EROSION RATES AND MARS CLIMATE. M. Golombek[1] , N. Warner[1], V. Ganti[2] and M. Lamb[2], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; [2]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125.

Introduction: New erosion rate data during the past 20 Ma from fresh impact craters imaged by the *Opportunity* rover coupled with long-term erosion rates through time better constrain the link with the long-term evolution of climate on Mars. Erosion rates derived from gradational changes at the landing sites are generally 3-5 orders of magnitude lower than the slowest erosion rates on Earth suggesting that liquid water has not been an erosional agent since the Hesperian [1]. In contrast, erosion rates estimated from changes in Noachian age crater distributions and morphologies and denudation events on Mars are comparable to slow continental erosion rates on Earth suggesting that liquid water was an erosional agent [e.g., 1]. Erosion by liquid water is also indicated by valley networks, indicating an enhanced role of fluvial erosion [2], and the occurrence of layered sedimentary rocks [3].

In this abstract, modern era erosion rates are presented that further elucidate the processes and short-term rates of erosion from eolian activity. These rates are compared with rates determined over longer periods and larger spatial scales to better understand the role of hiatuses and spatial averaging in the erosion rate data [4] and derive true average process rates that can be compared more confidently with the operating erosional agent and the climate.

Erosion Rates in the Modern Era: A morphometric and morphologic catalog of ~100 small craters imaged by the *Opportunity* rover over her 33.5 km traverse between Eagle and Endeavour craters on Meridiani Planum show craters in six morphologic classes [5]. The age of each morphologic class of crater has been determined from crater size-frequency distributions of craters in the catalog, on the plains, and the age of the latest phase of granule ripple migration [6]. Very fresh craters (<50-200 ka) have elevated rims, blocky rims and ejecta, and they are superposed on the granule ripples. Moderately fresh craters (~200-600 ka) have elevated rims, partially planed off blocky ejecta, sandy interiors, and ripples that merge with their rims. Fresh craters (~1-3 Ma) have elevated rounded rims, mostly planed off blocky ejecta, blocky inner walls and ripples that merge with their rims. Somewhat degraded craters (~4-6 Ma) have slightly elevated rims, shallow sandy interiors, completely planed off ejecta blocks, and ripples that modify their rims. Moderately degraded craters (~7-9 Ma) have flat rims, no ejecta and ripples that merge with and follow the edge of the crater. Very degraded craters (~10-20 Ma) are rimless very shallow, sandy depressions, with no ejecta.

The rate of degradation and erosion of different age craters calculated from sand filling the interiors, erosion of ejecta blocks, and flattening of rims shows a clear decrease with increasing time. Moderately fresh craters that formed in the past ~200-500 ka have an average degradation rate of ~1 m/Myr. The erosion/degradation rate drops to 0.7 m/Myr for the past 2 Myr, 0.2-0.3 m/Myr for the past 5 Myr, and 0.03-0.2 m/Myr for the past 7-20 Myr (Fig. 1).

This decrease in erosion rate is consistent with simple reduction in scarp slope via downslope creep of material. We have modeled this process by analytically solving a form of the linear diffusion equation 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 [7, 8]. The model accurately predicts the observed decrease in estimated erosion rate from 1 m/Myr at about 1 Ma to about 0.1 m/Myr at ~10 Ma (Fig. 1) and argues that the decrease in erosion rate is simply due to the reduction in slope with time.

Erosion rates as high as 1 m/Ma have been reported for the recent past and probably represents the maximum short-term rate for eolian erosion on Mars. Erosion of ejecta blocks to liberate blueberries around Concepción crater has been estimated at about 1 m/Myr in the past 10 ka [6]. Erosion and smoothing of boulders on a ~1 Ma inactive alluvial fan has been estimated at ~1 m/Ma [10]. Finally young very lightly

