Note: Text from the document we received is given in *blue italics*. Our comments are in non-italicized black.

Response to *Response to "Impact Origin of Sediments at the Opportunity Landing Site on Mars"*

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The impact origin for Meridiani deposits proposed by Knauth et al.[1] is inconsistent with the observed distribution and composition of hematite-rich spherules in the deposits, and with the style of cross-stratification observed. It is also inconsistent with regional geologic relationships.

The chance to address the discussion by Squyres et al. gives us an opportunity to expand our interpretation using their new analyses recently published in *EPSL* and discussed here. We conclude that all features observed to date at the Opportunity landing site are more reasonably explained by impact surge than by either their original interpretations in *Science* or by the new interpretations in *EPSL*.

Knauth et al.[1] suggest that the distinctive spherules in the deposits observed by Opportunity are either accretionary lapilli or condensation spherules derived from an iron meteorite impactor. If either hypothesis were correct, the spherules should show concentrations along bedding planes. Such sorting occurs due to hydraulic segregation of particles with different settling velocities, and commonly concentrates out-sized particles along bedding planes in successions of flow-emplaced strata (Lowe et al.[2], see also Fig. 5b of Knauth et al.[1]). In all outcrops observed to date by Opportunity, spherules are highly dispersed relative to bedding. The bedding planes observed at Meridiani represent surfaces formed during reconfiguration of the bed in response to scouring during flow bursting, migration of three-dimensional bedforms with frontal scour pits, and/or decreases in the sediment concentration of the flow. This conclusion is independent of flow mechanism. However, spherules are dispersed nearly uniformly across all strata, even at obvious erosional surfaces in the sequence at Burns Cliff[3]. They are not concentrated along these surfaces, despite clear evidence that the surfaces truncate spherule-bearing strata and represent erosion of spherule-bearing sediments. The spherules therefore must have developed in situ, after deposition of the sediments.

The Lowe et al. (2003) reference and Fig. 5b of Knauth et al. (2005) refer to spherules that settled through sea water and are thus inappropriate for assessing sorting or bedding characteristics of base surges. The analogy to Mars is only with regard to the size, shape, and immense areal distribution of the spherules. The suggested hydraulic segregation due to differences in settling velocities in granular multiphase flows is not supported by theory

or observation. The experiments and theory of Bagnold (1954, 1956) have instead been successfully applied to base surges (Wohletz, 1998). Accretionary lapilli in terrestrial surge deposits have been observed concentrated along bedding planes, but they are also commonly dispersed throughout beds (e.g., McPhie et al., 1989). In some cases, they even collect near the middle or top of beds (e.g., Waters and Fisher, 1971). Accretionary lapilli from the Chixculub impact are dispersed in amounts of 3% to 20% throughout the matrix of a 2 to 5 meter thick impact surge deposit exposed 330-470 km from the impact site (Pope et al., 2005). Deposition of surge deposits commonly involves scouring rapidly alternating with deposition, even in a single event. Truncation of spherule-bearing strata is therefore completely consistent with surge deposition.

Spherule composition is inconsistent with formation as lapilli or impact spherules. The spherules contain >32% Fe, mostly in the form of crystalline hematite[4-6]. Oxidation of iron-rich basaltic glass particles in accretionary lapilli cannot plausibly produce such a composition; we know of no basaltic liquid that contains such high levels of iron[7].

Mars basalts are much richer in Fe than terrestrial counterparts (e.g., Burns, 1986). Accretionary lapilli composed purely of Shergotty-type martian basaltic glass would have about 20% FeO (Laul et al., 1986). Those formed from dense cumulates of Fe-rich silicates or, especially, of Fe-sulfides (e.g., Burns and Fisher, 1990) could have many times this. Even further Fe-enrichment in the impact surge clouds might be possible through preferential impact volatilization of certain components and in the already-formed lapilli through post-impact (diagenetic) leaching of soluble salts. Metallic oxide phases in explosive plumes separate and condense over a wide range of oxygen fugacity, temperature, and pressure. Hematite particles are known to concentrate in the outer parts of some terrestrial basalt accretionary lapilli (Moore and Peck, 1961). An iron impactor could contribute even more iron. There are thus many sources for iron-rich accretionary lapilli on Mars.

