MARS AND THE LATE HEAVY BOMBARDMENT: 2011 UPDATE. 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: Martian impact cratering can probably be assumed to date from the same episode of bombardment that cratered the Moon (the so-called Lunar Cataclysm). Based on dating of returned samples of lunar impact melts, this episode has been assigned to the approximate interval 4.0-3.8 Ga. The Late Heavy Bombardment (LHB) on Mars and other terrestrial planets, if it occurred, presumably spanned the same geologically short time interval.

Much current and past geological literature on Mars tends to minimize the effects of cratering, or implicitly assumes that the bombardment of Mars was diffusely continuous from its formation at about 4.5 Ga until about 3.5 Ga, an interval called the Noachian. In light of the LHB model, the Noachian interval of Mars may actually have been quite short, with the record of the first half-billion years having been largely destroyed or buried.

The preservation of martian craters from about 3.8 Ga onwards implies that Mars has largely been dry and cold since then. Other than continued cratering at a reduced rate, the major planetwide process appears to have been extremely slow erosion and deposition by the wind. Important local contributions were made by basaltic volcanism, landslides and debris flows, ground ice (leading to terrain softening), glaciers (including rock glaciers), catastrophic flooding in outflow channels, minor surficial melting and sublimation, and extremely minor chemical and physical weathering. Still, the ancient craters remain, and cratering remained a major process, as revealed in detail by the wanderings of the two rovers (scattered metallic meteorites, crater wall exposures of sediments, and local ejecta).

The catastrophic cratering of the LHB, in addition to completely resurfacing the planet, should have resulted in loss of hydrosphere and atmosphere to space. How then to explain the widespread evidence of ancient drainage networks, crater lakes, buried clay horizons, and surface sulfates (including acid sulfates)? These features are widely cited as evidence that Noachian Mars was warm as well as wet, and furthermore was literally bathed in sulfuric acid, supposedly (acid fog model) owing to atmospheric enrichment in volcanogenic sulfur dioxide (SO_2) to provide the greenhouse warming that carbon dioxide (CO_2) couldn't.

Inasmuch as these "warm, wet, acid" geological features coincide in time and space with the cratering of the LHB, the simplest hypothesis (think Occam's Razor) would be that they are directly related. That is, the LHB itself is sufficient to explain most of them, especially their transient nature, although local volcanism, especially in the Tharsis region, was occurring at the same time, and gradually waned afterwards.

Impact-related Alteration and Salt Reworking. Before the onset of the LHB (i.e., prior to about 4.0 Ga), Mars presumably had more of an atmosphere and hydrosphere than at present; it also appears to have had a magnetic field (but none since). Given its distant position relative to the Sun, and inability to retain a thick atmosphere, most surface water was probably present as ice, nevertheless. Freezing, then sublimation of surface and subsurface water, as an alternative to liquid water evaporation, would concentrate and crystallize soluble salts, sulfates first (because they are the least soluble) [1].

Following each major impact, or at the height of the LHB (when many smaller impacts followed in close succession), enough steam should have been generated to create a temporary greenhouse, and condensation of and alteration by this steam is adequate to explain Noachian water-related features – widespread clays with some carbonate minerals, drainage networks, and ephemeral lakes. If the impact target was sufficiently enriched in iron sulfides or various sulfate salts, the steam condensate would have been acid (i.e., acid rain). However, such acidity would have been ephemeral too, given that Mars consists largely of basic silicates rich in MgO, FeO, and CaO. That is, the liquid acid would have neutralized itself rapidly against basaltic rock, unless flash freezing or evaporation preserved the acid in solid form as ferric acid sulfates, such as those observed by the two rovers. Another way to create this mine dump mineralogy [2] would be for the impact to scatter shattered iron sulfides, which could later oxidize during damp diagenesis (as suggested by Roger Burns). Neutral salts could similarly result from impact scattering of salty target materials or flash evaporation and freezing of brines. The important point is that highly unstable acid surface waters are NOT required to make acid and other sulfate salts (so-called "evaporites"), because salty impact deposits could have derived their salts via impact reworking of salts of various origins from various target areas [1].

By the time of the near-surface geological interval able to be investigated by the two Mars rovers (i.e., by the tail end of the LHB or Noachian), much of the martian hydrosphere and atmosphere had presumably already been lost to space (via impact erosion), and Mars would already have been colder and dryer. Smaller, younger impacts would have simply reworked older, thicker impact deposits. Impact-generated steam would probably condense as snow or ice, at least far from the impact site, especially for smaller impacts. Lack of exposure to liquid water presumably accounts for the excellent preservation of features (including metastable acid sulfates), lack of salt recrystallization, and minimal erosion at the two rover sites.

