UTILIZING GIS IN MARTIAN IMPACT CRATER STUDIES

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ABSTRACT:

The Mars Crater Morphology Consortium was formed in 1997 to facilitate exchange of martian impact crater data among researchers through standardizing nomenclature, integrating crater databases into one community-accessible GIS-based system, encouraging collaborations among researchers, and organization of Mars crater-related workshops and conferences. This paper reports on the nomenclature system we have recommended for use with martian impact crater ejecta morphologies and the status of merging existing crater datasets into one GIS-based system.

I. BACKGROUND

1.1. Mars Crater Morphology Consortium

The Mars Crater Morphology Consortium was organized in 1997 to address issues related to martian impact crater morphologies and in particular to consider the possible integration of existing crater inventories into one system. Various researchers have collected datasets of martian impact crater characteristics beginning with the early Mariner missions to Mars. These datasets were compiled to address different aspects of cratering on Mars, such as the geologic evolution of the planet (Barlow, 1988), cratering mechanics and crater formation (Roddy et al., 1986), distributions of particular crater morphologies and their implications for subsurface properties (Kuzmin et al., 1988; Costard, 1989; Barlow and Bradley, 1990), studies of the planet's degradation history (Craddock and Maxwell, 1990, 1993; Craddock et al., 1997), and the morphometric characteristics of craters (Garvin and Frawley, 1998; Garvin et al., 2000). We felt that this large number of datasets could contain important information which might not be readily apparent until they could be directly compared. As a result we formed the Mars Crater Morphology Consortium consisting of researchers who had compiled such databases or otherwise were interested in issues related to martian impact craters. The authors of this paper are the current members of the Consortium (founding member David Roddy passed away in 2002).

1.2. Consortium Goals

Mars Crater Morphology Consortium workshops have been held at the US Geological Survey (USGS) in Flagstaff, AZ, in May 1998, July 1999, and October 2000, 2001, and 2002. The 1998 meeting defined the goals of the Consortium efforts: (1) understand the scientific content of each inventory, (2) identify methods to integrate the inventories and make them available to not only the Consortium members but also the planetary community at large, and (3) explore new science applications for the inventories. The various datasets included in this effort are described in detail in section 2.1. We quickly realized that a GIS system would be the best mechanism for integrating the large number of craters and associated attributes contained in these databases. The ESRI ArcInfo system was recommended by the USGS computer staff as a powerful, user-friendly, and readily available GIS system which could fulfill the needs of this effort. The Consortium agreed that the existing datasets would be merged into a single Mars crater database using ArcInfo. Individual researchers would provide their crater inventories to

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the USGS who would begin integrating them into a single ArcInfo based catalog. The integrated catalog would be archived at USGS-Flagstaff and, once in its final form and after approval from the Consortium, would be placed on-line for all researchers to access. Crater data acquired through new research efforts could be incorporated into the integrated catalog through submission of the data to the Consortium, whose members would review the information and make any suggestions for format changes before giving their approval to USGS to include the new data. Information about recommended formats is found in section 2.2.

The goal of integrating the various crater datasets is to determine how such global analyses can be used to address questions about crater formation on Mars and the geologic evolution of the planet. Issues of particular importance to the Consortium members include the following:

- Can crater morphologies help identify regions that have contained or still harbor volatile-rich reservoirs?
- Can crater morphologies and morphometries help us constrain the degradational processes which have operated throughout martian history?
- How do differences in geologic materials affect the formation and distribution of impact craters with features such as central peaks and ejecta flow patterns?
- How do the morphometric properties of martian impact craters vary with latitude, terrain, elevation, etc?
- Are the "fluidized" ejecta patterns seen around most fresh martian impact craters the result of impact into subsurface volatile reservoirs, interaction with the thin martian atmosphere, or a combination of these processes?
- Can the combination of different information sources (such as MOLA, TES, THEMIS, MGS MAG, etc.) help in the identification of buried basins?

The integration of the existing crater inventories can help us address many of these questions. We also can better recognize the limitations of the current data and can therefore identify experiments for future missions which can extend our understanding of what impact craters are telling us about the martian environment.

