Degradation of Selected Terrestrial and Martian Impact Craters

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Degraded craters on Mars record the cumulative effects of the complex interplay between erosion, transport and deposition by competing intermittent processes. Fortunately, impact craters are instantaneous landforms common to both the Earth and Mars that are characterized by similar topography and local lithofacies. Deconvolving the signatures of individual degradation processes around young craters on Earth (e.g., drainage scale and density, changing wall slope, deflation features) allows calibrating degradation signatures around craters on Mars and places first-order limits on controlling processes and perhaps past climates. Such comparisons are valid despite differences in vegetation cover and time scales over which activity occurs on the two planets. Analysis of degradation at Meteor Crater, Lonar Crater, and Talemzane Crater reveals a terrestrial sequence of advancing degradation by fluvial, eolian, and mass wasting processes. At Meteor Crater, fluvial processes currently dominate primary erosion; however, combined deflation from the ejecta and both alluvium and colluvium make eolian processes most important in overall ejecta degradation. Lonar and Talemzane reveal that advancing fluvial degradation is characterized by larger drainages and decreasing wall slopes. At Talemzane, interior drainage basins reveal the rim-crest and pire headward regions of exterior drainage basins. When comparable degradation signatures resolvable at Viking resolutions are used in selected areas on Mars, important differences from the terrestrial sequence are revealed. All morphologies of craters in southern Ismenius Lacus (SIL) are typically incised by small valleys with low drainage densities, display rare alluvial deposits, possess walls sloped at the angle of repose, and are sometimes partially covered by airfall deposit remnants. Analogy with the terrestrial craters indicates signatures associated with advancing fluvial degradation should be readily detected on Mars. Together with other differences between degraded craters on the two planets, the paucity of fluvial signatures in SIL implies that mass wasting and eolian activity predominated degradation of martian craters preserved since the Hesperian. Crater statistics for SIL indicate most craters were degraded during geologically brief intervals in the Noachian and mid-Hesperian. Therefore, fluvial signatures preserved in SIL imply any runoff since the Hesperian was short lived, locally debouched, and unrelated to rainfall.

INTRODUCTION

Degraded impact craters on Mars occur in a variety of geologic settings; hence, understanding their degradational state and style provides clues for controlling processes and past climates. Unlike most landforms, impact craters on Mars and Earth form instantaneously without competing gradational processes, and subsequent degradation reflects similar processes. But the different durations over which such processes may operate and the very different total exposure times can result in contrasting appearances. Studying the degradational styles and states of young terrestrial craters allows understanding the geomorphic consequences of each process while revealing the significance of differences. Similar terrestrial analogue studies are well established as an aid to understanding martian landform evolution including: outflow channels [Baker, 1982], valley networks [Mars Channel Working Group, 1983; Laity and Malin, 1985], eolian structures [Breed et al., 1979; Greeley and Iverson, 1985], landslides [McEwen, 1989], and the regolith [MacKinnon and Tanaka, 1989]. This study uses a similar approach by characterizing the degradational evolution of craters on Mars and constraining processes and climate responsible for their degraded form.

Common processes controlling degradation on the Earth and Mars include downhill transport via mass wasting, fluvial, and eolian activity. Considerable evidence demonstrates these same processes were/are also active on Mars [e.g., Carr, 1981]. However, important differences exist between the two planets. On Earth, erosion rates are affected by vegetation, lithology, and climate. Comparisons with Mars then requires terrestrial craters in flat-lying relatively unvegetated rocks in arid to sub-humid climate. In addition, lower martian gravity results in decreased runoff velocities, but increases the carrying capacity in fluvial systems [Mars Channel Working Group, 1983]. The influence of non-martian variables such as vegetation on the range in degradational morphology appears limited to factors of 2 to 3 at most. Although the terrestrial environment results in substantially higher average degradation over shorter time than on Mars, the degradation rate at any given time depends on the intensity and duration of the erosional process, i.e., climate. While important with regards to the rate at which degradational landforms evolve, these differences do not significantly alter the fundamental signature of individual processes: the first-order cumulative signature of degradation by an individual process should be similar on both planets. Other variables less important to overall gradational character include sensitivity to climate, slope, tectonics and other geomorphic thresholds [Eckis, 1928; Bull, 1964; Denny, 1965; 1967; Lustig, 1965; Scott, 1973; Schumm, 1977, Ritter, 1978; Bull and Schick, 1979; Leeder, 1982; Mayer et al., 1984], and can be used to place first-order constraints or define characteristic clues about changing processes and climate through time [e.g., McFadden and Bull, 1981; Wells et al., 1984; 1987; Peartree and Calvo, 1987; McFadden et al., 1989].

The present study uses field mapping to define the degradational history around the ~50,000 year old [Sutton, 1985; Nishiizumi et al., 1989; Zreda et al., 1991], 1.2-km-diameter Meteor Crater, Arizona (Figure 1, 35.3°N, 111.2°W). Degradation states of the progressively more degraded Lonar Crater in India (20.0°N, 76.5°E, 1.8-km-diameter, ~62,000 years old; [Grieve et al., 1988]) and Talemzane Crater in Algeria (33.3°N, 4.0°E, 1.75-km-diameter, 0.5–3.0 mil-
Fig. 1. High-resolution air photo of the ~50,000-year-old Meteor Crater in north-central Arizona (1.2-km diameter, 35.3°N, 111.2°W). The dashed and dotted line marks the approximate limit of the continuous ejecta, whereas the dashed line and (a) highlights a region of semi-enclosed drainage on the west side of the crater as discussed in the text. White arrows denote the flow direction of selected drainages around the crater. Note the pronounced difference in the expression of drainages on the outer flank and ejecta of the crater from those incising largely relict debris chutes on the interior wall. The patchy saltation transport windstreak mostly east and northeast of the crater is easily distinguished despite the minimal thickness of constituent sediments (generally less than 15 cm thick). Buildings on the north rim of the crater (top) house a museum and staff apartments. Chavez Pass Road runs west of the crater.
The mass of material eroded by individual processes can be calculated and differences in degradational style associated with changing slope in and around the craters can be defined.

