SEDIMENTATION BY IMPACT CRATERING ON MARS. D. M. Burt[1], L. P. Knauth[2], and K. H. Wohletz[3] [1]School of Earth and Space Exploration, Arizona State University, Box 871404, Tempe, AZ 85287-1404, dmburt@asu.edu, [2]same, knauth@asu.edu, [3]Los Alamos National Laboratory, Los Alamos, NM 87545, wohletz@lanl.gov.

Introduction: Four years of exploration by the two Mars rovers Spirit and Opportunity has found excellent outcrops of layered, fine-grained sediments on opposite sides of Mars (Gusev Crater and Meridiani Planum) that resemble each other closely. Common characteristics include fine grain size, fine layering, ubiquitous cross-beds (mainly at shallow angles, but also with apparent trough shapes), salty nature (locally especially sulfate-rich in a surficial zone at Meridiani Planum), enrichment in acid sulfates (identified mainly as jarosite at Meridiani and unspecified inside Gusev) and local presence of tiny spherules in the rock (slightly larger, more abundant, and hematitic at Meridiani). A feature so far unique to Meridiani sediments seems to be local, tiny crystal-shaped cavities; features unique to Home Plate in Gusev include what appears to be a single small impact sag in bedding and slightly coarser grain sizes at the very base of the exposed section (similar, less resistant layered rocks, with one zone highly enriched in silica, appear to lie beneath).

Despite this close family resemblance, layered sediments at the two landing sites have been interpreted as having wholly different origins. For Home Plate, phreatomagmatic volcanic surge deposition is favored [1], with possible eolian sedimentation on top, whereas for Meridiani Planum, the favored explanation [2,3] involves an extremely complex series of events involving acid playa lake sedimentation and salt evaporation, wind erosion, transport, and deposition of mixed soluble salt grains, multiple episodes of ground water rise and fall through these salty sediments, wind erosion of salty sand grains and more evaporation, surface water flow that didn't dissolve any salts, and formation of hematitic concretions over a wide area in highly permeable salt-sands. A more recent suggestion for Meridiani describes it as a super-giant desert oasis, fed by evaporating artesian acid springs from a global-scale confined aquifer [4].

A major problem with these completely different explanations for highly similar rocks is that orbital imaging reveals that they are far from unique [5]. That is, thick erosional remnants of similar-appearing ancient layered rocks rich in sulfates (and with occasional cross-beds visible even in orbital images, and some intervening boulder beds) appear to be widespread in the equatorial regions of Mars, near the topographic edge of the heavily cratered Southern Highlands. These rocks can fill ancient craters to above their rims. The conventional explanations have mainly included some combination of sedimentation by wind, water, glaciation, or explosive volcanism. Beginning with talks in 2004, we suggested a far simpler idea – impact surge sedimentation [6,7] caused by intense impact cratering, probably during the Late Heavy Bombardment at about 3.8 Ga. This simple explanation is consistent with the highly cratered surface of Mars and accounts for virtually all features observed to date, without the improbabilities and inconsistencies of alternative explanations. An objection often voiced for this explanation is that there are virtually no terrestrial analogs, owing to constant tectonic and erosional destruction of continental soft layered rocks, including those derived from occasional impacts. Surge deposits associated with recent volcanic and nuclear explosions therefore provide the best observable terrestrial analogs. Ancient lunar impact materials probably provide an unacceptable analog owing to the Moon's lack of atmosphere and subsurface volatiles.

On frozen, dry, yet volatile-rich Mars, with its virtual lack of tectonics, rainfall, or chemical weathering, impact-derived fine sediments appear subject only to extremely slow erosion by the wind. The distal facies of an impact surge cloud derived from a frozen, salty and/or briny basaltic target could account for all of the sedimentary features observed by the rovers [6]. Likewise, phenomena associated with Fe-rich vapor condensation in the steamy, salty surge cloud could explain the blue-gray hematitic spherules at Meridiani, including their uniform sphericity and size, general lack of clumping, Ni-enrichment, high temperature origin indicated by shiny (specular) hematite, and huge lateral extent [6]. The ubiquitous acid sulfates can be explained via either direct acid condensation in the sulfur-rich surge cloud or by oxidation of impact-excavated sulfides [7]. Diagenesis and weathering (including preferential frost leaching of chlorides, possibly leaving the Meridiani crystal cavities) followed impact deposition.

