HEMATITE "MICROBERRY" WIND RIPPLES: EOLIAN CONDITIONS FOR A TERRESTRIAL MARTIAN ANALOG FROM THE JURASSIC NAVAJO SANDSTONE, UTAH-ARIZONA.

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Introduction: A unique set of conditions produces complex coarse-grained wind ripples that include tiny, iron oxide micro-concretions from eolian Jurassic Navajo Sandstone of the Vermillion Cliffs at the Utah-Arizona border. Although the micro-concretions occur in many Navajo Sandstone exposures, this local site has the convergence of: contrasting physical conditions between well-cemented concretions and weakly cemented host rock; weathering processes to release the concretions from the host rock; and sufficient wind to concentrate, accumulate, and work the concretions into ripple forms. Terrestrial concretions are already established as analogs to the hematite-enriched spherules (blueberries) on Mars [1-4], but this special occurrence also shows remarkable morphologic resemblance to wind-blown regolith at Meridiani Planum (Fig. 1).

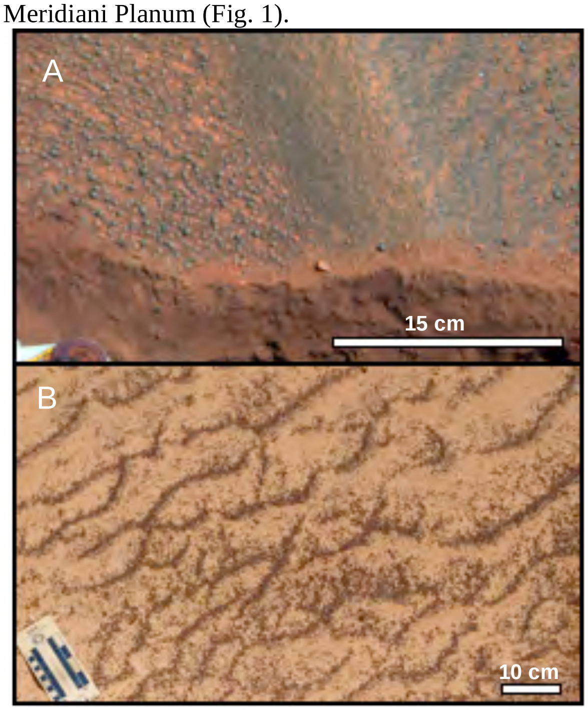

Figure 1. Representative micro-concretion ripples from (A) Meridiani Planum, Mars imaged by the MER Opportunity (Pancam stretched false color image, Sol 367B, Seq P2550; photo credit: NASA/JPL/Cornell) and (B) Jurassic Navajo Sandstone of Northern Arizona.

Micro-concretions typically form by diffusion and where they are well cemented, they can weather out of chemical reaction fronts as discrete solid spherules (Fig. 2), loosened from the host eolian sandstone. The micro-concretion spherules of this study have an average diameter of 1.5 mm. Micro-concretion grain mass averages 0.0056 g. Average grain mass of medium-grained quartz sand derived from the host rock is ~0.000075 g. The grain mass ratio is ~74:1 (Fig. 3).

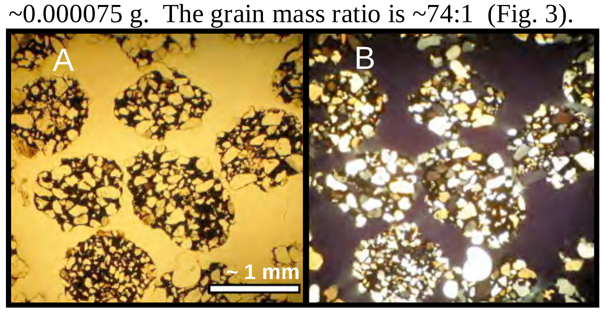

Figure 2. Petrographic thin section of spheroidal micro-concretions in plane light (A) and crossed nicols (B). Dark hematite cement encases eolian quartz (light) grains.

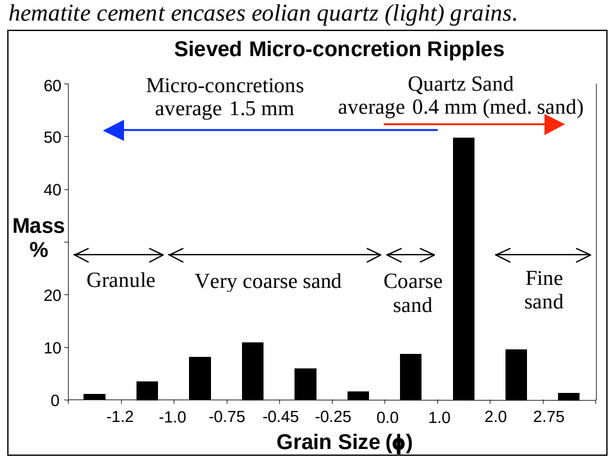

Figure 3. Grain size distribution of quartz sand and micro-concretions from sieved samples. Grain size scale is non-linear.

Discussion: The micro-concretions can be worked into coarse-grained ripples in shallow depressions and alcoves where winds are strong or funneled. Predominately westerly winds entrain sand to actively abrade sandstone walls to release micro-concretions. These micro-concretions are then organized into trains of straight to sinuous, in-phase, coarse-grained micro-concretion ripples and catenary out-of-phase ripples (Figs. 1 and 4). These are local, complex, and transient wind ripples that possess irregular and bifurcating crests. Ripple trains extend in pathways up to 14.5 m and are characterized by 5 mm thick accumulations of micro-concretions on the windward/stoss sides and crests of the asymmetric ripples (Fig. 4). On the leeward faces and in the ripple troughs, micro-concretion accumulations are scattered and generally only a surface coating. The average micro-concretion ripple index (wavelength to height) is 18.