Impact Density Currents and Spherules. Unlike the Moon and Mercury, Mars has two important features in common with Earth - the presence of an atmosphere and of abundant subsurface volatiles (mainly water on Earth, mainly ice on Mars). These features imply that the LHB on Mars should have been distinct from the LHB the Moon and Mercury. (Young martian rampart craters, believed to form via impacts into an icy substrate, reflect this distinctness.) Contrary to what is commonly implied, its dilute atmosphere and abundant ices do not mean that ancient Mars resembled ancient Earth, which planet has always been far larger and closer to the Sun.

On Earth, cross-bedded fine-grained sediments, locally containing various types of small spherules (glassy condensates and accretionary lapilli), are known to be deposited via explosions that vary from nuclear to volcanic to impact-derived. These explosion-deposited sediments (for volcanism called base surge or, more recently, pyroclastic density current deposits) can greatly resemble sediments deposited by flowing water or wind, a fact that has led to multiple misattributions [3]. In places, small radial scours caused by vortices, or bomb sags caused by the landing of ballistic ejecta, or overriding of obstacles and deposition on slopes (original dip), can help identify such sediments. In this regard, a deep scour is present at the top of a large cross bed in the Burns Cliff exposure, Endurance Crater, Meridiani Planum, a bomb sag has tentatively been identified in the cross-bedded sediments at Home Plate, Gusev Crater, and original dip appears common in deposits both in Gusev (Home Plate area) and Meridiani (e.g., where salty sediments appear to have overridden enormous, ancient Endeavor Crater).

These deposits formed by explosions can vary from wet to dry, depending on the initial steam content. Spherical accretionary lapilli typically form in relatively wet deposits, via condensation of sticky steam onto particles in a turbulent, dilute density cloud. Accretionary lapilli, unlike sedimentary concretions, tend to be strictly size and shape limited and unclumped; they also can contain high temperature minerals. Millimetric spherules of unspecified composition occur in a distinctive horizon beneath Home Plate in Gusev Crater; somewhat larger (up to about 5mm) and more abundant spherules occur in cross-beds in various near-surface horizons all along the Opportunity Rover traverse in Meridiani Planum. The most common (at least 50%) phase in these lapilli appears the crystalline, specular, high temperature form of hematite (so-called gray hematite, with detected enrichment in Ni); their blue-gray color in synthetic color images lead to the spherules initially being called “blueberries”. Other than some doublets and a linear triplet, the spherules tend to be unclumped and uniform in size (within a given horizon or erosion area); they show no evidence of concentration or growth or clumping by moving or mixing groundwaters. Wind erosion has exposed them as a lag deposit across Meridiani Planum, where they may have been impact reworked, in part.

Impact Glass Alteration. A common phase in basaltic explosion deposits (phreatomagmatic types, wherein steam explosions result from explosive mixing of basaltic magma and water) is yellow-orange palagonite, or hydrated and oxidized volcanic glass. Palagonite, or allophane, a similar phase, is believed to be common on Mars. Rather than forming by volcanism, palagonite (or allophane) could have originated by hydration and oxidation of impact glasses in steamy impact explosion clouds. Gray or specular hematite could also have formed in this fumarole-like environment.

Terrestrial impact cratering commonly results in silica alteration and deposition by hot springs. Such alteration, followed by impact scattering, could account for the silica-rich fragmental horizon identified beneath Home Plate, Gusev Crater. This horizon occurs above the one containing the spherules.

Conclusion: Deposition by dilute impact-related density currents seems to require either a volatile-rich target or an existing atmosphere or both, and Mars had both. By the tail end of the LHB, when the cross-bedded distal impact deposits (our interpretation [4]) and spherules at Meridiani Planum and Home Plate (Gusev Crater) presumably formed, Mars was already dry and cold. Available surface evidence at both Meridiani and Gusev gives no indications of flowing or standing surface water. Mars is still an impact-dominated planet, and many of its most interesting features apparently date from and could have resulted directly from the LHB.

References (most omitted)**:** [1] Knauth, L.P. and Burt, D.M. (2002) *Icarus 158*, 267. [2] Burt D.M et al. (2006) *Eos*, *87*, 549. [3] Burt D.M. et al. (2008) *JVGR*, *177*, 755. [4] Knauth L.P. et al. (2005) *Nature*, *438*, 1123.