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Title: Quantitative Assessment of Uncertainties in Modeled Crater Retention Ages on Mars

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Abstract

With increasing high-resolution coverage of Mars' surface, crater count analysis is being used to estimate the formative ages of small depositional features ($< 1000 \text{ km}^2$) to constrain timing of climate-driven events. We introduce a probabilistic cratering model that quantifies how modeled age estimates vary strongly with crater obliteration rates (β , defined as the combined rate of erosion and infilling), minimum crater diameter counted, and surface area size. Model results show that crater obliteration introduces significant uncertainty on small surfaces, where moderate obliteration rates ($\beta \sim 25 \text{ nm a}^{-1}$) require surface areas of about $10,000 \text{ km}^2$ to date 2 to 3 Ga surfaces accurately, and strongly obliterated surfaces ($\beta = 200 \text{ nm a}^{-1}$) require surface areas up to $100,000 \text{ km}^2$. In practice, smaller areas can nonetheless be analyzed probabilistically by estimating a range of likely obliteration rate and modeled age combinations and optimizing these values relative to observed crater count data, resulting in a distribution of possible modeled surface ages and associated β . We demonstrate this method using data from the Coprates Chasma landslide ($\sim 200 \text{ km}^2$) and numerous fan and delta deposits in the Gale crater region. Although the deposits in and around Gale are less than 1000 km^2 , a probabilistic analysis enables us to suggest that deltaic deposits in and near Gale have a higher probability of being older ($\sim > 3 \text{ Ga}$) than nearby fans ($\sim 1 - 3 \text{ Ga}$). This analysis provides a simple quantitative framework for assigning probable surface age ranges for small features on Mars.

1. Introduction

[1] Methods for determining absolute model ages of Martian surfaces using the observed size-frequency of craters have been developed and refined over the past several decades (Daubar et al., 2013; Hartmann, 2005; Hartmann et al., 1981; Hartmann and Neukum, 2001; Ivanov, 2001; Kite and Mayer, 2017). These cratering models, combined with superposition relations, are the main methods for assigning model ages for interpreting the geologic history of Mars (e.g., Tanaka et al., 2014), as ages derived from cosmogenic dating are currently limited to Gale Crater (Farley et al., 2014). Combining a chronology and crater production function, the spatial density of craters on a surface (i.e., number of craters of diameter d / surface area) can be compared to expected crater densities for surfaces of known ages (i.e., isochrons) to estimate the age of a surface (e.g., Hartmann, 2005, 1966; Michael and Neukum, 2010). However, erosional or infilling processes can erase craters from the surface (i.e., obliteration) (e.g., Chapman and Jones, 1977; Craddock and Maxwell, 1990; Golombek et al., 2014; Hartmann, 1966), possibly leading

to an apparent model surface age being less than the true age of the surface. Also, larger impacts will often destroy smaller craters, hence the term “crater retention age” in acknowledging post-formation obliteration effects (Hartmann, 2005; Hartmann et al., 1981; Hartmann and Neukum, 2001; Ivanov, 2001; Neukum et al., 2001; Robbins, 2014; Smith et al., 2008).

[2] Erosion and deposition processes change crater populations, often preferentially removing craters from the small-diameter end of the distribution (Hartmann, 1971; Kite and Mayer, 2017; Michael and Neukum, 2010; Chapman et al., 1969; Smith et al., 2008). Michael and Neukum (2010) describe a procedure for deriving model surface ages for regions that have experienced partial resurfacing events where a limited range of crater sizes have been removed (typically the smaller crater sizes). They note that the shape of the fall-off (or roll-off) curve from the crater size-frequency distributions can vary with time and resurfacing process, and these effects are compounded due to a combination of image resolution, erosional effects, and count fatigue (Robbins et al., 2014). Smith et al. (2008) developed a quantitative model to explicitly address how erosion and infilling affects crater size-frequency distributions and they show that low to moderate long-term erosion and infilling can make an ancient surface appear geologically young due to erasure of small-crater populations. Kite and Mayer (2017) also address small crater degradation, expanding on the range of processes that can lead to crater obliteration and find results that are qualitatively consistent to that of Smith et al. (2008). For larger diameter craters, Michael and Neukum (2010) suggest that, assuming a complete count, deviation of crater size-frequency data above the “best-fit” isochron is an indication of a non-random spatial distribution of craters within the study region, though the deviation must be statistically significant (Robbins et al., 2018a). These deviations can result from fragmented impacts from a single event or from secondaries that were not identified before counting.

[3] While these small and coarse tail effects can be problematic in general when assigning model surface ages, they are likely to cause especially large errors when attempting to date small surface areas. The smallest craters are susceptible to obliteration, image resolution, and count fatigue limitations, and dating surfaces using just a few large craters can lead to erroneously old model ages. But with the increase in high-resolution imagery of Martian surfaces (Malin et al., 2007; McEwen et al., 2007), smaller scale depositional features ($<1000 \text{ km}^2$) such as alluvial fans, deltas, landslide deposits, and valley networks are being discovered and dated, some into the Amazonian (e.g., Anderson and Bell III, 2010; DiBiase et al., 2013; Grant and

Wilson, 2011; Kraal et al., 2008a, 2008b; Moore and Howard, 2005; Morgan et al., 2014; Palucis et al., 2016, 2014; Palucis and Dietrich, 2014). These features are inferred to require the presence of liquid water, and as such, accurate dating would provide major constraints on the hydrologic and climatic history of Mars. And while it has been recognized that uncertainties in model surface ages on smaller areas are likely large due to the combination of chance sampling of the crater production rate (van der Bogert et al., 2015; Warner et al., 2015) and uncertainty in obliteration rates (Smith et al., 2008), the standard practice has been to simply ignore smaller craters that deviate systematically from an isochron and to ignore the few large craters due to poor statistics (e.g., Grant and Wilson, 2011; Robbins et al., 2011). From the remaining crater size bins, a model age is assigned based on the isochron with several crater size bins falling on it. Assigned error bars are a function of the spatial density of 1 km craters counted and the inverse of the square root of the total number of craters counted (" $1/\sqrt{n}$ uncertainty"; e.g., Michael et al., 2016). It has also been suggested that uncertainties be estimated using bootstrapping techniques, which are more statistically robust and there are no *a priori* assumptions about the data structure, which often imposes symmetric uncertainty (Robbins et al., 2018a). In either case, it is unlikely accurate model surface ages (and associated errors) are assigned to small depositional features (e.g. deltas and fans), where all crater sizes that are present are likely affected by erosion and infilling (Smith et al., 2008).

[4] To better define model age uncertainty, we have developed a simple, probabilistic cratering model, building on the work of Warner et al. (2015), van der Bogart (2015), and Smith et al. (2008), that specifically addresses the role of erosion and infilling when assigning a model surface age to small depositional features on Mars. This model quantifies the effects of surface area, crater size, and crater obliteration rates (β , following the convention of Smith et al. (2008), which is the combined rate of crater rim erosion and crater infilling) on model age estimates derived from crater size-frequency distributions, specifically focusing on determining the errors in model ages derived from areas ranging from 100,000 km² down to ~10 km². Non-obliterated cratered surfaces (i.e., surfaces where erosion and infilling are not considered) are addressed first, before considering how long-term β affect model surface age uncertainty. From this, a method for determining the most probable model surface age and β combinations for actual crater size-frequency distributions is described. This work is partially based on the growing interest in dating small-scale features such as alluvial fans and deltas (e.g., Grant et al., 2014), and as such,

this methodology is applied to Martian depositional features (i.e., a landslide and several alluvial fan and delta deposits).

