The effect of secondary craters on surface ages derived from impact craters. E. B. Bierhaus[1], [1]Lockheed Martin Space Systems Company (edward.b.bierhaus@lmco.com).

Introduction: Primary craters – caused by the direct impact of asteroids or comets onto a solid surface – eject chunks of that surface, often at sizes and speeds sufficient to make "secondary" craters. The realization that secondaries reside within the primary crater population first occurred during the intense scrutiny of the Moon leading up to the Apollo program [e.g. 1]. Since that time, the number of secondaries, their distribution, and their effect on an impact-based chronology has been in debate [a recent sampling includes 2-7].

This topic has received significant attention especially in recent years because of the new wealth of high-resolution imagery from a variety of planetary surfaces. These image data enable measurement of craters at sizes for which secondaries are abundant (i.e. less than a few km), as well as mapping of small geologic units. The small geologic units often do not bear the imprint of large craters, and so researchers must turn to small craters to derive ages – yet it is these crater sizes at which the contamination from secondaries is most problematic. Key questions include: (1) How do secondary populations vary between different surfaces on the same body, and between solar system objects? (2) Are there cases when the accumulation of primaries+secondaries preserves accurate chronology? And if so, are those cases present in the image data?

Secondary Populations: Secondary crater populations are conveniently, if crudely, divided into two basic populations: adjacent and distant secondaries. Adjacent secondaries form a dense annulus of craters around their parent primary out to a few parent-crater radii; distant secondaries can be globally distributed, and are either clustered or spatially random [3]. The spatially-random secondaries are also known as "background" secondaries.

Different researchers take different approaches when accounting for the presence of secondaries in the crater population. The Neukum [e.g. 8] and Hartmann [e.g. 5] chronologies seek to exclude "obvious" secondaries from their measurements, where "obvious" secondaries include adjacent secondaries and clustered secondaries. This approach requires that the ongoing accumulation of primaries and background secondaries preserves accurate chronometric information. A second approach is to avoid altogether using small craters, below some certain size, to derive surface ages. This approach considers secondaries as complicating at best, or eliminating at worst, the chronological value of the observed small crater population. The appropriateness of a given approach depends on the number and distribution of secondaries relative to the primaries.

Crater and Ejecta Scaling Laws: Crater sizes and ejecta properties are well described by scaling laws [e.g. 9,10], which are quantitative relationships between impactor properties, target properties, and the resulting crater size. Scaling laws apply to the question of secondaries in (at least) two ways:

(1) They quantify the relationship between impact speed and surface gravity on the resulting primary crater. A single-sized impactor will make a different-sized primary crater given different impact speeds and target surface gravities. This difference is modest between, e.g. the Moon and Mars, but is rather significant between the moons of the outer solar system. The different-sized primary crater affects not only the resulting crater size-frequency distributions (SFD) expressed on the surface, but also effects the amount of ejecta launched that can create secondary craters, because ejecta volume goes as D^3.

(2) They describe the velocity distribution of material ejected from the primary crater as it forms; this ejected material is the source of secondary craters. For a given-sized impactor, a higher impact speed will not only make a larger primary crater, it will also result in a broader range of ejection velocities.

Given a single-sized impactor, key values include impact speed, target surface gravity, target mechanical strength, and target escape velocity. The target mechanical strength is important to understand the formation of small craters, which includes both primaries and secondaries. For secondaries in particular, target strength controls v_{min}, which is the minimum speed necessary for a chunk of ejected material to make a secondary crater rather than land as a discrete block [11]. Observations of ejecta around small lunar craters find ejecta blocks [12,13], whereas ejecta around large craters [e.g. 14] generate secondary craters. There is a transition size at which the distance between ejection location and deposition becomes sufficiently far, and require a high-enough ejection velocity, that the block makes a secondary.

Relative magnitude of secondaries across the solar system. The number of secondary craters generated by a primary impact is a function of the size of the primary crater, v_{min}, and v_{esc}, where v_{esc} is the escape speed of the target body [see 11,15]. The primary crater size controls the amount of ejected material, v_{min} defines the lower-limit of that ejected mass that can make secondaries, and v_{esc} defines the upper-limit of the mass that can make secondaries (i.e. material that escapes the target body cannot make secondaries). Figure 1 illustrates that a single-sized impactor will generate different secondary crater populations on different surfaces: a 1 km asteroid will make many more secondaries on Mercury relative to Mars; a 1 km comet will make many more secondaries on Europa than on Pluto.

