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THE ORIGIN AND SIGNIFICANCE OF LUNAR MICROCRATERS, J. B. Hartung, NASA-MSC, Houston, Texas 77058, Friedrich Horz, NASA-MSC, Houston, Texas 77058, D. E. Gault, NASA-Ames Research Center, Moffett Field California 94035

Investigators of sub-microscopic impact craters (1 to 200 microns in diameter) on lunar materials have suggested that the craters were formed by the impact of secondary lunar particles ejected during a larger impact event (1, 2, 3, 4). Other workers assume craters in this size range are due to the primary impact of extralunar material (5). Investigators of craters (100 microns to over 1 cm in diameter) on rock surfaces conclude that the dominant cratering process is the primary impact of extralunar particles (6). We offer the following evidence and arguments that all craters displaying glass-lined pits in the 1 micron to cm range are caused by primary impact:

1. In laboratory cratering experiments using aluminum projectiles greater than 0.4 mm in diameter and impact velocities of up to 7 km/sec, no glass-lined pits were produced in cold soda-lime glass targets (7). Cratering experiments using microparticle accelerators and micron-sized projectiles produced flow phenomena or melting at impacts of about 2 km/sec (8, 5). Accordingly, minimum impact velocities required to produce glass-lined pits of micron and mm size are about 2 km/sec and 7 km/sec respectively. In contrast to laboratory-produced pits, the geometry of crater lips surrounding micron-sized lunar impact pits indicate that a larger amount of melt was produced which in turn is evidence that even the micron-size lunar craters are generated by impact velocities significantly larger than 2 km/sec.

2. In general, rock surfaces exposed to space (based on lunar surface photography) always display a population of microcraters whereas buried rock surfaces often display no craters. Obviously, most cratering of rocks occur while they rest on the lunar regolith. Therefore the distribution of glass-lined pits on the entire exposed surface of a rock (9) is incompatible with a secondary origin, because secondary (lunar) particles generally cannot impact at velocities higher than 2.4 km/sec, the lunar escape velocity.

3. Rock 12054 is a prime example for accumulating such a primary crater population on its exposed parts while at rest on the lunar surface. Craters with diameters as low as 50 microns were observed optically on a glassy surface on this rock. The morphology of these craters is identical to the same size craters on glassy materials from the lunar fines permitting the conclusion that the larger impact craters on glass spherules from lunar fines are also primary. Smaller craters on glass spherules, those with pits generally less than 5 microns, differ in morphology in that no spall zones surround the pits. However, the larger pit-plus-spall craters and the smaller pit-only craters form a genetic continuum based on the observation of concentric fractures representing incipient spallation around pit-only craters (10). Thus the entire size range of craters showing evidence of shock produced melting is apparently the result of primary impacts.

4. Based on laboratory cratering experiments for a single event, one should expect a negative correlation between the amount of material ejected and the ejection velocity of that material. The bulk of crater ejecta will not be accelerated above 2 km/sec (11); indeed most ejecta should travel at velocities below 1 km/sec (12). Therefore, individual ejecta particles from one large impact traveling at relative velocities in excess of 2 km/sec have a low probability of occurrence. For each hypervelocity impact of genuine

secondary nature, a large population of genuine low speed secondary craters (without melt phenomena) should be detected. Since this is not the case, it is taken as evidence that secondary impact is not the dominating cratering process.

5. Based on a summary of satellite-borne meteoroid detection experiments a differential mass spectrum of interplanetary dust has been derived (13). Cratering experiments using a microparticle accelerator provide a basis for calibrating observed microcraters in terms of impacting particle mass (8, 5). Based on observations of lunar microcraters, a differential mass spectrum of impacting particles has been obtained and agrees very well with that based on satellite-borne experiments. Thus, the observed size distributions of impact craters correspond to the previously known mass distribution of primary, interplanetary particles.

The origin of mm-sized impact pits due to primary micrometeoroids seems to be established according to the above arguments. However, problems for the origin of micron-sized craters by primary impact are as follows:

1. Material of definite lunar composition was observed lining impact pits on a metallic particle and interpreted as projectile remnants (2). It is not likely that primary impact alone would produce this result, however, the possibility exists that subsequent secondary deposits which are omnipresent in the lunar fines may have contaminated the interior of the impact crater.

