REGIONAL INVESTIGATIONS OF THE EFFECTS OF SECONDARIES UPON THE MARTIAN CRATERING RECORD.

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Motivation: We consider the following paradox: if Zunil-type impacts can generate tens of millions of secondary craters on Mars approximately once every million years [1], then why do so many martian crater counts show so little isochronal evidence (e.g., [2]) of secondary “contamination”? We suggest three possible explanations for this incongruity:

(1) *Atmospheric Pressure Variations*: lower pressures at low obliquities may have facilitated massive secondary generation at the time of the Zunil impact; alternatively, higher pressures at high obliquities may have inhibited secondary cratering from other Zunil-sized impacts.

(2) *Target Material Strength*: Zunil impacting into a notably weak regolith may have augmented secondary crater production relative to similar-sized craters.

(3) *Surface Modification*: secondary craters from previous Zunil-sized impacts may have once been just as prominent as those emanating from Zunil, but have since been obliterated by rapid resurfacing over the past 100 Myr.

As part of a newly-funded MDAP, we will conduct regional investigations of secondary cratering to help distinguish amongst these three potential explanations.

Background: Impact craters currently provide the only mechanism for age dating planetary surfaces other than the Earth and Moon. Isochrons represent the predicted size-frequency distribution (SFD) of a crater population for a given surface age. To derive ages on Mars, lunar isochrons are scaled to account for the ratio of meteoroids at the top the martian atmosphere relative to the Moon as well as the relative differences in gravity and average impact velocity (e.g., [3]).

Secondary craters are generated by fragments of material ejected during a primary impact to form additional impact craters. The crater counts used to develop the isochron systems excluded any obvious secondary craters such as clusters and chains aligned radially with the primary crater [3]. However, high-velocity fragments can travel far from the primary crater to form isolated craters that may be indistinguishable from a primary crater. Large numbers of these background secondaries have been hypothesized to exist (see refs in [3]), but it remains unclear how and if such background secondaries contribute to observed crater SFDs.

Several studies (e.g., [1,4]) have presented compelling evidence that secondary craters are likely to be numerous on planetary surfaces and may even predominate at small sizes—for example, Prieblich *et al.* [5] estimated that Zunil, which is likely the youngest $D \sim$ 10 km impact on Mars, produced approximately 100 million secondaries greater than 15 m in diameter.

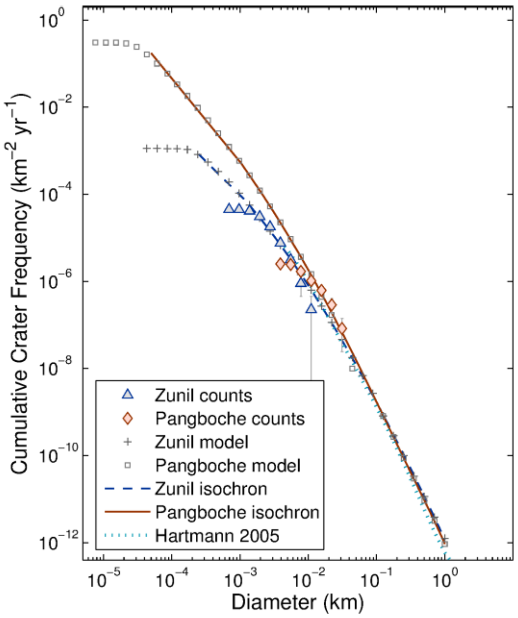

Figure 1. Modeled annual SFDs for the locations of Zunil and Pangboche craters and isochrons derived from polynomial fits. The crater counts from the two locations are scaled to the same time/area for comparison with the annual isochrons.

Yet, somewhat contradictorily, numerous other studies have shown that fitting crater counts to predicted isochrons remains a robust method for dating surfaces [2,6,7], thereby implying that secondary craters should NOT be a significant contribution to the overall crater population. These latter results are strongly supported by our recent Monte Carlo modeling [8] that generates primary-only crater isochrons assuming impactors with the observed mass distribution of terrestrial bolides and encounter velocities appropriate for Mars. We conclusively demonstrated that small ($D <$ 100 m) primary-only crater populations are consistent with observed crater SFDs on Mars [8].

Mars Test Cases: Zunil and Pangboche Craters. For example, our model of primary crater production fits the *Hartmann* [3] isochrons for Mars remarkably well at Zunil [8]. The crater Zunil (7.8°N, 166.1°E) was studied because it is likely the last $D \sim$ 10 km scale crater to form on Mars, with an estimated age of ~1 Ma [1,2]. Hence the distribution of small craters on its proximal ejecta should be relatively free of distant secondaries originating from other craters. Crater counts were conducted on a ~5 km^2 area north of the crater rim. Fig. 1 shows that our modeled SFD, which accounts for an atmosphere with a surface density appropriate for an elevation of -2.8 km, overlaps with the *Hartmann* [3] 1 Ma isochron scaled to an annual SFD.