Results from study of these terrestrial craters are then compared with the gradational morphology associated with craters in southern Ismenius Lacus, Mars (30°–35°N; 325°–360°W, Figure 2), in order to develop first-order constraints on gradational activity. Southern Ismenius Lacus (SIL) was selected for study because it preserves evidence for crater degradation by mass wasting, eolian, and fluvial processes and is covered by Viking images with a relatively high resolution of 40–45 m/pixel. As a first step towards understanding how the activity of individual processes affects the amount and style of degradation in a changing climate, the geologic and climate setting of SIL and the terrestrial craters is reviewed. Next, common degradation signatures associated with craters on both planets are described. These signatures are used to assemble a first-order degradational sequence for the terrestrial craters that is then compared with the martian degradational signatures to infer past processes and climate.

**Comparisons of Geologic and Climate Settings**

**Craters in Southern Ismenius Lacus**

Geologic setting. SIL lies within a broad area of low thermal inertia centered on Arabia [Zimbelman, 1986]. Much of the surface is heavily cratered and some portions are either stripped or mantled (see Figure 2). Remnants of more widespread layered deposits bury some crater floors and rare examples of both pedestal craters and inverted topographic features occur (e.g., valley networks; Grant and Schultz, 1991b). Raised rims around many craters were destroyed during this epoch (defined as rimless if the raised rim surrounds less than 50% of the crater). The second gradational epoch occurred during the Hesperian and was dominated by emplacement and modification of a volatile-rich air-fall deposit [Grant and Schultz, 1991b; 1991c; 1991d]. An earlier end to the Hesperian activity in eastern sections allowed more complete preservation of air-fall deposits than farther west where gradation continued until the peak of outflow channel formation [Greeley and Guest, 1987]. Gradation in eastern SIL ceased contemporaneously with ridged plains emplacement to the east [Dimitriou, 1990] and the end of air-fall deposition/erosion elsewhere on the planet [Schultz, 1988; Schultz and Britt, 1986; Schultz and Lutz, 1988; Grizzaffi and Schultz, 1989; Grant, 1990; Grant and Schultz, 1991b]. The thickness of air-fall deposit remnants in SIL indicates an original accumulation of up to several hundred meters. Crater Cerulli formed between the two gradational epochs and coincident with late volcanic activity at Syrtis Major. Finally, the decreasing size of preserved valley networks and craters affected by degradation from the Noachian to the Hesperian gradational epoch demonstrates that the overall intensity of gradation decreased with time in SIL (Figure 3).

**Young Terrestrial Craters**

Geologic setting. All three craters selected for study are unglaciated and occur in flat-lying rocks of sedimentary or volcanic origin. At Meteor Crater, the lithologically diverse Triassic Moenkopi Formation (mudstones to sandstones) unconformably caps a sequence of Permian Kaibab dolostone/limestone and the Permian Toreweap and Coconino sandstones [McKee, 1954; Shoemaker, 1960; 1987; Shoemaker and Kieffer, 1974]. By contrast, Lonar is in basalt flows of the Cretaceous Deccan Traps [Fredriksson et al., 1973] and Talsemzane cuts sub–horizontal Eocene limestones [Lambert et al., 1980]. Each crater preserves portions of a raised rim, varying amounts of fill, and continuous ejecta [Shoemaker, 1987; Shoemaker and Kieffer, 1974; Grant and Schultz, 1991a; Fredriksson et al., 1973; Lambert et al., 1980; McLone and Greeley, 1987].

At Meteor Crater, a 30–60 m high raised rim is largely confined to within ~300 m of the rim–crest (0.5 crater radii beyond the rim–crest or 0.5R) and is eroded to a smoothed, undulating form ~30 m or 2.5% of the diameter. Crater fill is ~100 m thick [Fredriksson et al., 1973; Grant and Schultz, 1991b; 1991c; 1991d]. The much older Talemzane crater retains a breached raised rim that is 27 m high, rounded, and confined to within ~0.3R of the rim–crest (measured from Figure 1 in Karpoff [1963]). The much older Talemzane crater retains a breached raised rim that is 27 m high, rounded, and confined to within ~0.3R of the rim–crest (measured from Figure 1 in Karpoff [1963]). Preliminary estimates suggest wall backwasting (from a cross-section in Lambert et al., 1980) accounts for ~9% widening of Talemzane. Average wall

**CLIMATE SETTINGS**

**Geologic setting**. Analyses of crater statistics and regional surface morphology reveal at least two epochs of increased gradation affected the geomorphic evolution of SIL (Figure 3) [Grant, 1990; Grant and Schultz, 1991b] and were likely related to periods of more clastic climate induced by release of either recycled xenogenic material [Schultz, 1988; Grant and Schultz, 1990] or juvenile endogenic atmospheric volatiles. The first epoch occurred from the time of the Hellas and Isidis impacts until the time of mid to late Noachian highlands intercrater plains formation [Grant and Schultz, 1991b; Greeley and Guest, 1987]. Raised rims around many craters were destroyed during this epoch (defined as rimless if the raised rim surrounds less than 50% of the crater). The second gradational epoch occurred during the Hesperian and was dominated by emplacement and modification of a volatile-rich air-fall deposit [Grant and Schultz, 1991b; 1991c; 1991d]. An earlier end to the Hesperian activity in eastern sections allowed more complete preservation of air-fall deposits than farther west where gradation continued until the peak of outflow channel formation [Greeley and Guest, 1987]. Gradation in eastern SIL ceased contemporaneously with ridged plains emplacement to the east [Dimitriou, 1990] and the end of air-fall deposition/erosion elsewhere on the planet [Schultz, 1988; Schultz and Britt, 1986; Schultz and Lutz, 1988; Grizzaffi and Schultz, 1989; Grant, 1990; Grant and Schultz, 1991b]. The thickness of air-fall deposit remnants in SIL indicates an original accumulation of up to several hundred meters. Crater Cerulli formed between the two gradational epochs and coincident with late volcanic activity at Syrtis Major. Finally, the decreasing size of preserved valley networks and craters affected by degradation from the Noachian to the Hesperian gradational epoch demonstrates that the overall intensity of gradation decreased with time in SIL (Figure 3).
Fig. 2. Geomorphic map of study area in southern Imenius Lacus (SIL), Mars. Note the occurrence of relatively small (~5-km diameter) pristine craters whose ejecta has been modified by valley network formation (dashed and dotted outline). An abundance of these craters occur in the north-central west section of the mosaic and on the ejecta surrounding crater Cerulli. Several other locations within the region (labeled) appear stripped or buried by probable air-fall deposits. The relative size of pristine craters decreases slightly towards the east; super pristine craters (completely unmodified at available resolution) were only distinguished in the western quarter of the study area. Many of the degraded craters lack a well-defined raised rim (though some of these still retain identifiable ejecta). Most mapped ridges display a north-northwest to south-southeast trend. Western and eastern portions of the map cover approximately 30°–36°N, 342°–1°W and 30°–35°N, 325°–342°W, respectively. Mapped using Viking 211 series mosaics 5959–5962 compiled from images from Revs. 212S–199S with ~40–50 m/pixel resolution or ~1.5X Landsat TM resolution.
Inferred History NW Arabia