2. Methodology

2.1 Model description

[5] In both the non-obliterated and obliterated cratered surface versions of the model, large surfaces (i.e., at least 10 times larger than subsampled surfaces; referred to as “parent surfaces”) were generated with crater populations defined by the Hartmann isochrons for Mars from ages of 3.7 Ga (Late Noachian) down to 0.5 Ga (Late Amazonian) (2004 iteration, Hartmann, 2005). We used crater diameters ranging from 16 m to 1024 km, where diameter was increased by 2^i km (i ranging from -6, -5.5, ..., 9.5, 10), following Hartmann (2005) binning. We did not investigate surfaces older than 3.7 Ga since resurfacing rates in the Early to Middle Noachian were high and crater size-frequency data from that period are considered suspect (e.g., Irwin et al., 2005). Importantly, for the model presented here, we assumed that the Hartmann model for crater size-frequency distributions (i.e., isochrons) are precisely known, invariable in time, and inherently account for crater obliteration due to other impacts, as larger impacts inevitably lead to the destruction of smaller craters (Hartmann, 1964). The center coordinates of each crater were assigned an x and y location using MATLAB’s random number generator. This ensured that craters of each size were randomly assigned locations over the entire area, as crater clusters from fragmented impactors or secondary impacts are typically excluded from counting areas (Michael et al., 2012). The only imposed constraint in setting up where craters were located on each generated surface was that all craters for a given age, as defined by Hartmann (2005), must be present. For example, for a 3.5 Ga surface that is 200,000 km², the Hartmann isochron dictates that there are 407 randomly distributed craters that are 1 km in diameter and 4 craters that are 10 km in diameter. No deviation was allowed from the Hartmann model, as we wanted to isolate the effects of erosion and infilling processes on assigning model ages of Martian surfaces. If two craters of the same size were assigned the same x and y location, we randomly assigned a new location for the second crater. Larger craters could not “destroy” smaller craters, as that would lead to exogenic obliteration effects that are already accounted for in the Hartmann (2005) size-frequency distribution. This ensured that when we performed a crater count analysis on our parent surface, the computed surface exposure age was exactly equal to the age we assigned the parent surface. The model is not a landscape evolution model, and as such it did not

evolve over time or consider regional topography. This model also did not try to reproduce any true physical processes, like fragmentation mechanics to generate secondaries. This allowed the model to remain computationally efficient, while still providing insight on the effects of erosion and infilling and sample area on model surface ages from crater size-frequency data.

[6] Parent cratered surfaces were then randomly subsampled over smaller and smaller areas ($10,000 \text{ km}^2$ down to 10 km^2), where the number of subsamples ranged from 100 to 1000 (only three outputs are shown in Figure 1a, for simplicity). The x and y coordinates for the upper left-hand corner of the subsampled area were chosen using MATLAB's random number generator, the only condition being that the entire subsample area fell within the large area. The crater populations contained within each sampled area were binned (root-2 binning; see Michael and Neukum, 2010), tallied (total number of craters with a given diameter divided by the subsampled area), and compared to Hartmann's 0.1 to 4.0 Ga isochrons (Figure 1b). All crater bin sizes were used to assign a model age to a subarea, except in the cases where we wanted to test how different crater diameter ranges influence resulting model surface age interpretations or when we ran the model in 'Monte Carlo' mode (see Section 2.2 for details). A model age for each subarea was assigned as the best fit between the crater size-frequency data from that subarea and a known isochron (at 0.1 Ga intervals), calculated by minimizing the root mean square error normalized to the spatial crater density. In almost all cases, cumulative crater size-frequency distributions are reported. We checked ~ 10 crater size-frequency distributions from each run to ensure that the model calculated subsample ages agreed within 0.2 Ga with those calculated using the CraterStats II software (Chronology system: Mars, Hartmann 2004 iteration; Chronology function: Mars, Hartmann (2005); Production function: Mars, Hartmann (2005); cumulative fit; root-2 binning), a standard tool for determining model surface ages from crater size-frequency data (Michael and Neukum, 2010). The resulting histograms of subsampled model ages were often not normally distributed (e.g., Figure S1). Therefore, median and interquartile surface ages were used to compare between different model parameters.

[7] To test the effects of obliteration of craters by erosion of their rims and infilling of their central depression we incorporated the model of Smith et al. (2008) into our probabilistic cratering model. Similar to Smith et al. (2008), we did not consider local oblitative processes, like basalt flows, which have been shown to uniquely affect the shape of the crater size-frequency distribution (Hartmann et al., 1981). The Smith et al. (2008) model is based on an

equation that balances steady production (number of craters per year) with a constant rate of obliteration (% craters per year):

$$N(t, d) = \frac{p(t, d)}{\lambda(d)} (1 - e^{-\lambda(d)t}) \quad (1)$$

where N (craters km^{-2}) is the abundance of the measured craters at time (t , Ga), p is the crater production rate (craters $\text{a}^{-1} \text{km}^{-2}$), and λ is the crater-loss function (a^{-1}), which is itself a function of β , the obliteration rate (defined in detail below) which is the combined rate of erosion and infilling (nm a^{-1}). N , p , and λ are all functions of crater diameter (d , in km). To ensure that results on obliterated surfaces could be directly compared with non-obliterated surfaces, the production function ($p(d)$), was taken to be the 2004 Hartmann distribution ($N_H(t, d)$) (Hartmann, 2005), divided by the surface age (t , Ga):

$$p(t, d) = N_H(t, d)/t \quad (2)$$

This results in a model that exactly reproduces the Hartmann distribution when β approaches 0. This production function differs slightly from the production function used by Smith et al. (2008), who assumed that the production function was constant over the past 3.5 Ga and used best-fit functions of Hartmann's data (2005) divided by 3.5 Ga. However, the differences do not significantly affect model results.

[8] The expression for λ is the ratio between β and the depth-diameter relationship for primary craters (ξ):

$$\lambda = \frac{\Psi\beta}{1000\xi}; \quad (3a)$$

$$\xi = \begin{cases} 0.2 d & d < 5.8 \text{ km} \\ 0.42 \ln(d) - 0.01 & d \geq 5.8 \text{ km} \end{cases} \quad (3b)$$

where ξ is based on a best-fit function of crater depths for fresh primary craters from satellite images by Pike (1980) and Ψ is a correction factor for incorporating secondaries, based on the modeling work of McEwen et al. (2005). The choice of depth-to-diameter is most important for

craters less than 1 km, which are the most likely to be erased from the geologic record due to erosion and infilling. Dauber et al. (2014) used craters ranging from 0.0025 to 0.055 km and found $\xi = 0.17d^{1.06}$, and Watters et al. (2015) looked at the deepest craters between 0.025 and 5 km and found $\xi = 0.223d^{1.012}$. For simplicity, we kept the Pike (1980) relation used by Smith et al. (2008), which predicts crater depths between the Dauber et al. (2014) and Watters et al. (2015) relations. Robbins et al. (2018b) provide a comprehensive summary of published work on these relations, most for craters >1 km, and note that the scatter for Mars is large due to terrain variations. Smith et al. (2008) acknowledge that the influence of secondary cratering is controversial, especially when used with the Hartmann production function, and therefore suggest that their model results should be taken as providing lower limits for a given β value (i.e., there may actually be more small craters on a given landform due to spatial heterogeneity of secondary production or secondaries constitute a greater fraction of small craters on Mars compared to the Moon (McEwen et al., 2005)). The correction for secondaries was therefore ignored in our application of the model (i.e., $\Psi = 1$), except when making direct comparison to results of Smith et al. (2008), where it is calculated as:

$$\Psi = \begin{cases} 1 + \frac{0.1225}{0.1225 + d^2} & d < 1.2 \\ 1 & d \geq 1.2 \end{cases} \quad (4)$$

[9] For the purpose of this paper, β values were varied between $10^{-5} \text{ nm a}^{-1}$ (effectively no erosion and infilling) and 400 nm a^{-1} . According to Smith et al. (2008), erosion and infilling rates almost an order of magnitude larger (i.e., $\beta > 1000 \text{ nm a}^{-1}$) likely occurred mainly in the Noachian (>3.7 Ga; Hartmann and Neukum, 2001). Global erosion and infilling rates across Mars, however, likely vary greatly depending on location and lithology. Smith et al. (2008) calculated β values in Gusev Crater to be 4.7 nm a^{-1} , where measured erosion rates were converted to β assuming that all eroded material was deposited within craters (Golombek et al., 2006a). Likely owing to its sulfate-rich composition (Arvidson et al., 2006), Meridiani Planum exhibited β values of 13.5 to 108 nm a^{-1} (Golombek et al., 2006b; Smith et al., 2008). We note that when Smith et al. (2008) sum estimated deposition rates for the MER landing sites with measured erosion rates (Golombek et al., 2006a), erosion accounts for $\sim 20\%$ of β .

