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Possible mechanism for explaining the origin and size distribution of Martian hematite spherules

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ABSTRACT

Mysterious hematite spherules, also known as “blueberries”, observed at Meridiani Planum on Mars have been widely accepted as concretions which are formed by precipitation of aqueous fluids. One of the biggest mysteries is that all observed Martian blueberries are limited in size with maximum diameter of 6.2 mm. In contrast, terrestrial concretions are not size limited. In this article, we discuss significant differences between Martian blueberries and Earth concretion analogs. Puzzling observations from Mars Exploration Rovers Opportunity and Spirit suggest that the spherules may not be concretions but are cosmic spherules formed by ablation of meteorites. The perfect spherical shape of spherules, their observed size limit, and all other physical properties are easily explained by a meteorite ablation model. Evidence that some of these spherules are only few years old strongly constrains concretion and other growth mechanisms related to aqueous processes that require the existence of water on Mars in its recent history. The large number of hematite spherules in Meridiani Planum may be due to a big rare iron meteorite impact event in this region sometime in the past.

1. Introduction

On January 24, 2004, the Mars Exploration Rover Opportunity landed in Eagle crater on Meridiani Planum. This site was chosen because earlier MARS Global Surveyor TES data showed it to contain large amounts of the mineral hematite (Christensen et al., 2000). Because on Earth, hematite is formed through aqueous processes, the discovery of hematite in Martian soil suggests the past presence of water. One of the surprising discoveries of the Rover was the presence of large numbers of hematite spherules (Klingelhöfer et al., 2004; Squyres et al., 2004a; Squyres et al., 2004b), now commonly known as “blueberries”. Initial scientific investigation (McLennan et al., 2005; Squyres et al., 2004a; Squyres et al., 2004b) suggested that the blueberries and their fragments are the primary carriers of hematite at the site. The hematite in the Martian soil is mostly observed on the surface, and the subsurface soil in the excavated trenches is dominated by basaltic sand. The blueberries are typically 4 mm in diameter, mostly perfect hard spheres with very fine grain and no observed internal structure. The entire inventory of the observed spherules is suggested to be within the upper 1 cm thickness of the surface soil (Calvin et al., 2008; Christensen et al., 2004; McLennan et al., 2005; Squyres et al., 2004a; Squyres et al., 2006a; Squyres et al., 2004b).

For the past 9 years, most of the scientific community has widely accepted that the Mars blueberries are concretions (Calvin et al., 2008; Christensen et al., 2004; Glotch and Bandfield, 2006; Glotch et al., 2006; Kula and Baldwin, 2012; McLennan et al., 2005; Sefton-Nash and Catling, 2008; Squyres et al., 2004a; Squyres et al., 2006a; Squyres et al., 2004b; Squyres et al., 2009; Squyres et al., 2006b). Possible concretion terrestrial analogs have been found in southern Utah, in the Jurassic Navajo Sandstone (Chan et al., 2004; Chan et al., 2005), and in Lake Brown, Australia (Bowen et al., 2008). However, a comparison of the iron oxide concretions from the Navajo Sandstone and images and scientific data made available by NASA reveals remarkable differences between the terrestrial concretions and Martian blueberries. Here we present evidence that indicates that the blueberries are not concretions and suggest that instead they are of meteoritic origin.

2. Physical properties of Earth concretions and Martian spherules

By definition, a concretion is a compact mass of mineral matter, usually spherical or disk-shaped, embedded in a host rock of a different composition. Concretions are formed by precipitation of mineral matter from the liquid phase, usually about a nucleus. The physical mechanism of nucleation and growth is required for the formation of concretions. This growth mechanism puts no limit on

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the size of the concretion. Concretions on Earth are large (centimeters to meters) (Abdel-Wahab and McBride, 2001; Chan et al., 2004) and seem to have no size limit. In contrast, all blueberries found on Mars are limited in size (diameter less than 6.2 mm) (Calvin et al., 2008; McLennan et al., 2005; Sefton-Nash and Catling, 2008). Apart from the size difference, concretions come in variety of shapes and are rarely perfect spheres (Bowen et al., 2008; Chan et al., 2004). The interior of a Mars spherule is hard, uniform, and extremely fine grained (Arvidson et al., 2004; Herkenhoff et al., 2004). Terrestrial concretions are not spherical but metallic looking shells, which enclose the grains of the host matrix as part of the concretion mechanism (Bowen et al., 2008). Fig. 1 shows the picture of few terrestrial concretions from Jurassic Navajo Sandstone, southern Utah. The concretions have been cut in half to reveal the interior structure. The figure illustrates that these concretions are not perfect spheres and do not show a size limit. The sizes of these Earth spherules are also much larger than the Martian spherules which have the upper size limit of 6.2 mm . The interior structure of the concretions is different than the outer layer.

