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Standardizing the nomenclature of Martian impact crater ejecta morphologies

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Abstract. The Mars Crater Morphology Consortium recommends the use of a standardized nomenclature system when discussing Martian impact crater ejecta morphologies. The system utilizes nongenetic descriptors to identify the various ejecta morphologies seen on Mars. This system is designed to facilitate communication and collaboration between researchers. Crater morphology databases will be archived through the U.S. Geological Survey in Flagstaff, where a comprehensive catalog of Martian crater morphologic information will be maintained.

1. Introduction

Fresh Martian impact craters are typically surrounded by ejecta structures that differ in morphology from the radial ejecta patterns seen around lunar and Mercurian craters. The Martian ejecta structures are typically composed of one or more layers of material, commonly displayed in a lobed pattern. These structures have been described by a number of adjectives, including fluidized, lobate, rampart, splosh, and flower. Although originally thought to be the result of wind erosion on the basis of Mariner 9 image analysis [*McCauley*, 1973; *Arvidson et al.*, 1976], Viking Orbiter images revealed that these structures were distributed globally and likely the result of emplacement by fluidization processes, either from impact into and vaporization of subsurface volatiles [*Carr et al.*, 1977; *Wohletz and Sheridan*, 1983] or by ejecta entrainment by the thin Martian atmosphere [*Schultz and Gault*, 1979; *Barnouin-Jha and Schultz*, 1998]. Now as more details about the ejecta morphologies and morphometries become available because of the Mars Global Surveyor and upcoming Mars Surveyor missions, it is apparent that a standardized system of nomenclature is needed to facilitate the exchange of data between researchers who compile crater data for use in studies on erosional history [*Craddock and Maxwell*, 1990, 1993; *Craddock et al.*, 1997; *Grant and Schultz*, 1990, 1993; *Barlow*, 1995; *Hartmann and Esquerdo*, 1999], implications for subsurface volatiles [*Cintala and Mouginis-Mark*, 1980; *Mouginis-Mark*, 1981, 1987; *Kuzmin et al.*, 1988; *Costard*, 1989; *Barlow and Bradley*, 1990; *Barlow*, 1994; *Boyce and Roddy*, 1997; *Costard and Gosset*, 1998; *Demura and Kurita*, 1998], crater morphometries and formation [*Roddy*, 1977; *Cintala et al.*, 1976; *Wood et al.*, 1978; *Melosh*, 1989; *Garvin and Frawley*, 1998; *Garvin et al.*, 1999], and the general geologic history of the planet [*Soderblom et al.*, 1974; *Tanaka*, 1986; *Barlow*, 1988; *Hartmann*, 1999].

This article describes a system of nomenclature recommended by the Mars Crater Morphology Consortium for use when describing Martian impact structures. The Consortium, composed of this article's authors, met at the U.S. Geological Survey in Flagstaff, Arizona, in May 1998 and July 1999 to discuss and develop these recommendations. The Consortium members have been actively involved in utilizing Martian impact craters in a number of studies over the past 20 years, and several have produced catalogs of crater characteristics. These databases contain information that is often complementary to but not contained in the other crater catalogs. One of the goals of the Mars Crater Morphology Consortium is to combine the existing crater databases into one system that can be queried for information on crater location, size, shape, preservational state, ejecta and interior structures, and morphometric characteristics (crater depth, rim height, central peak height and width, central pit diameter and depth, ejecta extent and sinuosity, etc.). Because of the variety of classification systems, many using different terminology to describe the same morphology, the Consortium agreed that the first course of action was to standardize the nomenclature for crater morphologic features. The first features to be standardized are the ejecta morphologies.

2. Recommendations

Martian ejecta blankets have been classified into many different groups because of the range of morphologies identified from the Viking Orbiter imagery. However, in general, the morphologies can be divided into three main groups:

1. Layered ejecta patterns, where the ejecta blanket is composed of one or more complete or partial sheets of material surrounding the crater, appear to have been emplaced by fluidization processes, although some structures show evidence of subsequent eolian erosion.
2. Radial ejecta blankets, which are similar to the ejecta patterns around lunar and Mercurian craters, are believed to be emplaced by secondary material ejected along ballistic trajectories.
3. Combination structures show both layered and radial patterns.