II. MARTIAN CRATER DATASETS

2.1. Data Sources

The crater inventories included in this effort were derived to investigate different aspects of the martian environments and the planet's geologic evolution. As a result, some are global while others are regional in extent. Some focus on ejecta morphologies, others focus on morphometric characteristics such as the crater shape and properties of central peaks. Some focus only on fresh craters, others consider craters in various stages of degradation, and still others include all craters. Some were produced from the Viking photomosaic maps, others from the Mars Digital Imaging Maps (MDIMs), and an increasing number are using Mars Global Surveyor (MGS) data. The integration of all these crater inventories, while promising to yield important new results, is a major undertaking due to the variety of characteristics included as well as the different data sources from which they were derived.

The *Catalog of Large Martian Impact Craters*, compiled by Nadine Barlow, is generally considered to be one of the most complete datasets. This catalog contains information on 42,283 impact craters distributed globally as measured off the Viking 1:2,000,000 photomosaic maps. Each catalog entry includes the MC subquadrangle on which the crater is located, an identification number, the latitude and longitude of the crater center, the crater diameter (and minor diameter, if the crater is elliptical), the terrain on which the crater is superposed, the preservational state of the crater, ejecta and interior morphology classifications, diameter of a central pit (if applicable), and the azimuthal angle of orientation if the crater is elliptical. The Catalog is currently undergoing revision utilizing MGS data (Barlow, 2000). Mars Odyssey (MO) information also will be included as they become available. Elevation, morphometric data for the crater interior and ejecta blankets, general mineralogic, and thermal inertia information is being added in the Catalog revision.

David Roddy and Nancy Isbell also utilized the Viking 1:2,000,000 scale photomosaics to digitize over 4300 martian craters and their related physical parameters, primarily in the western hemisphere of Mars (0-180°W longitude). They only included craters which displayed one or more of the following characteristics: (a) minimally degraded with a diameter of 10 km or more, (b) partial or complete ejecta blanket, (c) central peak(s) and/or central pit(s) in a central peak, (d) secondary crater ejecta field(s), (e) pedestal/rampart ejecta features, (f) multirings, and/or (g) an unusual morphologic feature. The minimal amount of information on each crater included a crater number identifier, latitude and longitude, and a digitized trace of the rim crest. Where present, digitized traces of crater wall terraces, the crater wall base, the base of the central peak(s), central pit(s), paths of ejecta chains, and other features amenable to digitization were included. They also noted features such as flat floors, hummocky flat floors, ballistic ejecta, etc (Roddy et al, 1998).

The Viking 1:2,000,000 photomosaics also served as the data source for Ruslan Kuzmin's and Francois Costard's crater inventories. Both databases only look at craters retaining an ejecta blanket. Kuzmin's crater inventory includes craters with both "fluidized" and "dry" ejecta morphologies and each entry includes latitude and longitude of the crater, the crater diameter, diameter of the ejecta, and type of ejecta (Kuzmin et al., 1988). Costard's dataset focuses on 2600 craters displaying fluidized ejecta blankets between ±80° latitude. Information includes crater location (latitude and longitude), classification into 3 types of fludized morphologies, and ejecta mobility (the ratio of the maximum ejecta extent to the crater radius) (Costard, 1989; Costard and Gosset, 1998).

Robert Craddock's crater studies focus on the degradational processes affecting martian impact craters. Initially based on Viking MDIM analysis and input from the Barlow Catalog, the latest work has been utilizing MGS Mars Orbiter Laser Altimeter (MOLA) information to better analyze the morphometries of craters in various stages of degradation. The data are limited to specific regions, primarily in the ancient Noachian-aged terrains (Craddock and Maxwell, 1990, 1993; Craddock et al. 1997; Craddock and Howard, 2002).

The most complete inventory of crater morphometric properties is being compiled by James Garvin, Susan Sakimoto, James Frawley, and their colleagues using MOLA topographic data (Garvin and Frawley, 1998; Garvin et al., 2000). This detailed catalog uses centerline MOLA profiles to estimate crater depth, rim crest diameter, rim height, cavity volume, cavity slope, cavity shape, ejecta thickness, rampart heights, and estimated amounts of crater infill. This catalog is expected to be released to the Consortium and the general public in middle to late 2003.

Peter Mouginis-Mark and Joseph Boyce are utilizing a slightly different technique when utilizing MOLA data to obtain crater geometry measurements (Mouginis-Mark et al., 2003). Their C++ computer program (for use on MS Windows platforms) utilizes the MOLA 1/64th degree digital elevation model to study the 3-dimensional shape and volume of the crater cavity, rim materials, and ejecta blanket. This research is focusing on spatial variations in crater geometry in the martian northern plains which might indicate variations in target properties or the resurfacing history of Mars.

