CRATER DATING OF GEOLOGICAL UNITS ON MARS: METHODS AND APPLICATION FOR THE NEW GLOBAL GEOLOGICAL MAP.

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Introduction: The renaissance of Mars exploration starting with Mars Global Surveyor (and still continuing) improved and broadened our understanding of Martian geology. Consequently, a revision of the Viking-based 1986/87 global geological map of Mars was required [1-3]. The new global geological map of Mars [4] records detailed observations and analysis of surface morphology, texture, and structure. However, the study of impact crater populations of geological units is also essential for relative and absolute age relations. Furthermore, crater statistics also aid in identifying and interpreting geological processes that reshaped the planet's surface. Estimates of the duration of erosional and depositional processes [e.g., 5] as well as the thickness of deposition [6,7] are determinable providing a level of both spatial and temporal detail to geological maps that was previously unavailable.

The main objective of this work is to detail a principal method as to how crater-based temporal relationships on Mars were determined and used in the identification of global geological units and the interpretation of the resurfacing history of Mars. We present: (1) descriptions of representative geological and stratigraphical "type locations" for geological units from the perspectives of both the mapper and the crater counter, (2) the identification of (degraded) impact craters, (3) the validation of the measured crater population for randomness [8], (4) a new scheme to visualize the resurfacing history of a geological unit, (5) the derivation of crater model ages using the software Craterstats [9], and (6) the interpretation of crater statistics and derived model ages. (See also [4] for description and application of a second, less-precise but globally complete methodology used in the global map.)

Crater counting methods: Crater counts were performed on HRSC and CTX data using the ArcGIS extension *CraterTools* [10]. Crater model ages from crater statistics were analysed with *craterstats* [9].

Identification of type locations: Determining crater model ages of geological units requires careful selection of the counting area. Defining type locations for regional units based on morphological and geological aspects is one task, whereas outlining areas suitable for age determinations is a different challenge. Our approach was to have mappers initially identified several potential crater-counting types areas of sufficient areal extent per unit. Those areas were refined by the crater counter, who identified most suitable counting area(s) for each unit. Availability of images as well as estimated number of craters to be analysed (old vs. young surface) determined the area size and image basis (HRSC vs. CTX).

Identification of impact craters: Recognising impact craters is not always straightforward. Multiple geological features can form near-circular landforms (e.g., volcanic craters, calderas, collapsed lava tubes, pseudo-craters, pit craters, sublimation pits, etc.). Misidentification of impact craters can also be due to unfavourable illumination conditions (e.g., conical hills may appear as circular depressions). Therefore, multiple datasets, including THEMIS IR day/night and MOLA, were employed to verify circular features--in particular, in regions where volcanic and tectonic processes, or the presence of subsurface ice, are prevalent surface modifiers. Buried, flooded, or exhumed craters also need to be identified and included in the crater statistics of geological units. However, if a portion of the rim of buried craters is not exposed, their diameters cannot be determined with accuracy. As a result, such craters were excluded from the dataset since they belong to an older, underlying unit.

Surface dating: The method for finding absolute crater model ages from measured crater populations has been described and elaborated in many papers [e.g., 11-13]. We used *craterstats* to derive and validate absolute model ages [9].

Validation of crater statistics: Crater counts need to be examined for secondary craters grouped in clusters often of similar diameters or are arranged in arrays (cf. herring-bone pattern)[e.g., 14,15]. Those fields of secondary craters have to be excluded from the counting area. Each of the crater counts made in the scope of the mapping project was tested for randomness using methods described by [8]. The analysis indicates where clustering is present in a crater population, and if present, at what scale it occurs.