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Table 1. Correlation of New Morphology Terminology With Previous Nomenclature

Nomenclature	Reference
Layered Ejecta Structures	
Pedestal (P)	
Pedestal	*McCauley* [1973]
Pedestal	*Arvidson et al.* [1976]
Pedestal	*Head and Roth* [1976]
Mound	*Johansen* [1979]
Lump	*Johansen* [1979]
Single-layer pancake (SLEPC/SLEPS)	
Polar	*Johansen* [1979]
Type 6	*Mouginis-Mark* [1979]
SS	*Horner and Greeley* [1987]
Type 3	*Costard* [1989]
Pancake	*Barlow and Bradley* [1990]
Single-layer rampart (SLERC/SLERS)	
Type 1	*Mouginis-Mark* [1979]
Class 4	*Blasius and Cutts* [1980]
SR	*Horner and Greeley* [1987]
Type 1/flower	*Costard* [1989]
Single lobe	*Barlow and Bradley* [1990]
Double-layer rampart (DLERC/DLERS)	
Composite	*Johansen* [1979]
Type 2	*Mouginis-Mark* [1979]
Class 3	*Blasius and Cutts* [1980]
D	*Horner and Greeley* [1987]
Type 2/rampart	*Costard* [1989]
Double lobe	*Barlow and Bradley* [1990]
Multiple-layer rampart (MLERS)	
Flower	*Johansen* [1979]
Type 3	*Mouginis-Mark* [1979]
Class 2/flower	*Blasius and Cutts* [1980]
MR	*Horner and Greeley* [1987]
Multiple lobe	*Barlow and Bradley* [1990]
Radial Morphologies	
Radial (SLER)	
Lunar	*Johansen* [1979]
Class 1/lunar	*Blasius and Cutts* [1980]
Type 4	*Mouginis-Mark* [1979]
Radial	*Barlow and Bradley* [1990]
Combination Morphologies (e g., SLERSR)	
Transitional	*Johansen* [1979]
Type 5	*Mouginis-Mark* [1979]
Diverse	*Barlow and Bradley* [1990]

Table 1 provides a listing of some of the terminology that has been used to describe craters in these basic groups.

The Mars Crater Morphology Consortium recommends the following changes in nomenclature:

First, layered ejecta patterns that have undergone substantial erosion owing to eolian activity, resulting in the crater and ejecta being perched above the surrounding terrain, shall be referred to as "pedestal craters" (Pd). The ejecta blanket of a pedestal crater is typified by a sharp edge (no distal ridge) that drops off to the lower elevation of the surrounding terrain (Figure 1a).

Second, other layered ejecta patterns shall be referred to as "layered ejecta craters" (LE).

1. Layered ejecta craters surrounded by only a single layer of material shall be called "single-layer ejecta" (SLE) (Figure 1b).

2. Layered ejecta craters surrounded by two layers of material shall be called "double-layer ejecta" (DLE). The inner layer of the DLE morphology has a smaller diameter than the outer layer and is usually superposed on the outer layer (Figure 1c).

3. Layered ejecta craters surrounded by three or more complete or partial layers of material shall be called "multiple-layer ejecta" (MLE) (Figure 1d).

4. The single-layer, double-layer, and multiple-layer categories are further modified by terms describing the shape of the ejecta terminus. Those layered ejecta patterns terminated by a distal ridge or rampart shall be modified by the term "rampart" (R) (i.e., Figure 1d). Hence a single-layered ejecta pattern terminated in a distal ridge would be called a "single-layer ejecta rampart." Layered ejecta patterns that terminate in a concave slope will be modified by the term "pancake" (P) (Figure 1e).