**Table 1. Slope of Crater Walls**

<table>
<thead>
<tr>
<th>Terrestrial craters</th>
<th>Average, deg</th>
<th>Range, deg</th>
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<tbody>
<tr>
<td>Meteor Crater</td>
<td>—</td>
<td>30°-90°</td>
</tr>
<tr>
<td>Lonar Crater</td>
<td>—</td>
<td>35°-36°</td>
</tr>
<tr>
<td>Talemzane Crater</td>
<td>—</td>
<td>22°-35°</td>
</tr>
<tr>
<td>SIL pristine craters</td>
<td>27°</td>
<td>24°-35°</td>
</tr>
<tr>
<td>SIL degraded craters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rimless without ejecta</td>
<td>28°</td>
<td>17°-40°</td>
</tr>
<tr>
<td>Rimless with ejecta</td>
<td>29°</td>
<td>20°-36°</td>
</tr>
<tr>
<td>Rimless, ejecta buried</td>
<td>27°</td>
<td>—</td>
</tr>
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slopes are 22°-35° (Table 1) and an unknown, but significant amount of fill buries the floor [Lambert et al., 1980].

The ejecta deposits at these craters record a different response to erosional processes. Continuous ejecta at Meteor Crater extends ~2.0R beyond the rim–crest, and most exposed deposits are compositionally dominated by relatively resistant Kaibab Formation fragments. Ejecta north and east of the crater is mantled by a thin (generally <15 cm thick), but prominent windstreak (J.A. Grant and P.H. Schultz, submitted paper, 1992). Ejecta at Lonar occurs at least 0.6R from the rim–crest and retains both stratified ejecta and fallback units [Fredriksson et al., 1973]. At Talemzane, ejecta is preserved outside the rim–crest [Lambert et al., 1980], but remains incompletely mapped.

**Climate History:** Past conditions at Meteor Crater are best constrained and were wetter than present for ~2–3 thousand years near the time of the Pleistocene/Holocene transition (~10 ka or thousand years ago) and during a pluvial period from ~25 ka until roughly 15 ka [e.g. Morrison and Frye, 1965; Smith, 1979; Smith and Street-Perrott, 1983; Van Devender, 1990; Van Devender et al., 1987; May er et al., 1984; Benson and Thompson, 1987a; 1987b; Wells et al., 1985; 1987; Thompson et al., 1986; Betancourt, 1987; Betancourt and Van Devender, 1981; COHMAP, 1988; Spaulding and Graw lich, 1986; Forrester, 1987]. Much of the period 25–50 ka at Meteor Crater possibly averaged wetter than present and was punctuated by wetter episodes [e.g., see Morrison and Frye, 1965; Benson, 1978; Mifflin and Wheat, 1979; Smith, 1979; Benson and Thompson, 1987b].

By contrast, present conditions at Lonar were preceded by a wet period from ~9–6 ka and wet conditions occurred at Talemzane from ~24–18 ka and ~6 ka [Street-Perrott and Harrison, 1985; COHMAP, 1988]. An interval of drier conditions may have persisted at Talemzane from ~13–9 ka [Street-Perrott and Harrison, 1985; COHMAP, 1988].

**Common Degradational Signatures**

Southern Ismenius Lacus displays a high density of valley networks, and the relatively high resolution of Viking image coverage allows mapping of airfall deposits remnants, talus and deposits, and fluvial systems <100 m across around both fairly pristine and rimless craters. The distribution airfall mantled versus unmantled areas helps define the role of eolian activity, whereas talus deposits combined with measure of wall slopes identifies sites of mass wasting or fluvial incision. Drainage density and scale records aspects of the degree and duration of fluvial dissection which can be combined with mapping of alluvial deposits to infer fluvial transport capacities.

On the Earth, these same variables can be defined and combined with additional data to place quantitative constraints on efficiency of individual processes in crater degradation. For example, comparison of drainage density, drainage gradients and relief ratios, and the geo-hydrologic properties of the substrate constrains runoff efficiency. Moreover, the distribution and grain size of alluvium directly measures changing transport capacity, stream power, and indirectly, climate [Cooke and Warren, 1973; Wells et al., 1987; Dohrenwend, 1987]. Finally, the sediment budget within a drainage basin details the interplay between fluvial, colluvial, eolian, and mass wasting processes through time. These terrestrial data set the stage for interpreting the martian record, but must be defined. Consequently, the following description of common degradation signatures first considers those identified around the terrestrial craters.

**Young Terrestrial Craters**

**Meteor Crater.** Unconstrained resolution at Meteor Crater allows drainage mapping at scales ranging from meters to the 30 m/pixel resolution of Landsat Thematic Mapper (TM) images that approaches the 40–45 m/pixel resolution of Viking imagery of SIL. Radial gullies draining the flanks of Meteor Crater are 1–5 m wide, 1–2 m deep, and have a density of 8.6 km/km², 3.4 km/km², and 0.0 km/km² as determined from field mapping, air photos, and TM imagery, respectively (Figure 4). Drainage divides are generally de-
Meteor Crater Drainage Density

Fig. 4. General drainage map of Meteor Crater and surrounding region. Intermittent radial gullies draining the outer flank form a density of 8.6 km/km² out to 0.6R from the rim-crest. Preexisting systems beyond the limit of the crater (a) that was examined in detail in order to constrain the importance of various gradational processes. Drainage in the semi-enclosed basin was defined by original ejecta relief, but occur along alluvial fan spines in several localities. The relief ratio of these drainage basins is 0.07.

