IMPACT SPHERULES VS. DIAGENETIC CONCRETIONS: ORIGIN OF SEDIMENTS ON MARS.

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Introduction. After the two Mars Exploration Rovers MER A (*Spirit*) and MER B (*Opportunity*) landed on Mars in 2004, with a main goal of searching for evidence of past water, their observations were largely interpreted in light of this goal. Interpretations based on observations made by the Mars Science Laboratory (*Curiosity*) after 2012 reflect the same goal. The landing sites were chosen based on necessarily ambiguous orbital indications of past water activity. The ground observations themselves do not require sediment deposition by liquid water, and many features (e.g., primitive basaltic sediment compositions, persistent acidic salts and olivine, abundant amorphous materials and immature clays, nearly ubiquitous low-angle cross-bedding, low sediment bulk densities, high sediment friability, relatively high Ni content, dominantly planar scouring at unconformities, evidence of original dip, abundant impact spherules of various types - see below) can actually be interpreted as good evidence against water deposition, despite claims to the contrary.

Features that might be unique to aqueous deposits appear to be completely lacking. These could include actual fissile shale beds, channel-confined conglomerates, small channels themselves and scours such as flute marks, strong lateral facies changes related to streams or lakes, post-depositional dewatering textures such as sediment deformation and load casts, oscillation ripple marks made in shallow water, discrete evaporitic salt layers, and finally, actual mud cracks (polygonal cracks in dried mud that are clearly filled with the overlying sediment, not joints filled with later diagenetic mineral veinlets). The putative “dessication cracks” at Gale [1] [2] appear to us to be vein-filled joints, by this criterion. Note that polygonal joint systems can form in many rock types, including base surge deposits, by various geologic processes, including simple cooling.

To us, the ground observations to date most strongly support rapid sediment deposition as the result of ancient (Noachian) impact bombardment. This was followed by variable local hydration and alteration of sediment by neutral ground waters (at Gale) and by surficial acid condensates, then erosion and redistribution of early sediment by later impacts and wind.

Unlike many other planetary bodies, early Mars had an atmosphere and, by most indications, abundant water during its heavy bombardment stage. The water could have been present as ice or liquid brine or even hydrated salts or clays for this hypothesis. A warm and wet early Mars is not required. An atmosphere plus impact-vaporized solids or liquids would have caused turbulent density currents to form that, for huge impacts, could travel long distances (hundreds to thousands of km) while depositing cross-bedded layers of gravel, sand, and dust. Such bedded impact deposits superficially resemble terrestrial deposits deposited by water or wind, or that were formed by volcanic blasts and pyroclastic density currents (volcanic base surge deposits) [3] vs.[4]. They also characteristically form during tests of nuclear weapons, which is where they were first observed, named, and described. This superficial resemblance to normal sediments has led to many mistaken geologic field interpretations on Earth [5].

Despite the thin present Martian atmosphere, a possible modern analog of this depositional process has recently been described [6] as LARLE (low aspect ratio layered ejecta) that can surround young impact craters at a distance. The inference is that a volatile-rich target generated base-surge type density currents, whose thin and easily-eroded deposits were partially preserved owing to their youth.

Spherules of Meridani Planum and Gusev Crater. MER B (Opportunity) landed on what was inferred to be a giant hot spring system, as revealed by an extensive specular hematite infrared signature on the orbital TES instrument. This type of hematite typically forms in hot hydrothermal waters or fumarolic vapors, prompting the hot spring hypothesis. Instead, MER B imaged a Meridiani Planum surface covered with numerous small (< 7 mm) shiny spherules rich in gray specular hematite, that were shortly dubbed “blueberries” owing to their size and blue-gray appearance (their blue aspect being partly an imaging artifact, or caused by tarnish). This accumulation was a lag deposit formed by surficial wind erosion of the friable cross-bedded sandstones that contained these dense spherules in dispersed form.

We immediately suspected that these spherules could represent iron-rich accretionary lapilli formed by sticky particle accretion to a nucleus in a turbulent, steamy, salty, acid cloud resulting from one or more major impacts into the Martian surface, because Mars is more iron-rich than Earth, and hematic coatings even occur on terrestrial lapilli. The basaltic sandstones containing them would be formed by related density currents. Spherioidal accretionary lapilli are well known from volcanic blast beds and also have been recognized from major impact sites on Earth. Their concentric formation mechanism is analogous to forming (by freezing) spherical hailstones in the moist upper levels of a turbulent thundercloud. The possibility of "hematite hailstones" was discussed by the MER science team but instead they were called normal sedimentary concretions formed during diagenesis.

