# DISTANT SECONDARY CRATERS AND AGE CONSTRAINTS ON YOUNG MARTIAN TERRAINS.

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**Introduction:** Are small (less than ~1 km diameter) craters on Mars and the Moon dominated by primary impacts, by secondary impacts of much larger primary craters, or are both primaries and secondaries significant? This question is critical to age constraints for young terrains and for older terrains covering small areas, where only small craters are superimposed on the unit. If the martian rayed crater Zunil [1] is representative of large impact events on Mars, then the density of secondaries should exceed the density of primaries at diameters a factor of ~1000 smaller than that of the largest contributing primary crater. On the basis of morphology and depth/diameter measurements, most small craters on Mars could be secondaries. Two additional observations (discussed below) suggest that the production functions of Hartmann and Neukum [2] predict too many primary craters smaller than a few hundred meters in diameter. Fewer small, high-velocity impacts may explain why there appears to be little impact regolith over Amazonian terrains. Martian terrains dated by small craters could be older than reported in recent publications.

Many craters are obvious secondaries, closely associated with the primary crater and with distinctive morphologies such as shallow, irregular shapes and occurrence in chains and clusters, sometimes with distinctive herringbone patterns [e.g., 3]. However, there has been a longstanding controversy about the relative abundances of small primaries versus distant secondaries on the Moon. Distant secondaries produced by high-velocity ejecta fragments are more circular and isolated than the obvious secondaries near the source crater, and are therefore difficult to distinguish from degraded (shallow) primaries. Shoemaker [4] hypothesized that there may be enormous numbers of these distant or background secondaries.

**Crater Production Functions:** Hartmann and Neukum [2,5,6] have published model production functions (HPF and NPF) for craters on Mars. Both of these models are based on the assumptions that (1) objects striking Mars over time have the same size-frequency distribution as objects that cratered the moon [7] and (2) small craters on the Moon and Mars are dominated by primaries. Many recent studies have compared crater counts to the HPF or NPF, concluding that some lava flows, flood channels, landslides, and lobate debris aprons have very young ages, less than 10 Ma. Furthermore, the absence of impact craters superimposed on some terrains at high latitudes suggests ages of less ~0.2 Ma [8,9]. These interpretations have garnered much attention because they suggest that fluvial and volcanic activity and climate change occurred in the very recent geologic past, perhaps correlated with the most recent cycle of high obliquity [10]. However, age constraints based on small craters must be reconsidered if secondary craters dominate the population.

**Zunil:** This 10.1-km diameter crater in the young volcanic plains of Cerberus has rays of secondary craters extending up to 1600 km from the primary [1, 11]. This is the first discovery of a large rayed crater on Mars, similar to rayed craters like Tycho on the Moon. Zunil provides a well-preserved example of a primary crater with enormous numbers (~$10^7$) of distant secondary craters. There are few secondary craters within ~16 crater radii; they were almost all formed at greater ranges. There are almost none of the "obvious secondary craters" that are routinely excluded from crater counts for age dating.

A simulation of a Zunil-like impact [1, 12] ejected ~$10^9$ rock fragments capable of forming distant secondary craters ≥10 m; many rocks would escape Mars and could become Martian meteorites found on Earth. According to the simulation, ~70% of the craters larger than 10 m in diameter form at distances of 800 to 3500 km, whereas most craters larger than 50 m form within 800 km of the primary.

Is the number of secondary craters produced by Zunil unusually high? From the spallation model of Melosh [13,14] we expect impacts into competent targets with little regolith to produce the highest number of distant secondaries. The Cerberus Plains, the youngest large-scale lava plains on Mars, should be ideal terrain for the production of distant secondary craters. However, the regolith layer is considered unimportant when thinner than the projectile radius, so a 200-m-radius projectile (producing a 6.7 km crater in the simulation of [14]) would be insensitive to a regolith layer thinner than 200 m. Therefore, craters larger than just a few km should not be affected by the comparatively thin regolith over Hesperian and Amazonian terrains. We cannot rule out the possibility that the number of secondaries produced by Zunil is typical of impacts into lava plains of Hesperian or Amazonian age, or from large (>100 km diameter) craters over any terrain. Completing Shoemaker's study (from telescopic images) of secondaries from Tycho, which impacted in the lunar highlands, may be the best way to confirm that $10^7$ secondary craters from a single primary impact is not unusual.