5. The rampart and pancake terms are further modified by the adjectives "sinuous" (S) (i.e., Figure 1d) and "circular" (C) (i.e., Figure 1e), describing the general sinuosity of the ejecta blanket. Ideally, the designation of S versus C will be based on an actual quantitative measurement of the ejecta sinuosity, such as the lobateness method described by *Barlow* [1994]. Using the lobateness system, ejecta morphologies with lobateness values

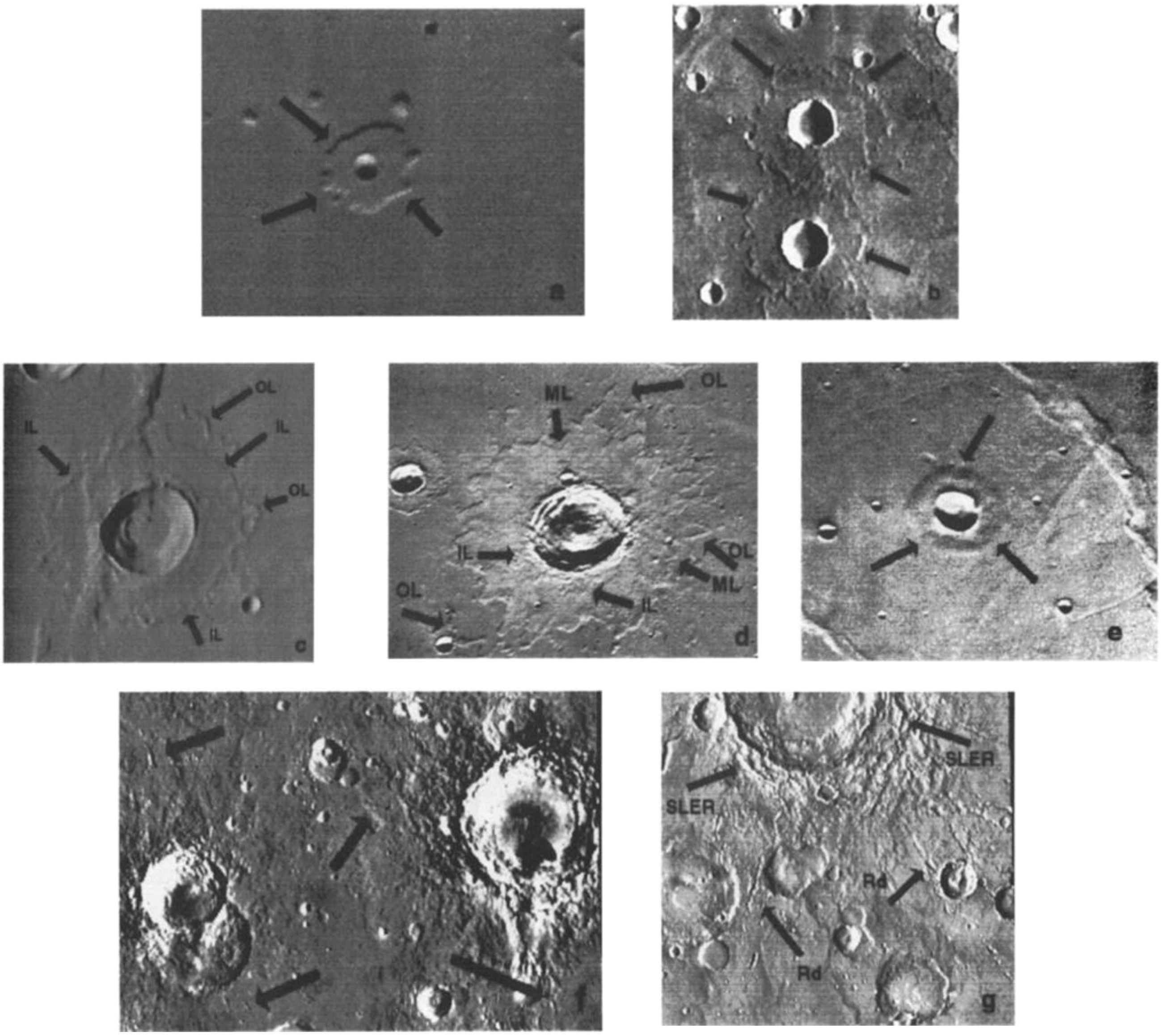

Figure 1. Examples of the new ejecta morphology classifications recommended by the Mars Crater Morphology Consortium. Arrows point to the distinguishing ejecta features. (a) A 1.5-km-diameter pedestal (Pd) crater, located at 11.4°N, 161.5°W, (Viking Orbiter image 886A09). (b) Two single-layer ejecta rampart sinuous (SLERS) craters. The top crater is 18.1 km in diameter and located at 8.80°N, 72.13°W. The bottom crater is 18.9 km in diameter and located at 7.96°N, 72.16°W (Viking Orbiter image 858A56). (c) A 9.6-km-diameter double-layer ejecta rampart sinuous (DLERS) crater, located at 21.42°N, 79.02°W (Viking Orbiter image 555A24). IL identifies the inner ejecta layer; OL denotes the outer ejecta layer. (d) A 33.9-km-diameter multiple-layer ejecta rampart sinuous (MLERS) crater, located