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June 13, 2005

Dr. Marilyn Lindstrom
Code SE
NASA Headquarters
300 E Street, S. W.
Washington, D. C. 20546

Re: NASA Grant No. NAG5-10603

Dear Dr. Lindstrom:

We are pleased to include Dr. Jennifer Grier's final Summary of Research for the above-referenced grant.

Please let us know if you need any additional information.

Sincerely,

Elaine Owens

Elaine Owens
Office Manager

pc: Ms. Renée Luna, Office of Naval Research
Ms. Brenda L. Smith, NASA GFSC

Final Technical Report
Summary of Research

Testing the Hypothesis of Young Martian Volcanism:
Studies of the Tharsis Volcanoes and Adjacent Lava Plains

NASA Grant Number: NAG5-10603
Mars Data Analysis Program
Period of Performance: 03/01/01 - 02/28/05

Principal Investigator
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Final Report

Introduction

We experienced much success in reaching our stated goals in our original MDAP proposal. Our work made substantial contributions towards an integrated understanding of the counting and calibration of crater data on Mars, and changing nature of the Martian surface influenced by craters, water, and wind, and their general relationship to Martian geothermal history. We accomplished this while being to responsive to the rapid changes in the field brought about by several key NASA missions that returned data during the life of the grant.

Our integrated effort included three stages:

The first major area of research (Crater Count Research) was conducted by Jennifer Grier (P.I.), Lazslo Keszthelyi (Collaborator), William Hartmann (Collaborator), with assistance from Dan Berman (Graduate student) and concerned the mapping and the collection of crater count data on various Martian terrains.

The second major area of study (Absolute Age Calibration) was conducted by William Bottke (Co-I) at SWRI, and concerned constraining the nature of the Moon and Mars impactor populations to create better absolute age calibrations for counted areas.

The third major area of study was the integration and leverage of this effort with ongoing related Mars crater work at PSI (Integrated and Continuing Studies – Older Volcanoes), headed by David Crown (PSI Scientist), assisted by Les Bleamaster (PSI Scientist) and Dan Berman (Graduate Student).

1. Crater Count Research

This first aspect of our program was on Mars related crater counts and the dating of young volcanic terrains. It was approached as three related tasks, the overall thrust of which was to shed light on our understanding of the most recent geothermal history of Mars, and the interplay of wind and water in that understanding.

Task 1 – Mapping and Dust Cover:

A. We determined good surfaces for counting based on minimal dust cover, and mapped the major volcanic forms on the Tharsis volcanoes. Maps tagged with indicators for both dust cover and major volcanic constructs were created for the major Tharsis shield volcanoes as well as Olympus Mons. TES data have shown that dust mantles exist over much of the Tharsis region, and it is critical that the ages of the terrains counted do not appear artificially young due to dust cover of some of the craters. Our results indicate that the effects of dust "softening" on the crater profiles can be identified, usually as craters below a given diameter rapidly become eliminated from the sample population. Data for craters above this diameter do not appear changed from an expected production profile.

Task 2 - Counting on Tharsis area flows:

A. Using information from Task 1, we identified areas with the least amount of dust modification for the production of apparent age estimates of the underlying lava surfaces. The MGS MOC and MO THEMIS image databases were systematically searched to identify those areas in the Tharsis region with maximum utility for crater chronology studies. The subset of images deemed appropriate for analysis were identified and acquired. A sampling of these were processed using ISIS (Integrated Software for Imagers and Spectrometers) software developed by the USGS Astrogeology Team for integration into a GIS (Geographical Information Systems) database at PSI. The GIS database, which also includes Viking MDIM 2.1 image and MOLA gridded topography (128 pixels/degree) base layers, facilitates extrapolations between MOC, THEMIS, and Viking datasets, calculation of crater count areas, and evaluation of slope and elevation-dependent effects.

B. Crater counts using MOC and THEMIS images were performed on the following volcanic units/features: a) Olympus Mons flanks and caldera, 2) Pavonis Mons flanks and caldera, 3) Arsia Mons flanks and caldera, 4) volcanic plains of central Tharsis.

C. Results for these "young" volcanic features (using calibration to be described in Major Research Area 2) include:

1) Model ages between 10 and 100 My for the younger flank flows and between 100 My and 1 Gy for the older flank flows of Olympus Mons.
2) Model ages between 100 My and 1 Gy for the older flows on the flanks, and between 10 My and 100 My years for the younger flank flows and the caldera of Pavonis Mons.
3) Model ages between 100 My and 1 Gy for the caldera floor of Arsia Mons.

Task 3 - Counting on other young Martian terrains:

A. A collaborative effort was initiated with Dr. Devon Burr of the USGS to help elucidate the connection between the timing of lava and water flow on Mars. The PI Grier collected and plotted crater data from three aqueous flood channels around the Cerberus Plains. Crater counts as well as geomorphology and topography allowed these channels to be interpreted as spatially and temporally separate, as well as very young. See publications list for details of the study.

B. The crater counts completed by Berman for the Tharsis region have been used for comparison to studies of crater populations on volcanic units/features in the Martian southern highlands northeast of the Hellas Basin as well as those for potential ice-rich surfaces (i.e., mantling deposits, debris aprons, valley floor deposits). The volcanic units studied include various surfaces of Tyrrhena Patera, Hadriaca Patera, and Hesperia Planum. Results for ice-rich features show model (crater retention) ages of the last few My to tens of My for small craters in the upper tens of meters.