[10] A model similar to the Smith et al. (2008) model was developed by Kite and Mayer (2017), but instead uses a power-law, where the power-law exponent of the crater size-frequency

distribution is used to identify erosional processes (e.g., diffusion, advection, resurfacing). The use of the Smith et al. (2008) model was chosen as it allows for modification of the Hartman (2005) isochrons consistent with observation (i.e., creating the pronounced crater roll-off for smaller diameter craters independent of crater measurement fatigue (Robbins et al., 2014), finite image resolution, and atmospheric screening (Hartmann, 2005)), without having to specify a specific geomorphic erosional process. Smith et al. (2008) also demonstrated their model's ability to reproduce roll-off curves for crater size-frequency data at Gusev Crater, Meridiani Planum, and a landslide deposit on the floor of Coprates Chasma.

2.2 Monte Carlo mode application to observed crater size-frequency data

[11] The model presented here was also used in 'Monte Carlo' mode to determine model surface ages and β values likely to produce observed crater size-frequency data of actual martian surface features. This was accomplished by generating parent surfaces over a range of ages (0.1 to 4 Ga, in 0.1 Ga increments) and β values (10^{-5} to 400 nm a^{-1} , in 5 nm a^{-1} increments) and subsampling each of them 1,000 times using an area equal to the surface area of the martian feature of interest (e.g., an alluvial fan or delta). For each subsample, a corresponding crater size-frequency distribution was generated, based on the craters within that area. Crater size-frequency data generated by subsampling the parent surfaces were then compared to crater size-frequency data from the martian feature of interest. Because we are comparing 'real' crater size-frequency data to model-generated size-frequency data, and the real data is inherently affected by crater measurement fatigue (Robbins et al., 2014), finite image resolution, and atmospheric screening (Hartmann, 2005) (not just erosion and infilling), we typically do not use the entire crater diameter range to compare the crater size-frequency distributions. In most cases we use crater diameters that are 0.125 km or larger, as these diameters are easily observable on CTX and HiRISE imagery. The martian surface feature was then assigned a probable model age and β value when the spatial density of craters (N) in a given size bin (i) for the model generated count matched the observed count (i.e., crater size-frequency data from the martian surface feature) in all size bins within 25% (i.e., $\frac{|N_{\text{observed}}(i) - N_{\text{modeled}}(i)|}{N_{\text{modeled}}(i)} < 0.25$ for all crater bins, i). The narrow value of 25% was chosen to make quantitative comparisons of assigned model ages for varying survey area sizes and crater diameters. This choice also resulted in the highest percent of correct matches when validating the model with synthetic crater size-frequency data from a range of known surface ages, areas, and obliteration rates (see Supporting Information).

2.3 Crater size-frequency data from martian features

[12] Crater size-frequency data for the Coprates Chasma landslide on Vallis Marineris was extracted from Quantin et al. (2004; Figure 11a, ID 38, note that ID is mislabeled in their figure). Cratering maps were generated for Gale Crater's entire wall and floor by mapping onto CTX imagery in ArcGIS using CraterTools software (Kneissl et al., 2011). Some secondary craters may have been included in the counts, but care was taken to avoid including obvious rays or clusters of craters. In general, the resolution of the CTX data (6 m/pixel) enabled minimum reliable detection diameters down to 35 to 60 m (Malin et al., 2007). Crater areas and diameters were then extracted for various depositional features around Gale Crater, including the Pancake delta (Palucis et al., 2016), and crater frequency plots were compared to isochrons. For the Peace Vallis fan, there was complete HiRISE coverage, such that the cratering maps were generated from HiRISE data. Our crater size-frequency data were nearly identical to those presented in Grant et al. (2014) for the Peace Vallis fan. For inferred alluvial fan and delta deposits in the Gale region (e.g., Di Achille and Hynek, 2010; Ehlmann and Buz, 2015; Hauber et al., 2013; Irwin et al., 2005; Palucis et al., 2016), we used the same methodology as that in Gale Crater, where crater size-frequency data were generated using CTX imagery and CraterTools software.

[13] Model MATLAB scripts to generate Figures 2, 5, 7, and 8, as well as the crater size-frequency data files (.diam) used as input for Figures 7 and 8, are provided as Supporting Information.

3. Results

3.1 Non-obiterated cratered surfaces

[14] In the absence of crater obliteration due to erosion and infilling (i.e., $\beta = 10^{-5}$), the cumulative crater size-frequency data for smaller diameter craters for each of our subsampled areas fell along the parent surface isochrons (Figure 1). This is expected, given the high densities per unit area for smaller crater diameters. However, even in this case of no obliteration, deviations from parent surface isochrons were apparent at larger crater sizes. For example, in Figure 1, we show a parent surface with a true age of 2 Ga sampled at 1,000 km² (only three areas are shown in Figure 1a). Craters with diameters smaller than 0.71 km fell on the 2 Ga isochron, while craters with larger diameters did not necessarily fall on the same isochron (Figure 1b). Nonetheless, the model assigned an age of 1.9 Ga or 2.0 Ga to each of the three crater size-frequency outputs shown in Figure 1b, because of the higher spatial density of small

diameter craters compared to somewhat deviant larger diameter craters. We note that, as explained in Section 2.1, the model assigns an age using the best fit between a crater size-frequency distribution and the Hartmann (2005) isochrons at 0.1 Ga intervals. Thus, when we say the model assigned an age of 1.9 Ga, the precision is ± 0.1 Ga. Each of the three examples in Figure 1b use the same sample area (1000 km²) on the same parent surface (area of 20,000 km²). The variation between individual sites illustrates how differences can arise by chance.

[15] Crater size-frequency data from modeled surfaces provided accurate model ages across a range of tested sample areas (10, 100, 1000, and 10,000 km²) and parent surface ages (1, 2 and 3 Ga) (Figure 2), provided that small enough craters were included or the sampled area was large (i.e., Figure 2d). The abscissa in each plot represents the smallest (minimum) crater diameter included in the regression to define the model age. Progressive points to the right record the calculated age when smaller craters are not included (i.e., the modeled age corresponding to 250 m is the model age based on craters only 250 m and larger). The number of craters used to assign an individual model age varies, but can be estimated from the Smith et al. (2008) model (which modifies the Hartmann isochrons to account for erosion) and the sample surface area (e.g., for a 1 Ga parent surface with no erosion and a 10 km² sample area (Figure 2a), ages are based on ~ 3000 craters with $D_{min} = 16$ m and ~ 1 or 2 craters with $D_{min} = 1$ km). As expected, for any known age, the smaller the tested sample area, the smaller the minimum crater diameter needed to be included to ensure an accurate model age (empirically, $\sqrt{\text{tested area}}/(\text{minimum crater diameter}) \gtrsim 200$). Where these small craters were not included, sample surfaces were assigned model ages that ranged over billions of years, spanning multiple epochs. This large range of assigned model ages was most pronounced at medium parent surface ages (e.g., 2 Ga). When only large minimum crater sizes were used, model surface ages were systematically overestimated, with the effect increasing with smaller sample areas. In these cases, returned surface ages were either 0 Ga (due to the fact that no craters of that minimum size or larger were in the count area) or the returned surface ages were systematically overestimated, suggesting that ages will have large uncertainty when the cutoff diameter is comparable to the surface area.

