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FINAL REPORT

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"STATISTICAL MODELS OF LUNAR ROCKS AND REGOLITH" Allan H. Marcus, Principal Investigator

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INTRODUCTION.

The original research proposal for this grant suggested a variety of mathematical, statistical, and computational approaches to an investigation of the interrelationship of lunar fragmental material and regolith, lunar rocks, and lunar craters. The project developed in four phases. The first two phases were essentially mathematical, exploring first the sensitivity of the production model of fragmental material to assumptions, and then completing earlier studies on the survival of lunar surface rocks with respect to competing processes. The third phase (not yet completed) combines earlier work into a detailed statistical analysis and probabilistic model of regolith formation by lithologically distinct layers interpreted as modified crater ejecta blankets. The fourth phase has dealt with problems encountered in combining these results into a comprehensive multipurpose computer simulation model for the craters and regolith.

PHASE 1. Sept. 1971 - April 1972.

Before any computer simulations could be attempted, it was necessary to explore the sensitivity to parameters and model functions of the basic crater model. An extensive analysis of the gross rate of production of lunar fragmental material was developed. The model dealt exclusively with the mean volume of material per unit area (translated into regolith thickness) as a function of time, without considering the variable distribution of thickness spatially. Even so, difficult numerical integrations were required. Fortunately, one of the research assistants, Mr. William Dupont, had very extensive experience in computation of numerical integrals and was able to successfully complete this project. The results were presented at the American Geophysical Union meeting in April, 1972 and subsequently published in Icarus (1).

The model proved to be distressingly sensitive to small differences in parameters which were within the limits of uncertainly of the experiments from which the parameters were estimated. (It was almost essential to overinterpret the laboratory data). Small changes in scaling law exponents and fresh crater diameter distribution exponents induced order-of-magnitude variations in mean regolith thickness. Variation of ad hoc diameter limits (the minimum and maximum crater diameters affecting the region) induced similarly large variations. The model produced very plausible values for mean regolith thickness, but so did most other models. The model made some clear but counter-intuitive predictions e.g. the possibility of a statistical reverse bedding with older surfaces having a smaller surface density, but higher proportion of very large blocks and boulders. This then became the next major research effort.

PHASE 2. April, 1972 - December, 1972

In order to determine the lifetimes for destruction of lunar surface rocks by erosion (microcratering) and shattering (macrocratering), it was necessary to obtain recent empirical information on the returned lunar samples. I accordingly visited the NASA Manned Spacecraft Center in Houston on April 4-5, 1972 for informative discussions with Drs. Fred Horz, David McKay, and Jack Hartung. They described their own work and recent (as yet unpublished) correlated studies by Don Gault at NASA-Ames. I subsequently developed an extensive analytical model by which the survival lifetime distributions of lunar rocks could be compared for a variety of possible fates - single-event burial, multiple-event burial, shattering, and erosion. The shattering and erosion models were based on recent studies by Gault (2) greatly improving on both my own earlier study (3) and that of Shoemaker (4). The burial model was extremely sensitive to the effective crater volume distribution exponent $\alpha = (S-2)/h$, where S is the exponent of the fresh crater diameter distribution and h the exponent of the crater rim height-diameter distribution. The value $\alpha = 1$ is a critical dividing line, and the experimental value of α was believed to be close to 1.0. However, a "small-crater" model with α much larger than 1.0 was also developed and seemed to give quite useful results.

The results were reported at the American Geophysical Union meeting in San Francisco in December, 1972. The paper (5) was subsequently submitted for publication, but critically reviewed because of a failure to provide comparisons of predicted and observed exposure lifetimes. Such comparisons require access to information not readily available to me: There are presently no plans to extend this research.

A side-effect of my discussions with Hartung was a careful reconsideration of the concept of crater saturation, possibly applicable to densities of microcraters on lunar rocks (6).

PHASE 3. January 1973 - April 1973.

