CLIMATE CHANGE ON MARS FROM EROSION RATES AT THE MARS EXPLORATION ROVER LANDING SITES. M. P. Golombek[1], J. A. Grant[2], L. S. Crumpler[3], R. Greeley[4], R. E. Arvidson[5], J. F. Bell III[6], C. M. Weitz[7], R. Sullivan[6], P. R. Christensen[4], L. A. Soderblom[8] and S. W. Squyres[6], [1]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, [2]Smithsonian Institution, Washington, D.C. 20560, [3]New Mexico Museum of Natural History and Science, Albuquerque, NM 87104, [4]Arizona State University, Tempe, AZ 85287, [5]Washington University, St. Louis, MO 63135, [6]Cornell University, Ithaca, NY 14853, [7]Planetary Science Institute, Tucson, AZ 85719, [8]U. S. Geological Survey, Flagstaff, AZ 86001.

Introduction: The geomorphology of a surface and the erosional and depositional processes that have acted on a surface provide clues to the climatic and environmental conditions that have affected it through time. At the five landing sites on Mars (Viking Lander 1, Viking Lander 2, Mars Pathfinder and the two Mars Exploration Rovers), the nature of features observed from the surface, when combined with the regional geologic setting of the landing sites derived from orbital data and ages from the density of impact craters, can be used to infer the net change (erosion or deposition) as a means of quantifying the rates of geomorphic change. Because erosional and depositional processes that involve liquid water typically operate so much faster than eolian processes, the net change in the surface along with the presence or absence of process specific morphologies can be used to infer whether liquid water was involved and thus the climatic conditions. In this paper the surficial geology and gradation history of the surfaces traversed by Mars Exploration Rovers (MER) in Gusev crater and Meridiani are used to argue for a dry and desiccating environment dominated by impact and eolian processes since the Hesperian [1].

Arvidson et al. [2] used Viking Lander 1 images of a crater rim to show that its rim height versus diameter ratio is close to that expected for a fresh crater in agreement with the population of fresh craters seen in orbiter images, thereby limiting the net erosion to less than a few meters over the lifetime of the surface. At the Viking Lander 2 site, inspection of the surface in concert with orbiter images of pedestal craters more loosely limited the amount of deflation to roughly 300 m over the lifetime of the surface [2]. At the Mars Pathfinder landing site, the surface investigated by the lander and rover appears similar to that expected after formation by catastrophic floods and small net deflation of 3-7 cm is indicated by exhumed soil horizons, sculpted wind tails, pebble lag deposits and ventifacts [3]. Because all of these surfaces date from the Late Hesperian or Early Amazonian, the inferred small net change over time coupled with the occurrence of only eolian erosional features argues that the wind has acted solely on the surfaces and by inference that the climate has been dry and desiccating, similar to today, for the past ~3 Ga [4].

In contrast to the small changes to Hesperian and Amazonian surfaces visited by the Mars landers, a wide variety of geomorphic indicators argue that certain older Noachian terrains were subject to a possible warmer and wetter environment in which liquid water was more stable than it is at present. Many large Noachian craters are rimless and have shallow flat floors arguing they have been eroded and filled in by sediment [5]. Erosion of these craters, including many crater lakes, and the formation of valley networks argue for relatively high erosion rates [5,6] involving liquid water, possibly driven by precipitation. The presence of widespread regularly layered sedimentary rocks and distributary, meandering channels have also been used to argue for the persistent flow of water and deposition in standing bodies of water in the Noachian [7,8], a scenario that is also supported by identification of phyllosilicates and sulfates in Noachian and layered terrain by OMEGA [9].

Late Noachian layered sedimentary rocks, examined by Opportunity are "dirty evaporites" that were likely deposited in acidic saline interdune playas [10]. Sediments were subsequently reworked by wind and in some locations surface water and later underwent extensive diagenesis via interaction with groundwater of varying chemistry [11]. The lower and middle parts of these evaporites likely were deposited by eolian dunes and sand sheets, respectively; the upper unit includes small festoon cross beds that indicate deposition in flowing surface water [11]. By analogy with similar deposits on Earth that formed in salt-water playas or sabkhas, deposition of these sediments probably occurred in a wet and likely warm environment in the Late Noachian on Mars.