Kenneth Tanaka and James Dohm maintain crater databases which were derived from the Viking MDIMs during regional studies (Thaumasia, Polar Regions, etc.). These databases primarily include crater location, size, and preservational information since they were acquired to determine age relationships of different units (Dohm and Tanaka, 1999; Tanaka and Kolb, 2001; Kolb and Tanaka, 2001). Other focused datasets analysis include Joseph Boyce's analysis of the smallest craters which display a "fluidized" ejecta morphology (Boyce et al., 2000), Jeff Kargel's inventory of the sinuosity ("lobateness") of martian impact craters (Kargel, 1989), Horton Newsom's MSG-based analysis of large impact basins (Newsom et al., 2003), Nathalie Cabrol's catalog of possible paleolake craters (Cabrol and Grin, 1999), and Jennifer Ramstad's analysis of pedestal craters (Ramstad, 2001).

2.2. Nomenclature and Formats

The richness of crater data contained in the various inventories described in section 2.1 quickly revealed that integrating these diverse datasets into the ArcInfo-based catalog and conducting investigations which would produce useful results would be a challenge. Logistically, we needed a way to be able to merge all information about a specific crater from the different datasets--i.e., ArcInfo needed to be able to identify specific attributes that would be identical among the different crater inventories. The latitude and longitude of the crater would be the logical choices. However, the Mars Control Net has evolved over time as the planet's shape and center of mass have been refined (Archinal, et al., 2002). Coordinates estimated from the Mars 1:2,000,000 photomosaics often vary from those obtained off the Viking MDIMs which in turn are offset from the latest control net derived from MOLA. In addition the new MOLA-referenced datasets utilize an east longitude system whereas the older datasets utilize the original aerographic coordinate system based on west longitudes. The latter problem is easy to remedy but the first problem is much more difficult. Since coordinates in MDIM 2.1 will be tightly controlled by MOLA topography, the Consortium will require all crater inventories to list crater locations using this system. Student support may be required to revise the coordinates in the existing datasets if an automated method cannot be developed.

The Consortium also quickly recognized that the lack of a standard nomenclature system has led to many different descriptions for the same features. This is particularly problematic when discussing ejecta morphologies. The ejecta morphologies found around minimally degraded martian impact craters have been variously described as pedestal, pancake, rampart, mound, lump, flower, radial, lunar, transitional, diverse, single lobe, double lobe, and multiple lobe as well as less descriptive terms such as Types 1 through 6 and Classes 1 through 4. One of the first tasks tackled by the Mars Crater Morphology Consortium was to propose a standardized classification system for the different ejecta morphologies (Barlow et al., 2000). Since the actual mechanism(s) involved in the formation of the different ejecta morphologies is still under debate (Carr et al., 1977; Schultz and Gault, 1979; Wohletz and Sheridan, 1983; Barnouin-Jha and Schultz, 1998; Baratoux et al., 2002; Stewart et al., 2003), the Consortium recommended a generic terminology which has no implications for the mechanism(s) involved in ejecta formation. The general classification system consists of layered ejecta structures (which includes ejecta morphologies previously described as pedestal, pancake, rampart, lobate, and/or fluidized), radial morphologies (previously called radial or lunar-like), and combination morphologies (previously called transitional or diverse). Subclasses are described by the number of ejecta layers, the sinuosity of the ejecta blanket, and the characteristics of the ejecta terminus. Barlow et al. (2000) also provide a table which correlates the previously used nomenclature classes with the new system.

The nomenclature associated with martian impact crater interior morphologies has been more consistent than that for the ejecta morphologies. Central peaks, peak rings, central pits, wall terraces, etc. are terms commonly used by all investigators. As a result, the Consortium does not see a current need to standardize the nomenclature for these features.

2.3. Current Dataset Comparisons

Barlow, Roddy, Kuzmin, Costard, and Boyce have provided their crater inventories to the USGS where Trent Hare has ingested them into the ArcInfo GIS system (Figure 1). As expected, offsets occur in the locations of the craters due to the slightly different crater coordinates in the various datasets. Nevertheless, general correlations between the different datasets are observed. Craters with fresh ejecta morphologies show strong correlations between the different data sets, indicating that few of these craters have been missed when all the inventories are considered. Ejecta designations, when the new nomenclature is utilized, also show good correlations between the different data sets, although the MOLA-based catalog by Garvin, et al. may indicate some differences compared to the image-based datasets. In particular, MOLA analysis of craters designated as single layer ejecta pancake (SLEP) in the image catalogs is typically revealing that these ejecta morphologies display a distal rampart at the ejecta terminus and should therefore be classified as single layer ejecta rampart (SLER) structures. Nevertheless, the integration of these datasets compiled by different researchers will provide a more consistent inventory than any individual dataset.

