SEDIMENTARY CONCRETIONS VS. IMPACT CONDENSATES: ORIGIN OF THE HEMATITIC SPHERULES OF MERIDIANI PLANUM, 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]School of Earth and Space Exploration, Arizona State University, Box 871404, Tempe, AZ 85287-1404, knauth@asu.edu ,[3]Los Alamos National Laboratory, Los Alamos, NM 87545, wohletz@lanl.gov,.

Introduction: Although they have been labelled aqueous concretions [1], the "blueberries" or Ni-enriched hematitic spherules found by the Mars rover Opportunity at Meridiani Planum little resemble typical terrestrial concretions, including concretions locally disseminated in the Navajo Sandstone of Arizona and Utah, with which they most commonly have been compared [2]. Similarly, the flat-lying, finely layered, sulfate-rich clastic rocks containing the Mars spherules, with their intricate patterns of low-angle cross-beds, little resemble the eolian quartz sand dunes of the host Navajo Sandstone, although they have likewise been attributed to wind (and locally, flowing water: [1]). These interpretation problems (and many more: [3,4]), were implied by Pancam images taken up to three years ago. Later imaging involving probably millions of tiny spherules further emphasized their astounding uniformity in size and shape.

Owing to possible problems with the eolian/aqueous interpretaion, alternative explanations were sought. Given the impact-dominated nature of Mars, and the lack of evident volcanism anywhere in the Meridiani vicinity, the most logical alternative appeared to be some combination of impact phenomena [3,4]. The distal facies of an impact surge cloud (analogous to volcanic/pyroclastic surge or nuclear explosion surge) appears adequate to explain all of the bedding features [3]. Likewise, as discussed here, phenomena associated with vapor condensation in the surge cloud could explain the hematitic spherules, including their uniformity and huge lateral extent. The saltiness was explained by some combination of impact excavation of salts present in the regolith (probably beneath ice), plus weathering of impact-excavated sulfides [4]. Diagenesis and weathering would have followed impact deposition.

Sedimentary Concretions: Concretion growth is fairly well-understood and documented.

Size. Concretions precipitate from aqueous solution during diagenesis (chemical change) of an already-deposited rock; their limiting size is therefore related only to the supply of chemical reactants (via fluid movement or diffusion through a stagnant pore fluid) and to the location and timing of nucleation. Inasmuch as concretions are matrix-supported, they can reach very large sizes (up to centimeters or even meters in diameter), typically intermixed with much smaller sizes. In contrast, the Meridiani spherules are highly limited in diameter, with virtually all under 5 mm.

Shape. Inasmuch as bedding controls fluid flow and chemical diffusion, concretion growth is typically affected by the sedimentary fabric of the enclosing rock. In strongly bedded rocks concretions tend to be notably flattened or elliptical, and to be restricted to certain beds. They also grow as highly irregular shapes or masses. In contrast, virtually all Meridiani spherules are close to perfectly spherical, despite the extremely strong sedimentary fabric of their host rocks.

Clumping. Concretions nucleated in close vicinity very commonly grow together in clumps of 2, 3, or many individual nodules of random mutual orientation and degree of intergrowth; clumping is especially evident near sites of abrupt chemical change, such as redox fronts or where different brines have mixed. In contrast, Meridiani spherules are only very rarely clumped in apparent doublets and only one or two linear triplets have been imaged (out of possibly millions photographed). No large clumps (>3) or masses or sites of abrupt chemical change (apparent reaction fronts) have been imaged. In other words, Meridiani rocks display no evidence of brine migration or mixing.

Host rocks. Concretions are typical of somewhat permeable clastic sedimentary rocks (e.g., sandstones, siltstones, and shales). The extremely low permeability of mature shales is presumably a late diagenetic feature (i.e., is acquired during or after concretion growth). Diagenetic chert concretions are also typical of many carbonate rocks, whose diagenetic history also involves late reductions in permeability. Other than celestine nodules, presumably formed by simple evaporation of water near the gypsum-rich edges of playa lakes, we are unaware of anything resembling concretions formed diagenetically in terrestrial evaporites, presumably because rapid salt crystallization (and the resulting interlocking texture) implies zero permeability almost from the beginning. Forming sedimentary concretions in the salt-rich Meridiani beds therefore strikes us as highly improbable–the salts, even if wind-blown grains originally, should have recrystallized rapidly when exposed to an aqueous solution.

Composition. In keeping with their sedimentary origin, concretions tend to have a fairly simple mineral composition – commonly calcite, microcrystalline quartz (chert), or hematite or goethite. More rarely, they may consist of other carbonates, iron sulfides, or simple sulfates. Given their slow growth from aqueous solution, concretions would not be expected to contain high concentrations of unusual trace elements, such as the Ni reported to be enriched in the Meridiani spherules [5]. Given that Ni^{2+} cannot be oxidized in aqueous solution, it should not substitute for Fe^{3+} in hematitic concretions, especially given that it partitions into Mg^{2+} minerals such as sulfates and clays. This also applies to absorption. (Some Ni^{2+} goes into hematite at high temperatures, but this is irrelevant for concretions.)

