CRATER MORPHOLOGY, MODIFICATION, AND PRODUCTION POPULATIONS: SOME CAUTIONS WHEN USING CRATERS TO DERIVE AGE ESTIMATES.

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Introduction: Impact craters display specific characteristics when they first form, although their morphologies vary depending on their size, the body on which they occur, and the local environmental conditions. For example, impacts into ice-rich targets produce features such are layered ejecta blankets and central pits which are rare or absent in craters forming on volatile-poor bodies. Craters are subsequently modified by the environment—such effects can range from topographic relaxation in ice-rich targets (i.e., icy satellites, Mars) to deposition and erosion by surface geologic processes (volanic, tectonic, aeolian, fluvial, and/or glacial processes). The influence of the local enviromment on crater morphology and modification are reflected in the resulting crater size-frequency distribution curves and need to be considered carefully when interpreting ages derived from crater density analyses.

Pristine Craters: Investigation of pristine craters on planetary surfaces as well as craters produced by large chemical and nuclear explosions on Earth provide the general characteristics of fresh crater morphology [1]. Impact craters are formed in three stages [2]. During the contact and compression stage, the impacting object transfers its energy to the target, which forms the crater during the excavation stage. Transient crater diameter, crater depth, upraised rim, and ejection of material to form the ejecta blanket are established during the excavation stage. Formation of central peaks or pits and collapse of oversteepened walls to create wall terraces occur during the modification stage, along with any subsequent longer-term crater modification by external processes.

Laboratory experiments, hydrocode modeling, and studies of impact and explosion craters have revealed relationships between transient crater diameter and crater depth, crater volume, rim height, central peak diameter, ejecta distance, etc. [3-5]. However, environmental conditions can affect these relationships. For example, the simple-to-complex transition diameter (D_{sc}) scales inversely with the surface gravity of the body [3], but also is influenced by the target material [6, 7]. As a result, D_{sc} can vary even across a single body, as is the case for Mars where near-surface ice at higher latitudes reduces D_{sc} by about a kilometer from the value at the drier lower latitudes [6]. Depth-diameter relationships also are affected by target properties, as evidenced by very different equations for the icy satellites [7] in comparison to the inner solar system [8]. Thus morphometric relationships can vary considerably, even for pristine craters on different terrains on the same body.

How do we distinguish a pristine crater from one slightly modified? Most researchers use a combination of crater depth, rim height, and presence of ejecta and interior morphologies to distinguish a pristine crater [9, 10]. But new craters forming in different target materials can vary in appearance and morphometric properties such that pristine craters in some target materials do not follow the standard relationships between crater diameter and other parameters. In the case of Mars, the presence of visible or thermally-distinct rays can be used to identify craters that formed relatively recently, but these rays do not form on all terrain and are erased more rapidly in some materials than in others [11]. The distinction between a pristine and a slightly modified crater is not a major concern in many cases related to crater-derived age dating, but the effects of target material on crater morphology and morphometry do need to be considered when selecting the craters to be used in age-dating analyses. This is particularly true when using small craters, where target strength properties dominate the mechanics of crater formation, or when trying to distinguish primary from secondary craters based on crater morphology and morphometry.

Crater Modification: Crater modification occurs by a variety of mechanisms, including removal of small craters by seismic shaking, relaxation of larger craters in ice-rich target materials, and erosion/burial of craters by various geologic processes. The magnitude of these modification processes varies among different solar system bodies and even between different regions on the same object. For example, Mercurian craters have been modified by volcanism, tectonism, and cratering process, whereas these processes as well as fluvial and glacial modification have affected Martian craters. Because crater depth is proportional to crater diameter, smaller craters are more easily removed from the cratering record through infill and burial.

Using crater size-frequency distribution (SFD) analysis to estimate the age of a surface requires that only craters superposed on that surface be used in the analysis. This is where a careful inspection of each crater is necessary to determine whether that crater post-dates or pre-dates the surface to be dated. Inclusion of craters which formed prior to the surface will produce an age which is older than the actual surface. This is one reason why crater databases compiled using automated systems often yield inaccurate results—

these systems typically map all circular features as craters but provide no information about whether a particular crater is embayed. The result is an average age of younger and older surfaces sampled by craters of different sizes.

Resurfacing resets the smaller crater population by burying the pre-existing population of craters with depths on the order of the thickness of the new surface. Evidence of resurfacing is seen by a shallower slope of the smaller-diameter crater curve on a SFD plot. Fitting the production and chronology functions to this segment of the crater curve provides an estimate of the timing of the resurfacing event (or in some cases, multiple events). However, not every small deviation from the isochron reflects a different resurfacing event. Identification of resurfacing events based on one or two points on a SFD curve are highly suspect. Consideration of the error bars help to resolve some of these issues, but other considerations, such as contamination from isolated secondary craters, need to be carefully evaluated.

Crater SFD Analysis: Not all of the downturn in the frequency of small craters on ancient surfaces can be attributed to erosion. There is accumulating evidence from both observation and dynamical modeling that the inner solar system has experienced two populations of impacting objects with very different size-frequency distributions [12]. The cratering record preserved on the heavily cratered regions of the Moon, Mercury, and Mars displays a multi-sloped SFD, unlike the approximately single-sloped SFD of younger terrains throughout the inner solar system. The multi-sloped SFD of heavily cratered regions (“Population 1”) is similar to the SFD of the main belt asteroids and is attributed to the Late Heavy Bombardment influx of projectiles into the inner solar system by gravitational resonance sweeping across the asteroid belt during migration of the outer solar system planets [12]. Population 1 impactors were deficient in projectiles that would produce craters less than about 70 km in diameter. Population 2 impactors, recorded on the younger surfaces of the inner solar system, display a single-slope (-3 differential slope) distribution function, consistent with the present-day SFD of inner solar system-crossing asteroids.

The realization that the SFD of craters on heavily cratered regions was different from that recorded on younger surfaces led to suggestions that the multi-sloped curve was due to saturation or erosion of the single-sloped SFD. However, the realization that non-saturated surfaces such as the lunar Orientale Basin displayed a SFD with the same multi-sloped shape showed that saturation was not the dominant cause [12]. The fact that heavily cratered regions of Mercury, Mars, and the Moon all display a similar multi-sloped SFD in spite of very different erosional environments revealed that not all of the downturn at the smaller crater diameters was the result of erosion [13]. Thus, deviation of the small crater SFD on ancient terrains from a single-sloped distribution function cannot be entirely attributed to erosion. This distinction between one versus two production populations also leads to much of the difference in ages obtained from the Hartmann versus Neukum chronologies [14]. It should be noted that the outer solar system satellites display very different crater SFD curves from the inner solar system—planetocentric and a higher percentage of cometary impacts may be responsible for the cratering record in the outer solar system [12]. In any case, the production functions for the Moon cannot be directly extrapolated to the outer solar system and thus age information derived from the lunar crater chronology function cannot be applied to this region. Production functions must be independently derived based on dynamical considerations of the impacting population(s) in this region [15].

Conclusions: The use of crater SFD analysis is the primary way of deriving surface age information. While the technique is well-established and provides reasonable ages for the bodies in the inner solar system, researchers need to be cognizant of the limitations of the technique when interpreting their chronology results. The uncertainties provided by error bars, contamination from unrecognized secondary craters, terrain effects on crater diameter, ensuring that craters used to date a surface actually post-date that surface, and use of the proper production function for the impactor population are all important considerations when interpreting the cratering record and deriving formation ages of planetary surfaces.

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