LUNAR SELF-SECONDARY CRATERING: IMPLICATIONS FOR CRATERING AND CHRONOLOGY.

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Introduction: Secondary cratering is a critical yet poorly understood aspect of the impact cratering process. Secondary craters are produced by blocks of material ejected from the primary crater that subsequently impact the surface forming smaller individual craters and clusters of craters. Secondary craters have long been recognized on all planetary bodies and rudiments of their formation is understood on the basis of laboratory experiments, large-scale explosions, and theory. However, their spatial distribution, frequency of occurrence and size distribution are not well understood.

Crater Chronology: Crater counts provide a basis for establishing relative and absolute model-dependent ages for planetary surfaces. The more craters, the older a surface. Using a calibration curve derived for the Moon, and extended to Mars and other bodies, a model-dependent absolute age can be derived from crater size frequency distributions (CSFD) [**1-2**].

The sine qua non for impact crater chronology is that a surface has zero impact craters immediately after formation. Additionally, it is assumed that all craters on a surface are primary (produced by projectiles impacting from space).

The presence of secondary craters will contaminate crater counts (increasing the frequency) by adding craters to the population that are not primary impact craters. Classically, secondary craters are described as occurring in chains or clusters beyond the limits of the continuous ejecta and can be recognized as such and excluded from counts. More recently, however, distal secondaries that do not occur in clusters were recognized on Mars [**3-4**]. In the past these craters were not considered to be of secondary origin and thus were included in counts, artificially increasing CSFDs.

Another poorly understood aspect of secondary cratering is the presence of what are considered self-secondary craters on the continuous ejecta and melt deposits of Copernican-age lunar craters [**5**].

Regardless of their origin, the presence of unidentified secondary craters increases the frequency of craters above that produced by the primary impacts. The result is that a surface appears older than its actual age. In addition, if a surface contaminated with unidentified secondaries is used as a calibration point the result will be an over-estimate of the impact flux.

Self-Secondary Cratering: A number of recent studies [**5-9**] of the crater frequency on the clastic ejecta and melt materials of Copernican-age lunar craters using LROC NAC and Kaguya images have documented that the frequency of craters and the slopes of the CSFD are spatially variable for a given impact event. In addition, the frequency of craters on melt materials is always lower than on the adjacent clastic ejecta. These observations suggest that small crater populations superposed on young craters are contaminated with a significant number of self-secondaries.

The observation that impact melt has a lower crater frequency than associated clastic ejecta is not new, but dates to the 1960s. When this difference was first noted, it was interpreted as indicating real, significant differences in the age of the ejecta and melt surfaces, (melt surfaces being younger). This age relation and the morphology of the materials were used as an argument for young volcanism associated with impact craters [**10-11**].

This same type of crater frequency variation (melt vs. clastic) was noted at Tycho crater by Shoemaker et al. [**12**]. They interpreted the spatial variations and differences to be the result of self-secondary cratering. The mechanism envisioned debris launched into near-vertical trajectories that subsequently re-impacted the newly formed ejecta and melt surfaces (trajectories must be near-vertical or the debris will land beyond the continuous ejecta blanket).

Melt vs. Ejecta Crater Frequency: There are two possible explanations for the difference in CSFDs. The first is that the difference in frequency at a given diameter is an artifact of the strength differences between the impact melt and the clastic ejecta [**9**]. Impacts into a strong, solid target (melt) will produce a smaller crater than an impact into a weak, particulate target (ejecta). The argument has been made that if a correction is applied to account for strength difference, the frequency difference can be resolved. The second explanation is that the difference is produced by the waning flux of self-secondary debris [**5**]; most debris has reimpacted the surface before the melt is emplaced such that melt is exposed to a lower flux of secondaries than was the ejecta. Consistent with this scenario is the observation that melt material is observed to bury small-diameter craters on the ejecta. These craters are too small and the ejecta material too thick for these embayed craters to be "ghost" craters formed on the pre-impact surface. This relation demands that some of the craters on the clastic ejecta formed before the melt was emplaced.

The difference in CSFDs between the melt and the ejecta is certainly influenced by the strength difference of the target materials. However, if that were the complete explanation, then the ratio of the crater frequency between the ejecta and the melt should be a constant and proportional to the strength difference. However, the ratio of the frequencies between melt and ejecta vary among Copernican-age craters suggesting the problem is more complex. A strength difference will also not account for spatial variations in the crater frequency on both melt and ejecta surfaces.

Unusual crater-form features occur on melt surfaces that are interpreted to be the result of impacts into still partially molten impact melt. Such features are circular but are shallower and have lower crater-wall slopes than normal impact craters and they are restricted to impact melt surfaces. Their morphology is similar to low-velocity experimental craters into viscous (clay/slurry) targets [**13-15**]. If these features do represent impacts into unsolidified melt, it indicates the flux of self-secondary debris was still significant during and after melt emplacement.

Discussion: The question can be asked whether self-secondary cratering is an important consideration in terms of cratering chronology. If the total number of self-secondary craters on the ejecta and melt is relatively large, then the age of these surfaces will appear to be older than their real age. If that surface is used as a calibration point for estimating the cratering flux (e.g., Copernicus, Tycho, Cone, North Ray craters), then the excess number of craters will indicate a flux that is greater than the real flux.

While geologic relations demonstrate that self-secondary cratering occurs, the percentage of craters on the ejecta that are self-secondaries is unclear. It is difficult to distinguish between primary and secondary craters that are tens to a few hundreds of meters in diameter. Since the self-secondary bolides follow near-vertical trajectories, the resulting craters are circular. In theory, the depth of a secondary crater might be shallower than a primary crater but elevation data with sufficient spatial resolution is limited.

Secondary craters are typically assumed to begin beyond the continuous ejecta blanket based on the observations and modeling of ejected debris. However, the observations detailed above indicate that self-secondary cratering must also occur on the continuous ejecta and melt materials. Self-secondary craters have been noted on the ejecta blankets of some planetary craters [**16**].

Self-secondary craters occur on nuclear and large chemical explosion craters [**17-18**], for example, the ejecta blanket at the Sedan Crater (390 m diameter; 104 kT TNT). Given that these craters were observed immediately after the impact they must have been produced during the excavation of the crater.

Modeling studies of ejected debris do not predict self-secondary craters. This is likely due to the fact that relatively little material is launched into a near-vertical trajectory and is thus unresolved in the models. But, that small amount of material is sufficient to form a significant number of small craters on the continuous ejecta blanket. Laboratory craters also exhibit self-secondary craters, but this has been little discussed and noted only in passing [**19**].

Conclusions: The geology of clastic ejecta and impact melt and data on the frequency and statistics of small-diameter craters on those materials suggest that self-secondary cratering must occur. Such effects have been noted on craters as small as Cone Crater (340 m) [**5**] suggesting that it is a typical part of the cratering process. If self-secondary craters represent a significant fraction of the craters on Copernican-age craters, then the surfaces will appear to be of greater age. For those craters that are used as calibration points, the result will be an estimated flux that is higher than actually occurs. Resolution of the number and significance of self-secondary impact craters will require precise and accurate absolute age dates for a suite of young craters on the Moon (i.e. Giordano Bruno, Necho, Moore F, Aristarchus, Tycho craters).

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