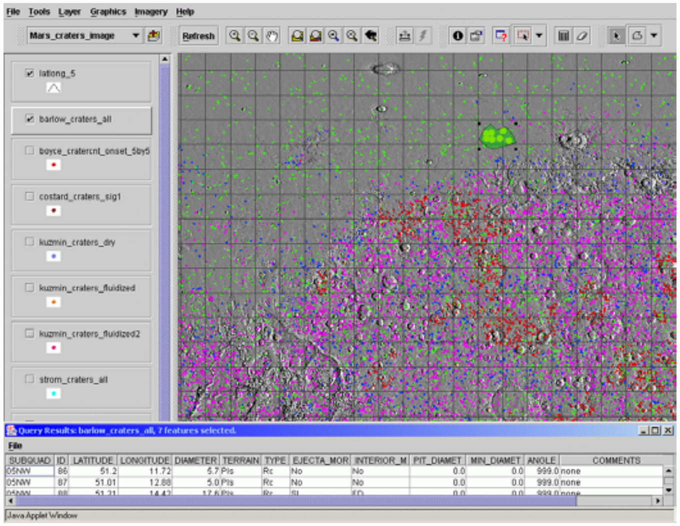

Figure 1. Example Page of Integrated Crater Catalog. This image shows craters of different preservational classes in the Barlow catalog. Green indicates the freshest craters, red and purple are moderately degraded craters, and blue represents highly degraded craters. The base is the 1 km MOLA hillshade. The table shows details on selected craters within the green polygon. The area shown is the Chryse Planitia and Arabia Terra regions, along the martian highland/lowland boundary.

The incorporation of the crater datasets into a GIS format also facilitates the completion of information for an individual crater. This was the primary purpose of this effort—to combine the datasets so that information collected by one researcher could be combined with the information collected by others in order to provide a detailed description of each crater on Mars. For example, the digitized information about crater interior morphologies contained in the Roddy and Isbell catalog supplements the descriptive entries for these features in the Barlow catalog. The Garvin et al. MOLA-based crater inventory will greatly enhance the existing datasets when it is incorporated into the integrated catalog. The new MOLA-based database of Boyce and Mouginis-Mark will include vector data for attributes such as the crater rim crest and distal margin of the ejecta layers, thereby facilitating their incorporation into GIS layers.

3. FUTURE DIRECTIONS

3.1. Database Issues

Barlow's *Catalog of Large Martian Impact Craters* is the most complete of the datasets for craters ≥5 km in diameter and the Consortium has agreed to use that dataset as the base for the integrated catalog. Ongoing and future revisions to attribute columns will therefore be concentrated on the Barlow dataset and additional crater inventories will be integrated with it. The immediate focus of the Consortium effort is to incorporate the MOLA-referenced coordinates for each crater (MDIM 2.1). The USGS members of the Consortium are tasked with this effort. Concurrently, Barlow is continuing the revision of the *Catalog of Large Martian Impact Craters* using MGS and MO data. A preliminary copy of this revised version will be provided to the USGS by the time of the 2003 Consortium workshop. At the workshop, the Consortium will discuss the schedule for the debut of the web-based integrated catalog.

3.2. Research Projects

A major incentive for the formation of the Mars Crater Morphology Consortium was to encourage research collaborations between Consortium members by identifying questions raised by analysis of the integrated crater catalog. One of the major questions recognized by the Consortium is how well the current models for crater and ejecta formation describe the morphologies/morphometries actually observed with martian impact craters. As a result, the Consortium effort has grown from primarily researchers involved in analysis of crater morphologies to those who model the crater and ejecta formation processes. The topographic information provided by MOLA has greatly improved our ability to directly compare the models with the observed crater characteristics. This combined effort promises to dramatically advance our understanding of the parameters which influence crater formation on Mars, including the role of impact angle, subsurface volatiles, particle sizes, and other target and projectile properties.

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