# DEGRADATION OF SMALL CRATERS ON MERIDIANI PLANUM AND EROSION RATES ON MARS.

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**Introduction:** The *Opportunity* rover has imaged about 100 small craters (mostly 2-30 m diameter) during the 33.5 km long traverse between Eagle and Endeavour craters on Meridiani Planum, Mars. These craters are in a wide variety of morphologic states that have evolved from fresh blocky craters to highly eroded and shallow depressions ringed by planed off crater rim outcrop blocks [1]. This degradation sequence is produced by abrasion and infilling from abundant basaltic sand that has effectively smoothed the topography. Because small impact craters have a well-understood initial geometry that is directly related to their diameter, simple morphometric measurements of craters can be used to measure changes from when they first formed. We use these data and a timescale for crater formation and modification developed from size-frequency counts and isochrons to estimate recent erosion rates on Mars [1]. These rates are compared with rates determined over longer periods and larger spatial scales to better understand the role of hiatuses in the erosion rate data and derive true average process rates that can be compared more confidently with the operating erosional agent and climate [1].

**Crater Morphology:** A morphometric and morphologic catalog of ~100 small craters imaged by the *Opportunity* rover between Eagle and Endeavour craters on Meridiani Planum show craters in six morphologic classes [1]. The freshest, class 1 craters have elevated rims, blocky inner walls, and ejecta, and they are superposed on the granule ripples. Class 2 craters have elevated rims, partially planed off ejecta blocks and inner walls, sandy interiors, and ripples that merge with their rims. Class 3 craters have elevated rounded rims, mostly planed off blocky ejecta, blocky inner walls, and shallow sandy floors and ripples that merge with their rims. Class 4 craters have slightly elevated rims, shallow sandy interiors, completely planed off ejecta blocks, and ripples that modify their rims. Class 5 craters are mostly sandy depressions, with flat rims, no ejecta and ripples that merge with and follow the edge of the crater. Class 6 craters are rimless, very shallow, mostly sandy depressions, with no ejecta and pervasive ripples.

The age of each morphologic class of crater has been determined from size-frequency distributions of craters in the catalog, the crater retention age of small craters on Meridiani Planum, and their age with respect to the latest phase of granule ripple migration. Class 1 craters are younger than the latest phase of granule ripple migration and are therefore <50–200 ka. Class 2 craters are older than the latest phase of granule ripple migration and thus ~200–600 ka. Class 3–5 craters are ~0.6–2 Ma, ~2–4 Ma, and ~4–10 Ma, respectively. Finally, class 6 craters are about ~10–20 Ma based on the crater retention age of small craters on Meridiani Planum [1].

**Crater Degradation:** The rate of crater degradation is determined by comparing its depth, ejecta block size, and rim height, with that expected for a fresh hypervelocity impact crater and dividing by its age [1]. The rate of deposition of sand into craters drops from ~1 m/Myr for craters 1 Ma to ~0.2 m/Ma for craters 10–20 Ma. The rate of erosion of ejecta blocks drops from ~0.3 m/Myr for craters 2-4 Ma to 0.1 m/Myr for craters ~15 Ma. Finally, the rate of erosion of crater rims is ~0.05 m/Myr for classes 5 and 6 craters that are 7–15 Ma. As a result, the rate of degradation of craters decreases by an order of magnitude from 1 Ma to 15 Ma.

This decrease in erosion rate is consistent with simple reduction in scarp slope via downslope transport of material. We have modeled this process by numerically solving a form of the nonlinear, radially symmetric diffusion equation [2] that depends only on the scarp slope, height, and the diffusivity, a term that characterizes the erodibility of the material and the vigor of the downslope motion (Fig. 1). The model accurately predicts the observed order of magnitude decrease in estimated erosion rate (Fig. 1) and argues that the decrease in erosion rate is simply due to the reduction in slope with time.

**Erosion Rates throughout Time:** Erosion rates as high as 1-10 m/Ma have been reported for the recent past and probably represent the maximum short-term rate for eolian erosion on Mars [e.g., 1]. Erosion rates calculated over longer timescales in the Amazonian and Hesperian (80-235 Myr, marked LA on Fig. 2) are about an order of magnitude slower (~0.01 m/Myr) than those estimated for the past 10 Myr.

Erosion rates averaged over the ~3 Gyr from the landing sites [e.g., 1] are even slower (marked H-A) with the middle two quartiles at ~0.02-3x10$^{-4}$ m/Myr. Because the means of the 100 Myr and 3 Gyr estimates are similar, we interpret these rates as being long-term averages for eolian erosion during the Hesperian and Amazonian [1].