After studying surface activities, I once again considered the regolith dynamics. My earlier regolith model (7) was extended to more realistic crater blanket geometries (8). The existence of lunar core tube samples opened up the possibility of studying a layered lunar regolith in terms of its ejecta blanket layers (the basic element of the crater model). A series of detailed statistical analyses were performed on core tube layer data from Apollos 12, 14, 15, and 16. These were reported at the American Geophysical Union meeting of April 19, 1973. A number of critical comments were received: (1) Layers had little real meaning or physical significance, unlike terrestrial geologic strata. (2) Spatial cross-correlations of layers with similar properties were needed. I subsequently reevaluated the data with respect to these two points. The layers had a variety of consistent, operationally-well-defined differences; (9) but it was not possible to decide if they constituted lithologically distinct beds from the same ejecta blanket, or were aggregates of different but lithologically similar blankets which could not be individually distinguished. A number of techniques were used to seek spatial correlation or coherency of layers from four

Apollo 16 core sites, but no conclusive evidence was found. Some layers resemble others in the same and other tubes, but the order is completely scrambled due to subsequent cratering and mixing. The statistical identification of coherent regional blankets would confirm both the reality of layers as ejecta blankets and the validity of the crater model, and the identity (10) of the layers.

The statistical methods used so far have been relatively model-free. More powerful methods require a probabilistic model. Even the simplest realistic models show unexpected complexity, due to: the fixed length of the sample; the truncation of the bottom-most layer; regional lithologic cross-contamination (11); the highly skewed nature of the layer thickness distributions. The usual small-sample optimal statistical methods do not fit this problem, and additional methods based on short samples from a Markov renewal process are being developed. Fragments of a manuscript are ready, but, because of the frustratingly inconclusive nature of these results, it is not possible to issue a technical report of acceptable scientific quality at this time. Additional studies are progressing and may be reported at the April 1974 A. G. U. meeting.

PHASE 4. April 1973 - August 1973

As a result of the comments received at the AGU meeting, I returned to the possibilities of computer simulation. Most of the computation (both self-instruction and testing out of component submodels) was done on the remote terminal installed in Maryland Hall across from my office. I also attended the Fourth Pittsburgh Symposium on Modeling and Simulation on April 24, 1973. The result of the extensive computations was that, while I learned much about large-scale computer models, I learned little about the Moon. During the course of this grant, I became familiar with a number of unpublished studies (12) (13) and published studies (14) (15) (16) which also investigated lunar fragmental thickness distributions by deterministic and stochastic simulations. Of these studies, those by Lindsay (13) and Oberbeck et. al. (15) (16) proved to be the most sophisticated and together effected nearly all of the innovations in simulation described in the proposal for this grant. The computational logic is detailed by Lindsay (13). Oberbeck et. al. included the redistribution of materials by subsequent primary and secondary craters, including the shielding effects of the regolith (15) (16).

In general these simulations have similar unsatisfactory properties, mainly: (a) Inability to deal with edge effects accurately, or to minimize edge effects by modeling a sufficiently large region. (b) Strict additivity or superposition of elevation changes without allowance for mass wasting slump and down-slope movements of loose material. The real moon is smoother than the model moons! (c) Devastating sensitivity to uncertain or ad hoc parameters and unknown model functions. These include lower and (especially) upper diameter limits for craters, shape of the ejecta blankets, and fresh crater diameter exponent S. (d) Incorrectly chosen inputs which should be revised on the basis of recent results on impact mechanics (17) and ejecta blanket shape (18). (e) Insufficient attention to the fact that ejecta blankets are clumpy and irregular, with oscillating radial and circumferential patterns as well as a smooth radial variation. (f) Only Lindsay's simulation deals with the probability of survival of blanket integrity. To trace turned-over layers in a computer simulation, one would have to digitize layer thickness on a scale of 1 to 5 centimeters and mark each layer with an identifying symbol, a task that greatly exceeds the memory of available computers.

I do not wish to add to existing polemics on the failures of large-scale models e.g. (19); merely to point out problems that emerged from the original proposal.

CONCLUSIONS AND SUMMARY

1. Useful analytical methodology has been developed for determining the gross rate of production of lunar fragmental material and for estimating the lifetime of lunar surface rocks with respect to competing processes of destruction or burial. The numerical results require extensive modification in light of recent data and experiments on impact mechanics.

2. Serious analytical problems requiring further study remain for the statistical analysis and theoretical interpretation of regolith layers in lunar core tube samples.

3. Large-scale multipurpose computer simulations are unlikely to be helpful in understanding regolith dynamics. Special-purpose small-scale simulations and theoretical analyses (for all their shortcomings) are likely to provide a more useful methodology, being less sensitive to incorrectly or incompletely specified inputs and to accumulation of errors. This is particularly true for intrinsically highly variable quantities such as lifetimes with respect to competing processes.

4. The most helpful experiment in establishing the validity of an impact-generated regolith model would be a network or grid of core-tube samplers, to determine the spatial coherence and integrity of regolith layers, their variability, and their potential utility as indicators of lunar microstratigraphy.

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