Surficial Geology of the MER Landing Sites: Spirit's observations of the surficial geology of the cratered volcanic plains at Gusev indicates they were modified chiefly by impact and lesser eolian activity [12,13]. The plains are dominated by shallow circular depressions called "hollows," that have rocky rims and smooth, soil-filled centers. Observations of rock mineralogy, chemistry and texture (from microscopic images) revealed dark, fine-grained olivine basalts with thin coatings of dust and weathering rinds [14]. The basalts appear to have been emplaced as relatively fluid lava flows [15] with vesicular clasts and rare scoria similar to inflated lava flow tops. Observations of the interior of the relatively fresh crater Bonneville indicate that it impacted into a rubble layer locally up to 10 m thick, likely derived from impact gardening of the basalt flows [12,13].

Many of the rocks at Gusev show evidence for partial or complete burial, followed by exhumation [12,13,16]. These include two-toned rocks with a redder patination along their bases, ventifacts that originate from a common horizon above the soil (suggesting that the lower part of the rock was shielded), rocks that appear to be perched on top of other rocks, and some undercut rocks, in which the soil has been removed around their bases. In places where clear evidence for localized deflation is seen, estimated depths of deflation range from 5 to 27 cm [16]. Our interpretation is that excavation during impact deposited ejecta with widely varying grain sizes and fractured rocks, whose fine fraction was in disequilibrium with the eolian regime [12]. Deflation of the ejected fines exposes more fractured rocks, and created a population of perched coarser fragments. The transported fines are trapped within nearby depressions (craters) creating the hollows [13].

Spirit traversed from the cratered plains into the older Columbia Hills (Early Hesperian in age [17,15]). Rocks that make up the Columbia Hills show strong chemical and mineralogic evidence for aqueous processing [18], consistent with an early wet period in Mars history. The existence of “exotic” ejecta on Husband Hill not present on the plains argues for the emplacement of this ejecta on the surface prior to cratered plains basalt flooding and the persistence of the ejecta to the present limits the total erosion to of order meters since the Early Hesperian [19].

The plains surface that Opportunity has explored is dominated by granule ripples formed by saltation induced creep of a lag of 1-2 mm diameter hematite spherules (called blueberries) underlain by a poorly sorted mix of fine to very fine basaltic sand [20]. The hematite spherules are concretions derived from the saltating sand eroding the underlying weak layered sulfate-rich sedimentary rocks. Eolian erosion of the weak sulfate bedrock is also revealed by a number of impact craters in a variety of stages of degradation that were visited by Opportunity. The craters observed range from fresh, relatively unmodified craters such as Vega, Viking and Fram to highly eroded and infilled craters such as Eagle and Vostok and document progressive eolian erosion of the weak sulfate bedrock and infilling by basaltic sand [21]. Counts of these craters including those <250 m in diameter, which are clearly sparse in orbital images, demonstrate that the average surface age of the basaltic sand and granule ripple surface is Late Amazonian [22]. Furthermore, comparison of the measured crater density at Meridiani Planum with Hesperian age surfaces such as Viking Lander 1 and 2, Mars Pathfinder, and Gusev shows dramatically fewer craters. The dearth of craters at Meridiani argues that the entire Hesperian cratering record has been erased, further attesting to the erosion of older Noachian craters and terrain at Meridiani and of layered terrains in general [7].

Erosion Rates at the MER Landing Sites: The observed redistribution of 5-27 cm of ejected fines across the Gusev cratered plains represents the cumulative change of the surface since basalt flows formed the surface at the beginning of the Late Hesperian, or ~3.5 Ga [15]. This net gradation provides an estimate of the average rate of erosion or redistribution via the vertical removal of material per unit time, typically measured on Earth in Bubnoff units (1 B = 1 μm/yr) [23]. An average 10 cm of deflation or redistribution at the site yields extremely slow average erosion rates of ~0.03 nm/yr or between 0.01 nm/yr and 0.08 nm/yr (of order 10^{-5} B, where 1 B equals 1 μm/yr, which equals 10^{3} nm/yr). Deflation and redistribution of a single layer of fines about 10 cm thick would also fill all the hollows [1]. The persistence of exotic ejecta on Husband Hill emplaced prior to the basalt flows of the cratered plains, limits erosion of the Columbia Hills to of order meters [19] since the mapped surface age of Early Hesperian. Erosion of several meters of material since the end of the Early Hesperian (3.6 Ga [4]), yields erosion rates of ~0.8 nm/yr for Husband Hill.

Slightly higher Amazonian erosion rates are implied at Meridiani Planum [1]. The loss of Hesperian craters indicated by the measured size-frequency distribution of craters records erosion loosely bracketed between 10 m and 80 m. Loss of 10-80 m of material at Meridiani Planum since the Hesperian (~3.0 Ga [4]), suggests erosion rates of 3.3-26.7 nm/yr.