The decrease in erosion rate with increasing time may be due to heavy-tailed hiatuses that separate the

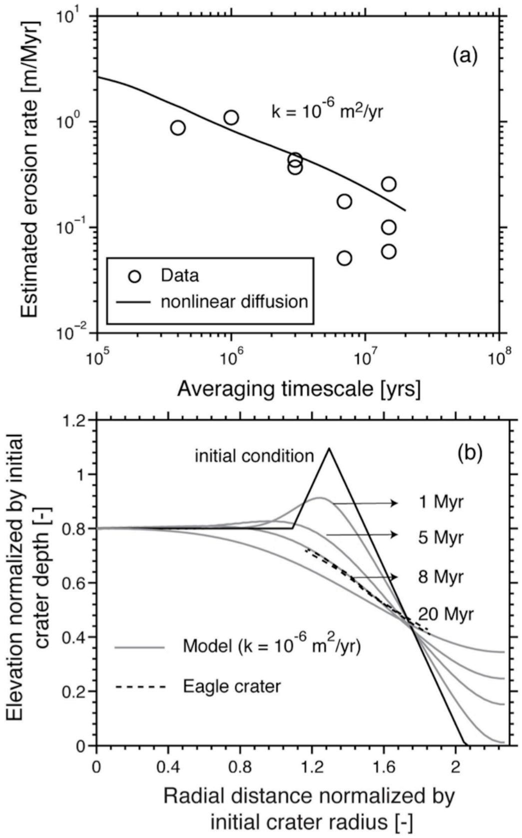

Figure 1 (a) Estimated erosion rate (from crater infill, ejecta block, and rim erosion for different class craters) and radially symmetric topographic diffusion model [2] versus averaging timescale for the diffusivity indicated shows that the decrease in erosion rate for small Meridiani craters can be explained by the decrease in slope of crater walls with time. (b) Plot showing temporal evolution of the crater profile where the radial distance is normalized by the crater radius and the elevation normalized by initial crater depth. With time, the crater rim rounds, the slope decreases, and the crater fills. Topographic profiles of Eagle crater [3] show good agreement with the model results.

actual erosional events [4]. For example, sediment accumulation rates have been shown to exhibit a negative power law dependence with the timescale of measurement due to periods of inactivity or hiatuses (sometimes referred to as timescale bias) [5]. The similarity of average erosion rates since 3 Ga when measured over 100 Myr and 3 Gyr together with the long spatiotemporal scales of averaging involved in these estimates, argues they are representative of the true long-term process rate that includes the hiatuses [4]. Comparing these rates to the slowest erosion rates on Earth calculated over similar timescales [e.g., 4, 6], shows that these erosion rates on Mars are 3-4 orders of magnitude slower. These rates are too slow for liquid water to be an important erosional agent and argues that erosion in the Hesperian and Amazonian on Mars has been due to slow eolian erosion in a dry and desiccating environment [1].

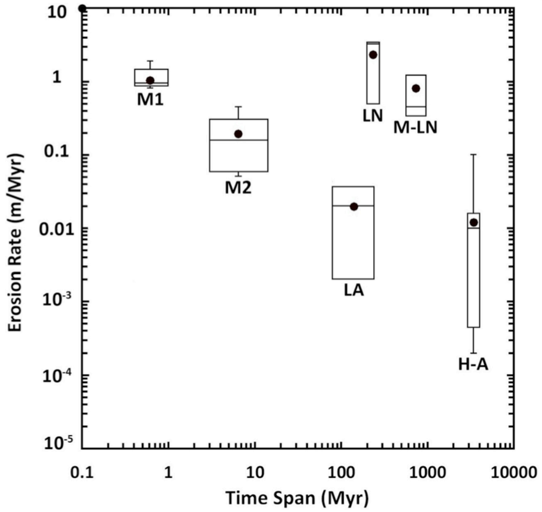

Figure 2. Box and whiskers plot of published erosion rates on Mars versus the timespan over which the erosion rate is calculated. Box height delineates the middle 2 quartiles of the estimates around the median (line), with the whiskers showing the extrema and the dot showing the mean; timespan of the rates in the box defines the width. Erosion rates marked M1 and M2 are from Fig. 1. Erosion rates marked LA are Late Amazonian, H-A are Hesperian through Amazonian, M-LN are Middle through Late Noachian, and LN are Late Noachian erosion rates rates (sources and additional explanation from [1].

In contrast to these slow rates, erosion rate estimates for the Middle and Late Noachian are around 1 m/Myr. Shorter timescale estimates (200-300 Myr) may be about 3 times faster than longer estimates over 500 Myr to 1 Gyr (Fig. 2, marked LN and M-LN), although the data overlap so they may not be different. We argue that these rates represent true long-term process rates for two reasons. First, the entire period of high erosion rates only occurred over this relatively short period of martian history and second, landscapes dominated by fluvial erosion on Earth have been shown to have relatively short hiatuses that can be averaged out over centuries to thousands of years [4].

These Noachian rates of erosion are 2-3 orders of magnitude faster than Hesperian through Late Amazonian rates and are similar to typical slow continental erosion rates on Earth that are dominated by liquid water calculated over similar timescales [4, 6]. Short-term erosion rates over Myr timescales during this period could be several orders of magnitude faster and thus similar to fast short-term erosion rates on Earth [6]. This similarity argues that Late Noachian erosion on Mars was also dominated by liquid water and that a more clement climate existed at that time [1].

**References:** [1] Golombek M. et al. (2014) JGR 119, doi: 10.1002/2014JE004658. [2] Pelletier J. & M. Cline (2007) Geology, 35, doi:10.1130/G23992A.1. [3] Grant J. et al. (2006) JGR 111, doi:10.1029/2005JE002465 [4] Von Hagke, C. et al. (2014) Geophys. Res. Abs., 16, EGU2014-9160. [5] Sadler P. (1981) J. Geology 89. [6] Portenga E. & P. Bierman (2011) GSA Today 21, 8.