Flank gullies typically incise higher gradient areas and deposit thin alluvial fans near the base of the rim (Shoemaker, 1960; Shoemaker and Kieffer, 1974; Roddy et al., 1975) that merge distally with areas of more diffuse drainages. Together with thin wedges of colluvium, this alluvium partially buries ejecta in low-relief swales along the lower flank. Fans and diffuse drainages average ~1.0-1.5 m and ~0.3-0.7 m thick, respectively, and typical colluvium thicknesses are 20-40 cm. Relative to the volume of incised upstream reaches, the volume of associated alluvial deposits is large. Although diffuse drainages are identifiable in air-photos and TM imagery (Figures 1 and 5) alluvial fans are not.

Inside Meteor Crater, most gullies occur in relict debris chutes along the steep walls and give drainage densities of 13.7 km/km² and 4.3 km/km² when measured from air photos and Landsat coverage, respectively. The ability to identify these gullies in TM imagery reflects their position in debris chutes where cross sections are exaggerated relative to gullies outside the crater (Figure 5).

Direct measure of grain sizes in the mapped alluvial and colluvial sinks on the ejecta at Meteor Crater defines the transport capacity of processes responsible for their formation and allows comparison with eolian transport capacity (Grant, 1990)]. Subsequent definition of the thickness of alluvial, colluvial, and eolian deposits mapped within a semi-enclosed drainage basin on the west flank of Meteor Crater allows conversion into the volume and mass of sediment transported by individual processes.

Samples from alluvium on ejecta around Meteor Crater demonstrate that blocks larger than 15–20 cm (average axis) are generally not transported and accumulate in situ. For example, the mean grain size of sediment in the fans and diffuse drainages is 3.2 phi (0.11 mm) and 2.9 phi (0.14 mm), respectively. Although all alluvium has a mode at 3.0–4.0 phi (0.13–0.06 mm), a small mode at grain sizes larger than ~1.5 phi (~2.5 mm) distinguishes fan sediments from diffuse drainages. Broader grain size distributions are found in some small, distal, active fans receiving sediment from steeper portions of the flank. Grain size characteristics of alluvium differs considerably from those of colluvium (mean of 1.9 phi or 0.44 mm and no well-defined mode), pristine ejecta (mean of ~0.65 phi or 1.6 mm and modes at sizes larger than ~2.0 and 3.75 phi or ~4 mm and 0.074 mm), and windstreak sediments (mean and mode of 2.5 phi or 0.18 mm). Ejecta grain sizes indicate moderate to high hydraulic conduc-
tivity (Figure 6) which together with an absence of appreciable run-off from ejecta surfaces over a five year study period implies high infiltration capacity. Most ejecta, alluvium, and colluvium surfaces
outside the crater are armored by thin (1–3 cm thick), coarse–grained lag deposits evolved in situ during erosion of fines [Grant, 1990].

Mapping of alluvial, colluvial, and eolian deposits and their thicknesses are used to define the sediment budget in a semi–enclosed drainage covering 475,000 m² of the western crater flank (Figure 4). Depositional environments inside the basin include: exposed ejecta (buried by <20 cm colluvium) that comprises 38% of the surface, mostly (72%) in near–rim regions; colluvium covering 26% of the basin and surrounding ejecta on the lower flank; and alluvial fans and diffuse drainages that bury 19% and 17% of the surface, respectively. The distribution of these deposits can be converted to volume estimates using sample pits and ground penetrating radar profiles to constrain thicknesses [Grant and Schultz, 1991], but require corrections to account for any transport out of the basin. Inclusion of 13,000 m³ fans and 55,000 m³ diffuse drainage immediately north and south of the basin accounts for surface wash across basin divides and yields a total of 120,800 m³ alluvium in initial volume estimates. Next, ~15 cm colluvium lies buried beneath most alluvium and represents 25,500 m³ of sediment for a total initial colluvium volume of 62,400 m³. Each of these initial volume estimates includes a 5–cm correction for vertical dissolution, but do not account for deflation.

Deflation off alluvium in the basin is constrained using: phreatophyte mound relief on diffuse drainages, subsurface alluvium versus surface coarse–grained lag sedimentology, and the paucity of exhumed carbonate coated blocks. A minimum deflation of ~15 cm from alluvium is given by phreatophyte mound relief on diffuse drainages; however, a more realistic estimate is obtained by examination of lag deposits capping most alluvium. These 1–3 cm thick lags contain ~10 times more coarse fragments (>2 mm) than the subsurface alluvium and could be produced by up to ~30 cm deflation (assumes lags formed in situ by accumulation of coarse grains without eolian deposition [Grant, 1990]). Because deflation of more than 2–3 times this amount from the alluvium would destroy lateral continuity with colluvium and ejecta and exhume numerous carbonate coated blocks, a maximum of ~70 cm deflation is predicted. Comparable deflation is estimated for continuously exposed ejecta based on analyses of windstream sedimentology and volume [Grant, 1990] (J.A. Grant and P.H. Schultz submitted paper, 1992).

Deflation from colluvium in the basin can be constrained using stratigraphic position and grain size. First, colluvium occurs above the ejecta and beneath most alluvium, thereby indicating an intermediate exposure age. Second, relative to the Kaibab ejecta, colluvium is depleted at coarse grain sizes (>10 cm) and enriched (by 1/3) at grain sizes susceptible to deflation (grains smaller than <1.0 phi by analogy with windstream sediment). Because age and susceptibility to deflation should cancel when considering colluvium versus ejecta deflation, minimum, best, and maximum estimated deflation for the two deposits are comparable: 20 cm, 45 cm, and 70 cm, respectively [Grant, 1990] (J.A. Grant and P.H. Schultz submitted paper, 1992).

Deflation from ejecta prior to burial beneath colluvium and alluvium (as well as deflation from colluvium before being covered by alluvium) also needs to be accounted for. Assuming buried ejecta surfaces were exposed for an average of 1/2 the crater age gives a best estimate of deflation of ~1/2 that predicted for the continuously exposed ejecta or ~25 cm. There was no deflation if burial occurred immediately after emplacement, but may have been as much as 55 cm if the burial age is only ~10,000 years or the minimum probable age of most deposits (0.8 times the maximum 70 cm deflation estimated for the continuously exposed ejecta [Grant, 1990]) (J.A. Grant and P.H. Schultz submitted paper, 1992). Colluvium beneath alluvium averages ~1/2 the thickness of exposed colluvium. Again assuming a burial age of 1/2 the crater age implies deflation is ~1/2 that of the exposed colluvium or ~25 cm. Arguments similar to those outlined for deflation of buried ejecta yields comparable minimum/maximum values of 0/55 cm for the now buried colluvium.

