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Mars sedimentary rock erosion rates constrained using crater counts, with applications to organic-matter preservation and to the global dust cycle

Edwin S. Kite*, David P. Mayer

University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, USA

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ABSTRACT

Small-crater counts on Mars light-toned sedimentary rock are often inconsistent with any isochron; these data are usually plotted then ignored. We show (using an 18-HiRISE-image, $> 10^4$-crater dataset) that these non-isochron crater counts are often well-fit by a model where crater production is balanced by crater obliteration via steady exhumation. For these regions, we fit erosion rates. We infer that Mars light-toned sedimentary rocks typically erode at $\sim 10^2$ nm/yr, when averaged over 10 km^2 scales and 10^7–10^8 yr timescales. Crater-based erosion-rate determination is consistent with independent techniques, but can be applied to nearly all light-toned sedimentary rocks on Mars. Erosion is swift enough that radiolysis cannot destroy complex organic matter at some locations (e.g. paleolake deposits at SW Melas), but radiolysis is a severe problem at other locations (e.g. Oxia Planum). The data suggest that the relief of the Valles Marineris mounds is currently being reduced by wind erosion, and that dust production on Mars $<$ 3 Gya greatly exceeds the modern reservoir of mobile dust.

1. Introduction

Sandblasting, aeolian infilling, and wind deflation all obliterate impact craters on Mars, complicating the use of crater counts for chronology. Aeolian resurfacing is particularly confounding for dating sedimentary rocks, because these soft materials can be rapidly eroded by the wind. Yet wind erosion of sedimentary rocks is much more than a source of noise, for four reasons. (1) Rapid exhumation by wind erosion is required for near-surface preservation of ancient complex organic matter (a target for future landers). Near-surface complex organic matter on Mars is destroyed by radiation in $< 10^8$ yr, so the surface must be refreshed by exhumation (Kminek & Bada, 2006; Pavlov et al., 2012, 2014; Farley et al., 2014; Grotzinger 2014). (2) The pace and pattern of recent wind erosion is a sorely-needed constraint on models of terrain-influenced aeolian erosion – i.e. landscape-wind feedbacks (Kite et al., 2013a; Day et al., 2016). (3) Wind erosion is a source of dust, and the global dust reservoir will disproportionately sample fast-eroding regions. (4) Basin-scale aeolian exhumation is intrinsically interesting. Uncommon on Earth (Rohrmann et al., 2013), it has probably been a dominant landscape-modifying process on Mars since 3 Gya and perhaps earlier (e.g. Bridges et al., 2014; Greeley et al., 2006; Golombek et al., 2014; Farley et al., 2014). There is direct evidence for globally–distributed saltation abrasion on Mars today. However, the extent to which the deep erosion of Mars' sedimentary rocks can be explained by uniformitarian rates and processes remains unknown.

For these four reasons, we seek to constrain Mars sedimentary rock erosion rates, averaged over the 10^7–10^8 yr timescales relevant to recent topographic change and to the preservation of complex organic matter.

The only proxy for Mars wind erosion rate that is globally available is the size-frequency distribution of impact craters. Crater-formation frequency is nearly uniform across Mars' surface (Le Feuvre & Weizcorek, 2008). Therefore, crater density can be compared to a model of crater production (as a function of diameter and time) to estimate age (e.g. Michael, 2013). However, the best-fit crater-production function usually deviates strongly from the observed crater size-frequency distribution (CSFD) for light-toned Mars sedimentary rocks (a subset of Mars sedimentary rocks that includes the sedimentary rock mountains in Valles Marineris and Gale; Malin & Edgett 2000). For those terrains, high-resolution images show fewer small craters than anticipated from the number of large craters (e.g. Malin et al., 2007). Moreover, sedimentary rock ages inferred from small-crater frequency can be less than those of adjacent materials that are crosscut by the sedimentary

* Corresponding author.
E-mail address: kite@uchicago.edu (E.S. Kite).

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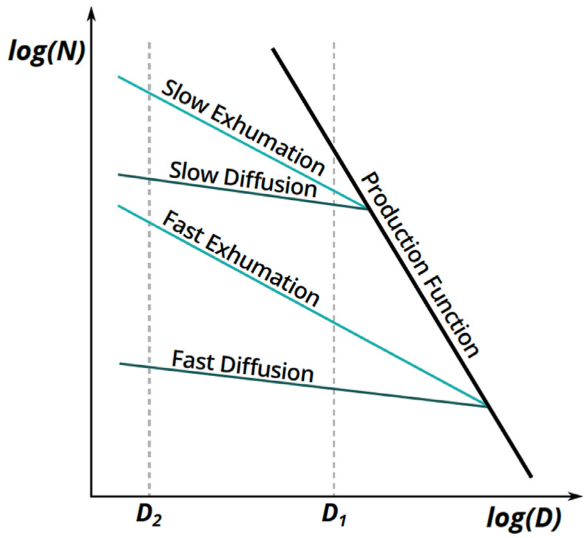

Fig. 1. Crater frequency (N) is set by the pace of crater obliteration at a given D, and the slope dN/dD is set by the process of crater obliteration. Because crater depth $d \propto D$ (crater diameter), obliteration occurs by exhumation in a time $\propto D^1$, and by diffusion in a time $\propto D^2$.

rocks. These data cannot be explained by differences in rock-target strength (Dundas et al. 2010; Kite et al., 2014). These effects appear at crater sizes up to 1 km and so cannot be attributed to limited image resolution (image data are now available at 25 cm/pixel: McEwen et al., 2010). These discrepancies are usually attributed to "resurfacing", and scientists working on Mars CSFDs either fit an age to the very largest craters on sedimentary rock terrains, or avoid sedimentary rock areas entirely (Platz et al. 2013). Although off-isochron CSFDs have been used to explore resurfacing processes for decades (e.g. Hartman, 1971; Chapman & Jones, 1977), the prevailing procedure is to parameterize resurfacing as one or more events, not an ongoing process (Michael, 2013).