[16] An example of the consequences of not including small enough diameter craters is also shown in Figure 3, in which the range of modeled crater size-frequency ages obtained from 100 repeat subsamples is plotted against the known age of the parent material. For a 10 km²

sample area using 0.125 km as the smallest crater diameter, modeled ages corresponded to a range of parent surface ages of over 1 Ga (i.e., measured ages within the interquartile range of a parent surface age). This means that if crater size-frequency data collected with these parameters predicts a model surface age of 2 Ga, the surface may have a true age between about 1.5 and 2.5 Ga (even for the condition of no obliteration).

3.2 Obliterated cratered surfaces

[17] Model-generated cumulative crater densities at four β values ($\beta = 0, 10, 100$, and 1000 nm a^{-1}) (Figure 4) show that erosion and infilling processes will preferentially obliterate small crater sizes, causing modeled crater size-frequency data to ‘roll-off’ and lie below the isochron of the parent surface age. This results in model surface ages that are systematically younger than the true surface age. For example, crater size-frequency data from a parent 2 Ga surface, with an area of 1000 km^2 and a moderate obliteration rate ($\beta = 10 \text{ nm a}^{-1}$), was assigned a model age of only 0.5 Ga using a minimum crater diameter bin of 16 m. Surfaces with higher obliteration rates ($\beta = 10 - 100 \text{ nm a}^{-1}$) were assigned model ages of less than 0.1 Ga (the lowest age tested by the model).

[18] In contrast to the non-obliteration case, more accurate model surface ages were often obtained by omitting small crater sizes when assigning dates. For example, Figure 5 is the same plot as Figure 2, except now with a β value of 10 nm a^{-1} . Reasonably accurate model surface ages were calculated using 500 m as the minimum crater diameter with surfaces of 1,000 and 10,000 km^2 . To date smaller surfaces, smaller crater sizes must be used (e.g., a minimum crater diameter of 177 m for 10 km^2 surfaces and 250 m for 100 km^2 surfaces), but even then, assigned model ages spanned a range of more than 1.5 Ga for the middle 50% of modeled surfaces (i.e., the interquartile range of non-Gaussian distribution of ages). If these smaller craters are not used, the model age is greatly over-predicted.

[19] In Figure 6 the minimum surface area required to obtain an accurate model age is plotted as a function of the obliteration rate constant for three known ages (1, 2 and 3 Ga) of parent surfaces. We tested 17 possible surface areas that ranged from 10 to 100,000 km^2 (hence the kinks in the lines for each age). In addition, the minimum crater diameter used in assigning a model age is reported adjacent to the corresponding data point. Ensuring accurate dating of obliterated surfaces (i.e., 75% of modeled surfaces within ± 0.5 Ga of parent surface age) required surface areas larger than 10,000 km^2 for β values greater than 25 nm a^{-1} on surface ages

of 2 and 3 Ga, and as large as 75,000 km² surfaces for β values greater than 50 nm a⁻¹ (Figures 6 and S3). 1 Ga surfaces could be accurately dated with much smaller surface areas (i.e., less than 1,000 km² for β values up to 100 nm a⁻¹), as less time had passed for obliteration processes to act on these surfaces. In general, the greater the obliteration rate, the larger the minimum crater diameter that must be used to approach the actual date, which has been known, but hard to quantify (Michael and Neukum, 2010; van der Bogert et al., 2015; Warner et al., 2015; Williams et al., 2018). Older surfaces also required larger minimum crater diameters for accurate dating (e.g., for $\beta = 100$ nm a⁻¹, $D_{min} \sim 2$ km for 2 Ga and $D_{min} \sim 8$ km for 3 Ga). The overlap between the 2 and 3 Ga curves in Figure 6 is likely due to the fact that the 2 and 3 Ga isochrons (as defined by Hartmann, 2005) are closer together than the 1 and 2 Ga isochrons (in crater spatial density versus crater diameter space).

3.3 Assigning model age distributions to martian surfaces

[20] While Figures 5, 6, S2 and S3 offer insights into the minimal surface area and cutoff crater diameter to use for dating obliterated surfaces, they are difficult to apply in practice, since they require *a priori* knowledge of a surface's β value, which is generally not known and difficult to determine independent of the model, and a surface's age, which is what one is trying to determine. Additionally, a surface of interest may simply not be large enough to date accurately, given its true age and β value. An alternative approach is to use the cratering model presented here to generate a large number of test crater size-frequency data over a range of ages and β values and determine which of these crater size-frequency datasets most closely matches the observed crater size-frequency data (see Section 2.2 for details on how ages are assigned). This does not provide a single model age or β value for a surface, but results in a distribution of likely values. We illustrate the difference between more traditional crater count methods and our model for the Coprates Chasma landslide deposit, before exploring several more examples of our method in Section 3.4.

[21] Quantin et al. (2004) used crater count analysis to date the chronology of landslides in Valles Marineris, counting areas ranging from 3 km² to 5304 km². We will focus on a 2,000 km² landslide within Coprates Chasma (ID 38, where only 200 km² of the surface was used for dating), as this deposit was also re-analyzed by Smith et al. (2008) using their erosion and infilling model. Quantin et al. (2004) used MOC (1.5 to 12 m/pixel) and THEMIS (18 m/pixel) imagery to map craters and found most craters on the deposit had diameters between ~16 m and

~300 m. The craters were then binned by diameter in square root-2 diameter bins and plotted as a function of the number of craters per km². An exposure age of 400 Ma was assigned (where uncertainties were not explicitly reported, but authors suggest all ages are within a factor of 3, so 133 Ma to 1.2 Ga), based on the two largest crater size bins (i.e., diameters > 177 m) (Figure 7a, red line). They argue that the surface was not extensively eroded based on preservation of low relief grooves on the debris aprons (~30 to 60 m deep). Smith et al. (2008) fit the crater size-frequency data of Quantin et al. (2004) in which the combination of a β value of 54 nm a⁻¹ ($\pm$ 37 nm a⁻¹) and a ~3 Ga isochron age (uncertainties in age not reported) gave a best fit (Figure 7a, black dashed line). They suggested that the observed grooves could be preserved even with β values this large. This substantially older model age matched the chasm floor age, potentially challenging the chronology of landslides that Quantin et al. (2004) developed.

[22] Quantin et al. (2004) and Smith et al. (2008) each reported a single, very different, model age based on their assumptions about β values (and neither considered the effects of small areas). However, our model shows that a range of model surface ages and β values could produce the crater size-frequency data observed by Quantin et al. (2004). If the obliteration rate was indeed low to moderate (e.g., $\beta < 10$ nm a⁻¹), the model surface age Quantin et al. (2004) reported (400 Ma) would be expected to be quite accurate (i.e., within ~0.1 Ga; Figures 2 and 5, assuming a 100 km² surface is similar to a 200 km² surface). At a much higher obliteration rate (e.g., $\beta = 100$ nm a⁻¹), 1 to 3 Ga surfaces would be incorrectly assigned model ages of 0.5 to 1 Ga (interquartile range), even with the largest crater bins that Quantin et al. (2004) mapped (Figure S2, assuming a 100 km² surface is similar to a 200 km² surface). Smith et al. (2008) consider erosion and infilling (and report an old model age for the deposit), but they do not account for surface area effects. Applying our cratering model in Monte Carlo mode, it is also possible to compare modeled crater size-frequency data over a range of ages and β values (not just those presented in Figures 2 and 5), while considering the mapped surface area of the deposit.

[23] Figure 7b illustrates the strategy. The initial parent surface for each age and β combination was set to have an area of 10,000 km² (50x the area of the deposit of interest), where ages ranged from 0.1 to 3.7 Ga (incrementing every 0.1 Ga) and obliteration rates from $0 < \beta \leq 400$ nm a⁻¹ (incrementing every 5 nm a⁻¹, such that a total of 80 different β values were tested). While we used a maximum $\beta = 400$ nm a⁻¹, β was likely <100 nm a⁻¹ since if we assume that erosion accounts for ~20% of β (as estimated at the MER landing sites by Smith et al.