Using these corrected volumes, the total mass of fluvially transported and deflated sediments on the ejecta at Meteor Crater can now be estimated. First, the mass of alluvium (fans and diffuse drainages) in the basin is between 280,000 and 520,000 metric tons with a best estimate of 360,000 tons (for a density of ~1800 kg/m³). Second, colluvium mass is between 190,000 and 500,000 tons, but is likely closer to 330,000 tons (for a density of ~2000 kg/m³). By comparison, deflation from ejecta in the basin (density of ~2150 kg/m³; Reagan and Hinze, 1975) amounts to between 80,000 and 620,000 tons with a best estimate of 340,000 tons [Grant, 1990] (J.A. Grant and P.H. Schultz submitted paper, 1992).

At face value, then, the total mass transported by fluviatile processes (alluvium plus colluvium, assumes colluvium is formed by surface wash) appears to be twice that removed by eolian deflation; however, active deflation from developing alluvial and colluvial deposits could affect these relative roles. If colluvium is entirely the result of mass wasting (i.e., nonfluviatile transport) then primary fluviatile erosion...
still equals or slightly exceeds deflation. This situation is unlikely because the ejecta surface is anchored by blocks and surface terraces are not observed. Primary fluvial erosion should account for ~40% total primary erosion even in the following extreme case where (1) colluvium is formed by equal surface wash and mass wasting; (2) deflation from the alluvium and colluvium is minimal (i.e., minimize mass of the deposits); and (3) deflation from exposed ejecta is maximized. Such an extreme case is also unlikely because eolian deposits downwind of the semi-enclosed basin are dominated by sediments whose modal grain size reflects deflation from alluvium rather than ejecta (based on comparisons of alluvium and windstreak grain sizes [Grant, 1990]) (J.A. Grant and P.H. Schultz submitted paper, 1992). However, alluvial, colluvial, and eolian processes may be more interrelated than what these inventory estimates provide.

When the mass of ejecta deflated by primary eolian activity is now combined with the mass due to secondary deflation of alluvium and colluvium, eolian activity ultimately transports up to 2/3 the entire inventory of sediment eroded by all processes around Meteor Crater. Paradoxically, the fluvial activity that dominates primary gradation revealed by the mapped drainage systems also exposes large inventories of easily deflated fine-grained material. By contrast, overall degradation inside Meteor Crater is dominated by fluvial and lesser mass wasting activity as indicated by the large size of alluvial fans, occurrence of relict debris chutes, and a relatively small volume of eolian deposits [Shoemaker and Kieffer, 1974].

An additional clear signature of impact crater degradation is related to rearrangement of regional drainages and burial of the distal ejecta by alluvium (Figure 4). Most regional systems in the vicinity of Meteor Crater are subparallel and northeast draining [Shoemaker and Kieffer, 1974]; however, a radial pattern predominates in and around the crater out to ~2.0R from the rim. Pre-crater drainage is disrupted west of the crater and isolated from downstream segments east of the rim (Figure 4). Farther south, the trunk valley of the same drainage is blocked and diverted through local ejecta highs south of the rim before debouching into a preexisting system to the east (Figure 4).

Lonar and Talemzane Craters. Both Lonar and Talemzane are more degraded than Meteor Crater based on comparisons of preserved rim/wall morphology, amount of crater fill and continuous ejecta, and degree of fluvial dissection. Although more quantitative studies paralleling the study at Meteor Crater remain to be completed, rim/wall morphology and drainage patterns clearly indicate more advanced stages of fluvial degradation than are observed at Meteor Crater. Drainages inside Lonar are up to ~30 m wide, comprise a density of 4–5 km/km² (derived from air photo), and are eroding distinct "notches" in the rim–crest. Cultivation of the lower flanks masks alluvial deposits comparable to the fans and diffuse drainages at Meteor Crater.

Talemzane is the oldest and most degraded of the three terrestrial craters as demonstrated by the subdued, deeply incised rim and low slopes of interior walls (Table 1). Headward erosion by interior drainages creates breaches in the rim and beheads upper flank watersheds. Runoff from the wall together with that captured from the upper flank emplaces coalescing alluvial fans near the base of the wall, increases crater infilling, and decreases exterior stream power and drainage scale by robbing drainages of discharge from high gradient headward reaches. Incised breaches in the rim are up to 150–175 m wide and the drainage density of the larger interior systems is 6–7 km/km² as measured from an air photo. Poor detection of small drainages outside the crater precludes drainage density calculation there. Similarly, alluvial deposits outside the crater remain poorly defined. Despite the currently stripped appearance of the crater walls, buried deposits along their base reflect more active mass wasting in the past [Lambert et al., 1980].

Martian Craters in SIL

The study of terrestrial analogs helps to focus examination of craters in SIL on identification of process sensitive signatures: windstreaks and other eolian deposits, mass wasting features, wall slopes, drainage density, and drainage scale. In general, craters in SIL preserve a range of degradational characteristics including a total of ~25% larger than 1–2 km in diameter that lack well-defined raised rims. Many craters in eastern SIL are buried by air–fall deposits, but windstreaks in all areas are rare. The walls of some craters are collapsed and others display evidence of more sustained mass wasting (e.g., talus deposits and debris chutes; Figure 7). Crater walls in SIL are sloped at 270–30° (Table 1) regardless of degradation state. Despite a high density of valley networks in SIL (by Martian standards), many show no clear association with craters. For example, examination of Viking mosaic 211–5959 reveals that crater Cerulli superposes Marias Valles, thereby requiring incision predates the crater and occurred during Noachian gradation.

Valley networks in SIL preserved since the Noachian gradational epoch are large (Marias Valles is ~5 km wide) and have low densities (0.015–0.020 km/km²; Figure 3) when derived from watersheds.