Obvious problems with this hypothesis were that actual diagenetic sedimentary concretions, rather than spherical, tend to be highly irregular in shape and, at the very least, tend to be distinctly flattened along more permeable bedding planes (e.g., so-called Moqui marbles that can form in homogeneous aeolian sandstones), tend to be highly variable in size, rather than sorted to a uniform small size range, tend to be concentrated along chemical reaction fronts, generally related to fluid oxidation or mixing, tend to clump together at such sites (unlike merely a couple of loose doublets and a single triplet found at Meridiani), and tend to be made of low temperature minerals, not dense specular hematite. Furthermore, the bizarre diagenetic scheme devised for their formation and growth was improbably complex and inconsistent with available observations. Nevertheless, the concretion hypothesis for the mysterious Meridiani spherules quickly became dogma and has remained so.

Very similar but rarely-mentioned shiny spherules are locally abundant in shallowly cross-bedded sediments found as an erosional remnant perched on a site called Home Plate in Gusev Crater, as imaged by the Spirit Rover (MER A). These sediments, which in most respects, including their spherules, appear similar to those at Meridiani, were designated as volcanic base surge deposits on the basis of a single putative bomb sag (actually a basaltic rock on a projecting horizontally-layered ridge, as imaged from above). This hypothesis ignored the problem that there were no obvious volcanic eruption sites in the vicinity, and it ridiculously seemed to imply that ballistic ejecta result only from volcanic blasts, and not from impact-caused blasts (the site is in Gusev Crater and is surrounded by innumerable impact craters of various sizes and ages). An impact origin for these sediments and their contained spherules, with or without the dubious bomb sag, has always seemed far more logical to us.

Concretions of Gale Crater. The recent description [7] of abundant types of perfectly normal sedimentary concretions formed by complex aqueous diagenesis of fine-grained, commonly cross-bedded sediments deep inside Gale Crater, as imaged by MSL, the Mars Science Laboratory (Curiosity Rover), seems to reopen the spherule debate. The concretions occur in various sizes and shapes and appear to have formed at various times from various fluids and in various horizons. They commonly clump together. Although some are misleadingly referred to as "spherules," they actually appear to be rounded equant lumps or lumpy aggregates. Unusually, some broken "spherules" appear to be hollow inside, possibly owing to growth around a bubble or late dissolution of the core. Other concretions are referred to as "flat," and display strongly preferred growth along bedding planes. Still others are referred to as "dendritic" owing to their unusual shapes. A final, very common, classification is referred to as "irregular" which apparently covers any shape not easily classified by one of the previous ones.

Although no comparison with Meridiani spherules is made in the paper, many Gale concretions retain evidence of remnant host rock laminations (a feature lacking in the Meridiani spherules), but none display evidence of differential compaction (compaction of surrounding sediment after the concretions formed). Such differential compaction is a type of dewatering texture (lacking at Gale and elsewhere). Despite sparse evidence, the authors conclude that the concretions were formed during late-stage diagenesis, after full compaction had already occurred, although this hypothesis seems unlikely from a permeability standpoint.

Although larger spherules are rare in Gale, typical sub-millimetric glassy impact melt spherules are common in sandy exposures [8]. Cross-bedded and other sediments in Gale tend to be finer-grained than at Meridiani Planum and Gusev Crater (Home Plate), implying that large accetionary lapilli could have dropped out before distal, dusty density currents reached Gale Crater (and presumably died in its depths).

Conclusions. There are no sedimentary features at the three sites visited by Mars rovers that require deposition by liquid water, although some later neutral liquid ground water, inside Gale Crater at least, seems to be needed for diagenetic formation of veins, various clay minerals, and diverse concretions. Acid, salty steam seems implicated in the formation of density currents resulting from major impacts, especially those that deposited shiny hematitic accretionary lapilli (spherules) at Meridani Planum and in Gusev Crater. Descending acid condensates, generally in minor amounts, seem implicated in the near-surface deposition of acid sulfate salts and possibly silica at all three sites. Based on available evidence, impact cratering could have remained as a dominant form of sediment deposition on early Mars, even for Gale Crater.

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