(2008)), then depths of erosion would range from negligible up to 20 m per Ga, potentially allowing for the observed preservation of grooves on the debris aprons. The subsample area was chosen to match the crater count area from Quantin et al. (2004) (i.e., 200 km²) and the number of subsamples for each surface age and β combination was set to be 1000 (allowing for statistical robustness but practical model run times). Figure 7b shows the histogram of model runs where an output model surface age and β combination match the crater size-frequency plot generated by Quantin et al. (2004) (using all of the crater size bins shown in Figure 7a). This method provides a picture of possible and likely model surface age and β combinations for a surface. Figure 7c reports the percent of model runs for β less than 100 nm/a and ages less than 3.8 Ga that match the data well. In this case, model surface ages between 0.5 and 1 Ga are most likely (~20% of matching crater size-frequency data), but model surface ages up to 3.5 Ga are reasonable (5 to 10% of matching crater size-frequency data; Figure 7c; see Figure S4 and S5 for example model fits). The cratering model therefore suggests that using crater count analysis on such a small feature where moderately high β values may apply simply does not contain enough information to meaningfully date this small surface. Detailed geomorphic mapping, relative age relationships, and dating of overlying or underlaying larger surfaces must therefore be used to constrain timing in these cases. Further examples of this method are explored below.

3.4 Case study: relative timing of alluvial deposition in and near Gale Crater

[24] There is growing interest in dating small-scale features such as valley networks, alluvial fans, and deltas. Palucis et al. (2016) used several depositional features (i.e., alluvial fans and deltas) around the rim and wall of Gale Crater, as well as around Gale's central mound, Aeolis Mons, to show that Gale experienced local surface runoff and erosion and likely hosted several large lakes. Two such features within Gale Crater are the Peace Vallis fan (80.5 km²), near the *Curiosity* landing site, and the Pancake delta (117 km²), located east of Farah Vallis (Palucis et al., 2016). Using standard crater size-frequency analysis, and a minimum crater diameter of 0.25 km, one would conclude that the Peace Vallis fan is significantly younger (1.4 Ga $\pm$ 0.2 Ga; $1/\sqrt{n}$ uncertainty) than the Pancake delta (3.2 Ga $\pm$ 0.3 Ga; $1/\sqrt{n}$ uncertainty) (Figure 8a). A minimum crater diameter of 0.25 km was chosen for dating the Peace Vallis fan and the Pancake delta because it is expected to give the best results for approximately 100 km² surfaces with minimal obliteration (i.e., $\beta \leq 10$ nm a⁻¹; Figure 5). The young model age of the Peace Vallis fan agrees with previous crater size-frequency analysis of the “upper fan unit” of

Peace Vallis, which Grant et al. (2014) determined to be ~1.2 Ga (range of uncertainty not reported). As there is no geomorphological reason to split Peace Vallis into two units (Palucis et al., 2014), it was treated as a single unit in this study. A model age of 3.2 Ga for the Pancake delta agrees with the interpretation offered by Palucis et al. (2016) that most of the major depositional and geomorphic evolution (i.e., deposition and erosion to form the central mound, Aeolis Mons, and deposition of the deltas during the time of large lakes) ended by ~3.3 Ga (+ 0.1/-0.3 Ga, $1/\sqrt{n}$ uncertainty).

[25] However, the Peace Vallis fan has undergone ~ 20 m of erosion at its lower end and has eroded up to 5 m on its western flank based on paleo-channel deflation depths (Palucis et al., 2014). If the β value is about 10 nm a^{-1} (5 m per ~1 Ga and assuming erosion is 20% of β) the model age of the Peace Vallis fan may be ~1.2 Ga (uncertainty not reported; Grant et al., 2014) to 1.4 Ga ($\pm 0.2 \text{ Ga}$; $1/\sqrt{n}$ uncertainty) (Figure 5). The higher erosion amount (20 m) corresponds to β values of about 75 to 20 nm a^{-1} depending on the actual surface age of the fan (e.g., 1 - 3 Ga) and assuming erosion is the *only* process contributing to crater obliteration (i.e., $\beta = \frac{20 \text{ m}}{\text{surface age (Ga)}}$). If other processes, such as infilling from dust or aeolian-transported grains, also contribute to crater obliteration, then the β value will be higher (as before, if we assume that erosion only accounts for 20% of the β value (Golombek et al., 2006b), then β values range from 33 to 100 nm a^{-1}). With a β value of 100 nm a^{-1} , model surface ages of 1 Ga and 3 Ga would be indistinguishable (Figure S2).

[26] As was done for the Coprates Chasma landslide, some insight into likely model surface ages can be provided by comparing observed crater size-frequency data to modeled surfaces over a range of ages and β values, as explained above for Figure 7. Since there were no constraints on β for the Pancake delta from geomorphic features (e.g., paleo-channel deflation depths or erosional remnants), we used β values up to 400 nm a^{-1} (based on upper bound estimates of erosion and infilling in Valles Marineris (Komatsu et al., 1993)). For the Peace Vallis fan, Figure 8b shows that the most probable model surface age is between 1.0 Ga and 2.0 Ga with β values less than 50 nm a^{-1} (where β is a combination of erosional and infilling processes), but model ages between 0.5 Ga and 2.5 Ga are reasonably likely. Model ages greater than 3.0 Ga are most probable for the Pancake delta (Figure 8c), with model ages less than 2.5 Ga unlikely (i.e., less than 10% of matching surfaces). Comparing the two features with β values

for the Peace Vallis fan restricted to less than 100 nm a^{-1} (as discussed above) suggests that the Peace Vallis fan may be younger than the Pancake delta (Figure 8d). There is still, however, a small probability that the two features share a model age between 2.5 Ga and 3.5 Ga. Note that restricting β values for the Pancake delta to values less than 100 nm a^{-1} only slightly increases the probability that the two features share a model age of 2.5 Ga to 3.5 Ga (Figure S6). Probabilistic dating of these deposits illustrates the point that many exposure ages may be possible for the same data set, requiring additional geologic, geomorphic, or cross-cutting relations to determine timing.

3.5 Case study: fan and delta features in the Gale Crater region

[27] Regional to Gale Crater, depositional features similar in scale and morphology to the Peace Vallis fan and Pancake delta have also been mapped, suggestive of larger bodies of water in the northern lowlands (e.g., Di Achille and Hynek, 2010; Ehlmann and Buz, 2015; Hauber et al., 2013; Irwin et al., 2005; Palucis et al., 2016; Rivera-Hernández and Palucis, 2019). These depositional features are typically small ($< 1,000 \text{ km}^2$) and most of the fans and deltas occur at different elevations, possibly recording different depositional events, but the relative timing between events is unknown. Figure 9 shows a map of the location of 20 such deltas and fans, each assigned a number-letter code (where D after the number stands for an inferred delta and F for an inferred alluvial fan). Adjacent to each feature we have also plotted a frequency histogram of model outcomes that matched our observed crater size-frequency data. These histograms were generated in a similar way to Figures 7c and 8d, only the model ages are binned into 0-0.9 Ga (red), 1-1.9 Ga (orange), 2-2.9 Ga (yellow) and 3-3.7 Ga (blue) bins. The colors are just a means of more easily visualizing the different columns. We used crater diameter bins greater than 60 m to ensure mapped craters were at least 10 pixels in diameter in CTX images. We have also calculated Poisson model surface ages for each feature using CraterStats II software (where the best fit age is shown with a black dashed line on each histogram and the grey box shows the reported range of uncertainty between the 16 and 84 percentile of a probability density function, Michael et al., 2016). In Figure S7, we show our results using the cumulative model surface age and uncertainties. We report the crater diameter range used for each deposit to get our best-fit Poisson model surface age in Table S1, and our best-fit cumulative model surface age in Table S2.