2. *Absolute Age Calibration*

William Bottke (Co-I) of SWRI was supported by this grant to investigate new means of determining and verifying R, the calibration factor between size-frequency distributions on the Moon and Mars. He has studied the computation of R using both a "top-down" and a "bottom-up" approach to verify the ratio. The "bottom-up" approach (following the methods introduced by Ivanov): (i) crater SFDs (size-frequency distributions) on Mars and the Moon were used to derive the SFDs of the projectiles,

(ii) the orbits and sizes of observed asteroids have been used to both calibrate the projectile SFDs and compute their associated impact velocities, and (iii) these values have been inserted into crater scaling laws, which were then used to determine crater production rates on Mars and the Moon and the value R. The limitation of this "bottom-up" approach is that, so far, observed (and potentially-biased) asteroids have been used to determine several important parameters.

Such results have now been checked using a "top-down" approach. Our computation relies on the recent work by Bottke, who constructed a model of the debiased orbital and size distribution of the NEO and IMC populations. The latter is defined as the population of the asteroids with main belt-like semi-major axis and inclination, and which intersect the orbit of Mars within a secular cycle of the eccentricity oscillation.

From this model, Bottke computed the impact rates between debiased populations and Moon/Mars. To account for secular variations in Mars/Moon e,i values over time, we compute their evolution over the next 10 Myr using recent analytical approximations. Collision probabilities and mean impact velocities were computed between these values and a grid of test particles uniformly distributed in (a,e,i) space, with each particle representing a component of the NEA and IMC debiased populations. Our results indicate the interval between $H < 18$ impacts on the Moon, ~ 11 Myr, is over 10 times longer than that for Mars, while the mean impact velocities of material striking the Moon (~ 19 km/s) is twice that of objects striking Mars (~ 10 km/s). Thus, using these numbers, we calculate that the ratio of $H < 18$ impactor striking Mars over that of the Moon per square km per year $R_b = 2.8$. Computing R requires the conversion of H into projectile diameter d and crater diameter D. Using typical impact velocities, we find the $D_M/D_m = 0.63$, very close to that found previously. Assuming $b = 1.8$, we estimate that $R = (D_M/D_m)^b * R_b = 1.2$.

This value is only slightly higher than that found using the "bottom-up" approach, showing that both the "top-down" and "bottom-up" approaches lead to a reasonable and reliable value for R. This calibration factor is then used in the calibration and generation of "isochrons" within the size-frequency distribution plots after the manner of Hartmann.

From these plots determined the ages of crater counted terrains using the most advanced computational and statistical methods currently available. Bottke and Hartmann published the results from this and directly related research in several manuscripts, partially funded from this grant.

3. *Integrated and Continuing Studies – Older Volcanoes*

The work conducted under this grant is complementary to a different MDAP-sponsored project at PSI (David Crown, PI) focusing on understanding the populations of impact craters on older volcanoes on Mars, particularly the Martian highland paterae (Tyrrhena, Hadriaca, Amphitrites, and Peneus Paterae) and ridged plains of Hesperia Planum. Central to this ongoing work has been the creation of a GIS database to facilitate geomorphic and topographic analyses as well as crater counting studies. Synthesis of results from studying crater statistics on young and old Martian volcanic features is essential for developing the appropriate techniques to be used to accurately constrain the volcanic history of Mars.

A. Dr. Leslie F. Bleamaster has been supported by this grant to assist in this synthesis and overall establishment of the databases and tools for analyses of Martian crater populations using new datasets, such as MOC and THEMIS. Results include the following:

1) Crater counts using MOC and THEMIS images on southeastern flanks of Hadriaca Patera including adjacent portions of the channeled and smooth plains and Dao and Harmakhis Valles floor materials. Counts are consistent with earlier Viking results and extensive dissection of the volcano by fluvial activity as well as with regional stratigraphy derived in Viking-based analyses.
2) Search, identification, acquisition and image processing for crater analyses and three-dimensional visualization of Hadriaca and Tyrrhena Paterae, and Hesperia Planum.

B. Results of Hellas region work and comparative analyses supported by both MDAP grants:

1) Volcanic surfaces of highland paterae (Tyrrhena and Hadriaca Paterae) exhibit old surface ages from Viking, THEMIS, and MOC crater counts indicating that crater count analyses of high resolution images are useful (i.e., at least some ancient volcanic surfaces are not completely reworked, buried, or eroded at small scales). This shows potential for important constraints to be derived regarding chronology of volcanism on Mars.
2) Viking and THEMIS counts generally match the shapes of the isochrons developed by Hartmann and Neukum, and model ages from THEMIS images (craters between ~250 m – 1 km in diameter) provide age constraints consistent with earlier Viking results.
3) MOC images show effects of local variability and may or may not be consistent with THEMIS- and Viking-based analyses. Integration of crater statistics over the full size requires complementary geologic analyses of surfaces of interest to assess morphologic indicators of potential modification. MOC crater counts can be used in combination with THEMIS and Viking counts to evaluate both emplacement ages and erosional history.

Conclusion

Our work was successful and provided insight into cratering on the Martian surface, the evolution of the surface of Mars from volcanic, aeolian, and fluvial action, and the nature of the Mars/Moon impactor population. This work required robust data collection and computation, and strengthened partnerships between PSI researchers, and those at other institutions such as the USGS and SWRI. Several young scientists benefited from the grant, and additional projects are already underway which leverage our results and continue to build on our knowledge base.

Manuscripts and Publications

The grant contributed, in whole or in part, to work published in a large number of papers and abstracts, which follow. Some work was also supported under other grant programs. Work by the PI on the Decadal Survey, while not directly research related, is not covered under any other grant and is so presented here.

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