at 26.59°N, 38.55°W (Viking Orbiter image 827A01). IL indicates the inner ejecta layer, ML identifies the middle ejecta layer, and OL denotes the outer ejecta layer. (e) A 7.7-km-diameter single-layer ejecta pancake circular (SLEPC) crater, located at 26.10°S, 69.04°W (Viking Orbiter image 608A29). (f) Single-layer ejecta radial (SLERd) craters. The large crater on the left is 75.3 km in diameter and located at 24.36°N, 10.79°W (MDIM image Mg25n012). (g) A 107.2-km-diameter single-layer ejecta rampart circular radial (SLERCRd) crater, located at 32.32°N, 337.9°W (MDIM image Mg30n337). Rd indicates the radial component of the ejecta blanket, while SLER identifies the single-layer ejecta rampart portion of the blanket.

≤1.5 would be classified as circular, while those with larger lobateness values would be defined as sinuous. Thus a crater identified as being surrounded by a single-layer ejecta rampart with a lobateness value of 2 would be classified as single-layer ejecta rampart sinuous (SLERS).

Third, following the above nomenclature procedure, radial ejecta patterns will be referred to a "single-layer ejecta radial" (SLERd) (Figure 1f).

Fourth, combination patterns (Figure 1g) will be denoted by combining the above nomenclature. For example, a single-layer

