THE POPULATION OF SECONDARY IMPACT CRATERS ON MARS. S.J. Robbins[1] and B.M. Hynek[1,2], [1]LASP, 3665 Discovery Dr., University of Colorado, Boulder, CO 80303, [2]Geological Sciences Department, UCB 399, University of Colorado, Boulder, CO 80309. stuart.robbins@colorado.edu

Introduction: Impact craters are the most ubiquitous exogenic feature on planetary surfaces in the solar system. They have innumerable applications, but one of their primary utilities is to model surface ages: if there are more craters per unit area on one surface, then it is older than another with fewer craters. This very basic method requires the assumption that the craters formed spatially randomly and stochastically with time. Unfortunately, secondary impact craters belie both these assumptions: They form in a geologic instant from cohesive ejecta blocks launched by a primary impact ("primary"), and while they may be spatially correlated with that primary, this is not always the case. Studies have suggested that, overall, the population of secondary impact craters ("secondaries") on Mars is greater than the population of primaries for crater diameters $D \lesssim 1$ km [*e.g.*, 1]. The study presented here tests that hypothesis by assessing the diameters at which secondaries start to dominate over primaries globally, and we extend this to show the dominance on a regional level, as well.

Crater Identification: The recent publication of a massive global crater database that is statistically complete for all Martian craters $D \geq 1$ km (approx. 385,000 craters) with an additional ~250,000 craters $D < 1$ km [2] forms the base dataset for this work. It is used in conjunction with THEMIS Day IR global mosaics (≫99% coverage, 100m/px [3]). The database's craters were searched multiple times for those that appear to be morphologically distinct secondary craters (*e.g.*, Fig. **1**). Secondaries were craters identified by the following characteristics [4-7]:

- tightly clustered relative to surrounding craters,
- part of a herringbone ejecta pattern,
- entrained within a much larger crater's ejecta,
- and/or are highly elongated with one major axis end being shallower than the other end.

Fig. **2** shows the non-uniform contamination of secondary craters across Mars.

A caveat for this method is that it very likely under-estimates the true population of secondary craters because, by their nature, we cannot distinguish between primaries and "lone" secondaries that some argue form part of a global, background secondary crater population [*e.g.*, 1]. We also cannot recognize if secondary craters start to dominate for crater diameters <1 km because the crater catalog is not complete for those craters globally (though is in some locations).

Another factor that contaminates our results are crater clusters formed by an impactor breaking up soon before impact because these can display morphologies very similar to secondary crater clusters [8]. However, while this is a contaminant, we argue these kinds of crater clusters are themselves an additional contaminator of the primary crater population because, like secondaries, they form in a geologic instant and are tightly clustered spatially; they should also be a spatially random contaminant, unlike secondaries. Ergo, their removal – or estimate of what crater would have formed from an intact primary – would also be necessary for applications of primary craters such as age-modeling.

Analysis: To determine a "global" value for the dominance of secondaries, two cumulative crater size-frequency distributions (SFDs) were calculated – one for primaries and one for secondaries. If the secondaries' SFD intersected and grew larger than the primaries' at any diameter, that would be considered the transition diameter. To calculate this on a more useful regional basis, a 500, 1000, and 1500 km moving radius from every center of a 1°×1° grid of the planet was taken and the craters within were analyzed in a similar manner.

Results: The global Mars results show that there is no intersection in the SFDs, so the population of secondaries did not dominate over primaries. They were approximately 25% of all $D \approx 1$ km craters, however, indicating significant contamination; though SFD slopes indicate the fraction may be 2× our estimate. We would need to have under-identified secondary craters by a factor of 4–5 for secondary craters to dominate over primaries for $D \leq 1$ km. We find they comprise only 1.5% of the $D \geq 5$ km crater population.

Fig. **3** shows the results of performing this analysis over a 1°×1° grid with a 500 km radius around each point. We performed the analysis for where secondaries match the primary population, where the onset diameter of secondary contamination is only 50% the abundance of primaries, and where it is 25% the abundance of primaries (alternatively: when 50%, 33%, and 20% of the craters per bin are secondaries). There are only four areas where the secondary crater population matches the primary crater population, and all are at $D \leqq 5$ km with most $\lesssim$3 km: the young, large Lomonosov and Lyot craters, north of Holden crater, and between Cryse planum and Valles Marineris.

Secondary craters reach 50% the population of primaries over more of the planet, and with a threshold of them equal to 25% of primaries, numerous "hotspots" of contamination are evident. With this threshold, there are regions where the secondaries are significant contaminators at the $D \approx 3$ km level.

Distribution-wise, Fig. **2** clearly shows that morphologically identifiable secondary craters are far from uniform (with the caveat that background "field" secondaries that look like primaries could not be detected). There also appears to be no correlation with unit type (*i.e.*, most young volcanic terrain showing contamination similar to older highlands), though broadly one could say that Amazonian plains are mostly devoid of contamination for $D > 1$ km except around Lyot and Lomonosov craters.

Discussion and Implications: Many researchers go by a broad "rule of thumb" that secondaries become important in Martian crater populations for $D \lesssim 5$ km. Ergo, for many applications where larger craters can be used, a cut-off of 5 km is made. What we have shown here is that this rule of thumb is generally accurate and that while secondaries may reach ~20% of the population of $D \approx 5$ km craters in a few areas, one may typically ignore their contributions for $D > 5$ km.