Visualisation of resurfacing history: For the purpose of examining the resurfacing, it is useful to calculate, for example, the ratio r of the number of craters observed in the interval 5-16 km to the number that would be expected in that interval based on the N(16) value [N(16) represents the cumulative number of craters larger or equal to 16 km in diameter]. We also calculated similar ratios for N(2), N(1) and N(0.5), relative to N(5), N(2) and N(1) respectively. Where the ratio is 1, this indicates that the population conforms to

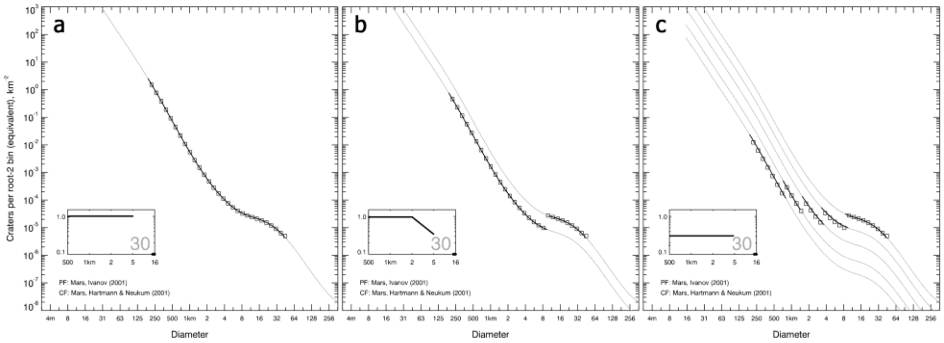

Figure 1: Differential crater count plots with inset resurfacing graphs for idealised populations a) corresponding to the production function, b) showing a single resurfacing event, c) showing multiple resurfacing events.

the production function. Where it falls below 1, resurfacing is indicated at that scale. For example, if *r*(2) is 0.1, 90% of N(2) craters have been erased relative to those larger than 5 km. A resurfacing graph is reduced in information compared to a complete crater plot but gives an at-a-glance impression of both the crater density and resurfacing history (Fig. 1).

Interpretation of model ages and discussion: Geodynamic processes such as volcanism, fluvial and aeolian sedimentation and erosion, and tectonics that reshape planetary surfaces will ultimately modify (or completely bury or erase) the existing crater population. Such processes are recorded in the crater size-frequency distribution measured on uniform geological units. Geodynamic processes forming regional-scale geologic units act on different timescales depending, for example, on latitude and altitude, topographic gradient, climatological conditions, provenance of material, and the presence of large craters/basins. Therefore, erosion, sedimentation, reworking, and redistribution within a geologic unit can be more progressed in one area than in another. The crater-counting method returns the age where a major geologic process (here prevalent on a regional scale) terminated, leaving a stable surface where impact craters accumulated over time. The onset of unit formation cannot be determined. The shape of the CSFD, however, reveals valuable information about the intensity of surface-modifying or resurfacing events. In some instances, conclusions can be drawn about the duration of a resurfacing event. Based on the crater size-frequency distribution inferences about the nature of resurfacing event(s) can be made such as short term surface modification (e.g., volcanic resurfacing), aeolian overprint affecting primarily smaller crater diameters, and gradual resurfacing due to continuous impact cratering.

From a set of potential type locations, 48 areas from 22 mapped units were suitable for crater counting. Through our consequently applied approaches in measuring crater populations, we achieved a consistency in model ages, which are coherent with the interpreted stratigraphy. In most cases, resurfacing ages were derived from crater statistics. Sometimes the resurfacing age was used to define the unit age rather than the base age.

Based on our model ages, for the first time in a map of Mars age assignments were included in unit names. However, we also clearly outline the limitations (see below) of using the crater-dating technique for this global mapping approach where compromises were made, for example, in selecting counting areas representing the unit's characteristic crater population versus selecting geologically homogeneous surfaces.

Surface dating from crater counts for regional geological units as performed in this study has limitations. There are several factors potentially contributing to erroneous results during the utilisation of the crater-dating technique: 1) surface heterogeneity at larger scales and the assumption of 2) consistent rates of sedimentation or erosion across (regional) geological units, 3) discarding surface details to meet mapping guidelines, and 4) inadequate selection of appropriate crater counting areas, identification of impact craters, analysis of resultant crater statistics, and interpretation of derived crater model ages.

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