[28] Standard crater size-frequency methods suggests all of these features (based on the best-fit Poisson model age), except for the Pancake delta (PD), are less than or ~ 2 Ga (though with uncertainties, fans 1F and 4F and delta 7D could be greater than 2 Ga), and 10 of the 20 features are very young (<1 Ga). Similar results are also obtained using best-fit cumulative model surface ages (Figure S7, Table S2). This would imply that the region had recent fluvial activity. However, using our probabilistic model, we find that in all but two cases (the Peace Vallis fan (PV) and delta 5D), it is more likely that most of these surfaces are older than 1 Ga, and 13 of the 14 features identified as deltas are most likely older than 3 Ga. Interestingly, the fan features (1F through 5F) show equal probability for model ages between ~ 1 Ga and ~ 4 Ga over a range of β values (Table S1). There is the possibility that most of these small features are young, as suggested by traditional methods, but the probability of that is low. As is the case for the Coprates Chasma landslide deposit and the Peace Vallis fan and Pancake delta, better constraints on the timing of these features would require more work to determine the extent of erosion and infilling that has occurred, or detailed mapping and crater count analysis of larger surfaces that formed prior to and/or after fan and delta formation.

4. Discussion

4.1 How small is too small?

[29] A key question since the discovery of small depositional features on Mars is how small of an area is too small to accurately assign a model surface age from cratering statistics? Michael and Neukum (2010) argue that the area over which craters are counted is not important, but rather it is the number of craters counted that controls measured ages. Their Poisson analysis suggests that for very young and very old surfaces, relatively few craters need to be counted (order of 10 craters) to achieve a narrow ($\pm \sim 0.5$ Ga) probability curve centered on the true age of the surface. For surfaces 2 to 3 Ga, closer to 100 craters need to be counted to achieve approximately the same narrow distribution of model ages. The difficulty in using the Michael and Neukum (2010) model is that one needs to know the age of the surface *a priori* to know the minimum number of craters to count, and there is no indication of which crater-size classes should be used when comparing measured crater densities to an isochron. We show here, in agreement with others (e.g., van der Bogert et al., 2015; Warner et al., 2015; Williams et al., 2018), that sample area is a more important control on the uncertainties of crater size-frequency derived model ages. For example, Warner et al. (2015) performed detailed crater size-frequency

analysis over four 10,000 km² martian surfaces, and assigned model ages to each surface using traditional methods (model ages spanned from 3.02 Ga +0.3 Ga/-0.77 Ga to 3.74 Ga +0.03/-0.04 Ga, $1/\sqrt{n}$ uncertainty), and then subsampled and dated areas ranging from 100 to 1,000 km². In general, they found that 1,000 km² subsampled surfaces provided approximately the same model surface age estimates (when using the same minimum crater diameter) as the 10,000 km² parent surface, while the model ages for the 100 km² surface areas varied greatly (likely due to the spatial variability of cratering processes). They suggest that areas ~1000 km² or greater will provide accurate model surface age estimates assuming a large enough minimum crater diameter is used (in this case 1 km).

[30] While Warner et al. (2015) acknowledge obliterative processes, we can probe this more by comparing our model results to their fourth study region, in Acidalia Planitia, which they assign a “true” surface age of 3.02 Ga (+0.3 Ga/-0.77 Ga; $1/\sqrt{n}$ uncertainty) based on crater diameters 1 km and greater over a 10,000 km² surface. Assuming that erosion and infilling rates are negligible ($\sim 10^{-5}$ nm a⁻¹) our modeling suggests that the model age they assigned is likely accurate (Figure 2). However, when smaller minimum crater diameters are used, $D_{min} > 500$ m and $D_{min} > 200$ m, their assigned model surface ages decrease to 1.91 Ga (± 0.33 Ga) and 1.36 Ga (± 0.03 Ga), respectively. Figure 2 suggests that if erosion were indeed minimal as they proposed, the assigned model surface age should consistently be ~3 Ga, even when using minimum crater diameters down to ~60 m.

[31] The apparent model surface age decrease with minimum crater diameter suggests that this region of Acidalia Planitia has experienced some erosion and infilling (e.g., Figure 5). For example, for $\beta = 10$ nm a⁻¹, we would expect to see assigned model ages of 2.5 to 2.9 Ga (interquartile range) for a 3 Ga and 10,000 km² surface dated with minimum crater diameters of 200 to 500 m (Figure 5). This also makes sense with their results when subsampling 1,000 km² and 100 km² areas. For 1,000 km², our model predicts that a 3 Ga parent surface with 10 nm a⁻¹ of erosion and infilling will have assigned model ages of 3.2 to 3.6 Ga (interquartile range; median = 3.5 Ga) with 1 km minimum diameter craters, a model age of 2.4 to 3.1 Ga (interquartile range; median = 2.9 Ga) with 500 m minimum diameter craters, and a model age of 2.3 to 2.5 Ga (interquartile range, median = 2.4 Ga) with 200 m minimum diameter craters (Figure 5). Correspondingly, for 1 km minimum diameter craters, Warner et al. (2015) assign model ages of 3.4 Ga (± 0.2 Ga) to 3.7 Ga (+0.08 Ga/-0.2 Ga), for 500 m minimum diameter

craters model ages from 0.9 (± 0.44 Ga) to 3.4 Ga ($+0.1$ Ga/ -0.4 Ga), and for 200 m minimum diameter craters 1 Ga (± 0.07 Ga) to 1.5 Ga (± 0.1 Ga). For areas of 100 km², our model has assigned ages close to 4 Ga with 1 km minimum diameter craters, a model age of 1.7 to 3.5 Ga (interquartile range; median = 3.3 Ga) with 500 m minimum diameter craters, and a model age of 2.1 to 2.6 Ga (interquartile range; median = 2.3 Ga) with 200 m minimum diameter craters (Figure 5). Correspondingly, for the 1 km minimum diameter craters, Warner et al. (2015) assign relative ages of middle to late Noachian, for 500 m minimum diameter craters from 3.2 Ga ($+0.3$ Ga/ -2.2 Ga) to 3.7 Ga ($+0.1$ Ga/ -0.36 Ga), and for 200 m minimum diameter craters from 1 (± 0.25 Ga) to 2.37 Ga (± 0.4 Ga). While we get similar model age distributions to those observed by Warner et al. (2015), the fact that their model age distributions are often a bit wider (i.e., more spread) is likely due to the fact that β is higher than 10 nm a⁻¹ for this region and/or they have more spatial variability (due to possible clustering or localized erosion that is not accounted for in our model). If β values for this region are > 25 nm a⁻¹, the surface sizes required to accurately date obliterated surfaces could be as large as 100,000 km² (Figure 6), much larger than the minimum proposed by Warner et al. (i.e., 1,000-10,000 km²).

[32] We also note that for 2 Ga surfaces, even with small β values our model predicts that model ages assigned by crater count analysis may span more than 1 Ga on 1,000 and 10,000 km² surfaces with a minimum crater diameter of 1 km (Figures 2 and 5, see discussion in Section 4.3 below). Warner et al. (2015) may not have observed such a wide age distribution when subsampling 1,000 km² surfaces because they did not study any surfaces with “true” ages near 2 Ga. And while subsampling a surface may provide a precise date, that date may be incorrect. This is the case in our model, for example, at a β value of 10 nm a⁻¹ for all minimum crater diameters (except 500 m) on a 3 Ga, 1,000 km² surface (Figure 5).

[33] These comparisons illustrate that it is insufficient to select a single minimum sample area size and a single minimum threshold diameter in order to insure an accurate crater size-frequency analysis. Crater obliteration, even at relatively slow rates, introduces a strong dependency of calculated age on minimum crater diameter counted, especially for older sites, that can matter to sample areas greater than 10,000 km² (Figure 5). We explore this conclusion further in the next sections.