On the other hand, many researchers today use craters to date smaller features which require smaller diameter craters to have sufficient statistics for an age estimate. Our results show that one must be cognizant of secondary crater contamination because they can reach ~25% of the 1-km-diameter crater population over a broad range of the Martian surface2.

References: [1] McEwen & Bierhaus (2006) doi: 10.1146/annurev.earth.34.031405.125018. [2] Robbins & Hynek (2012) doi: 10.1029/2011JE003966. [3] Edwards *et al.* (2011) doi: 10.1029/2010JE003755. [4] Shoemaker (1962). [5] Shoemaker (1965). [6] Oberbeck & Morrison (1974) doi: 10.1007/BF00562581. [7] Robbins & Hynek (2011) doi: 10.1029/2011JE003820. [8] Popova *et al.* (2007) doi: 10.1016/j.icarus.2007.02.022. [9] Smith *et al.* (2001) doi: 10.1029/2000JE001364.

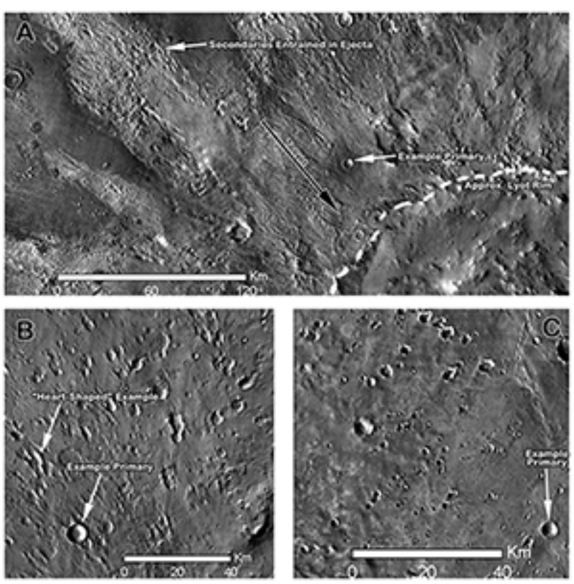

Figure 1: Examples of several different morphologies of secondaries that were identified (adapted from [7]).

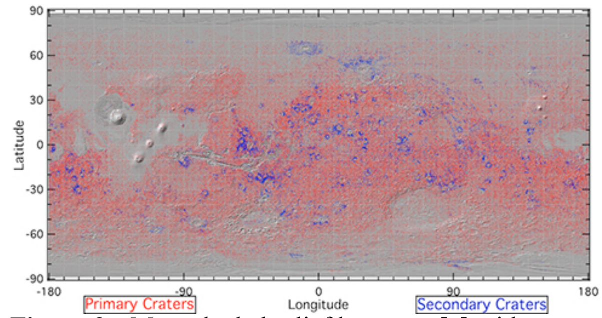

Figure 2: Mars shaded relief basemap [9] with craters with diameters ≥ 1.0 km from [2] overplotted as dots independent of crater size. Craters in red are those classified as primaries, craters in blue are those classified as secondaries.

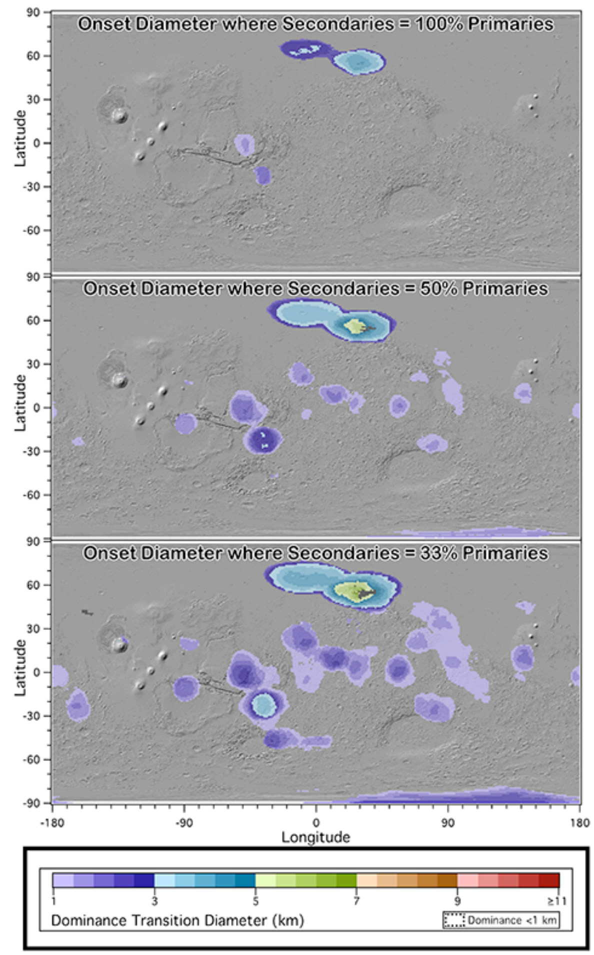

Figure 3: All craters in a radius 500 km from the center of each 1°×1° bin were extracted from the final database and plotted as CSFDs. If there was a diameter at which the secondary crater CSFD became greater than the primary crater CSFD, that was saved as the bin value (top row). If it reached half as much as the primaries, that was middle row bin value, and one-third as much was the value for the bottom row. This transition diameter is color-coded per the legend at the bottom, and bins where the primary crater population dominated throughout were left as empty (transparent).