Abstract. Shadow measurements on Viking Orbiter photography have yielded depths for 172 fresh martian craters spanning a diameter range of 0.7 to 80 km. Most craters studied are shallower than their lunar and mercurian counterparts. While the martian data exhibit a break in the depth/diameter distribution similar to those found for the Moon and Mercury, the "inflection" occurs at a smaller diameter on Mars, and the slopes below and above the break are respectively less than and greater than those of the other two planets. In addition to possible substrate-related transient cavity modification mechanisms, flash vaporization of proposed subsurface H$_2$O would alter the original impact-induced velocity field by enhancing horizontal to subhorizontal target flow and excavation, thus yielding shallower craters. On the basis of the observed distribution, it is suggested that this process is more active at diameters near the break in $a^{-1}p$ ($<4$ km), declining in efficiency with increasing diameter, and can account for many dissimilarities between the martian distribution and those of the Moon and Mercury, which cannot be reconciled with gravity, impact velocity, or projectile differences alone.

New depth data with greater accuracy and areal coverage than those acquired previously (Cintala, 1977) have been gathered for fresh martian craters through shadow measurements on high quality Viking Orbiter photography. The purposes of this report are to present these new depth/diameter data, to consider them in the context of similar measurements of lunar and mercurian craters, and to describe processes which could account for the observed interior morphometries.

Definition of Fresh Craters

The unique martian degradational environment (e.g., Florensky et al., 1977) has prompted "fresh craters" to be defined in this study as those with crisp rims over all or most of their perimeters and/or visible primary floor roughness (Head, 1975). It is believed that these criteria effectively segregate fresh craters with complex interior morphology from their more degraded counterparts. Because limited resolution does not allow detailed scrutiny of small (28 km) crater interiors in many images deemed suitable here (clear atmosphere, 0.2 km/pixel -- except for rare high-resolution frames), small craters with shadow shapes diagnostic of ages from $<5.0$ to 7.0 on the Pohn and Offield (1970) scale of degradation were also incorporated into the data set. Depth/diameter ratios of lunar craters with these relative ages do not differ significantly from those of their fresher counterparts (M.J. Cintala and J.W. Head, unpublished data); it is assumed here that this also holds in the martian case.

Data

Crater rim crest-to-floor depths were obtained using techniques developed earlier (Cintala et al., 1976a), with reference information provided in the JPL Viking Orbiter Mark IV Photographic Data Listing. Depths ($R_i$) were derived for 172 craters over a rim crest diameter ($D_r$) range of 0.7 to 80 km; these data are presented in Figure 1 and are available from AGU Microform Service, 2000 Florida Avenue, N.W., Washington, D.C. 20009.

The resulting distribution exhibits the break in slope characteristic of similar plots for lunar and mercurian craters (Figure 1, Table 1). The two least-squares fits which simultaneously minimize the standard errors of estimate are

\[ R_i = 0.157 D_r^{0.936} \]

for craters in the data set with $D_r \geq 3.6$ km (n = 45) and

\[ R_i = 0.258 D_r^{0.557} \]

for craters with $D_r < 3.6$ km (n = 127).

Interplanetary Comparisons

$R_i/D_r$ ratios predicted for small martian craters on the basis of gravitational acceleration and impact velocity are considerably greater than those actually observed (Cintala, 1979a); indeed, the observed depths are less than those expected for the apparent crater depths (i.e., the crater depth as measured from the original target surface). While shallower apparent crater depths probably play a major role in causing the observed $R_i/D_r$ ratios, lower rim heights -- a possible consequence of ejecta blanket lubrication by impact-released volatiles (Head and Roth, 1976; Carr et al., 1977; Mouginis-Mark, 1979a) -- might also contribute to a net shallowing of the martian craters. A detailed analysis of these crater depth components, however, must await more refined topographic data.

Arguments that crater morphology-morphometry relationships are controlled predominantly by gravitational acceleration (e.g., Pike and Arthur, 1979) are at odds with the results of a comparison between craters on Mars and Mercury, planets with surface gravities differing by only $\sim 3\%$ (Table 1). Small craters (i.e., those described by eq. (1)) on Mars are shallower than those on Mercury, the break in slope in the $R_i/D_r$ plot occurs at a smaller diameter, and the slope of the fit above the inflection is much steeper on Mars. In addition, martian and mercurian craters undergo transitions from simple
and the Moon appears to be the impact environment presented by Mars itself.

Discussion

It is evident from Figure 1 that the position of the break in slope in the martian distribution is controlled most strongly by the location and orientation of the 3.6 km branch. Insofar as the largest measured martian craters are comparable in depth to their mercurian counterparts, it appears that preferential shallowing of craters at intermediate diameters increases the slope of this curve, thus causing the inflection to occur at a diameter smaller than those in the lunar and mercurian cases. Attempts to fit two curves to the martian $R_i/D_r$ data above the break in slope were not definitive due to the scatter in the measurements.

Another approach, however, yields informative results. First, to compensate for the lack of large craters ($D_r > 40$ km) with shadow-derived depths, six of the freshest craters with depths determined from Mariner 9 ultraviolet spectrometer measurements (Barth et al., 1974; Cintala et al., 1976b) were added to the martian data set (triangles, Figure 1). Next, a fit was made to the points above the break in slope, and a record was made of the intersection of this curve with that described by eq. (1), which was projected to larger diameters. The smallest crater ($D_{min}$) was then deleted and the process was repeated on the remaining data; this continued until $D = 25$ km, where scatter began to dominate the results. For comparison, the same procedure was applied to the lunar data of Pike (1976). As smaller martian craters are excluded from consideration, it is obvious that the inflection diameter ($D_{inf}$) increases (Figure 2). In terms of the least-squares fit, this is a consequence of a regular increase in the coefficient (intercept) and an exponent (slope) decrease to values more similar to those found for the Moon and Mercury. No comparable trend exists in the lunar case. Thus, the results in Figure 2, along with the steepness of the slope above 3.6 km, are interpreted to be an indica-

Table 1: Least-squares expressions for lunar, mercurian, and martian fresh craters depth ($R_i$)/diameter ($D_r$) relationships.