Micro-Raman spectroscopy was used to identify the chemical compositions of terrestrial concretions. Raman spectra were measured at multiple locations on all the samples. Fig. 2 shows representative Raman spectra of terrestrial concretions showing the spectral differences between the interior brown grains and outer black grains. It is shown that the brown grains located inside the concretions are quartz. For comparison, Raman spectra of rose quartz, hematite and goethite minerals are also shown. The Raman spectrum of rose quartz is identical to the Raman spectra of brown grains from inside of the concretions which confirm that the interior structure is mostly quartz, with grain size of the order of 150 μm. The black grains located at the outer layer of concretion also show dominating quartz peaks along with additional Raman peaks associated with goethite. The Raman analysis indicates that the exterior shell layer is mainly quartz with a very thin coating of goethite. Our Raman analysis of iron oxide concretions is consistent with that of Knauth et al. (2005). Concretion cements around the grains of the host matrix, and hence grains of host matrix are always included in the terrestrial concretions (Bowen et al., 2008). The concretion mechanism does not explain or account for the perfectly size-limited, homogeneous hematite spherules excluding the grains of host soil found on Mars.

Another important fact is that on Earth erosion plays a critical role in the formation of concretions by removing the surrounding matrix and releasing the concretions. Therefore, the Earth concretion analogs are dull metallic objects that show signs of erosion and evidence of pitting. Often the outer surface also shows flow patterns, indicating the presence of aqueous media (Bowen et al., 2008; Chan et al., 2004). The erosion process also dictates that the Earth concretions are several thousand years old (Bowen et al., 2008).

Another puzzle is that Martian blueberries are mostly concentrated within 1 cm of the surface (Arvidson et al., 2004; Bowen et al., 2008; Squyres et al., 2004a; Squyres et al., 2004b). This observation is not consistent with the formation of mineral precipitation from ground-water. As the level of ground-water goes down, the concentrations of dissolved minerals are expected to increase in the subsurface soil. For the terrestrial concretions, relatively larger numbers are observed in the deeper soil (Bowen et al., 2008) below the 1 cm top layer. However, no blueberries were observed in the deeper soil when trenches were excavated on Mars (Christensen et al., 2004; Squyres et al., 2004a; Squyres et al., 2006a). This observation suggests that a physical mechanism capable of depositing spherules from the top is more favorable than mechanisms involving ground-water.

Previous research suggests (Squyres et al., 2004a; Squyres et al., 2004b) that hematite-rich spherules are embedded in the rock and erod from them. One of the images (Fig. 3) taken on sol 251

Fig. 1. Earth concretions analog. Picture of Earth concretion analog samples from Jurassic Navajo Sandstone, southern Utah (courtesy William Mahaney). Samples have been cut in half to show the interior structure.

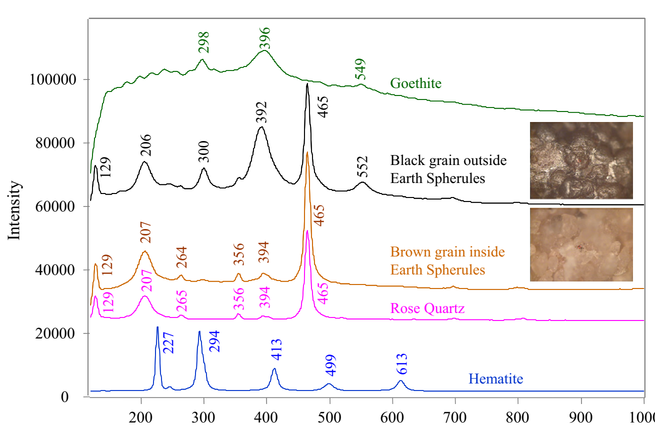

Fig. 2. Raman analysis of Earth concretions. Micro-Raman spectra of inner and outer grains of Earth concretions measured with 785 nm laser excitation. The Raman spectra of interior brown grains are identical to that of reference Raman spectrum of rose quartz. The black grains in the outer layer are goethite coated quartz.

Fig. 3. Blueberries on Wopmay Rock suggesting they landed from the top. Wopmay rock observed on sol 251 showing hundreds of fully exposed blueberries on it. Concentration of blueberries in region A is higher than that away from the rock (region B), and no blueberries are observed in the shadow of the rock as shown in region C; suggesting that these blueberries fell from the top. Image courtesy of NASA/JPL.