Fig. 7. Crater ~27 km in diameter and located at 32.7°N; 359.9°W. Catastrophic collapse of northeastern and southeastern sections of the wall cause backwasting and removal of raised rim sections. A remnant of the original raised rim remains isolated on the east side of the crater. Incised slopes in the southwestern corner of the crater resemble detached talus accumulations that are cut by debris chutes, thereby implying more sustained mass wasting contributes to gradation and backwasting of the crater wall. Image 211S04 (resolution 44 m/pixel).
defined by methods in Grant [1987] and Kochel et al. [1985]. Measured drainage densities on Hesperian surfaces are higher, but considerably lower than terrestrial values. For example, the drainage density inside Cerulli is 0.12 km/km² while values on its ejecta are 0.13 km/km² (Figure 3). Original densities were likely somewhat higher as some valley segments appear partially buried or display inverted relief, thereby suggesting more complete destruction of other valleys is possible. Younger valley networks (100–150 m wide) incising airfall deposit remnants formed during Hesperian gradation (Figure 3) and create densities of up to 0.85 km/km² and 0.36 km/km² in and around some craters (Figure 8). Although these values are among the highest measured on the planet [Schultz et al., 1985; Baker and Partridge, 1986; Grant, 1987] most craters in SIL are incised by much lower densities. Valleys around some craters are not uniformly distributed, but are confined to surfaces with greater slopes where densities up to 0.30 km/km² are measured (e.g., where the slope on ejecta is increased by emplacement on pre-existing crater walls; Figure 9a). The Hesperian valleys incise a range of surfaces including some craters as small as 5 km in diameter where valley segments are only preserved on elevated surfaces (e.g., remnants of airfall deposits or ejecta; Figure 9b); an absence of associated headward and distal reaches on adjacent, lower terrain implies such drainages are superposed.

Craters in SIL whose ejecta and/or rim-crests are dissected by valleys are rare relative to the number of craters mantled by air-fall sediments. Positive identification of alluvial deposits in and around most craters is also rare, such alluvial deposits are generally small and limited to partial filling of small primary or secondary craters on the ejecta or wall terraces (e.g., Cerulli, Figures 10a and 10b). Alluvium comparable to the diffuse drainages found around Meteor Crater is not yet observed.

**DISCUSSION**

Signatures identified in and around the terrestrial craters can be used to place first-order constraints on degradation styles and processes. In turn, this degradational sequence can be compared with the signatures associated with craters in SIL to infer processes responsible for their appearance. However, these comparisons possess limitations that must first be acknowledged. As noted earlier, differences in vegetation, lithology, and climate between the Earth and Mars accounts for a factor of 2–3 variability in overall degradation style and result in considerably higher degradation rates on the Earth. Relatively lower resolution coverage also hampers identification of subtle degradation signatures on Mars. While such factors preclude detailed quantitative definition of the role of individual processes in crater degradation on Mars, they do not alter the first-order signature of a process, especially at advanced degradation when the scale of diagnostic features increases.

**Terrestrial Signatures**

The following degradation sequence can be assembled for Meteor Crater, Lonar, and Tulemzane. Downslope mass wasting dominates initial degradation of the crater interiors as illustrated by relict debris chutes and aprons inside Meteor Crater. Fluvial activity quickly supersedes mass wasting as ejecta was stripped from crater walls and more coherent country rock became exposed. Outside the crater, initial primary degradation was briefly dominated by deflation prior to development of surface-stabilizing coarse-grained lag deposits (Table 2).

Following initial activity, primary degradation at the craters became controlled by fluvial processes as illustrated by gullies heading on the mid to upper wall and flank. By analogy with the interior of Meteor Crater where fluvial activity dominates degradation, higher stream power along systems incising relict debris chutes causes net backwasting of the wall, crater enlargement, and rim lowering (Table 2). Drainage outside the craters evolves at a significantly slower rate as lower slopes, residual gully floor block accumulations (>20–30 cm), and the high infiltration capacity of the ejecta all contribute to reduced runoff and lessened stream power (Table 2). These observations are consistent with the established paradigm that degradation rates depend on local relief. Nevertheless, the smaller systems outside the crater possess drainage densities and relief ratios indicating efficient surface drainage during high magnitude storm events [Horton, 1945; Patton and Baker, 1976]. The distribution of alluvium at Meteor Crater confirms that early drainage character remains controlled by original ejecta topography: incision occurs along steepest slopes (upper walls and flank) while deposition characterizes lesser slopes (crater floor and near the base of the flank) and low relief swales in the distal ejecta. In addition, surface wash and perched limited surface creep combine to form colluvial wedges around most ejecta highs.

Eolian activity is also important in early primary degradation outside the craters and predominates in some settings when the effects of secondary deflation from alluvium and colluvium are considered (Table 2). Surprisingly, little in situ evidence of this erosion persists at Meteor Crater: the wind streaks reflect only ~15 cm and ~35 deflation from Kaibab and Coconino ejecta source areas, respectively [Grant, 1990] (J.A. Grant and P.H. Schultz submitted paper, 1992); and eolian deposition inside the crater is minimal [Shoemaker and
Grant and Schultz: Degradation of Impact Craters

Dissected Area (212S21) in West Section of Mosaic

Fig. 8. (continued)

Kieffer, 1974]. Much of the remaining inventory of deflated sediments likely resides farther downwind.

Changes in rim-crest morphology from Meteor Crater to Lonar to Talemzane chart the cumulative effects of advanced fluvial degradation. The interiors of Lonar and Talemzane demonstrate that headward incision of the wall by an increasing density of larger drainages first creates "notches" and then large breaches in the rim (Table 2). Continued fluviation outpaces mass wasting as evidenced by steadily decreasing wall slopes and eventual erosion and/or burial of relict debris aprons by increasing alluvial fill. Comparisons among all three craters demonstrate that this activity results in backwasting of the wall, decreasing rim width, and widening of the crater (Table 2). Wall incision proceeds most rapidly where runoff is concentrated in gullies and eventually forms the rim breaches: other wall sections are more slowly eroded by surface wash. Outside the craters, advancing dissection is first accompanied by an increase in the

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size of drainages until rim breaches pirate headward portions of their watersheds, thereby reducing stream power and resulting in decreased drainage scale (Table 2).

The small scale of mapped fluvial systems at Meteor Crater suggests that the actual importance of early primary fluvial degradation would be overlooked when viewed at 40–45 m/pixel resolution available for SIL. Although some fluvial deposits at Meteor Crater (e.g., diffuse drainages) are resolvable in TM images (30 m/pixel), an association with individual gullies is not usually apparent (Figure 5). Moreover, the subdued signature of the diffuse drainages when viewed in a single TM band suggests that their detection in multispectral images reflects varying vegetative cover rather than morphology. Hence, difficulties in identifying fluvial signatures around relatively pristine impact craters at 40–45 m/pixel resolution may not preclude an important role by this process. At 40–45 m/pixel resolution the density of gullies on crater walls may be most measurable and serve as the best indicator of early fluvial degradation; however, more advanced fluvial degradation (e.g., at Lonar and Talemzane) produces fluvial (e.g., rim "notches" and breaches) of sufficient scale to allow easy detection. It is important to note that these more advanced fluvial signatures evolve prior to destruction of the raised rim.