Spatial distribution of secondaries. Because of varying surface gravities of planetary bodies, a given ejecta speed will launch a fragment different distances. In conjunction with v_{min}, the spatial density of adjacent secondaries, or even their existence, will vary depending on surface gravity. Figure 2 plots the minimum range to secondaries, from a primary, assuming a constant v_{min}=150 m/s. In reality v_{min} will vary between objects (e.g. rocky vs. icy bodies), but the general outcome remains the same. Higher-*g* objects will have adjacent secondary craters around (larger) primaries; at progressively smaller *g*, v_{min} results in greater distances, and dense annular clusters surrounding the primary won't appear, except for the largest primary craters. On the lower-*g* objects, v_{min} corresponds to travel distances that are significant fractions of the object's circumference. Ejecta that makes adjacent secondaries on a higher-*g* object may make a significant population of background secondaries on low-*g* objects.

Discussion: Simple combinations of impact speed, surface gravity, and escape speeds lead to significantly different secondary populations. Further variation occurs when considering differences between material properties – which aren't always uniform across a single body (e.g. fresh lava flows vs. ancient cratered regolith on Mars). When coupled with different impact rates due to different source impactors (asteroids for the inner solar system, comets for the outer solar system), or even a distribution of impact speeds for the same object, the number of secondaries and their distribution varies significantly across the solar system.

What does this mean for a crater-based chronology? At a minimum, it demonstrates that the accumulation of secondaries, relative to the primary flux, will vary between objects, so that scaling a production function between, e.g. the Moon, Mars, and Mercury must consider not just differences in impact rate and surface gravity, but also the production of secondaries as well. In addition, considering background secondaries as part of the crater production function can be problematic because that assumes there is a "representative average" of background secondaries that generally acts like a steady-state accumulation of primaries. Because of the variables related to secondary-crater production, it is not at all clear this is a valid assumption. Any given small surface unit will have different distances to the most recent secondary-generating impacts, and we don't yet know how the density of background secondaries varies as a function of range from their source primary; and ejecta volume varies significantly between smaller increments in primary crater sizes, so surface units with ages coincident with larger impacts could have many more secondaries. Observations of the direct impact rate on Mars [16] find rates below those predicted by production functions, suggesting that the inclusion of secondaries in the production function overestimates the impact rate of small objects.

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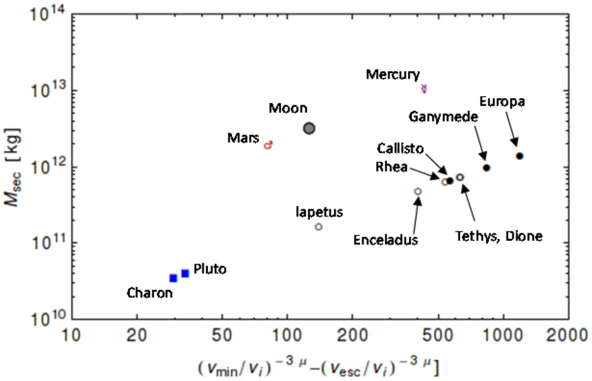

Figure 1. The amount of mass available to make secondaries, given a single-sized impactor (see [15] for details). The impactor is a 1 km asteroid for the rocky surfaces, and a 1 km comet for the icy surfaces. The rocky surfaces and icy surfaces follow different trends due to the different surface response (and to a lesser degree, the different density of the impactor).

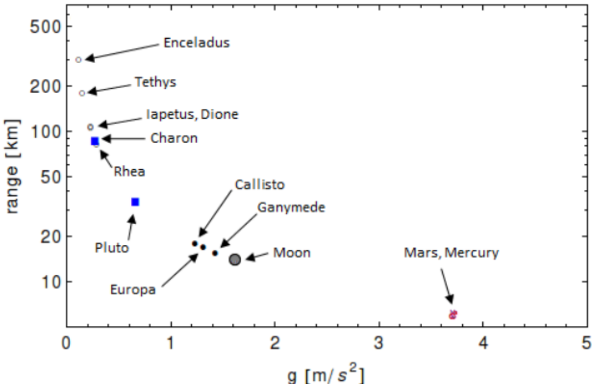

Figure 2. Range to the closest secondary, assuming a constant v_{min} = 150 m/s. See text for details.