Micro-concretions demonstrate reverse grading formed by two likely mechanisms, possibly in combination: 1) a common sieve or "Brazil nut" effect such that the micro-concretions typically "float" on top of the finer-grained quartz sand, or 2) motions typical of coarse-grained ripples in which the larger micro-concretion grains move in creep and are overrun by the ripple itself [5, 6] (Fig. 4). Wind gusts (measured at a height of ~5 cm from the air-sediment interface) that move the micro-concretions by low saltation are about 6.6 m/s, although micro-concretions can be moved in creep if sufficient sand is in traction at sustained wind speeds of ~4.5 m/s. Trenches through the complex concretion ripples reveal distinct, narrow (~5 mm) bands of micro-concretions representing sand burial of previously deposited micro-concretions during periods when wind speeds are sufficient to transport and deposit sand but are unable to mobilize micro-concretions.

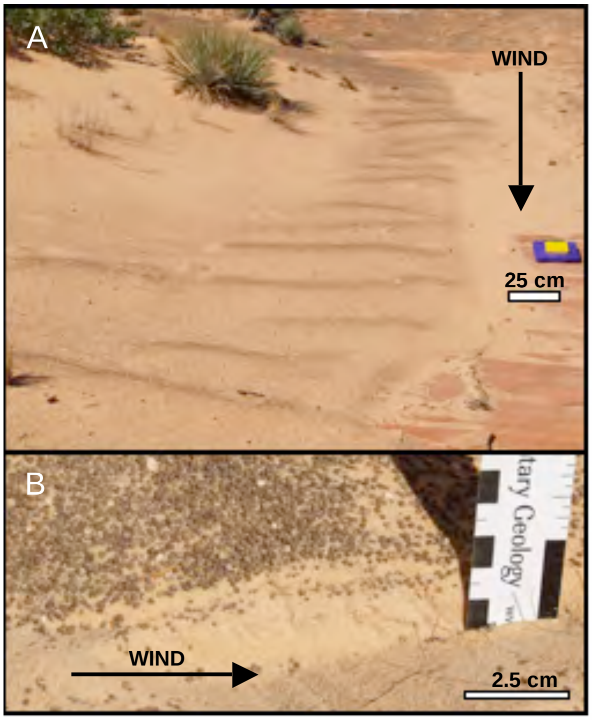

Figure 4. Navajo Sandstone micro-concretion ripples. (A) Predominately straight crested ripple train. (B) Micro-concretions form a thin (~5 mm) veneer on the windward/stoss side of ripples (B).

Aerodynamics of the terrestrial micro-concretion ripple systems reveal several characteristics:

1. Micro-concretions can be moved by eolian transport (requiring ~4.5 m/s wind, 5 cm above the surface). Larger sizes of concretions (e.g., 1+ cm sizes), that are very abundant, are too large for wind transport and hence form deflation lags instead of being reworked and transported.
2. Relatively tight micro-concretion population distribution allows wind to sort out very fine size differences to work the concretions into ripple forms. Inverse grading is enhanced by the density/specific gravity contrast of the coarse-grained micro-concretions vs. the fine-grained quartz sand. The largest micro-concretions mobilized (up to ~2 mm) tend to occur on the very crest of the ripples, as is typical of coarse-grained ripples [5, 6].
3. Strong wind gusts (possibly seasonal), eddies, and primary vs. secondary wind regimes give rise to the complex ripple forms in combination with limited area, limited sand supply, and other unusual geomorphic variables.

At Meridiani Planum, the mass ratio between the 1.5 mm Mars spherules (dubbed "microberries" by the NASA Mars Exploration Rover team [7]) and the basaltic, 100 micron sand likely ranges from 3000:1 to 6000:1, depending on the amount of hematite in the 1.5 mm concretions. This Mars ratio is higher than the terrestrial example, where the micro-concretions contain finer grained hematite and have incorporated quartz grains. However, extremely strong Martian winds [8] and very abundant microberries allow for better developed and more pervasive concretion ripples on Mars.

Conclusions: The remarkable Jurassic Navajo Sandstone micro-concretion accumulations and complex ripples are a useful terrestrial analog. This analog demonstrates the history of diagenesis and concretion formation in the host rock, stages of weathering, and final modern wind processes. The limited localized occurrence of these ripples is indicative of the number of environmental conditions required for their formation. These circumstances may be related and scaled to geologic and atmospheric conditions on Mars where similar ripples are far more abundant and exhibit a wider variety of ripple types (e.g., asymmetrical straight, sinuous and catenary ripples) in a stronger wind regime.

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References: [1] Chan et al. (2004) *Nature*, 429, 6993, 731-734. [2] Catling, D.C. (2004) *Nature*, 429, 6993, 707-708. [3] Chan et al. (2005) *GSA Today*, 15, 8, 4-10. [4] Ormö et al. (2004) *Icarus*, 171, 295-316. [5] Sharp, R.P. (1963) *J. Geology*, 71, 617-636. [6] Anderson R.S. and Bunas K.L. (1993) *Nature*, 365, 6448, 740-743. [7] Squyres et al. (2006) *Science*, 313, 5792, 1403-1407. [8] Jerolmack et al. (2006) *JGR*, 11, E12.