2. Some investigators have shown that phenomena normally associated with high velocity impact may be produced at significantly lower velocities if the target material is heated short of melting (7). However, their data do not show conclusively that impact at moderate velocities ($\approx$2 km/sec) can produce the characteristic pit-plus-spall craters.

3. Statistically, relatively more glass spherules possess populations of impact craters than do crystalline fragments (3, 7). One might expect relatively as many craters on crystalline fragments as on glass spherules from a random, primary-impact process. For optical studies there is significantly greater difficulty in identifying impact craters on crystalline surfaces than on glass surfaces (6). This situation may also exist for scanning electron microscope studies.

Pertinent exposure age measurements of the surfaces investigated are still missing and therefore conclusions about the absolute flux of micrometeoroids based on lunar microcrater population statistics are not possible. However, these statistics may be used to derive independently the differential mass spectrum of interplanetary dust particles. The important characteristic of this spectrum is that more mass impinges on the lunar surface in the form of $10^{-5}$ to $10^{-7}$ g particles than in any other equivalent size class.

For example, in a given time, over a given area, for every impact of a single one-gram projectile, there may be expected 1 million impacts of 10-microgram particles. The mass and the kinetic energy involved in the 10-microgram impacts would be 10 times that for the one-gram event, assuming equal impact velocities.

It is well known that high-velocity impact causes ionization, vaporization, and melting of solid materials. If the mass of material affected by these processes during a single impact is linearly related to the impacting particle mass, then we may conclude that more mass is ionized, vaporized, and melted by mm-sized cratering events than by craters of any other equivalent size.

Small scale cratering events must also be considered as a possible dominant mechanism for the horizontal transport of lunar surface materials. Similarly, the erosion and destructive fracturing of rocks is the result of the microcratering process. Finally, relatively greater amounts of the extralunar component in the lunar regolith presently arrive as exceedingly small particles than as large meteorites.

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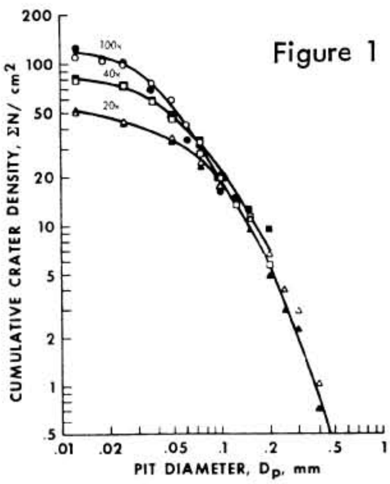


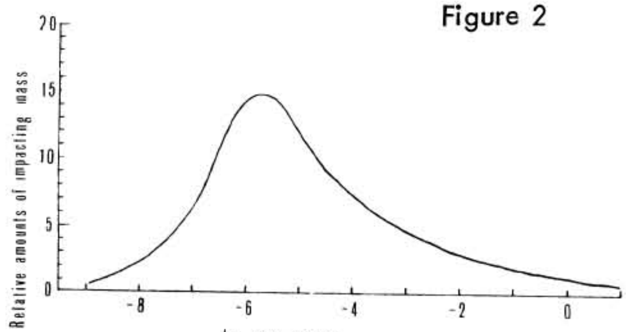


Fig. 1. Cumulative densities of microcraters obtained by optical studies on glass-coating 12054. Total crater counts: 967. Open and closed symbols represent independent counts of two observers. The difficulty to record quantitatively the very small craters is illustrated by the 3 branches at 20x, 40x and 100x magnification. Scanning Electron Microscope investigations on a glass spherule (10) indicate significantly greater crater densities for .01-.05 mm craters than indicated here.

Fig. 2. Differential mass spectrum showing the relative amounts of mass impacting the lunar surface in the form of different sized particles. The curve is based on a summary of data obtained by microcrater statistics (10) and satellite-borne particle detection experiments (13) with smoothing to eliminate an artificial discontinuity introduced by the mathematical representation of the data.

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