distally to 0.6R from the present rim-crest, ejecta in the basin (72%) occur on the steep upper flank (Figure 9). Overall erosion of the outer-continuous ejecta. As a sensitivity test using field observations and can provide an independent estimate of constrained as well. In spite of the number of necessary correction factors, the amounts and processes of degradation can be constrained. In this relationship, the maximum possible volume of sediment transported outside the basin is also used to calculate erosion.

**Sediment Budget Within Semienclosed Basin**

Field mapping delineates an enclosed drainage basin on the western crater flank (Figure 2). Surfaces within this basin can be divided into four surficial units on the basis of both field studies of the depositional environments and analyses of grain size and shape (Table 3b; Figure 9). First, an ejecta unit is distinguished in the map where Kakeb ejecta deposits are exposed or buried by less than 20-cm colluvium; this unit comprises 38% of the basin area. Second, a colluvium unit is recognized by thicker accumulations of deposits (20 cm to 40 cm deep) containing slightly rounded clasts (Figure 8b); colluvium covers 26% of the intrabasin surfaces. Third, distinctive, fine-grained alluvial fan deposits with coarsest fragments rarely >5 cm (Figure 8c) cover 19% of the basin, principally occurring between low, subradial, ejecta ridges. Fourth, fine-grained deposits extending (Figure 8d) from the alluvial fans are labeled diffuse drainage deposits and represent 17% of intrabasin surfaces. Most colluvial and alluvial fan surfaces in the basin are capped by coarse lag deposits.

The sediment volume represented by these four depositional units provides a minimum estimate for the volume of ejecta eroded and transported locally within the basin. Any sediment transported outside of the basin via fluviation, deflation, and dissolution must be constrained as well. In spite of the number of necessary correction factors, the amounts and processes of degradation can be constrained using field observations and can provide an independent estimate of overall erosion of the outer–continuous ejecta. As a sensitivity test for our derived erosion estimates, the maximum possible volume of sediment transported outside the basin is also used to calculate erosion.

**Initial calculation of the sediment budget within the basin.**

Most ejecta in the basin (72%) occur on the steep upper flank (Figure 9). Fans bury ejecta and thin distally to 0.6R from the present rim-crest, whereas diffuse drainages extend to about 1.25R (Figures 2, 3, 8c, 8d, 9). Therefore, erosion dominates the upper flank and leads to deposition over the outer–continuous ejecta. With this in mind, the total drainage basin area (AT) containing the volume of intrabasin deposits (VT) was divided into two parts: an upper flank, near–rim area dominated by erosion (AT) that retains minimal alluvium and colluvium (VT); and a more distal area of the continuous ejecta (Ao) that accumulates significant alluvium and colluvium (Vo) derived locally and from the upper flank of the raised rim (Figure 10). Hence,

\[
V_o = V_f + V_c + V_r + V_d
\]

where the subscripts c, c, f, and d correspond to the area/volume of ejecta, colluvium, alluvial fan, and diffuse drainage units, respectively. Unweathered ejecta originally characterized both near–rim and distal areas (Vr and Vo). Therefore, average erosion in cm (E) beyond the near rim is

\[
E = V_o / A_o.
\]

At present, however, minimal alluvium and colluvium near the rim (Vr) indicate that the total deposit accumulated in the basin (Vr) should be equivalent to the more distal accumulation of alluvial/colluvial deposits (Vo). These mass balance requirements yield the following two equations (including the density differences between ejecta and colluvium). First, the volume of distal continuous ejecta (Vd) must equal the total volume of ejecta eroded from (Ao) since crater formation

\[
V_d = V_r - V_o
\]

\[
A_o = A_t / A_r
\]

This relationship is illustrated in Figure 10. The quantities of Vr, Ar, Ao can be measured using the distribution and thickness of transported ejecta accumulated in the drainage basin. Subtraction of Vr from Vt gives the volume of sediment eroded (Vr) in equation (4a) from the distal–continuous ejecta area, Ao, in terms of values constrained by field observations. Therefore,

\[
V_t = V_r + (\Delta V_c + (\Delta V_f + (\Delta V_r) + (\Delta V_d))
\]

where Δ refers to the current inventory of the each depositional environment minus the contribution derived from near–rim sources. Previous studies provide working values for the initial, preerosion profile and the original volume of near–rim ejecta, Vr [Roddy et al., 1973; Roddy, 1978; Shoemaker and Kieffer, 1974].