Estimates of erosion rates derived in this manner are comparable with those resulting from the observed erosion and modification of young craters and ejecta by the saltating Meridiani sand [1]. The hematite bearing plains have very few impact craters and counts of small craters indicate a surface age of Late Amazonian [22]. In high-resolution images (e.g., Mars Orbiter Camera) the craters appear fresh, but observations by Opportunity suggest they are being eroded and modified by the saltating sand. Opportunity visited about a dozen craters in various stages of erosion and modification. The observed degradational sequence shows that so called “fresh craters” in orbital images constitute a sequence of craters in various states of erosion and infilling [21,1].

Consideration of current crater diameters, original fresh crater depths, and ejecta thicknesses [21], and the amount of erosion and infilling needed to produce the observed modification of craters bounds the amount of erosion to between 1-10 m. Erosion of 1-10 m needed to modify the craters over the Late Amazonian age of the surface (~400 Ma [4]), yields erosion rates of 2.5-25 nm/yr, which are comparable to those estimated from the loss of Hesperian craters.

The concentration of hematite-rich spherules (so called blueberries) on the surface as a granule lag [20], also yields comparable erosion rates. The blueberries make up only 1-4% of the volume of sulfate outcrop exposed in Eagle, Fram and Endurance craters [11], but make up about ~10% of the volume of the upper 1 cm of the sand [20]. For a 1% volume in the outcrop to produce a 10% volume in the upper 1 cm requires about 10 cm of erosion. Because of uncertainties in the volume fraction of blueberries within the overlying strata that eroded away and the fraction of the concretion population that may be eroding with time [20], if the total erosion of sulfates needed to produce the blueberry concentration near the surface were increased to 50 cm, the indicated erosion rate would be only 1.3 nm/yr in the Late Amazonian (~400 Ma).

Discussion: Long term average erosion rates during the Hesperian and Amazonian from deflation and filling of craters in the Gusev plains and those derived from erosion of Hesperian craters, modification of Amazonian craters, and the concentration of hematite-rich spherules in the soils of Meridiani are so low (Figure 1) that they indicate a dry and desiccating climate similar to today's for the past 3.5 Ga. Average erosion rates determined for the Gusev cratered plains (0.03 nm/yr) are comparable to those estimated in a similar manner for the Mars Pathfinder landing site (~0.02 nm/yr) [3] and for the Viking Lander 1 site (~1 nm/yr) [2] and argue for very little net change of these surfaces throughout the Amazonian and much of the Late Hesperian [3] or since ~3.5 Ga [4] (Figure 1).

Average erosion rates indicated from the loss of Hesperian craters, degradation of Late Amazonian craters, and concentration of hematite concretions from the Late Noachian evaporites at Meridiani Planum are around 1-10 nm/yr (Figure 1). These erosion rates are about 2 to 3 orders of magnitude lower than the slowest erosion rates on Earth (including the centers of low relief cratons calculated over comparably times) involving liquid water [23].