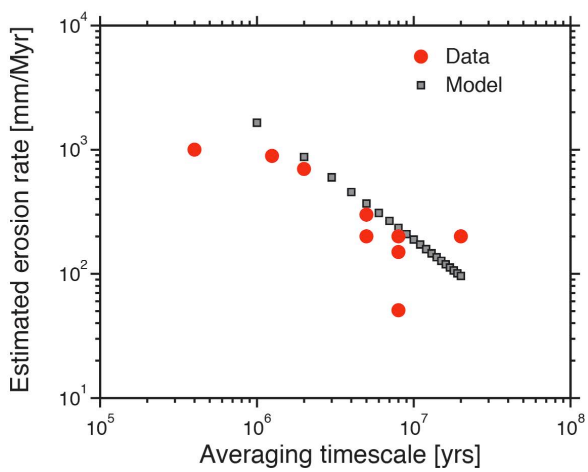

Figure 1. Graph of estimated erosion rate versus the timescale over which the erosion rate is calculated for the past 20 Ma assuming a diffusivity of 10^{-3} m^2 yr^{-1} [2, 9]. Red dots are data from Meridini Planum small craters and smoothing of boulders on a ~1.25 Ma inactive alluvial fan [10]. Black squares are the diffusion model.

cratered layered deposits on Mars in general require erosion rates of roughly 1 m/Ma to be free of craters [3, 11]. High erosion rates in the recent past at Meridiani Planum would be expected from the easily erodible sulfate sandstones, the abundant sand supply, and the evidence for recent mobility of sand [e.g., 6].

Erosion Rates throughout Time: Erosion rates calculated over longer timescales in the Amazonian and Hesperian are even slower than those estimated for the past 10 Myr. Erosion rates averaged over 80-400 Myr (marked 3 on Fig. 2) are derived from the concentration of blueberries at the surface and the degradation of small craters at Meridiani Planum over the Late Amazonian [1] and from cosmic ray exposure ages at Gale crater [12] and are about an order of magnitude slower (~10 mm/Myr) than those averaged over 10 Myr (marked 1 and 2). Erosion rates averaged over the ~3 Gyr from the landing sites [e.g., 1] are even slower (marked 4) with the middle two quartiles at ~1-10 mm/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.

The decrease in erosion rate with increasing time may be due to heavy-tailed hiatuses that separate the actual erosional events. 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) [13]. The similarity of average erosion rates since 3 Ga when measured over 100 Myr and 3 Gyr together with the long spatio-temporal scales of averaging involved in these estimates of erosion rate, argues they are representative of the true long-term process rate [4]. Comparing these rates to the slowest erosion rates on Earth calculated over similar timescales [e.g., 4], shows that the erosion rates on Mars are 3-4 orders of magnitude slower. These rates are too slow for liquid water to be an 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.

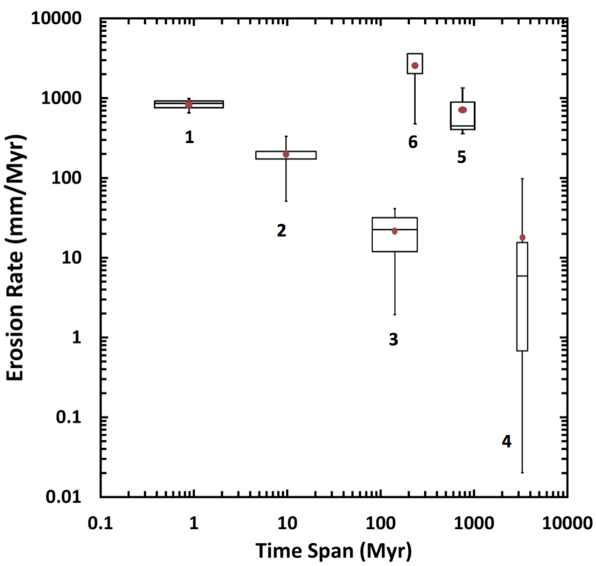

Figure 2. Box and whiskers plot of published erosion rates on Mars versus the timespan over which the erosion rate is calculated. Box height delineates the middle 2 quartiles of the estimates around the median (line), with the whiskers showing the extrema and the dot showing the mean; timespan of the rates in the box defines the width. Erosion rates marked 1 and 2 are from Fig. 1. Published erosion rate data are from sources specified in Table 1 in [1] and from [10], [14] and [12] (converted from scarp retreat to erosion rate of 3 m in 80 Myr), adjusted for the changes to the ages of the Martian epochs reported in [15] for the [16] production function.

In contrast to these slow rates of erosion, 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 5 and 6), 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 so longer term rates are not applicable 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 to derive true long-term process rates [4].

These Noachian rates of erosion are 2-3 orders of magnitude faster than Amazonian rates and are similar to typical slow continental erosion rates on Earth that are dominated by liquid water [18] and are comparable to long-term erosion rates over similar timescales on Earth [4]. 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 [17]. 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.

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