CLIMATE CHANGE FROM THE MARS EXPLORATION ROVER LANDING SITES: FROM WET IN THE NOACHIAN TO DRY AND DESICCATING SINCE THE HESPERIAN. M. P. Golombek[1], J. A. Grant[2], L. S. Crumpler[3], R. Greeley[4], R. E. Arvidson[5], and the Athena Science Team, [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 63135Washington University, St. Louis, MO 63130.

Introduction: Mars Exploration Rover Opportunity discovered sedimentary "dirty" evaporites in Meridiani Planum that were deposited in salt-water playas or sabkhas [1] in the Noachian [2], roughly coeval with a variety of geomorphic indicators (valley networks, degraded craters and highly eroded terrain) of a possible early warmer and wetter environment [3]. In contrast, the cratered plains of Gusev that Spirit has traversed (exclusive of the Columbia Hills) have been dominated by impact and eolian processes and a gradation history that argues for a dry and desiccating environment since the Late Hesperian. This paper reviews the surficial geology and gradation history of the plains in Gusev crater as observed along the traverse by Spirit [4] that supports this climate change from the two landing sites on Mars.

Columbia Memorial Station: The landing site is a generally low relief somewhat rocky plain dominated by shallow circular depressions and low ridges [4]. Rock counts show that ~7% of the surface is covered by rocks >4 cm diameter near the lander, but varies from 5% in the intercrater plains to up to ~35% near the rim of Bonneville crater [5]. The size-frequency distribution of larger rocks (>0.1 m diameter) generally follows the exponential model distribution based on the VL and MPF landing sites [6], although there are far more pebbles at the Spirit landing site.

A vast majority of the rocks appear dark, fine grained, and pitted. Many appear to be ventifacts, with flutes and grooves formed by impacting sand in saltation [7]. Most rocks appear coated with dust and some lighter toned rocks have weathering rinds whose formation may have involved small amounts of water. The chemistry and mineralogy of the rocks described elsewhere (and the pits as vesicles) appear to be consistent with olivine basalts [8] and the soil appears similar to soil elsewhere on Mars [9].

Hollows: Shallow circular depressions, called hollows generally have rocky rims and smooth soil filled centers. Perched, fractured and split rocks are more numerous around hollows than elsewhere and lighter toned (redder) rocks are common near eolian drifts [4]. Hollow morphology and size-frequency distribution strongly argue that they are impact craters rapidly filled in by eolian material. Excavation during impact would deposit ejecta with widely varying grain

sizes and fractured rocks, which would be in disequilibrium with the eolian regime. This would lead to deflation of ejected fines, exposing fractured rocks, and creating a population of perched coarser fragments. Transported fines would be trapped within the depressions creating the hollows. Trenching in Laguna hollow near the edge of the Bonneville ejecta exposed unaltered basaltic fines capped by a thin layer of brighter, finer, globally pervasive dust. The dust-free nature of sediment in the hollows coupled with their uniformly filled appearance implies relatively rapid modification to their current more stable form [4].

Bonneville Crater: Several lines of evidence suggest Bonneville is a relatively fresh crater with thin fill that was formed into unconsolidated blocky debris [4]. The largest rock increases from 0.5 m to 0.8 m to 1.3 m diameter as the rock abundance increases from the discontinuous ejecta, through the continuous ejecta to the rim, suggesting a relatively pristine ejecta blanket with a sharp, easily mapped edge. The rim is ~3 m high and although the crater is shallow (~10 m deep) the rubble walls show no signs of mass wasting and eolian material deposited inside is limited to 1-2 m thickness by protruding boulders. No bedrock is exposed in the walls, even where impacted by smaller craters in the wall. The low depth to diameter ratio of Bonneville and other small craters in and on its walls suggest that they formed as secondary craters [10].

Eolian Activity: The reddish soils appear to be cemented fines and sand (coarse and fine) and granules have been sorted into eolian bedforms. Bedforms consist primarily of meter-size ripples in which the crests have a surface layer of well-rounded coarse sands and the troughs consist of poorly sorted sands with a bimodal size distribution, with modes centered on fine sand (0.1 to 0.3 mm in diameter) and coarse sand to granules (1-3 mm in diameter) [7]. The larger grains are sub-angular to rounded and appear to be lithic fragments. The sand does not appear to be currently active, based on the presence of surface crusts and dust cover on the bedforms and the absence of sand dunes and steep slip faces. Many small rocks appear embedded and cemented in the soil, suggestive of a crusted gravel armor or lag.

Many of the rocks at Gusev show evidence for partial or complete burial, followed by exhumation [4,

7] (Figs. 1 & 2). These include the 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 from their bases. These observations suggest that surface deflation, perhaps highly localized, of 5 to 60 cm has occurred.
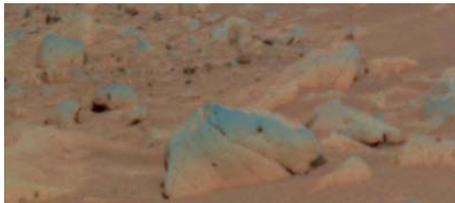
Fig. 1: Two toned rocks with redder patination along their bases.
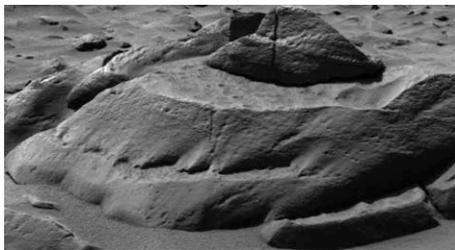
Fig. 2: Rock showing ventifacts at common horizon above its base.

