THE GLOBAL ACCUMULATION OF SECONDARY IMPACT CRATERS ON THE MOON.

T. M. Powell[1], L. Rubanenko[1], J.-P. Williams[1], and D. A. Paige, [1]University of California, Los Angeles, CA, USA (tylerpowell@ucla.edu).

Introduction: The relative importance of secondary craters on the accuracy of crater chronometry has been heavily debated since the 1960s. Early studies recognized that the accumulation of impact craters on a surface could be used to estimate its age. However, the discovery of abundant secondary craters in Ranger VII images of Mare Cognitum introduced a complication. Shoemaker (1965) [1] noted that a high percentage, possibly even a majority of the 300 m to 1 km scale craters on the Mare were secondary craters. This has since sparked a debate around whether secondaries dominate the observed size-frequency distribution (SFD) of small craters.

In this work, we address the over-arching question: What sized craters are safe to use for crater counting? The distribution of secondary craters can be determined if 1) the production rate of primary craters and 2) the distribution of secondary craters produced by individual primary craters are known.

Model Description: We develop a model to predict the globally averaged accumulation of secondary craters with time on the Moon, where each primary crater produces a distribution of secondaries [1, 2, 3].

Primary flux: The flux of primary craters larger than ~10 m is given by the Neukum production function (PF) [4]. To extend this to smaller size, we employ a power-law extrapolation of the Williams PF [5]. This generally agrees with the formation rate of small craters observed by the Lunar Reconnaissance Orbiter Camera within the last ~10 years [6].

Secondary Production: The distribution of secondaries produced by individual primary craters is less well established and likely varies with crater size, target properties, etc. However, counts of secondaries have been performed around impact craters on the Moon [1] and Mars [7], and around terrestrial explosion craters [1]. These studies show that the distribution of secondaries follows a power-law whose slope is significantly steeper than the slope of primaries: $b_s \approx 4$. The largest secondary produced is typically about $f \approx 5\%$ the size of the primary crater. Zunil crater on Mars is a notable exception to this, which produced secondaries with a slope closer to -5 but whose largest secondary is only ~2.5% its size [2].

It is important to note that this model presents the *globally averaged* accumulation of secondary craters. Actual crater density will be greater close to large primaries. However, for regions not contaminated by obvious secondaries, this model provides an upper limit to the density of unidentifiable 'field' secondaries.

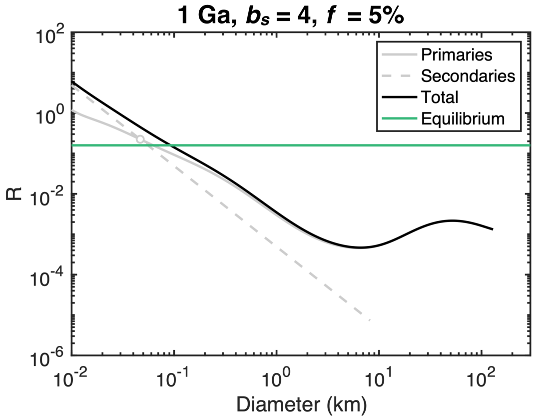

Figure 1. Example R-plot of primary craters and modeled secondary craters after 1 Ga on the Moon.

Results: Figure 1 shows the predicted SFD of both primary and secondary craters after 1 Ga for $b_s = 4$ and $f = 5\%$. The majority of large craters are primary. However, secondaries become more abundant globally below the crossover diameter: in this case ~50 m.

The SFD of the global secondary population is strongly controlled by the several largest primaries. The size of the largest primary increases non-linearly with time, so secondary flux also increases with time even for a constant primary flux. As noted by McEwen et al. (2005) [2], this causes crossover diameter to become larger for older surfaces. For example, the crossover diameter at 1 Ga is ~50 m but is <1 m for a 10 Ma surface. In most cases, the crossover diameter occurs at a crater density greater than the equilibrium crater

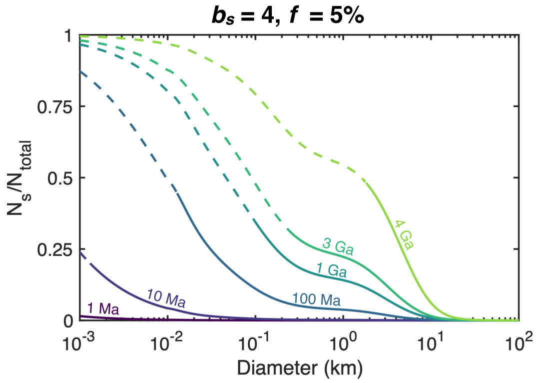

Figure 2. Model predictions for the global fraction of secondaries on the Moon. The dashed line notes when crater density exceeds equilibrium.

density: an observed 'maximum' density when for each new crater is formed, a crater of roughly the same size is erased [8]. As a result, much of the secondary-dominated portion of the SFD is not represented in the observed SFD.

Figure 2 shows the evolution of the fraction of secondary craters with time. The fraction of secondaries large enough to be considered in crater counting is fairly low for features younger than ~1 to 100 Ma. For features older than a few Ga, however, the number of km scale secondaries becomes comparable to the number of primaries. This generally agrees with the observations of Shoemaker (1965) [1] who found that the crossover diameter in Mare Cognitum was between 300 m and 1 km. It is important to note that *countable* secondaries (not at equilibrium) do not greatly exceed 50% of the total SFD. This indicates that secondary contamination should result in crater count errors of less than a factor of a few.

Conclusions: 1) The crossover diameter between primary and secondary craters increases with time; 2) features younger than ~1-100 Ma are not significantly contaminated by field secondaries, while features older than a Ga may be; 3) Our results are in agreement with the observed abundance of 300 m to 1 km scale secondaries in Mare Cognitum [1]; 4) Crossover usually occurs at crater densities above equilibrium, so most of the secondary-dominated portion of the SFD is not countable.

This methodology can be applied to other bodies if the primary production function and secondary distribution per primary are known.

References: [1] E. M. Shoemaker (1965) *The Nature of the Lunar Surface,* 23-78. [2] McEwen et al. (2005) *Icarus*, 176, 351-381. [3] Werner et al. (2009) *Icarus*, 200, 406-617. [4] Neukum et al. (2001) *Chronology and evolution of Mars, 55-86.* [5] Williams et al. (2014) *Icarus,* 235, 23-36. [6] Speyerer et al. (2016) *Nature*, 538(7625), 215. [7] Soderblom et al. (1974) *Icarus*, 22, 239-263. [8] Hartmann (1984) *Icarus*, 60, 56-74.