Climate variations at Meteor Crater induce mostly second-order changes in the position and sedimentology of alluvial deposition. For example, fans currently active are typically located farther from the rim and contain coarser clasts than more extensive, finer-grained, inactive fans. The inactive fans preserve a fairly uniform down-drainage grain size that may result from deposition during either (1) more sustained pluvial conditions when soils/vegetative cover were thicker and reduced run-off/stream power [Dohrenwend, 1987]; or (2) shorter term, flashier postpluvial climate when a fine-grained weathering–induced regolith created during wetter conditions was stripped by more intense, higher magnitude precipitation events [Mayer et al., 1984]. A similar situation occurs elsewhere in the southwest where active, coarser fans are farther from the mountain front than inactive, finer late–Pleistocene fans [e.g., Denny, 1965; Wells et al., 1987] and suggests that much of the fine-grained alluvium around Meteor Crater was deposited during the last pluvial. These measurable variations in depositional character with changing climate occur without shifts in overall degradational style.

A paucity of groundwater sapping morphology and a large ratio of alluvium to incised channel volume demonstrates fluvial systems are dominated by runoff following high magnitude precipitation events despite a high infiltration capacity. This is consistent with measured drainage densities, relief ratios, and the conclusion that drainages on the flanks of Meteor Crater once received sediment from mid and headward portions of their drainage basins rather than from erosion within incised channels as is currently the case.

Finally, formation of Meteor Crater locally deranged an other-

![Fig 9a. Relatively pristine crater and ejecta at 35°N; 345.6°W incised by valley networks where ejecta is superposed on higher gradient walls of an older crater. Valley density is 0.30 km/km² and is high compared to many other regions of Mars. Crater is in image 208S22 (resolution 48 m/pixel).](image1)

![Fig 9b. Examples of valley networks (arrows) around SII. craters <10 km in diameter. The two smaller, southwestern valleys appear to head on the ejecta/raised rim of a crater; however, downstream alluvial deposits are not easily identified. The network between the two craters lacks headward and distal sections and preserves mostly medial, trunk segments. Because this valley is preserved only where incision occurred into crater ejecta and not adjacent, lower surfaces, it may reflect superposed drainage formed when the region was more completely mantled by air-fall deposits. All valleys are northwest drainage. Craters are located at 33.2°N; 353.75°W in image 209S14 (resolution 44 m/pixel).](image2)
wise uniform pre-impact regional drainage pattern and created radial drainage in and around the rim. At least a component of this radial pattern persists at the more advanced stages of crater degradation represented by Lonar and Talemzane; hence, a high flux of impactors could lead to broad scale derangement of regional slopes and form areas of internal drainage. Such impact rates occurred in the past on Mars [Carr, 1981] and may explain widely varying degrees of valley integration on the planet [Grant, 1987].

Degradation Signatures in Southern Ismenius Lacus

The evolution of degraded craters in SIL can now be interpreted in the context of terrestrial analogy. Using the degradational sequence for the terrestrial craters that is constrained by geologic study, the martian craters can be examined for comparable degradational signatures. Analogy with the terrestrial craters indicates that the paucity of fluvial signatures recognized around some pristine craters in SIL at 40-45 m/pixel resolution may not preclude appreciable fluvial activity. However, an absence of fluvial signatures around craters without raised rims indicates that additional processes are also important in degradation. This statement is supported by drainage densities in and around rimless craters that are even lower than those measured inside Meteor Crater at similar resolution. The scale of fluvial features at terrestrial craters implies that significant fluvial activity in SIL should create rim breaches and higher drainage densities in and/or around degraded craters prior to raised rim destruction.

Other degradational processes that may account for the evolution of rimless craters in SIL include mass wasting and/or eolian deposition/erosion. For example, the walls of both pristine and degraded craters in SIL are frequently sloped at the angle of repose expected for fine-grained material. Analogy with terrestrial craters where wall slopes steadily decrease as fluvial degradation increases suggests that more sustained mass wasting plays a role in crater rim destruction in SIL. Geologic mapping [Lucchitta, 1978; Greeley and Guest, 1987; Grant, 1990] and thermal inertia values for SIL [Zimbelman, 1986] imply the surface is well mixed, brecciated, and contains abundant fine-grained sediment. Hence, early degradation of crater walls by mass wasting may not expose coherent lithologies...
that would slow the process. This statement is supported by the presence of craters in SIL without raised rims, but with preserved ejecta, thereby requiring rim destruction by backwasting rather than downwasting. Unlike terrestrial craters, the efficiency of mass wasting in SIL might only be reduced when talus accumulation outpaces talus removal/redistribution by other processes (e.g., fluvial). The presence of air-fall deposits in SIL suggests efficient eolian activity occurred during Hesperian gradation that might also contribute to removal or redistribution of fine-grained talus and sustain mass wasting of crater walls. Moreover, emplacement and subsequent partial

TABLE 2. Terrestrial Crater Degradation: Processes, Relative Importance, and Characteristics

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Abbreviations: 1=Low, Small; 2=Moderate, Medium; 3=High, Large

- Fluvial: Fluvial Degradation
- Eolian: Eolian Degradation
- Mass: Mass wasting
- D.S.: Drainage Scale
- D.D.: Drainage Density at resolutions of 30-50 m/pixel
- W.S.: Wall Slope
- Diam: Rim Crest Diameter
erosion/redistribution of these airfall sediments during the Hesperian could contribute to the masking of either crater rims or mass wasting deposits.

It needs to be emphasized that the subordinate role played by fluvial processes in crater degradation in SIL does not diminish the possible implications of valley network formation for past climate conditions. For example, formation of both Mariner Valles and smaller, higher density drainages during Noachian and Hesperian gradation, respectively, demonstrates that valley network evolution in SIL occurred during multiple epochs. Valley development during Noachian gradation was probably related to the subsurface release of water and/or surface runoff of precipitation [Carr, 1981; Baker, 1982; Mars Channel Working Group, 1983; Greeley, 1985]; however, the close association of the younger valleys to areas mantled by airfall material suggests incision was related to release of volatiles from the deposits. The larger scale and lower density of the Noachian aged valleys (Figure 3) likely reflects the enhanced preservation potential of larger systems.