**Most small Martian craters may be secondaries:** If Zunil is close to typical, distant secondaries alone could account for the numbers of small craters predicted by the NPF. If Zunil produced an unusually large number of secondaries, most small craters on Mars could nevertheless be secondaries if the production of small primary craters is significantly less than predicted by the NPF. Other evidence [1] is: (1) Most small craters near the Pathfinder landing site appear to be secondaries. (2) Measurements of 1300 small craters over Gusev crater and Isidis Planitia show that they have depth/diameter ratios of ~0.11 or less, consistent with lunar secondary craters and much shallower than expected for primaries. (3) The fine-layered deposits on Mars can be billions of years old yet erode fast enough to remove almost all small craters if the cratering is strongly clustered in time from secondary cratering.

**Mars may have fewer small primary craters than predicted by the HPF and NPF:** This conclusion is inescapable if most of the small craters on Mars are, in fact secondaries, because there are few, if any, published crater counts that show more small craters than predicted by the NPF or HPF. Two additional lines of evidence are: (1) The regolith thicknesses at past landing sites and over most Hesperian terrains appear to be far less than predictions from the HPF/NPF, suggesting that craters smaller than ~60 m form less often than predicted by these functions. (2) Age estimates on two large (23 and 29 km) craters, based on the HPF and NPF for small craters, suggest highly improbable events in the last 100 Ka. Alternatively, the production functions predict too many small primary craters. Atmospheric filtering or eolian processes cannot adequately explain the deficit (relative to HPF/NPF) of small primary craters, so the deficit probably reflects the true size distribution of small bodies ejected from the asteroid belt that cross the orbits of Mars and Earth. Recent modeling by Bottke et al. [15] supports this conclusion.

**Implications for Age Constraints on Young Surfaces:** Concerns about the origins and modification of small craters has led some investigators to avoid using craters smaller than ~1 km for age constraints [e.g., 16, 17]. However, there are very few if any craters larger than 1 km on the youngest Martian terrains, which are of great interest for the study of recent geologic activity or climate change, and we currently have no other way of estimating ages unless rates of change can be directly observed. The diameter at which secondaries start to dominate (Dc) must usually become smaller for younger terrains, so we can potentially date younger terrains (age constrained to first order by craters > 1 or 2 km) using craters smaller than 1-2 km, if a large and younger primary crater is not identified within a few hundred km. We modeled Dc as a function of the largest primary crater contributing secondaries, which corresponds approximately to the time-stratigraphic units of Tanaka [18]. We also calculated the diameters at which primaries are ten times as abundant as secondaries, which provides a reasonable "safe" limit for dating surfaces: 1600 m and 1200 m for the Early and Late Hesperian, respectively; 840 m and 420 m for the Early and Middle Amazonian, respectively. The calculations suggest that we could rely on craters smaller than 300 m on Late Amazonian terrains (except those near a large and younger primary crater), but we submit that the production function for primary craters smaller than ~300 m is poorly known, so 300 m is our suggested minimum crater size for chronology. (How well the production function is really known at larger diameters is a matter of continuing debate, but the published models generally agree to within a factor of 2 to 3.)

What is the maximum age we can assign to terrains free of any craters larger than 300 m? We expect the number of primary craters ≥300 m/km$^2$/Ma to be ~3.5 x 10$^{-5}$ via both NPF and HPF over the past 3.4 Ga. Therefore, the maximum cratering age is a function of the area of a crater-free unit. For terrains covering ~10$^2$ km$^2$, like sets of gullies and debris aprons within a large crater, the upper age limit is ~300 Ma, greater than the few Ma upper limit suggested by Malin and Edgett [19]. Mustard *et al.* [8] stated that the absence of craters larger than 100 m on the mid-latitude debris mantle indicates a maximum age of 0.15 Ma *via* the HPF. Recalculating based on the absence of craters larger than 300 m increases the maximum age to 10 Ma. If we assume a power-law slope of -3 for craters from 0.3-1 km diameter, then the maximum age increases to ~30 Ma. Since many gullies cut this debris mantle, their age limit is also ~10 to 30 Ma. There has been geologically recent activity and climate change on Mars, but we cannot justify correlations with very recent (order 10$^5$ yr) obliquity cycles [10] given our current state of understanding.

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