ORIGIN OF LAYERED ROCKS, SALTS, AND SPHERULES AT THE OPPORTUNITY LANDING SITE ON MARS: NO FLOWING OR STANDING WATER EVIDENT OR REQUIRED.

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Introduction: The "shallow acid sea-evaporite-concretion" interpretation for features observed at the Opportunity landing site on Mars [1] contains so many contradictions and problems that an alternative explanation seems necessary. Compelling evidence for past surface water has long been known, as recently summarized in [2], but the early warm, wet interval which allowed this apparently was short-lived. Loss of most of the surface water from the planet and subsequent freeze-down left residual water deep in the subsurface, probably in the form of ice, concentrated brines, and hydrated salts [e.g,, 3,4]. Large impacts [5] into a mega-regolith containing ice, brine, and salts could have produced stratified deposits with the character observed by the Opportunity landers. This mechanism provides a simple alternative explanation to the extraordinary "evaporating acid sea" process, which process would not have produced the observed set of features, but, instead, an entirely different set.

Problems with the "Shallow Sea" Hypothesis:

Acid-base imbalance. The surface and subsurface of Mars apparently has far more finely divided basaltic rock than it does liquid water, and this has been true for a very long time. The Mg,Ca,Na-rich basaltic rocks should then control the pH of any seas and groundwaters to neutral or alkaline, rather than acid, conditions. Concentration of dilute sulfuric acid by acid brine freezing [2] does not obviate this fundamental imbalance. The volcanic "acid mist" model sometimes invoked for sulfate formation on surfaces (of zero volume) is inadequate for volumetric acidification of seas or lakes (or groundwaters) for the same reason. The very existence of neutral salts indicates that acids **were** neutralized.

Lack of massive sulfides. By far the most common way to make jarosite is by local humid oxidation of sulfides such as pyrite or pyrrhotite. Add too much water and the jarosite dissolves incongruently, leaving behind hematite or goethite. Weathering of rare, huge uplifted Rio Tinto-like seafloor hotspring deposits of massive sulfide to produce acid, clay-lined rivers is uncommon even on Earth, and there is no evidence for such a feature on Mars. Formation of minor jarosite in situ, by damp oxidation of minor sulfide disseminated in the host rock, seems far more reasonable.

Hematite plus jarosite. If the hematite "concretions" formed by reaction of neutral ground waters with acid-precipitated jarosite nodules, as claimed, it is unlikely that there would be abundant jarosite left. In addition, jarosite typically forms crusts instead of nodules. "Liesegang rings" or color bands that represent a local acid-base or redox reaction front for the hematite-precipitating reactions have not been observed. All beds have a similar reddish color and this is incompatible with reactive fluids moving laterally through them.

Lack of clays. Igneous rocks do not dissolve congruently in acid – the Al and some of the Si are left behind as clay minerals such as smectites or kaolins. A longstanding claim of TES and now miniTES is that there are few, if any, clay minerals at Meridiani Planum. A jarosite-depositing acid lake should have produced abundant clay minerals. Instead, fresh basaltic sand is cited as a common constituent of the bedded rocks [1]. The apparent lack of clays is fatal to scenarios involving acid surface fluids.

Lack of mud cracks, ripple marks, and old shorelines. Bedding-controlled dessication cracks and ripple marks on bedding surfaces, such as would be expected for shallow waters that dried up episodically, are apparently lacking. The cross-bedding observed is not uniquely aqueous. The few polygonal cracks seen are **not** bedding controlled and could well be related to impact or other tectonic processes. Stepped surfaces of old shorelines, formed as the putative sea dried up, are not present. Instead, the erosion surface of Meridiani Planum appears to be remarkably flat and uniform.

Incompatible mixtures of sulfates (lack of "bathtub rings"). Mg-sulfates are the **most** soluble evaporitic sulfates, and Ca-sulfates are the **least** soluble [6]. Layered evaporites cannot be dominated by both Mg- and Ca-sulfates. Any selective evaporation process in a lake or sea should produce "bathtub rings" where the least soluble salt (typically gypsum) is precipitated first on the outside, and the most soluble last (typically halite, or, on Mars, hydrohalite) in the center (bull's-eye pattern). Therefore, if a mixture of salts of vastly different solubilities occurs in the layered rocks, it is more likely to have been deposited mechanically than chemically.