Navajo Sandstone concretions (Moqui marbles). Unlike the so-called Burns Formation of Meridiani, the Navajo Sandstone of northern Arizona and southern Utah consists of eolian quartz grains of uniform permeability. Locally, it contains uniformly–sized and spaced spherical hematitic (and goethitic) concretions [2]. As is typical of concretions elsewhere, these weather out of the rock, and where they litter the ground they can resemble the “blueberries” of Meridiani. However, outcrop examination almost anywhere will reveal that these actually are typical concretions – greatly non-uniform in size (locally up to many cm), locally flattened or highly irregular in shape, very commonly clumped together (including in huge masses or aggregates), and concentrated at reaction fronts, both along and across strike (with non-concretionary sandstone just beyond). Mineralogically, they barely contain enough hematite to cement the quartz grains together. Their resemblance to the Meridiani spherules is entirely superficial. A rover traverse of 10 km has revealed only very slight lateral changes in size.

Impact Condensates: Little is known about possible vapor condensates resulting from a large meteorite impact on Mars. What can be said is that the products of vapor condensation should be widely distributed, spherical, and severely limited in size (because, like hailstones, they are being supported by a turbulent cloud, and will fall if they get too large). This description fits the Meriani spherules exactly.

Direct condensates from vapor. During the impact, much of the impactor and everything in the direct target area can be vaporized, including Fe-rich silicate rock and its contained oxygen. Possible direct vapor condensates range from metals from metallic vapor (such as the millimetric iron spherules common around Meteor Crater, AZ), to quenched liquids (e.g., silicate glass spherules found on the Moon), to crystalline solids (e.g., ice, as in terrestrial hailstones, or crystalline hematite, possibly formed as in fumaroles). Other liquid condensates might include (depending on conditions) molten Fe-sulfides, molten salts, brines, or liquid water. Given the icy and salty nature of the Martian regolith, condensation of a brine appears most probable. Steam condensation to pure liquid water would be difficult on modern Mars, (icy hailstones should form instead, owing to low pressure), but higher past atmospheric pressures plus salts make liquid condensation less of a problem for Meridiani.

Accretionary lapilli. Condensing liquids are sticky, and the usual result in a particle-rich cloud is the formation of accretionary lapilli, nucleated on a wet particle (note: in volcanology, a lapillus is a pebble-sized clast). These spherules accrete or grow from the inside out, like a rolled snowball, and consist mostly of solid particles. Their inherent stickiness, in addition to diagenetic overgrowths, could account for rare doublets (well-documented in terrestrial ejecta) or very rare linear triplets. Depending on the uniformity of the surge cloud, they may or may not show visible concentric layering in cross section. They are far and away the most typical products of condensation in a particle-rich cloud, and commonly form on Earth via both impacts and explosive volcanism. They should also be common on icy, salty Mars, and might be enriched in Ni from either a metallic impactor or a metal sulfide-rich target [4]. Contrary to what has been claimed, unless they are somehow reworked, accretionary lapilli commonly are distributed within a matrix (as are the spherules at Meridiani), instead of occurring in a distinct layer.

Conclusions: The Meridiani hematitic spherules do not appear to be sedimentary concretions – they are far too uniform in their shape, size, and distribution, and their Ni-enrichment is difficult to explain by any sedimentary process. If they are instead condensation/accretion products resulting from impact [3], the crystalline hematite could represent oxidation of iron, glass, or molten sulfide–rich spherules, or more likely, of normal Fe-rich accretionary lapilli. Alternatively, the spherules might reflect accretion of crystalline hematite flakes that grew directly in the steamy surge cloud. That would make them actual hematite hailstones. A rare metallic impactor, or an unusually Fe-rich target, might account for the apparent uniqueness of the Meridiani hematite region [3]. On the other hand, the recent web report of hematitic spherules half a planet away in typical surge beds at “King George” in Gusev Crater (Home Plate area) suggests hematitic impact spherules might be relatively widespread on Mars, but too poorly exposed or not abundant enough to be detected from orbit.

References: [1] Squyres S.W. et al. (2004) *Science, 306*, 1731. [2] Chan M.A. et al. (2005) *GSA Today, 15*(8), [3] Knauth L.P. et al. (2005) *Nature, 438*, 1123. [4] Burt D.M et al. (2006) *Eos, 87*, 549. [5] Yen A.S. et al. (2005) *Nature, 436*, 49.