4.2 Importance of small versus large craters in surface age dating

[34] A key decision when assigning model surface ages is choosing the range of crater diameters that best preserve the true age of the surface. Typically, crater bins on the larger diameter end that lie along an isochron are used to constrain model age (e.g., Figure 8a), as it is known that smaller craters are subjected to image resolution effects (and crater count fatigue), as well as actual crater removal from the surface due to erosion and infilling. As the extent, duration, and intensity of the processes removing craters varies (see Auxiliary material in Smith et al., 2008), it usually requires some judgement on the part of the counter to determine the diameter ranges that most likely preserve the surface's true age. Michael and Neukum (2010) suggest that when younger surfaces are being dated, smaller diameter craters can be used as they occur with higher spatial density than larger craters, and hence it is sufficient to date over smaller areas. They also suggest that older surfaces should be dated with larger craters over larger areas. Our modeling shows that for surfaces of any age, if there is only minimal erosion and infilling (whether due to the surface being young or the surface is erosionally resistant and minimal resurfacing has occurred), then as crater count areas get smaller, smaller minimum crater diameters are needed to ensure an accurate model age. For these cases, minimum surface areas can be estimated using $\sqrt{\text{tested area}}/(\text{minimum crater diameter}) \gtrsim 200$, which was derived empirically from our model. For surface areas as small as 10 km^2 , the minimum crater size required for accurate model ages (less than $\sim 63 \text{ m}$) would be observable on a martian surface mapped by HiRISE (0.25 to 1.6 m/pixel; McEwen et al., 2007) and possibly by CTX ($\sim 6 \text{ m/pixel}$; Malin et al., 2007). When only the larger crater bins are used (Figure 2), even for areas as large as $10,000 \text{ km}^2$, errors in model surface age can span a billion years and typically over-estimate the true age. The presence of just a few larger craters within a small counting area can produce a high spatial crater density (number of craters per surface area) for the larger diameter bins, thus resulting in assigning an older model surface age. Warner et al. (2015) observed similar increases in assigned model surface ages with increasing minimum crater diameters. Of course, as the cutoff diameter of crater bins used begins to approach the counting surface area, the lack of larger craters creates large uncertainties (in our model, those surfaces can't be dated, hence the biased trend in returned ages to be older, Figure 2). Michael et al. (2016) have introduced a new method for evaluating crater chronology models for when n (where n = number of craters in a bin) is small, which relies on Poisson statistics and Bayesian inference (versus binning and best-fit approaches). They suggest that even in the case of no craters, a meaningful likelihood

function can be obtained (with inherent uncertainty) that can be used to assign model ages. Future work aims to integrate their Poisson/Bayesian model with our model to determine how erosion and infilling affects resulting likelihood functions and uncertainties.

[35] As erosion and infilling increases, the smaller crater diameters no longer preserve information about the surface's true age, and larger minimum crater diameters must be used (Figure 6). Importantly, as Figures 5 and 6 illustrate, this minimum crater diameter is not constant, rather it is a function of β , the area of the counting surface, and the actual age of the surface. For most surfaces, only the counting area is known with confidence, hence our use of the model to assess model age probabilities, as demonstrated in Section 3.3-3.5. As our model does not account for roll-off of smaller crater diameters due to image resolution effects or counter fatigue (only erosion and infill), the counter needs to decide an appropriate minimum crater diameter to report for their surface of interest (for example, for a surface where craters were counted using CTX imagery, crater diameters less than ~60 m would not be advisable as craters are less than 10 pixels, leading to inaccurate or incomplete crater identification).

4.3 Uncertainties in using crater size-frequency data for surface age dating

[36] Uncertainties using our probabilistic model (as interquartile ranges of calculated model surface ages) are a similar order of magnitude (within ~0.1 Ga) as those estimated by CraterStats II software (cumulative model), which calculates uncertainties as plus or minus the spatial density of 1 km diameter craters divided by the square root of the total number of craters counted, converted to model age by the martian chronology function (Platz and Michael, 2012). We note that this methodology for estimating uncertainty (i.e., using $N(1)$) may not be ideal for those performing crater count analysis on smaller surfaces, where 1 km craters may not be present, or on surfaces where a significant loss of craters has occurred within this size range (see discussion in Robbins et al. (2018a)). That issue withstanding, we show, for example, that a 2 Ga parent surface with no erosion and infilling dated with a 10 km² area and a minimum crater diameter of 62.5 m, CraterStats gives an uncertainty of ± 0.2 Ga (with ~100 total craters counted). The crater count model presented here yields an interquartile range of +0.15 to -0.1 Ga around the median (Figure 2) for this example. This suggests that the order of magnitude of the uncertainty one would assign to their model age would be similar using both the model presented here or the standard CraterStats II software package ($1/\sqrt{n}$ uncertainty) for non-obliterated surfaces. These uncertainties are distinct, however, from the systematic error inherent in

performing a crater count analysis on Mars due to uncertainties in the production and chronology functions and estimation of the ratio of the Moon/Mars impactor flux (Lane et al., 2003; Neukum et al., 2010).

[37] In probing the effects of erosion and infilling combined with sample area on model age estimates, we found that the largest errors (or the largest range of assigned model ages) were most pronounced at medium parent surface ages (e.g., 2 Ga). For surfaces that are equal to or younger than 1 Ga, if one looks at the cumulative crater frequency for 1 km crater diameters (i.e., $N(1)$, a standard diameter used by Hartmann and Neukum (2001) to go from cumulative crater frequency to a model age), small differences in model age result in large differences in $N(1)$. The same is true of surfaces older than ~3 to 3.5 Ga, where the exponential term of the chronology function becomes significant (reflecting the increased cratering rate at this time). For surfaces with ages between these times, $N(1)$ varies little, making it difficult to discern a 1.5 Ga versus 2.0 versus 2.5 Ga surface or compare surfaces that may have formed within this time frame.

4.4 Model limitations

[38] We present a very simple probabilistic model, and as such, it does not account for a number of effects that may be important when assigning model surface ages to actual martian landscapes. The craters in our model are randomly placed on the surface to purposely avoid effects from crater clusters (Michael et al., 2011). However, on real surfaces, fragmented impactors or secondary impacts can lead to a dense grouping of craters within the same size bin that may not be recognized as an obvious cluster to the counter (Warner et al., 2015). These clusters can dominate a cumulative fit, which in turn can affect how well the model can match the real surfaces in ‘Monte Carlo’ mode. Our model also relies on generating crater populations defined by the Hartmann isochrons (2004 iteration, Hartmann, 2005) (though it is straightforward to modify the model to use other established isochrons). These isochrons represent the *expected* crater size-frequency distributions for surfaces of a given age based on crater size-frequency distributions for radiometrically calibrated homogenous lunar surfaces converted to Mars. As such, this model does not explicitly account for impacts obliterating pre-existing craters (though Hartmann (2004) acknowledges that the downward curvature of the Hartmann isochrons towards smaller diameter craters is likely not just due to the production function, but also crater obliteration), which will locally lead to changes in the crater size-frequency distribution (especially over a small area). One can perform a non-randomness

analysis on their cratering data to assess whether observed crater populations have a random distribution (Michael et al., 2012; Warner et al., 2015). If not, similar to the case with crater clustering, missing populations due to crater-crater obliteration can affect the model when used in ‘Monte Carlo’ mode. Explicitly testing the effects of the order of impacts and how that might influence local erosion and infilling processes could benefit from a landscape evolution model approach (e.g., MARSSIM). Lastly, the model as presented here does not account for spatially variable erosion and infilling rates, though this would be fairly simple to alter within the current model framework.

5. Conclusions

[39] Erosional or mantling resurfacing changes the crater population on the surface of Mars. Here, a simple model to quantify the effects of sample area size, minimum crater diameter counted, and crater obliteration effects due to erosion and infilling (β values) on model age estimates derived from crater size-frequency data is developed. Results from this model suggest several general outcomes when using crater size-frequency data and analysis to ascertain martian model surface ages for small landforms. First, the minimum surface area needed to obtain the most accurate dates depends strongly on both surface obliteration (erosion and infilling) rate and on the choice of minimum diameter counted. Generally, the faster the obliteration rate, the larger the minimum surface area needed and the larger the minimum crater diameter that should be counted. Given uncertainty of both the likely age and obliteration rate, all crater size-frequency-derived model ages should ideally be expressed probabilistically, with that probability explicitly accounting for the effects of diameter size and obliteration rate for a given surface sample area. Second, for landscapes that indicate insignificant erosion, the minimum sample area for which an accurate date can be obtained is predicted from our model to be: $\sqrt{\text{tested area}}/(\text{minimum crater diameter}) \gtrsim 200$. Third, when accounting for the obliteration of craters, the model suggests that, in general, the most uncertainty in assigning model surface ages occurs around 2 Ga years. Younger surfaces preserve the smaller craters and older surfaces have had enough time to acquire larger craters, both improving the probability of obtaining the correct age. Fourth, crater count surfaces that are too small and obliterated too strongly (e.g., $<100,000 \text{ km}^2$ for $\beta > 50 \text{ nm a}^{-1}$) cannot give an exposure age within 0.5 Ga, because of loss of information at the lower end (due to erosion and infilling) and the upper end of the distribution (due to a low

probability of counting large craters). This results in crater size-frequency data fitting a wide range of surface exposure ages and β .