Local Br enrichment without chlorides. Bromide-enriched salts are so soluble that they are incredibly rare. Their apparent presence mixed with much less soluble sulfates is incompatible with the proposed evaporation process, because Br is concentrated in brines only during fractional crystallization of chloride salts. Abundant chloride salts should be present together with the Br, but are not. Again, mechanical emplacement from elsewhere seems indicated.

Spherule sizes, shapes, and spatial distribution. The hematitic spherules ("blueberries") have been interpreted as concretions, but unlike all known terrestrial concretions formed via chemical nucleation during flow of groundwater through layered sediments, they are uniformly spherical (as opposed to "spheroidal", a more inclusive sedimentological term), uniform in their size distribution (concretions have no implicit restrictions as to maximum or minimum size), and uniform in their distribution in the rocks (concretions commonly are concentrated in specific beds or along reaction fronts). The frequent analogy to hematitic spheroids in Utah and Arizona's Navajo Sandstone [7] is inappropriate because these vary widely in size and shape, are non-uniformly distributed in their parent units, formed along oxidation fronts, consist mostly of quartz sand, and were deposited by fluids of extremely low iron content (for comparison, basaltic lapilli on Mars might contain 20% original FeO). Unlike in terrestrial concretions, "doublets" and especially "triplets" are rare on Mars and the triplets line up in a straight line instead of forming at random angles. Clumps of four or more spheroids growing together to form larger concretions are common on Earth, but are not seen in the putative martian concretions. The uniform distributions in size, shape, and space suggest to us formation and winnowing via some physical, rather than purely chemical process, as seen in hailstones, impact spherules, and accretionary lapilli. For example, doublets are well known in impact spherules [8], and, conceivably, rare co-linear triplets might form as well.

Lack of strong concentric layering and of host-rock inclusions in spherules. The apparent rarity of concentric layering in broken spherules imaged to date might also suggest impact spherules instead of accretionary lapilli (they are not mutually exclusive). Hematitic concretions formed by groundwater flow through granular rock should be dominated by grains of the host rock, as menioned above for sandstone, but this feature is lacking. Spherules or lapilli condensed in a dilute turbulent cloud have no such restriction. Accretionary lapilli could be composed of particles so fine that they would not be visible at the scale of the the images transmitted.

Nature of cross-bedding. The finely layered martian sediments display cross-bedding at all scales and angles, including the giant, high-angle cross-bed recently imaged at "Burns Cliff" in "Endeavor Crater." The cross-bedding was initially ascribed to flowing water, despite a lack of channels or flute clasts. It is now at least partly acribed to dunes migrating across a dried lake bed [1]. Base surge deposits commonly exhibit fine layering and cross-bedding at all scales and angles [9], obviating the need for hypothesizing both dry and wet environments at the same time and place.

Alternative Impact Hypothesis: The ancient Noachian surface that surrounds and presumably underlies the Meridiani landing site rocks contains abundant impact scars, at all scales and of various ages. The Gusev Crater or Spirit landing site contains abundant basaltic ejecta (whereas lake beds were expected), as do prior landing sites. Proposing that the finely layered rocks at the Meridiani site also formed as a result of impact processes provides a simpler, alternative explanation [10,11]. Two of us have proposed that devolatilization and freeze-down of early Mars, possibly partly caused by impacts, led to the concentration of ground ice, deeper Ca-rich, near-eutectic brines, and still deeper salts in the subsurface regolith [3,4]. Later impacts into volatitile- and salt-rich targets redistributed the salts and brines across Mars, probably heterogeneously [3,4]. The layered rocks seen at Meridiani Planum could well have formed at this stage, with their distinctive bedding features caused by base surge processes [9]. Mechanical mixing of pulverized and vaporized rock, salts, brines, ices, and iron-rich impact spherules in surge beds could account for most the chemical incongruities cited above [10,11]. During the next 3-4 billion years the more hygroscopic and deliquescent salts (mainly chlorides) would dissolve and flow back into the regolith, and any reduced iron in spherules and reduced iron sulfide in ejecta would be oxidized, forming hematite and jarosite, respectively. The impact hypothesis appeals to us in its simplicity and in accounting for all features observed to date. The apparent rarity of hematite-spherule surficial deposits on Mars could, in part, relate to the rarity of surfaces not littered with ballistic ejecta from younger impacts or not covered by younger volcanic or eolian deposits.

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