Field mapping provides the inputs for each term in equation (5) leading to the average erosion in equation (3). Excavation and sampling of some portions of the ejecta in the basin demonstrate that the
Fig. 8. (a) Grain size distributions for proximal and distal windstreak sediments. All windstreak deposits at the crater are well sorted, have a mode at 2.5 phi, and show little variability with location. Windstreak grain size distributions from different composition source regions (i.e., Kaibab versus Coconino) are also remarkably similar. (b) Colluvial deposit grain size distribution from inside the semienclosed basin west of the crater. This and other colluvium samples are depleted in coarse fragments (>20–30 cm) and lack the prominent modes of in situ ejecta samples. In addition, the colluvium samples are enriched by a factor of 1/3 in sediment susceptible to deflation relative to the in situ Kaibab ejecta. Colluvium fragments are typically more rounded than in situ ejecta fragments. (c) Grain size distributions of coarse-grained surface-lag deposits from an alluvial fan and subsurface alluvium from inside the semienclosed basin. Coarse-grained fragments are concentrated on fan surfaces by 5X–18X relative to the subsurface material and suggest in situ accumulation from deflation of between ~15 cm and 30 cm alluvium. (d) Grain size distribution of sediment from diffuse drainage inside the semienclosed basin. Except for the largest sizes, the distribution is similar to that in the alluvial fans. Modes occur between 3.0 and 4.0 phi. Coarse-grained surface lags are less well developed or absent on most diffuse drainage surfaces.

average colluvial cover is close to the maximum 20 cm used in defining the mapped unit; therefore, Vc is 10,400 m³. The colluvium unit comprises 36,900 m³ (Table 3b) based on an average 30-cm thickness; however, additional colluvium beneath both fans and diffuse drainages is up to 15 cm thick and could contribute an additional 25,500 m³ of sediment. Hence, Vc is the sum of these two volumes, 62,400 m³ (Table 3b). The volume of sediment contained in the alluvial fans (Vf) and diffuse drainages (Ve) is 69,400 m³ and 51,400 m³, respectively (Table 4). These estimates include adjustments for possible fluvial transport out of the basin and into adjacent alluvial fans covering 13,000 m² and diffuse drainages over an area of 55,000 m². An absence of deposits from well-defined integrated drainages at minor drainage breaches limits more distal transport and qualitatively supports the validity of this adjustment. The following discussion focuses on additional corrections for deflation from basin surfaces. Each correction further includes a 5–cm adjustment for dissolution.

Corrections for deflation. Deflation from ejecta surfaces is estimated by dividing the volume of the windstreak by its source area. Losses from alluvium are estimated using the concentration of coarse fragments in alluvial fan-lag deposits relative to subsurface alluvium. Similarly, losses by colluvium deflation are estimated from the observed change in grain size distribution from the unweathered ejecta to the colluvium. Deflation values for each depositional unit are then given as "best" and "maximum" with alternative values for deflation given by their sums.

The windstreak area/average thickness downwind of Kaibab and Coconino ejecta source regions is 320,000 m²/5–10 cm and 410,000 m²/15 cm representing ~24,000 m³ and 61,500 m³ eroded sediment,
Fig. 9. Depositional environment map of the semienclosed drainage basin on the west side of the crater. Drainage divides that define the basin (dashed lines) are breached on the north and south. To compensate for material that may have been lost from the basin through these breaches, large areas of alluvial fan and diffuse drainage deposition adjacent to the basin were included in the calculations. Total basin area is 475,000 m². Mapped units include ejecta (182,000 m²), of which 72% lacks a thin colluvial cover and is located on the upper rim flank; thin colluvium (123,000 m²); alluvial fans (90,000 m²); and diffuse drainage (80,000 m²). Alluvial fans and diffuse drainage adjacent to the basin included in calculations cover an additional 13,000 m² and 55,000 m², respectively. Solid lines mark the location of selected cross sections in Figure 3. These volumes, however, only reflect the saltating component of deflation and require corrections to account for the under-represented fine fraction lost via suspension transport. Comparison between Kaibab and Coconino ejecta and windstreak grain sizes indicates a deficiency of windstreak sediment smaller than 0.009 mm (3.5 phi) that amounts to 95% (22,800 m³) and 30% (18,500 m³), respectively, of the sediment represented by the saltating fraction (Figures 7a, 7c, &e). Hence, the total volumes of sediment deflated from the Kaibab and Coconino ejecta source regions to form the present windstreak are 46,800 m³ and 80,000 m³, corresponding to a deflated sediment mass of 8.4 X 10⁷ kg and 1.4 X 10⁸ kg, respectively, for an assumed windstreak bulk density of 1800 kg/m³. Dividing the derived mass of deflated sediment by a bulk ejecta density of 2150 kg/m³ [Regan and Hinze, 1975; Roddy et al., 1975] reveals that 39,100 m³ and 66,900 m³ of the Kaibab and Coconino ejecta has been deflated. Dividing these volumes of deflation by their source areas (720,000 m² for the Kaibab and 200,000 m² for the Coconino) yields 13 cm and 34 cm eolian lowering of the Kaibab and Coconino ejecta, respectively. Because prevailing winds at the crater may be unchanged since impact [Breed et al., 1984], such estimates could reflect total deflation. The poor preservation potential of a windstreak suggests, however, that additional unrecorded deflation may have occurred as well.