The volume of identifiable alluvial deposits in SIL (Figures 10a, 10b, and 11) is small relative to the volume of the upstream valleys. A similar situation has been noted elsewhere on Mars [Lucchitta and Ferguson, 1983; Mouginis-Mark, 1985; 1987]. Together with the irregular distribution of drainages around some craters (e.g., Figure 9a), this observation indicates that valley formation reflects local rather than basinwide runoff of water. By analogy with Meteor Crater, basinwide runoff and erosion should create large deposits relative to valley volume. In addition, the small size of alluvial features in SIL suggests valley formation occurred during geologically brief intervals. Sustained release of water from any source would incise deeper valleys and cause additional deposition in the largely empty, local sinks. Furthermore, valleys around Cerulli (Figure 10) are uniformly preserved and conformable with each other, thereby indicating roughly contemporaneous activity. When considered together with the limited fluvial features preserved since Hesperian gradation, these characteristics indicate minimal precipitation and runoff since that time. Analogy with ejecta sedimentology at Meteor Crater suggests that the regolith in SIL possesses moderate to high hydraulic conductivity and infiltration capacity. Consequently, in the absence of high magnitude precipitation, infiltration and subsurface drainage will likely preclude significant, basin wide runoff. Although climate during Hesperian gradation was possibly more temperate than at present [Schultz, 1988; Schultz and Lutz, 1988; Groixaffi and Schultz, 1989; Grant and Schultz, 1990], analogy with terrestrial craters suggests late crater degradation in SIL was not dominated by precipitation–derived runoff.

A subordinate role by fluvial degradation in rim destruction in SIL contrasts with the conclusion of Craddock and Maxwell [1990; 1992] that fluvial downwasting accounts for the formation of rimless craters throughout much of the martian highlands. Moreover, our results indicate that raised–rim destruction by fluvial, mass–wasting, and/or eolian processes causes an increase in crater diameter in contrast with the proposed evolution by Craddock and Maxwell [1990; 1992]. These conflicting conclusions reflect in part the stage of degradation. On Earth, heavily eroded craters are typically expressed by structural roots of the crater interior, which are smaller than the original rim diameter [Orphal and Schultz, 1978; Grieve and Head, 1983]. Here we have emphasized observable signatures and consequences of the erosional process that eventually lead to such advanced stages of degradation. As a result, statistics compiled from degraded crater populations without accounting for erosional widening will yield slightly older than actual relative ages. Conversely, interpretation of statistics based on the Craddock and Maxwell [1990; 1992] model will provide a minimum relative age for all but the most degraded cratered surfaces. The correct approach should include an assessment of evidence for styles of erosional processes.

**SUMMARY AND IMPLICATIONS**

On the Earth, crater degradation produces distinctive signatures that can be identified through field investigations and can be used to quantify the changing rate and role of individual processes through time, thereby establishing a first–order degradational sequence. In general, fluvial activity dominates overall degradation of the examined terrestrial craters; however, in some arid settings the combined effects of combined primary and secondary deflation can ultimately dominate transport of weathered ejecta beyond the rim. Fluvial processes (and to a lesser degree mass wasting) dominates over all degradation of crater interiors. Drainage morphology around Meteor Crater remains controlled by gradients created during emplacement of the ejecta; hence, similar fluvial signatures should evolve around other craters where comparable geomorphic thresholds exist. Drainage inside the crater currently dissect relict debris chutes and results in exaggerated fluvial cross–sections. Mass wasting dominates initial degradation of crater walls, but is superseded by dissec-

*Fig. 11. Example of the relatively small depositional features (large arrow) associated with some valley networks (small arrows) around/within craters in SIL. Incised valley volume is large relative to the observed deposit volume, unlike the situation observed at Meteor Crater. SIL crater is at 31.25øN; 348.30W in image 206S07 (resolution 43 m/pixel). The steep front on the feature suggests formation occurred when the associated crater was partially filled by material that has since been removed.*
tion as resistant outcrops are exposed by backwasting.

Similar signatures of fluvial activity should be identifiable in and around degraded craters in SIL even though they may evolve over much longer time scales than on the Earth. Therefore, low drainage densities and a paucity of alluvial deposits associated with relatively pristine craters in SIL (both simple and complex) may not preclude fluvial activity or the possibility of a once more equable climate, but simply reflect the small scale of fluvial signatures during early fluvial degradation. The larger scale of fluvial features evolved around the more degraded Lonar and Taleczvane craters, however, indicates that such signatures (e.g., rim breaches, moderate drainage densities) should be identifiable around degraded craters in SIL yet are not. Hence, additional processes are needed to explain crater degradation. Crater walls sloped at the repose angle regardless of degradation state, a substrate inferred to be brecciated and contain abundant fine-grained sediment, and rimless craters with preserved ejecta, all suggest long-term mass wasting creates some rimless morphologies. Airfall deposition/redistribution may mask additional crater rims and deflate fine-grained talus from crater walls, thereby working with limited fluvial activity to sustain mass wasting. Regardless, drainage character in SIL implies that runoff was short-lived, occurred from local sources, and was not derived from precipitation-induced runoff since the Hesperian. This conclusion does not preclude a more dominate role by fluvial degradation during Noachian times; however, the signature of any such activity is not preserved in SIL.

Climate plays an important, secondary role in defining drainage character at Meteor Crater. For example, most alluvial deposition probably occurred during latest pluvial conditions, whereas fluviation under present climate is largely confined to gully floors and deposition of small, coarse, distal fans. Hence, morphologic relations between incised gullies and associated fans, sites and extent of deposition, as well as downvalley variations in alluvium grain size, record aspects of changing climate and precipitation through time and can be measured. Comparable analyses of most martian craters await high resolution images from Mars Observer.

Finally, derangement of regional drainage patterns by Meteor Crater implies that the high density of craters on Mars significantly redefines drainage basins. In some instances, watersheds may be wholly defined by crater rims, thereby influencing regional integration of valley networks. Examples of valley interruption occur along Namars Valles where the drainage is blocked by crater Cerulli. If the valley were active, this blockage would result in deposition southeast of Cerulli analogous to that observed southwest and south of Meteor Crater. Similar examples are observed in Margaritifer Sinus where impact has blocked Samara Valles, thereby resulting in upstream deposition and incision of a new trunk valley to the east (Figure 12).

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