<table>
<thead>
<tr>
<th>Planet</th>
<th>$D_r$ Range (km)</th>
<th>n</th>
<th>Relationship</th>
<th>Standard Error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moon</td>
<td>210.6</td>
<td>171</td>
<td>$R_i = 0.196 D_r$</td>
<td>+0.038</td>
<td>Pike, 1974</td>
</tr>
<tr>
<td></td>
<td>310.6</td>
<td>33</td>
<td>$R_i = 1.044 D_r$</td>
<td>+0.067</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\pm 0.301$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>29.8</td>
<td>178</td>
<td>$R_i = 0.176 D_r$</td>
<td>---</td>
<td>Malin and</td>
</tr>
<tr>
<td></td>
<td>39.8</td>
<td></td>
<td>$R_i = 0.910 D_r$</td>
<td>---</td>
<td>Deurisin,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\pm 0.260$</td>
<td></td>
<td>1977</td>
</tr>
<tr>
<td>Mars</td>
<td>23.6</td>
<td>45</td>
<td>$R_i = 0.157 D_r$</td>
<td>$\pm 0.057^*$</td>
<td>this paper</td>
</tr>
<tr>
<td></td>
<td>33.6</td>
<td>127</td>
<td>$R_i = 0.258 D_r$</td>
<td>$\pm 0.086^*$</td>
<td></td>
</tr>
</tbody>
</table>

*$^*$Given as the standard error of estimate of $R_i$ on $D_r$, from a fit of the form $\log_{10} R_i = \log_{10} a + b \log_{10} D_r$. 

Fig. 1. Shadow-derived vs. rim crest diameter for 178 fresh martian craters and least-squares fits to these data (Mariner 9 ultraviolet spectrometer points not included). Also illustrated are fits to lunar and mercurian fresh crater data, which were collected from photogrammetry and shadow measurements, respectively.
Fig. 2. Inflection diameter ($D_{\text{inf}}$) as a function of the smallest crater included in the least-squares fit ($D_{\text{min}}$) for martian (left ordinate) and lunar craters (right ordinate); see text for details. Note that $D_{\text{inf}}$ increases with $D_{\text{min}}$ for the martian craters while the lunar plot lacks any similar overall trend. The inset illustrates the shapes which the martian $R_i/D_r$ distribution would assume if just those craters greater than 10, 15, and 20 km in diameter were considered in deriving the branch with the shallower slope.

The results of many investigations strongly suggest that the near-surface layers of Mars contain considerable quantities of H$_2$O (e.g., Fanale, 1976). Such volatiles would probably play an important role in the excavation stage of the cratering process. Small events taking place in the dry upper portion of the fragmental martian surface layer (Augenbroe et al., 1979) would form craters differing little from those formed on the Moon and Mercury (Figure 3a). During larger events which tap strata with more abundant H$_2$O (Fanale, 1976), however, shock-vaporized water would expand along the paths of least resistance, which would be upward to subparallel to the target surface. The addition of the velocity field caused by this component of stress to that induced by passage of the impact-generated shock would enhance horizontal to subhorizontal target motion, causing shallower craters than would occur in a dry target (Figure 3b). Arguments formulated on the basis of Figure 2 suggest that this phenomenon is least active at the largest diameters, which is interpreted to reflect a subsequent decrease in H$_2$O content at the greatest depths considered here (probably due to the presence of less permeable/porous "bedrock." Figure 3c). The extent to which target rebound, wall failure, and other mechanisms affect large crater morphometry is poorly understood for any planet; substantial difficulty exists, therefore, in establishing the depth to the volatile-deficient region.

Nevertheless, on the basis of Figure 1 (region of overlap between the martian and mercurian crater depths) and comparable slopes for lunar and martian distributions (determined in generating Figure 2) it is estimated to lie on the order of ~2-4 km below the surface.

Sufficient quantities of free H$_2$O in the target might also affect such transient cavity modification mechanisms as wall failure and target rebound. Indeed, central peaks and slumped walls -- the appearances of which correlate with the "inflections" in the $R_i/D_r$ distributions on the Moon and Mercury (Head, 1976; Malin and Dzurisin, 1977) -- occur in craters with significantly smaller diameters on Mars than on the two "dry" planets (Wood et al., 1978). On the basis of interior morphology, the break in slope should thus be expected to occur at a correspondingly smaller diameter in the martian case.

Finally, while the effects of the present martian atmosphere on ejecta ballistics should be minimal in terms of fallback (Schultz and Gault, 1979; Settle, 1979), more severe drag phenomena could result from particle interaction with a localized transient high-pressure atmosphere induced by flash vaporization of subsurface volatiles (Cintala, 1979b). Any consequent fallback ejecta would also contribute to the overall shallowness of the observed martian craters.

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Fig. 3. Schematic representation of the martian cratering model described in the text. The approximate diameters at which these effects are interpreted to obtain are shown in the insets; stippling indicates relative volatile concentration.
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References


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