[40] Several examples are presented that illustrate a probabilistic approach to model surface age dating, whereby crater size-frequency data is compared to modeled data generated from surfaces with a range of ages and β values. This approach highlights that many model surface exposure ages may be possible for the same data set. Crater size-frequency data for the 200 km² Coprates Chasma landslide shows that although conventional crater count methods yield precise model ages, our model shows that ages between 0.5 and 3.5 Ga are equally reasonable. Modeling indicates that a range of model ages is possible for the 80 km² Peace Vallis fan (~1 to 2.5 Ga) and the 117 km² Pancake delta (~2 to 3.8 Ga) in Gale Crater, but overall, supports the prior interpretation that the Peace Vallis fan is younger than the Pancake delta. Similarly, deltaic features in the Gale crater region also have a high probability of being > 3 Ga, but model ages between 1 and 3 Ga are possible; the fan features have wider age distributions, with model ages between 1 and 4 Ga being equally likely. There is low probability (< 10%), however, that all these features formed in the last 1 Ga. Hence, although crater size-frequency analysis of such small depositional landforms will yield a wide range of model age values, it is possible, based on the probabilistic approach to suggest more likely model ages. The simplicity of this model makes it easily adaptable to surfaces of different areas and different planets where isochron data exists.

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Figure 1. a.) Example of a 2 Ga, 20,000 km² surface without obliteration ($\beta = 10^{-5} \text{ nm a}^{-1}$) from cratering model. For an area of 20,000 km², the Hartmann (2005) 2 Ga isochron predicts only one 4 km diameter crater, three 2 km craters, 161 500 m diameter craters, and ~18,000 125 m diameter craters. Black circles represent craters. Colored squares show 1,000 km² subsampled areas. b.) Cumulative crater densities for 1,000 km² subsampled surfaces shown in (a), with symbol colors and shapes corresponding to colored square sources. The model assigned ages of 1.9 Ga (blue circles), 2.0 Ga (red diamonds), and 2.0 Ga (black squares) to the subsampled surfaces. The plotted line shows the 2 Ga isochron.

Figure 2. Median (symbol) and interquartile range (error bars) of ages calculated by cratering model without erosion using a range of true parent surface ages (1, 2, and 3 Ga), sample areas (10, 100, 1,000, and 10,000 km²), and minimum crater diameters (for readability, data are slightly offset within some bins, e.g., the 250 m minimum crater diameter bin for a 10 km² area). Parent surfaces were 200,000 km², except for trials when the minimum crater diameter was 16 m and the parent surface was 20,000 km². Each set of conditions was tested using 100 iterations. Modeled surfaces without craters were omitted.

Figure 3. Range of possible parent surface ages (i.e., measured age was within interquartile range) that could produce a given measured age without erosion. 10 km² areas were sampled using a minimum crater diameter of 0.125 km. Parent surfaces were 20,000 km² and were sampled 100 times for each true age.

Figure 4. Output from cratering model at four β values. Each set of symbols shows cumulative crater densities for a single 1,000 km² test surface and $1/\sqrt{n}$ uncertainties. Parent surfaces had areas of 20,000 km², ages of 2 Ga, and minimum crater diameters of 0.016 km. The following model ages were assigned: $\beta = 0 \text{ nm a}^{-1}$: 2 Ga; $\beta = 10 \text{ nm a}^{-1}$: 0.5 Ga; $\beta = 100 \text{ nm a}^{-1}$: < 0.1 Ga; $\beta = 1000 \text{ nm a}^{-1}$: < 0.1 Ga. Plotted lines show 0.5 and 2 Ga isochrons.

Figure 5. Median (symbol) and interquartile range (error bars) of model ages calculated by cratering model with a β value of 10 nm a^{-1} using a range of true parent surface ages (1, 2, and 3 Ga), sample areas (10, 100, 1,000, and 10,000 km²), and minimum crater diameters (for readability, data are slightly offset within some bins). Parent surfaces were 200,000 km², except for trials when the minimum crater diameter was 16 m and the parent surface was 20,000 km². 100 iterations were run for each set of conditions. Modeled surfaces without craters were omitted.

Figure 6. Minimum surface area needed to calculate an accurate age (75% of data within 0.5 Ga of parent surface age) over a range of β values and parent surface ages. When multiple minimum crater diameters (D_{min}) gave the same minimum surface area, their range is listed. Parent surfaces were 200,000 km². For $\beta = 0$ nm a⁻¹, a 10 km surface was needed for all ages, with $D_{min} = 0.089$ km (data not shown). Each set of conditions was tested with 1000 iterations. Modeled surfaces without craters were omitted. See Figure S3 for range of model ages assigned to each point.

Figure 7. a) Crater size-frequency data and uncertainty (black squares, $1/\sqrt{n}$ uncertainty) of Coprates Chasma landslide on Vallis Marineris from Quantin et al. (2004). The largest two diameter bins were fit without erosion to a model age of 0.4 Ga, following Quantin et al. (red solid line). The entire range of craters was fit with erosion and secondaries to a model age of 3.2 Ga with a β value of 50 nm a⁻¹ (black dashed line), following Smith et al. (2008). b) Histogram of number of modeled, non-cumulative crater size-frequency data for surfaces of different ages and β values that closely matched crater size-frequency data in (a). Model parent surfaces used the secondaries model of Smith et al. and had a parent surface area of 10,000 km². Each surface age and β combination was tested with 1,000 model iterations. c) Percent of modeled crater size-frequency data that closely matched (a) over age with ≤ 3.8 Ga and $\beta \leq 100$ nm a⁻¹. Calculated from (b).

Figure 8. a) Crater size-frequency of Peace Vallis fan (black squares, $1/\sqrt{n}$ uncertainty) and the Pancake delta (red stars, $1/\sqrt{n}$ uncertainty) in Gale Crater. Crater size-frequency data were fit using diameters greater than 0.25 km. b) Histogram of number of modeled crater size-frequency data for surfaces of different ages and β values that closely matched Peace Vallis crater size-frequency in (a) with diameters greater than 0.088 km. Model parent surfaces did not use secondaries and had a parent surface area of $10,000 \text{ km}^2$. Each surface age and β combination was tested with 1,000 model iterations. c) Same as (b) but for the Pancake delta. d) Percent of

modeled crater size-frequency data that closely matched observed crater size-frequency data in (a).

Figure 9. Model age distribution histograms showing the percent of modeled crater size-frequency data that closely matched observed crater size-frequency data (Supporting Information; Table S1) for alluvial fan (tan diamonds) and deltaic (blue triangles) features in the vicinity of Gale crater. Crater size-frequency data were fit in the probability model using diameters greater than 0.125 km. The dashed lines on each histogram represent the Poisson (μ) best-fit model surface age (with errors reported in Table S2) following Michael et al. (2016). In all cases, the minimum crater diameter used for the CraterStats II fits were ≥ 60 m. All crater size-frequency data are in the Supporting Information.

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Journal Pre-proof

Highlights:

- Crater erosion/infilling introduces significant age uncertainty on small surfaces
- We present a probabilistic cratering model that quantifies these uncertainties
- Moderate erosion ($>25 \text{ nm a}^{-1}$) requires areas $>10,000 \text{ km}^2$ for accurate age dating
- We demonstrate this method using data from fan deposits in the Gale crater region