Nickel concentrations rule out an impact spherule origin. Iron meteorites invariably contain >5% nickel[8]; impact spherules from Meteor Crater contain ~7% Ni[9]. At Eagle crater, a spherule-free outcrop surface contained 13.1% Fe and 730 ppm Ni whereas an adjacent spherule-rich surface contained 24.1% Fe and 950 ppm Ni[5], for a difference of 11% Fe and just 220 ppm Ni. Enrichments of 11% Fe from an iron meteorite condensate should introduce >5,000 ppm Ni, far more than observed.

The Meteor Crater spherules in the cited reference are solidified melt droplets, not the condensation spherules we consider. In any case, impact condensation spherules are not just condensates of vaporized impactor but rather develop from condensation of intermixed vaporized target and impactor, with the target material overwhelmingly dominant. Meteoritic Ni is thus diluted enormously in the vapor cloud from which the spherules condense. The Meridiani measurements actually show that "Ni correlates with Fe" going from spherule-poor to spherule-rich areas indicating "similar chemical responses" of Ni and Fe in the spherule-forming process (Yen et al., 2005). This conflicts with the concretionary origin (McLennan et al., 2005) because Ni^{+2}, unlike Fe^{+2}, cannot be

oxidized in aqueous solution (e.g., Takeno, 2005). Therefore Ni^{+2} should not co-precipitate with, and cannot substitute for, Fe^{+3} in any of the insoluble Fe^{+3} minerals jarosite, goethite, or hematite. Target areas on Mars are likely to be Fe, Ni-rich (Burns and Fisher, 1990), so the Ni-Fe correlation is consistent with an impactor or component of the target (or both) being unusually enriched in both Fe and Ni.

Knauth et al.[1] argue that cross-stratification is typical of base-surge deposits. But we reach our conclusions about the implications of cross-stratification at Meridiani on the basis of its detailed geometric properties and within the context of observed grain size and sorting, not simply its presence or absence. We observe small-scale festoon cross-lamination at Eagle crater[10] and high-angle cross-bed sets at least 2 m thick at Endurance crater[3]. All sediments are fine to medium grained sand, and well sorted. The combination of steep foreset dip and textural features implies low velocity, subcritical flows, characteristic of fluvial and eolian transport.

None of the detailed geometric properties of strata at Meridiani are incompatible with base surge deposition (Wohletz, 1998). Indeed, the striking similarity of the sedimentary structures there to those of terrestrial base surges provoked our exploration of this possible origin. High-angle cross bedding of well sorted, fine-to-medium-grained, sand-sized material is common in base surge deposits. Allen (1984) noted difficulties with directly interpreting surge-generated structures using bedforms shaped by flowing water and related them instead to depositional rate, temperature, and moisture. Wohletz (1998) emphasized the controls of grain-size and volume fractions of gas and solids.

Knauth et al.[1] provide no illustration of angle-of-repose cross-stratification from impact-generated base surge deposits, either as evidence of migrating ripples, or as larger dunes.

Impacts on the early Earth were probably as common as those on other Solar System objects, but they and their deposits have been largely obliterated by plate tectonic and erosional activity. More recent examples are also severely degraded, so opportunities to illustrate terrestrial impact surge deposits are limited. Surges result from explosions, so terrestrial volcanic base surges are an adequate analogy for most aspects of impact surges. A high-angle cross-stratified volcanic base surge deposit of suitable scale is illustrated in Fig. 2 in Knauth et al. (2006).

Indeed, where cross-bedding has been observed in volcanic base surge deposits the cross-bed sets are poorly sorted and intimately associated with outsized pyroclastic debris ranging in size from lapilli to bombs. Furthermore, base surge sand waves show significant climb angles, preserve stoss-side strata and the dune crests, and generally have lower foreset angles[11].

These statements derived from Smith and Katzman (1991) apply to a comparison of the proximal, not distal, surge deposits in specific rhyolitic surges in New Mexico and their associated volcaniclastic strata. The authors of the reference specifically note that the criteria may apply “to varying degrees” to other study areas and specifically caution against using grain-size to make distinctions between surge and eolian deposits. Wohletz actually

worked with Smith on the surge deposits cited and emphasizes that the data were not meant to be taken as a generality about surge deposits, especially considering the numerous citations of surge deposit data to the contrary (Wohletz, 1998). Terrestrial base surges elsewhere can be well-sorted (Sheridan and Wohletz 1983) and entirely free of bombs and outsized clasts, particularly in the distal areas.