Note that the rollover in the model SFD due to atmospheric filtering (*D*~20 cm) occurs at diameters smaller than the rollover observed in the crater counts (*D*~2 m) resulting from the resolution limits (25 cm pix^{-1}) of High Resolution Imaging Science Experiment (HiRISE) images—although a reduction of slope due to the influence of the atmosphere is apparent for $D \lesssim$ 100 m. The consistent deviation from a power-law evident in both the model results and crater counts shows that our atmospheric model correctly captures the energy loss of impactors, and is consistent with the atmospheric model that has been incorporated into the *Hartmann* [3] isochrons.

We also generated model isochrons [8] to compare with crater counts conducted on the floor of Pangboche crater (17.2°N, 226.7°E), which lies near the summit of Olympus Mons at an elevation of 20.8 km with a diameter comparable in size to Zunil of 10.8 km. Pangboche lies at an elevation over two scale heights higher than Zunil with an atmosphere surface density an order-of-magnitude lower. Interestingly, Pangboche has characteristics similar to younger lunar craters [9], including impact melt deposits on the crater floor, which has been attributed to the thinner atmosphere and lack of volatiles in the basaltic target [10,11].

Crater counts conducted on the impact melt deposit on the floor of Pangboche (Fig. 2) yield a crater retention age of 63.3 Ma using the *Hartmann* [3] isochrons; using our isochron model from Zunil we derive a similar age of 70.4 Ma. However, if we model our isochron accounting for Pangboche's higher elevation / thinner atmosphere, we derive an age of 35.1 Ma (Fig. 2). Comparison of the two model isochrons reveals a greater downward curvature due to the greater atmospheric influence upon impactors at Zunil, **resulting in a factor 2 difference in age when accounting for the variations in atmospheric density [8].**

Our Monte Carlo simulations that we have run thus far do not incorporate the effects of secondary cratering, yet our sample cases produce excellent fits to martian isochrons (Figs. 1,2). These results are consistent with crater counts of the floors or ejecta of numerous recent martian craters (dating back to 30 Ma and 60 Ma, respectively) that show their fidelity to martian isochrons [2,7]. Therefore, we conclude that secondary cratering has not had a significant effect upon the observed size frequency distribution of most martian surfaces for the last 50+ Myr [8]. However, this conclusion is difficult to reconcile with the aforementioned evidence for abundant secondary craters [1,4].

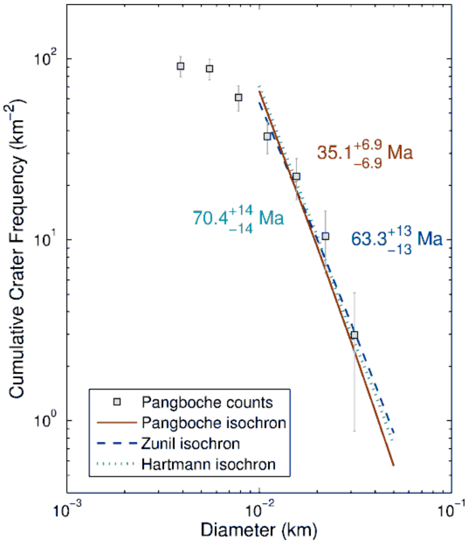

Figure 2. From [8]. Pangboche crater counts with age estimates using *Hartmann* [3] isochron, our -2.8 km elevation model isochron, and our 20.8 km elevation model isochron. Data is binned in √2 diameter bins and ages estimated using the Craterstats2 tool [12].

Regional Variations. In order to examine these isochronal incongruities further, we have begun a comprehensive exploration of secondary cratering on Mars to assess the effects of secondaries upon the martian cratering record. We will ultimately map the size/distance relationship of secondary crater fields from the 20 youngest large craters in each of the following regions of interest (ROI): Elysium Planitia, Tharsis Montes, and Terra Cimmeria. We will then model the size/distance relationship of secondaries from each of these 20 young large craters, exploring factors that might affect secondary generation / preservation (i.e., (1) - (3) above). Lastly, we will eventually integrate the 20 separate simulations into a combined regional Monte Carlo model of secondary crater production and modification in order to predict the extent of likely secondary "contamination" across the ROI.

For the current abstract, we will present the initial results of our regional analysis for the Elysium ROI, focusing on mapping and modeling of secondary cratrer fields from large young primary craters.

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