Home Plate area, Gusev Crater: Cross-bedded sediments in this area have been related [1] mainly to explosive interactions of basaltic magma with briny groundwater (phreatomagmatic eruptions). Evidence in favor of this volcanic surge hypothesis is the generally basaltic nature of the fragmental rocks, what appears to be an isolated bedding sag ("bomb sag") resulting from a piece of ballistic ejecta, the non-horizontal nature of much of the bedding (original dip is common in surge deposits) and the local presence of extremely silica-rich fragments reported from a low area called "Silica Valley" (stratigraphically beneath Home Plate proper). These rocks are presumed to record the effects of hydrothermal alteration. Finer grained rocks higher on Home Plate have been described as having a possibly eolian nature [1], despite their lack of large dune forms, perfect conformity with the steeply dipping surge beds beneath, and apparent lack of a means of lithification (wheras damp surge beds are basically self-cementing).

Other problems with the volcano hypothesis include the complete lack of volcanic features in the vicinity (no evident explosion craters or maars, tuff rings, cinder cones, lava flows, or other volcanic constructs) and the lack of direct signs of hydrothermal alteration (no quartz veins, alteration haloes, or siliceous mounds, for example). Also, hydrothermal alteration of basalt typically doesn't produce highly siliciceous rocks – rather it forms blue-green and green trioctahedral clay minerals and micas, plus epidote and possibly albite. Finally, given that impacts can cause them, small pieces of ballistic ejecta and hot springs alteration are not exclusive to exploding volcanoes, as was inferred.

All the rocks imaged by the Spirit Rover to date are fragments, and range from accumulations of large blocks to very fine-grained cross-bedded sediments. Given a lack of evidence that the siliceous rocks formed by alteration of basalt in place, they may represent a mechanical mixture, excavated by impact nearby. The simplest hypothesis is that all of the detrital rocks seen to date are impact-derived, some possibly from a local source. In addition, highly vesicular impact ejecta blocks could consist of fragments of congealed impact melt rather than lava.

Meridiani Planum: Available evidence generally fails to support the extremely complex series of aqueous and eolian events inferred to have formed the layered rocks at Meridian Planum [2,3]. The beds are flat-lying and salty, as in a playa lake, but none of them resemble lake beds or evaporite beds, in that they appear sandy and invariably cross-bedded. The cross-bedding mostly does not resemble that in dunes. The salt mixture, interpreted to consist mainly of nearly insoluble Ca-sulfate and highly soluble Mg-sulfates, seems unlikely for in-situ evaporation (instead it resembles a mechanical mixture), as does the near lack of chloride salts (despite a high Br/Cl ratio suggestive of extreme fractional crystallization of chloride salts). The highly acid lake or ground waters needed to precipitate jarosite appear incompatible with the highly fragmented and reactive basaltic (basic) regolith and sands of Mars. The failure of soluble salts to recrystallize into larger crystals is inconsistent with repeated brine immersion, as is the continued friability and high permeability of the beds. On Earth, recrystallized salts in evaporite beds are among the least permeable rocks known (best cap rocks for oil and gas deposits; used for storage of petroleum, gas, and radwaste).

Inferred surface flow of salty sands in water currents appears inconsistent with the horizontal nature of the surface and the lack of a braided stream pattern or other channels (not to mention solubility problems for the salts). The sole evidence for such surface flow, alleged trough-shaped cross-beds or "festoons" appear ambiguous in origin (they also form in surge deposits) and many appear to be simple artifacts of the downward viewing angle of the PanCam. An aqueous concretionary origin for the hematitic spherules is inconsistent with their perfectly spherical shape, their failure to clump together in masses, their strict size limitation of about 5 mm, their uniform and extremely widespread distribution in the rocks, their Ni-enrichment, and their apparent high temperature origin (high content of specular or blue-gray hematite). Actual hematitic concretions tend to be reddish-brown lumps or ellipsoids, commonly of highly irregular shape, size, and distribution. The spheroids at Meridiani in many respects resemble widely-distributed accretionary lapilli formed by terrestrial impact craters, such as Sudbury and Chicxulub, and the cross-bedded sediments resemble distal surge deposits formed by volcanic or nuclear explosions. The Meridiani surface appears to have been reworked many times by late impact events, redistributing hematitic spherules (as at Victoria Crater).

Conclusion: Existing explanations for Home Plate and Meridiani Planum sediments contain inconsistencies. Occam's razor suggests that these and many other higher-elevation, finely-layered, cross-bedded ancient rocks of Mars could have formed as impact-derived sediments, mainly impact surge and/or fallout deposits. Intense impact cratering on a planet with an atmosphere and abundant subsurface volatiles should have deposited such rocks in great abundance. Reworking of impact-derived sediments by wind, water, glaciers, explosive volcanism, and later impacts is certainly not excluded, wherever evidence directly supports it.

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