Implications for the Climate: Mapping and crater counts of Gusev show that the cratered plains are Late Hesperian/Early Amazonian in age [11]. The observed exhumation and deflation of the surface thus represents the cumulative change of the surface since ~3.0 Ga [12], as there is no evidence for repeated cycles of burial and exhumation.

The gradation and deflation of ejected fines of 5-60 cm and deposition in craters to form hollows thus provides an estimate of the average rate of erosion or redistribution from the vertical removal of material per unit time typically measured on Earth in Bubnoff units (1 B = 1 μm/yr) [13, 14]. The exhumation of rocks at Gusev suggest of order 10 cm average deflation of the site. Deflation and redistribution of a single layer of fines about 10 cm thick would also fill all the hollows observed, which over 3 Ga yields extremely slow erosion rates of order 0.1 nm/yr or 10^{-4} B (Fig. 3). Erosion rates this slow are comparable to those estimated in a similar manner at the Mars Pathfinder landing site (~0.01 nm/yr [15]) and at the Viking Lander 1 site (~1 nm/yr [16]) and argue for very little change of the surface implying a dry and desiccating environment similar to today's has been active throughout the Hesperian and Amazonian [15] or since ~3.7 Ga [12].

By comparison, erosion rates estimated from changes in Noachian age crater distributions and shapes are 3-5 orders of magnitude higher [see refs in 3, 15] and comparable to slow denudation rates on the Earth (>5 B) that are dominated by liquid water [13, 14] (Fig. 3). The climate inferred from the erosion rates derived from the cratered plains of Gusev therefore are in sharp contrast to the wet and likely warm environment documented in the Noachian age evaporates from Meridiani Planum [1] and the erosion rates for other Noachian terrains in which water was present and the climate may have been warmer and wetter. The erosion rates from Gusev as those from Viking 1 and Pathfinder strongly limit this warmer and wetter period to the Noachian, pre-3.7 Ga and a dry and desiccating climate since.
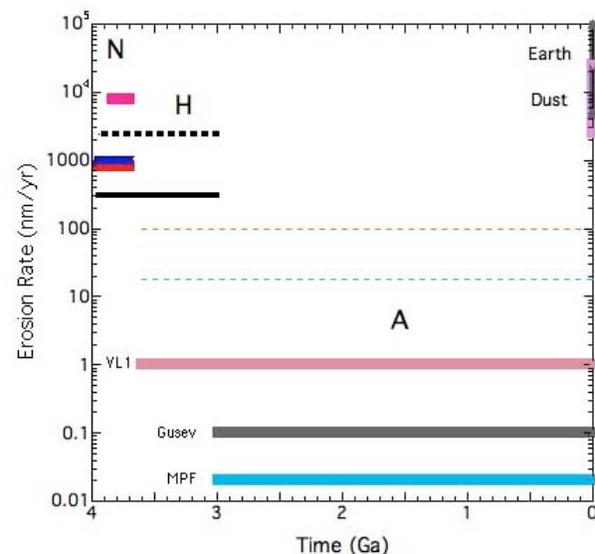
Fig. 3: Erosion rates versus time for the Spirit landing site compared with other landing sites and terrains for the three epochs of Mars history: Noachian (N) >3.7Ga, Hesperian (H) 3.7-3.0 Ga, and Amazonian (A) <3.0 Ga [12].

References: [1] Squyres S. et al. (2004) *Science 306*, 1709-1714. [2] Arvidson R. et al. (2003) *JGR 108(E12)*, 8073. [3] Carr M. (1996) Water on Mars, Oxford. [4] Grant J. et al. (2004) *Science 305*, 807-810. [5] Golombek M. et al. (2005) *LPS XXXVI*, this issue. [6] Golombek M. et al. (2003) *JGR 108(E12)* 8072. [7] Greeley R. et al. (2004) *Science 305*, 810-813 [8] McSween H. et al. (2004) *Science 305*, 842-845. [9] Gellert R. et al. (2004) *Science 305*, 829-832. [10] Hurst M. et al. (2004) *LPS XXXV,* Abs. #2068. [11] Kuzmin R. et al. (2000) *USGS Map I-2666*. [12] Hartmann W. & Neukum G. (2001) *Space Sci. Rev. 96*, 165-194. [13] Judson S. & Ritter D. (1964) *JGR 69*, 3395-3401. [14] Sanders I. & Young A. (1983) *Earth Surf. Proc. Landforms 8*, 473-501. [15] Golombek M. & Bridges N. (2000) *JGR 105*, 1841-1853. [16] Arvidson R. et al. (1979) *Nature 278*, 533-535.