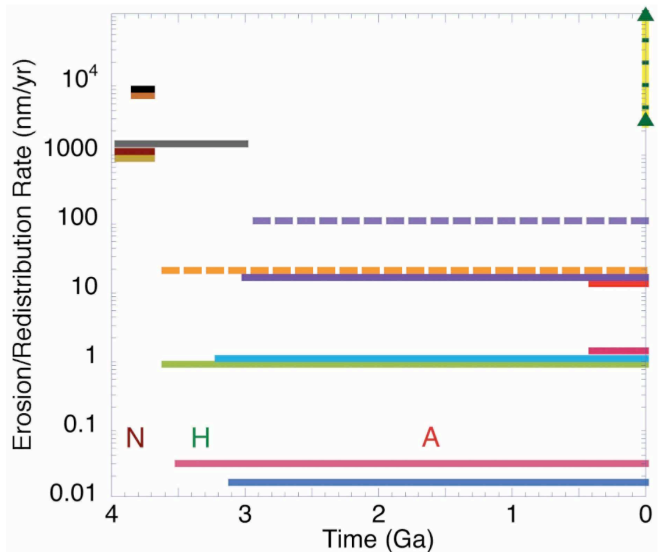

Figure 1: Erosion and redistribution rates versus time for the Spirit and Opportunity landing sites compared with other landing sites and terrains for the three epochs of Mars history: Noachian (N) >3.7 Ga, Hesperian (H) 3.7-3.0 Ga, and Amazonian (A) <3.0 Ga [4]. Noachian rates in black, orange, brown and tan; Noachian-Hesperian rate in grey; Late Hesperian through Amazonian rates in blue, rose, purple and green (and dashed); and Late Amazonian rates in pink and red (see [1] for sources). Vertical green and yellow rates with arrow end point are present day slow continental denudation rates on Earth and present day dust deposition and removal rates (~2-100 B), respectively [1], on Mars from the rovers and as inferred from dust devils observed by Spirit. Average erosion rates from Noachian terrains on Mars are comparable to slow continental denudation rates on Earth, suggesting a wet and warm environment. Average erosion rates after the Hesperian are 2 to 5 orders of magnitude lower and are consistent with the dry and desiccating environment of today.

By comparison, erosion rates estimated from changes in Noachian age crater distributions and morphologies on Mars are 3-5 orders of magnitude higher [5,24] than those derived from the landing sites and are comparable to slow denudation rates on the Earth (~5 B) that are dominated by liquid water [23] (Figure 1). An estimate of the erosion rates applicable to Meridiani in the Late Noachian just prior to when the sulfates investigated by Opportunity were deposited is about 8 B, or 8,000 nm/yr from denudation in western Arabia Terra [24].

Conclusions: An early warm and wet environment in the Late Noachian (>3.7 Ga) on Mars is indicated by Opportunity rover results on sulfate-rich "dirty" evaporites that were likely deposited in acid, saline interdune playas or sabkhas, roughly coeval with a wide variety of geomorphic indicators such as valley networks, degraded craters, highly eroded terrain, crater lakes and widespread layered sedimentary rocks. Rocks that make up the Columbia Hills also show strong chemical and mineralogic evidence for aqueous processing, consistent with an early wet period in Mars history.

Spirit's observations of the surficial geology of the Late Hesperian cratered volcanic plains at Gusev indicate that they were modified only by impact and lesser eolian activity. Localized eolian deflation of 5-27 cm of fines is indicated by two-toned rocks with a redder patination along their bases, ventifacts that originate from a common horizon above the surface, and perched and undercut rocks, and suggests eolian redistribution of an equivalent amount of sediment to fill impact craters to form the ubiquitous hollows. This deflation yields the cumulative change of the surface since the plains were deposited in the Late Hesperian (~3.5 Ga) and yields an average erosion rate of ~0.03 nm/yr.

Slightly higher erosion rates (~1-10 nm/yr) are implied since the Hesperian at Meridiani Planum. Loss of Hesperian craters indicated by the sparsely cratered surface and Late Noachian age of the sulfates suggests 10-80 m of erosion. Modification and erosion of young, Late Amazonian craters by the saltating sand that progressively planes off ejecta blocks, backwastes and covers blocky rims with sand and granule ripples, and fills crater interiors with sand, indicates 1-10 m of erosion and redistribution of sand in the Late Amazonian (since ~0.4 Ga). Concentration of hematite concretions ("blueberries") as a surface lag in the soils indicates 0.1-0.5 m of erosion. These higher erosion rates are consistent with eolian erosion of weak sulfates by saltating basaltic sand.

Long term erosion rates of ~0.01 to 10 nm/yr since the Hesperian are consistent with erosion rates calculated in a similar manner for the Viking 1 and Mars Pathfinder landing sites and are 2 to 5 orders of magnitude lower than the slowest continental denudation rates on Earth. These erosion rates are so low that they preclude liquid water as an active erosional agent and argue for a dry and desiccating climate. Such a climate is also consistent with the lack of chemical weathering affecting olivine basalt; olivine basalt sand; basaltic, non-hydrated dust; the lack of salt leaching of exposed sulfates at Meridinai; and the lack of evidence for erosion by liquid water from the gradation of craters at both landing sites (see discussion and references in [1]).

Erosion rates derived from previous studies of changes in Noachian age crater distributions and shapes and denudation of Terra Meridiani just before the sulfates were deposited are 2-5 orders of magnitude higher (10^3-10^4 nm/yr) than those from the Late Hesperian and Amazonian. These Noachian erosion rates are comparable to slow continental denudation rates on Earth that are dominated by liquid water. Erosion rates this high are consistent with a wet and warm environment in the Late Noachian and the deposition of sulfates at Meridiani Planum in salt water evaporitic playas or sabkhas.

Analyses of the geology and gradation histories of the landing sites and calculated erosion rates indicates the climatic change from wet and likely warm to dry and desiccating occurred sometime between the end of the Late Noachian and the beginning of the Late Hesperian or about 3.7-3.5 Ga.

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