**TABLE 4. Semienclosed Drainage Basin Field Mapping**

<table>
<thead>
<tr>
<th>Mapped Unit</th>
<th>Area, m²</th>
<th>% Total Basin Area</th>
<th>Uncorrected Volume, m³</th>
<th>Best Estimate of Corrected Volume, m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ejecta</td>
<td>182,000</td>
<td>38</td>
<td>10,400</td>
<td>164,700++</td>
</tr>
<tr>
<td>Colluvium</td>
<td>123,000</td>
<td>26</td>
<td>36,900</td>
<td>158,700§</td>
</tr>
<tr>
<td>Alluvial Fans</td>
<td>90,000</td>
<td>19</td>
<td>69,400*</td>
<td>99,900*</td>
</tr>
<tr>
<td>Diffuse Drainage</td>
<td>80,000</td>
<td>17</td>
<td>51,400+</td>
<td>91,900+</td>
</tr>
</tbody>
</table>

Total basin area is 475,000 m² (see Figure 9).

* Includes volume of additional 13,000 m³ alluvial fan adjacent to basin.
+ Includes volume of additional 55,000 m³ diffuse drainage adjacent to basin.
++ Includes volume of thin colluvium on ejecta, deflation from exposed and presently buried ejecta.
§ Includes volume estimate for buried colluvium, deflation from exposed and buried colluvium.

Allevium, colluvium, and deflated ejecta densities are 1800 kg/m³ (measured), 2000 kg/m³ (estimated), and 2150 kg/m³, respectively.
Several observations further constrain total deflation since crater formation. The windstreak is presently inactive as confirmed by superposition of 900-year-old volcanic ash from nearby Sunset Crater (E.M. Shoemaker, personal communication, 1989), a paucity of bedforms, and the widespread occurrence of vegetation. Because the regional climate has been relatively uniform and caused little erosion since the early Holocene [Nishizumi et al., 1991], the windstreak probably dates back to at least 8-10 ka or of postglacial or monsoon- nal age. A maximum of about 70 cm deflation from Kaibab ejecta can be estimated from the current windstreak inventory, the minimum age, and the assumption of uniform (but unrecorded) deflation over crater history. A lesser value of 45 cm total deflation from the Kaibab ejecta, however, provides a more realistic value based on the likelihood that the intensity of eolian activity is variable and climate sensitive (Table 3b). The calculation of $\Delta V_s$ in equation (5) further requires the approximate deflation from Kaibab ejecta prior to burial beneath alluvium and colluvium. If a similar rate of eolian stripping and an average burial age of half the crater age are assumed, a "best" estimate of 25 cm is derived. Ejecta burial by alluvium/colluvium as recently as 10 ka, however, yields a "maximum" estimate of 55 cm (Table 3b).

Alluvial fans in the drainage basin are mantled by coarse-lag deposits that can be used to estimate deflation more directly. Coarse-clast concentrations in fan-lags relative to underlying alluvium indicate that 30 cm deflation has occurred, a value adopted as a "best" for fans and diffuse drainages based on their similar fine-grained component. Because most alluvial surfaces in the basin are relatively young but relict, additional deflation from now buried surfaces is possible. A pluvial or monsoonal age for most alluvium is implied by the crater history. A lesser value of 45 cm total deflation from the Kaibab ejecta, however, provides a more realistic value based on the likelihood that the intensity of eolian activity is variable and climate sensitive (Table 3b). The calculation of $\Delta V_s$ in equation (5) further requires the approximate deflation from Kaibab ejecta prior to burial beneath alluvium and colluvium. If a similar rate of eolian stripping and an average burial age of half the crater age are assumed, a "best" estimate of 25 cm is derived. Ejecta burial by alluvium/colluvium as recently as 10 ka, however, yields a "maximum" estimate of 55 cm (Table 3b).