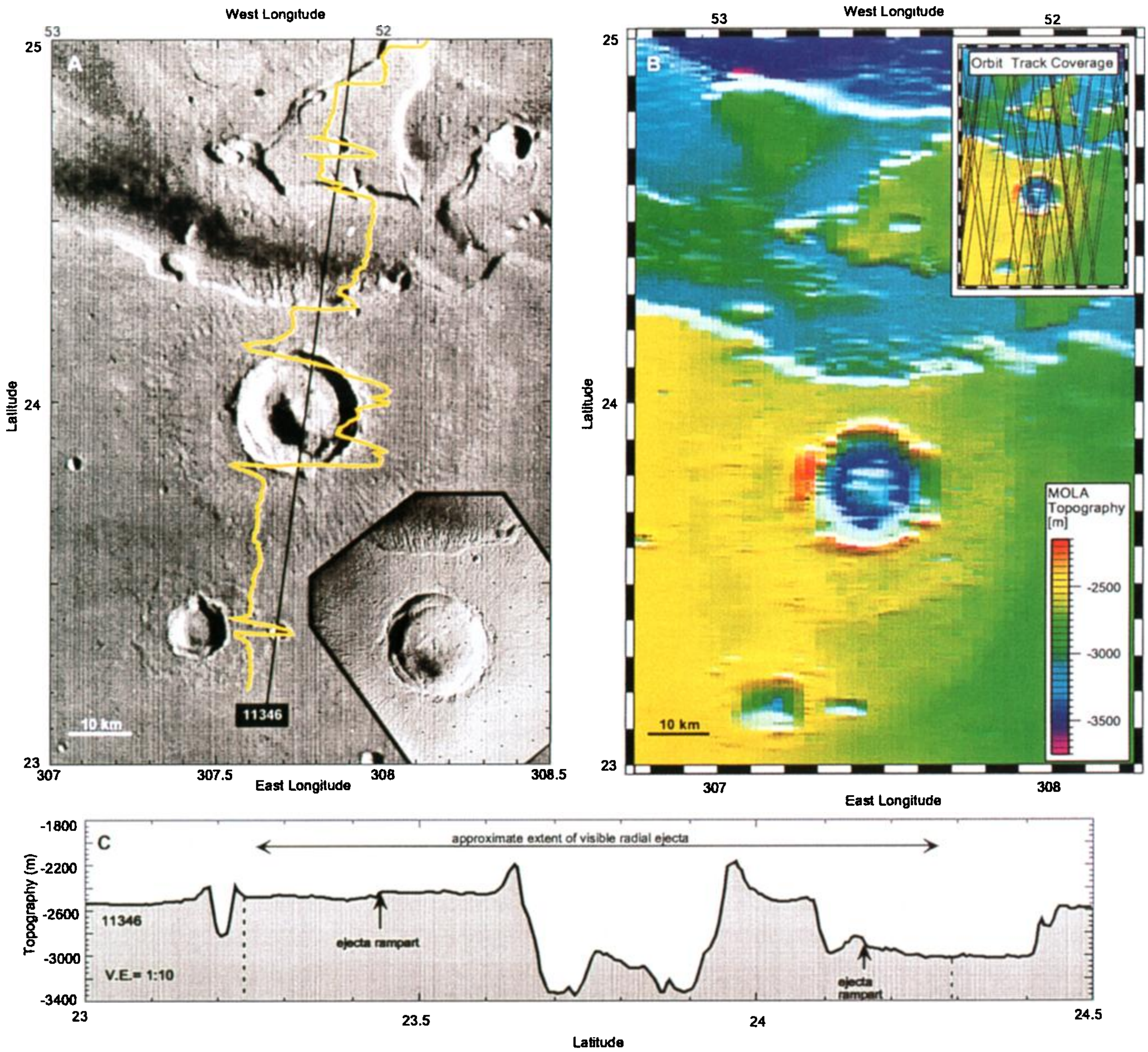

Plate 1. Viking Mars Digital Image Mosaic (MDIM), Mars Orbiter Laser Altimeter (MOLA) topographic profile, and digital elevation model (DEM) for the 20-km "radial ejecta" impact crater Poona, located at 24°N, 52.5°W. (a) Viking MDIM of Poona at a resolution of 256 pixels per degree, with superimposed MOLA centerline pass (in yellow) from MGS orbit 1346. The inset shows Poona in the high-resolution (43 m/pixel) Viking Orbiter image F0022A54. (b) Topographic grid of Poona with a resolution of 64 pixels/degree in longitude and 256 pixels/degree in latitude. The grid includes MOLA data through MGS orbit 5507 (early June 2000), and the orbit track coverage is shown, with local precision in the submeter range. (c) Full-resolution MOLA centerline profile, showing the gross crater topography as well as the topographically subtle (40-80 m) expression of ejecta ramparts (indicated with arrows) within the radial ejecta blanket visible in the Viking image, and the asymmetric central peak and inner cavity wall terraces.

rampart ejecta with sinuous ejecta that has a radial pattern superposed on it (i.e., the "diverse" morphology in *the Barlow and Bradley* [1990] nomenclature) will be called "single-layer ejecta rampart sinuous radial" (SLERSRd).

The correlation of the old terminology and the new nomenclature is shown in Table 1. This nomenclature may appear unwieldy upon first use. The Mars Crater Morphology Consortium discussed this issue but decided that this system is the most concise way of describing the large variety of ejecta morphologies found around Martian impact craters. This system also is flexible enough that future classifications that may arise due to the incorporation of new data (see next section on topography for an example) can be easily accommodated. The Consortium agreed that morphological nomenclature should avoid references to possible origins of these structures; thus "fluidized" and "ballistic" terms were rejected in favor of the nongenetic "layered" and "radial" terminology.

The Mars Crater Morphology Consortium recognizes that some researchers may find this recommended nomenclature restrictive and unusable for a particular project. In such situations the researchers are encouraged to develop their own system that will facilitate their analysis. However, upon archiving of the database, the researchers should indicate as closely as possible how their system correlates with the recommended nomenclature system so comparisons with other databases can be facilitated.