The paucity of small craters relative to large craters in easily-eroded sedimentary rock terrains can be understood if we consider resurfacing not as an event but as a process (Fig. 1). In this paper, we define a crater as "obliterated" if it can no longer be identified in a high-resolution optical image (i.e. HiRISE, ~25 cm/pixel). On Mars, fresh craters with simple morphologies have a depth-to-diameter ratio ~0.2 (Melosh, 1989). This relationship ensures that many crater obliteration processes (Table 1) remove small craters from the landscape more readily than larger craters. For example, suppose a landscape is being steadily and uniformly abraded at 100 nm/yr. On such a landscape, a 20 m diameter crater (initially ~4 m deep) has a lifetime of 40 Myr and a 100 m diameter (initially ~20 m deep) has a lifetime of 200 Myr. Extrapolating along a hypothetical, perfect crater production function from the observed density of 100 m diameter craters down to 20 m diameter, one would find that the observed density of 20 m diameter craters on the steadily eroding landscape is less than expected from the production function by a factor of (200 Myr)/(40 Myr) = 5. This correction factor is equal to the ratio of diameters for craters < 3 km (for which the initial depth of the crater is ≈proportional to the initial diameter of the crater; Watters et al. 2015). Therefore, for a steady grind-down process and for craters < 3 km in diameter, and approximating the CSFD in the crater-size range of interest as

$$N(>D) = kD^{-\alpha} \quad (1)$$

(where D is crater diameter), the effect of steady-state erosion is to subtract 1 from the slope-parameter α. It may be verified (by inspection of figures with a straight edge) that many published Mars sedimentary rock CSFDs have an "off-isochron" power-law slope that follows this rule. After the fingerprints of crater-obliteration have been identified using the parameter α, the rate of crater-obliteration can be constrained by assuming steady-state balance between crater production and destruction.

Competition between crater accumulation and obliteration has been modeled by Öpik (1965), Jones (1974), Chapman (1974), Catling et al. (2006), and Fassett & Thomson (2014), among others, but Smith et al. (2008) is the closest in intent to our work. Smith et al. (2008) use an analogy to radioactive decay to model size-dependent crater lifetimes for Mars craters, fitting erosion rates of ~10^3 nm/yr for a light-toned layered deposit at Arabia Terra and 30 nm/yr at Meridiani Planum. While we use different equations, our results are qualitatively consistent with those of Smith et al. (2008). The main differences are that we have a 100 × larger crater dataset, provide a more detailed treatment of errors, consider a wider range of processes, and apply the results to a broader range of problems. Small-crater degradation has been intensively studied along the *Opportunity* traverse (Golombek et al., 2006, 2010, 2014; Fenton et al., 2015). This site is very flat, erodes slowly (3–30 nm/yr) because of armoring by hematite granules, and the CSFD is well-fit by an isochron (71 ± 2 Myr). The *Opportunity* traverse is an outlier in that most light-toned sedimentary rocks on Mars erode quickly, are associated with steep slopes (and thus slope-winds), lack hematite armor, and have CSFDs that are not well-fit by isochrons. However, *Opportunity*'s close-up view provides constraints on small-crater degradation processes that have global relevance (Golombek et al., 2014; Watters et al., 2015): sandblasting swiftly ablates ejecta blocks and planes down crater rims, then sand-infill slowly mutes craters (left panel of Fig. 2). Crater expansion during degradation is minor.

This paper is about both a technique (§2–§4.1) and its application (§4.2–§8). Readers uninterested in techniques may skip to §4.2. In §2, we motivate our use of a steady-exhumation model, contrasting it with two alternatives: a one-big-pulse model and a diffusion model. Next (§3), we outline a workflow for obtaining erosion rates assuming steady exhumation. In §4, we present and analyze an example dataset obtained using 18 High Resolution Imaging Science Experiment (HiRISE; McEwen et al. 2010) images. In §5, we assess the implications of erosion rates for landscape evolution and the age of dust on Mars. In §6, we apply the resulting erosion rates to estimate organic-matter destruction. In §7, we discuss approximations, limitations, and open questions, as well as independent constraints from landslide-molds (Grindrod & Warner 2014) and cosmogenic isotopes (Farley et al. 2014). We conclude in §8.

2. Processes and process determination

Fitting erosion rates to CSFDs on rocky terrain raises questions about geology (§2) and questions about methods (§3). Turning to the geology questions first:

(1) *Are crater obliteration rates equivalent to landscape-exhumation rates?* Fresh craters have steep walls. Steep slopes are softened more rapidly than shallow slopes by diffusive processes. Diffusive obliteration times (for linear diffusion) scale as D^2. Therefore, a crater 5 × the diameter of another will survive 25 × as long, if diffusion is responsible for obliterating craters. This increases α by 2 (Eq. 1). Therefore, the CSFD allows steady exhumation and/or mantling by dust, sand or ash (α increased by 1) to be distinguished from the diffusive alternative (Table 1). In practice, we find that most of our CSFDs are better fit by "α increased by 1" than by diffusive-obliteration (Fig. 7a). Because the images we study have relatively good bedrock exposure