Deflation from colluvial surfaces can be constrained by contrast- ing constituent grain sizes and ages of the colluvium with the Kaibab ejecta. This approach reveals that the younger colluvium has a larger deflatable fraction. The younger age of the colluvium should approximately offset its greater deflation potential. Hence, working values previously derived for ejecta deflation ("best" = 45 cm; "maximum" = 70 cm) also should reasonably characterize the colluvium. Colluvium up to 15 cm in thickness is buried by alluvium that is ~1/2 the average thickness of the exposed colluvium; therefore, a "best" estimate of deflation prior to burial is 25 cm. Arguments similar to those used to estimate maximum deflation from buried ejecta limit deflation from buried colluvium to 55 cm at most.

**Modified erosion estimates.** Corrections for deflation in volume estimates for deposits in the basin allow calculation of "best" and "maximum" values for the various terms in equation (5), leading to an estimate for overall erosion. Deflation of 30 cm alluvium equates to 71,000 m$^3$ for a total alluvium volume of 191,800 m$^3$ (Table 4). "Best" estimated deflation from exposed and buried colluvium represents 96,300 m$^3$ sediment for a total of 158,700 m$^3$ colluvium (Table 4). Deflation from exposed and buried ejecta removed 154,300 m$^3$ (Table 4) for a total of 164,700 m$^3$. Summation of the corrected values and conversion to an equivalent unweathered ejecta mass/volume yields 1.0 $\times$ 10$^9$ kg/465,000 m$^3$ for the appropriate densities (Table 4). The total equivalent ejecta mass/volume of eroded sediment calculated using all "maximum" estimates becomes 1.6 $\times$ 10$^9$ kg/744,000 m$^3$.

Before the summed volume of eroded sediment can be used to estimate average outer-continuous ejecta erosion in the basin, the ejecta (V$_{eo}$) eroded from the near-rim (A$_e$) and deposited in more distal reaches (A$_0$, Figure 10) should be constrained further. First, a simplified model of near rim erosion predicts that erosion over the first 100 m outside the present rim crest decreases to values matching the more outer-continuous ejecta (Figure 10). This model is based on the power-law decay of elevation and slope away from the rim due to underlying structural uplift and ejecta thinning [Roddy et al., 1975; Garvin et al., 1989]. Widening of this high-elevation zone near the rim in increased estimates of the volume of ejecta eroded from the near rim (V$_{eo}$), which in turn cause estimates of the volume eroded more distally (V$_{eo}$) to decrease. Therefore, minimizing the near-rim high-elevation zone causes estimated erosion on the more outer-continuous ejecta to be maximized. Second, the 12 m to 15-20 m vertical erosion of the original rim crest [Shoemaker and Kieffer, 1974; Roddy et al., 1975; Roddy, 1978] is decreased to ~10 m and ~15 m lowering at the current rim position to account for 30 m erosional widening of the crater [Roddy et al., 1975; Roddy, 1978]. These values yield a near-rim area of the basin (A$_e$) of 57,000 m$^2$, a distal area (A$_0$) of 418,000 m$^2$, and near-rim volumes (V$_{eo}$) of 429,000 m$^3$ and 286,000 m$^3$ for 15 m and 10 m rim erosion, respectively. The remaining volume, V$_{eo}$, is the total-deposit volume minus V$_{eo}$, or 36,000 m$^3$ and 179,000 m$^3$ for 15 m and 10 m rim crest lowering, respectively. The resultant "best" estimate of average erosion of outer-continuous ejecta (V$_{eo}$/A$_e$) is from ~10 cm to ~40 cm for 15 m and 10 m rim crest lowering, respectively. Similar calculations of all "maximum" values limit average erosion of the outer-continuous ejecta to at most 110 cm.

Although erosion estimates derived from the intrabasin sediment budget incorporate a number of losses, such values can be validated by field observations and all are similar to estimates from the first approach involving grain size comparisons. In addition, denudation of the outer-continuous ejecta is maximized by minimizing the width and volume of the near-rim high-elevation zone. This point is illustrated by the difference in estimated erosion obtained using a near-rim volume based on a rim lowering of 10 m versus 15 m. Because the scale of depositional features in the basin and elsewhere at the crater is similar, the 0.4-1.1 m estimate of erosion on the outer-continuous ejecta should be representative.