3. Effect of Topography on Morphology Classifications

The morphologic classification recommendations presented herein depend almost exclusively on moderate to high spatial resolution imaging data. An additional perspective is rapidly becoming available as the spatial density of orbital laser altimetry that is currently being acquired by the Mars Orbiter Laser Altimeter (MOLA), a topographic profiling instrument aboard the Mars Global Surveyor (MGS), increases. Subkilometer spatial resolution digital elevation models (DEMs) with vertical accuracies as fine as 2-3 m RMS are now routinely achieved using MOLA data for the middle to higher latitudes of Mars. In addition, virtually all impact features larger than approximately 10-15 km have been traversed by at least one MOLA topographic transect. These transects provide highly precise information on crater geometric properties, many of which were previously unmeasurable or unmeasured. MOLA crater transects allow for determination of crater depth, cavity cross-sectional shape, ejecta thickness function characteristics, inner cavity wall slopes, terrace geometry, ejecta flank slopes, and many other properties. An initial summary of some of these newly measured parameters is given by *Garvin and Frawley* [1998], and interpretation of north polar region craters using MOLA transects is given by *Garvin et al.* [2000].

In three dimensions, impact craters on Mars remain an incredibly diverse population, with subtleties that are not yet captured by existing morphologic classification schemes. Virtually all topographically "fresh" impact features display some form of distal rampart, at what appears to represent the distal margin of a continuous ejecta blanket. In many cases this elevated or upturned margin displays very subtle relief with only 10-30 m of expression. For the first time, MOLA DEM format data allow for refined approximation of the preimpact surface in the form of a reference plane against which to reference such measurements as mean rim height, rampart relief, and many others. Layered morphologies display geometric properties that are as diverse as those that can be discerned from high-resolution images. As an example, the classic radial ejecta crater Poona, located at 24°N, 52.5°W, is shown in Plate 1. This 20-km complex impact crater displays an irregular central peak, is surrounded by a radially striated ejecta reminiscent of some lunar ejecta patterns, and appears to be relatively nondegraded in higher-resolution Viking-era images (Plate 1). However, as the MOLA centerline topographic transect reveals, the ejecta associated with this feature is layered, with a clearly defined rampart at the distal margin, as is typical for many of the impact features in the northern polar latitudes on Mars. The crater cavity is noticeably "U-shaped," beyond that which is most commonly observed for similarly sized impact features on Mars [*Garvin et al.*, 2000]. The depth-to-diameter ratio, or *d/D*, is 0.058, which attests to the pristine character of this crater. Finally, the thickness of the ejecta blanket decays sharply, with an exponent of –8.5, which is far in excess of the –3.0 ejecta decay exponent favored by previous workers for pristine lunar style impact craters [*McGetchin et al.*, 1973]. These new measurements for this one example of a well-analyzed impact crater suggest that another iteration of the Martian crater classification scheme may be required by the time subkilometer-scale DEMs are available for virtually all complex Martian impact craters. The combination of high vertical resolution DEMs from MOLA, together with 2 to 5 m/pixel imaging from the Mars Orbiter Camera (MOC), should allow for refinements to the classification presented herein. This is not to suggest, however, that the morphologic classification cannot stand on its own.

Thus, the new perspective that is soon to be provided globally by MOLA for Martian impact craters should permit refinement of existing morphologic classification approaches. The benefits of a combined morphologic-morphometric approach will then be possible. Such an approach will facilitate development of improved physical models of the ejecta emplacement and cavity growth processes associated with hypervelocity impact cratering under Martian conditions. Ultimately, the combined classification will permit the effect of target variables in space and time to be unraveled. MOLA DEMs for over 5000 impact craters cataloged in the existing *Barlow* [2000] database have been constructed and measured at the time of writing, and several thousand more will be measured by the end of this year.

4. Database Archiving

The primary purpose of recommending standards for the nomenclature of ejecta morphologies is to facilitate the cross-utilization of different crater data sets. All members of the Mars Crater Morphology Consortium who have developed such catalogs of crater data have agreed to update their databases using the new nomenclature. They also have agreed to archive their data sets at the U.S. Geological Survey in Flagstaff, where computer staff will combine the data sets into one comprehensive crater catalog. Any inconsistencies between the data sets will be resolved by the compilers of the affected data sets. This comprehensive catalog of Martian impact crater characteristics will be formatted for use with the Arc/Info and Arcview GIS systems [*Roddy et al.*, 1998a, 1998b].

Any researchers who wish to contribute data sets to this comprehensive catalog should contact the U.S. Geological Survey for information on the necessary formatting. Submitted data will be reviewed for content by members of the Mars Crater Morphology Consortium prior to acceptance into the comprehensive catalog.

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