**DISCUSSION**

The minimal amount of erosion that we derive for Meteor Crater's outer-continuous ejecta leads to the possibility that much of the ejecta might retain a relatively pristine form partly masked by vegetation, an alluvial and colluvial veneer, removal of finer scale textures, and loss of color contrasts on ejecta surfaces. As discussed next, this inference can be supported by the results of ground-penetrating radar studies [Grant and Schultz, 1991] of ejecta surfaces beneath the alluvium; by the scale of primary ejecta features still preserved; and by comparisons with preservation states of other landforms created by catastrophic events.

High-resolution ground-penetrating radar allows comparison of exposed and buried surfaces (Figure 11). Radar transects show that gradients on buried ejecta/alluvium contacts extrapolate continuously to exposed ejecta surfaces. Consequently, erosion has been limited since deposition of most of the overlying alluvium. In addition, ~1 m local relief on both buried alluvium/ejecta contacts and exposed ejecta is comparable. This observation indicates that incise-
Blocked Drainage South of Crater

Fig. 11. Ground penetrating radar transect across the alluvium that is filling a blocked drainage on the south side of the crater (see Figure 2 for location). Radar was used to confirm depths of alluvium around the crater and to provide additional information regarding the erosional history. Depth scales differ between ejecta and alluvium due to varying dielectric properties. An analog SIR-3 GPR from Geophysical Survey Systems, Inc., was used with a 500-MHz antenna to obtain data. The gradient along the contacts between alluvium and underlying ejecta is close to that on adjacent, exposed surfaces, thereby suggesting minimal vertical erosion since emplacement. In addition, the contact shows little evidence for fluvial incision and therefore erosion prior to burial.

ment prior to burial has been minimal (Figure 11). Hence, the maximum 1-m estimate of erosion on the outer-continuous ejecta is consistent with evidence from in situ features revealed by radar (Table 5).

As part of a separate study focusing on the styles and mechanics of ejecta emplacement (Schultz and Grant, 1989; P.H. Schultz and J.A. Grant, manuscript in preparation), we also sought to identify key ejecta signatures associated with emplacement. Careful examination of the crater exterior reveals the preservation of subtle, but unmistakable primary ejecta features. For example, several ~1-m thick distal ejecta lobes superpose low buttes ~2.0R north of the crater [Tilghman, 1905; Barringer, 1910] (Figure 1). These lobes persist despite exposure to prevailing winds (Figure 12). Their preservation in such an erosional setting suggests that it is inconsistent with wholesale 2–3 m removal of the outer ejecta as implied by some previous estimates. Moreover, preservation of scattered Kaibab ejecta blocks (~15 to 25 cm in diameter) beyond the continuous ejecta at distances up to 5.3R also implies minimal erosion (Table 5).

Although this study emphasizes the amount and styles of degradation, the total average erosion since crater formation provides an effective long–term erosion rate of 2 cm/ka that can be calibrated by derived rates for other diverse landforms. Derived long–term rates measured on other southwestern U.S. surfaces include basaltic cinder cones (1.1–2.8 cm/ka), dolomitic rocks (1.7–2.1 cm/ka), some plutonic rocks (0.2 cm/ka), and piedmont surfaces (0.5 cm/ka) as cited in other studies [Marchand, 1971; Turrin and Dohrenwend, 1984; Dohrenwend et al., 1986; Dohrenwend, 1987]. Average erosion rates along the steep near rim of Meteor Crater, however, are both expectedly higher [Shoemaker and Kieffer, 1974; Nishiizumi et al., 1991] and consistent with the paradigm that erosion is influenced by local slope and relief. Such time–averaged estimates, however, may not accurately reflect actual erosion rates at any given time.

The pristine state of ejecta around Meteor Crater is also comparable with the preservation of four other catastrophic landforms of similar age that contain abundant coarse fragments and have experienced generally dry (time–averaged) climate histories. First, exten-

| TABLE 5. Summary of Estimated Erosion of Distal–Continuous Ejecta at Meteor Crater |
|-------------------------------------------|-----------------|-----------------|-----------------|
|                                         | NR, m + | OC, m ++ |
| Coarsening of lags                       | —       | 0.8 | 1.0 |
| Basin sediment budget                    | 10–15*  | 0.4 | <1 |
| Ground penetrating radar                 | —       | <1 |
| Primary ejecta features                  | —       | <1 |

+NR=Near Rim (<0.5R).  
++OC=Outer–Continuous (>0.5R).  
*Modified estimates of near–rim erosion cited above; see text for discussion.
Fig. 12. One of several preserved distal-ejecta lobes on top of preexisting, elongate Moenkopi buttes located approximately 2.0R north-northwest of the crater. The lobe persists despite an elevated position and direct exposure to prevailing winds. The crater is to the left. View is to the west-northwest.

sive ejecta deposits are preserved around the >7000 year old [O'Connell, 1965; Milton, 1968; Baker, 1981] Henbury Craters in Australia and include ray/lobe features and closed impact depressions as small as 6 m in diameter with relief less than 0.5 m [Hodge, 1965; Hodge and Wright, 1971; Alderman, 1932; Milton, 1968]. Second, low-gradient, blocky surfaces on the ~18 ka [Stout, 1975; Johnson, 1978] Blackhawk landslide in California are also well preserved [Shreve, 1968]. Third, the 13-18 ka gravel/cobble bedforms in the Channeled Scabland of Washington [Baker, 1978] remain clearly recognizable and are not deeply eroded. Finally, some alluvial fans in the southwest United States preserve small, late Pleistocene/middle Holocene sheetflood bedforms [Wells and Dohrenwend, 1985; Wells et al., 1990]. Due to the catastrophic nature of events forming these deposits, the larger size fractions are less sensitive to further transport under normal conditions, a condition analogous to the observed preservation of outer–continuous ejecta at Meteor Crater.

The maximum 1-m erosion of the outer–continuous ejecta estimated here (Table 5) is consistent with amounts inferred by Phillips et al. [1991] and Pilon et al. [1991], but significantly less than the amount of erosion deduced by Shoemaker and Kieffer [1974], Roddy et al. [1975], Roddy [1978], and Nishiizumi et al. [1991](Table 2). This discrepancy may arise because workers citing higher denudation also concluded that considerable Coconino ejecta has been lost. Although transported sediments in the windstreak indicate up to 2–3 m of Coconino ejecta has been deflated from existing localized outcrops, more widespread erosion of Coconino ejecta seems unlikely for four reasons. First, the amount of Coconino that must be removed to account for this erosional state exceeds the maximum calculated volume of ejected Coconino sandstone [Roddy et al., 1975] by at least 2X. Second, sediments containing Coconino sands within alluvial and eolian depositional sinks in and around the crater are rare except in deposits directly downslope and/or downwind of existing Coconino ejecta exposures. The absence of an appreciable Coconino component in most alluvium and drainage systems/traps precludes its widespread occurrence initially. There is also a paucity of Coconino sediments in samples from a transect crossing stratigraphy on the crater floor. Any possible unsampled Coconino component at greater depth in the crater center must be volumetrically small and indicates that widespread deflation of Coconino ejecta has not occurred. Third, some near–rim exposures of Coconino ejecta occur at elevations lower than the adjacent alluvial terraces but are not mantled by washed down alluvium as would be expected for more extensive degradation. Finally, crater flanks remain poorly incised and interfluve areas remain unrounded, thereby indicating only incipient fluvial erosion [e.g., Ritter, 1986].

One implication of our results is that the volume of Coconino sandstone ejected probably lies between that predicted by Roddy et al. [1975] and Croft [1980](Table 1). Our results may be most consistent with those of Grieve and Garvin [1984], who model crater formation and predict a depth of excavation for Meteor Crater that is slightly greater than that of Croft [1980]. Such models likely require further refinement before they can be considered to reflect accurately all details of the impact process and crater formation.

The ground truth provided by field studies provides the necessary quantitative reference for identifying the signatures of degradation processes in different geologic and planetary settings. Comparisons of degradational states on more densely cratered surfaces can be used to infer the intensity and processes of degradation with allowances for different substrates. On Mars, such knowledge could be achieved using high-resolution Mars Observer data and would provide a general indicator of regional erosion. Conversely, the results might allow understanding past climates.
CONCLUDING REMARKS

The amount and styles of erosion around recently created landforms such as impact craters can be constrained quantitatively using two techniques based on field studies: comparisons between subsurface ejecta and surface ejecta–lag grain size properties and evaluation of the sediment budget within local drainage basins. At Meteor Crater, these methods place an upper limit of 1 m average erosion on degradation in response to contrasting climates around other craters on the Earth, Mars, and Venus.

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REFERENCES

Barringer, D.M., Meteor Crater (Formerly called Coon Mountain Butte) in Northern Central Arizona. 45 pp., Published by D.M. Barringer, 1910.
McFadden, L.D., S.G. Wells, and M.J. Jercinovich, Influences of eolian and