What Knauth et al.[1] illustrate in their Fig. 3b is a single low-angle scour and fill structure, rather than a series of cm-scale festoon cross-laminae that show multiple sets and multiple truncation surfaces (compare with Grotzinger et al.[3], Fig. 16).

Fig 3c (not 3b, which is a MER image) is an isolated "festoon" structure in a terrestrial surge deposit at the same scale as putative cross-stratification presented in Squyres et al. (2004b) and Grotzinger et al.(2005). Fig. 16 of Grotzinger et al. (2005) is a splendid example of small-scale trough cross-stratification on Earth, but no series of cross-laminae with multiple sets and multiple truncation surfaces similar to it at Meridiani have yet been published or presented. The lines drawn through some of the early MER images (Squyres et al. 2004b) are highly interpretative, do not resemble Fig. 16, and are not apparent to independent observers. Recently publicized "festoons" are simply flat beds and low angle cross-beds making contours on erosional topography (e.g. fig. 1 of Knauth et al., 2006) and are not actual examples of small-scale trough-cross stratification.

Similarly, their Figs. 3a and 4b show low-angle cross-stratification formed by low-relief scour and fill in the upper flow regime, or possibly as antidunes formed in supercritical flows. Such high velocity, rapidly fluctuating flows are typical of the hydrodynamic setting of a base-surge deposit; evidence for this, such as coarse grain size, poor sorting and outsized clasts are all absent at Meridiani.

Low angle cross-stratification is exceptionally common at Meridiani as it is in terrestrial base surges. Coarse grain size, poor sorting, and outsized clasts are common in base surges, especially in the proximal facies. However, these are certainly not defining characteristics. Fine grain size, good sorting, and lack of outsized clasts are all common in base surge deposits and are probably characteristic of distal impact surge deposits.

And notably, cm-scale festoon cross-lamination is absent in their figures, and to our knowledge has never been described from an impact-generated or volcanic base surge deposit.

Using the term "festoon" appropriately as a descriptive term without connation of depositional mechanism, the structure we illustrate in Fig. 3c is a demonstration that cm-scale festoon cross laminations are present even in the proximal facies of base surges, regardless of the depositional mechanism by which such festoons form. Two additional, side-by-side examples are shown in the lower part of Fig. 2 of McCollom and Hynek (2005) (much better copy at http://members.iinet.net.au/~boxer/images/24-33-TowerHill-Sandwaves.jpg). Ancient surge deposits from large terrestrial impact craters have low preservation potential and there have been few attempts to search for and describe them. There is every reason to expect they would have structures as observed for surges of other

origins. Small-scale cross-lamination is commonly illustrated in descriptions of terrestrial surges (Fig. 9c of Bryan et al. 2000, Fig. 9-22 of Fisher and Schmincke, 1984). Unless these are cross sections of rare straight-crested ripples, views in the direction of flow would show small-scale trough cross-stratification even if the mechanism that produced them is not equivalent to that in subaqueous flows.

The interpretation that water flowed on the surface at Meridiani rests entirely on the highly questionable claims that small scale trough cross-lamination has been observed there and that such structures cannot form in base surges. We challenge the first claim and see no basis for the second.

The scenario proposed by Knauth et al.[1] does not explain the sulfate salts at Meridiani without resorting to ad hoc explanations. They offer three possibilities. One is quantitatively inconsistent (small amount of S in the impactor), and the second is implausible (an impact into a sulfide-rich cumulate containing ice). The third (impact into sulfate beds) simply adopts our model and pushes it to another location.

Based on studies of SNC meteorites, sulfide cumulates should form commonly and abundantly in martian magmas and lava flows (Burns and Fisher, 1990). A large impact would therefore excavate iron sulfide. The unusual concentration of iron oxide specifically targeted as a landing site together with the surprising amount of sulfate may indicate that what was special at Meridiani was an impact into an area particularly rich in sulfide cumulates (such as occur locally even on Earth). Alternatively, iron sulfide components of martian impact ejecta could be so common that what was special was an iron impactor into ubiquitous sulfide cumulates. Oxidation during volatilization/condensation of iron sulfide is a simple explanation for the large amounts of observed iron oxide and sulfate. Sulfate must also be widespread in the martian megaregolith from the great evaporation event earlier in martian history in which up to 90% of the water was lost (Jakosky and Phillips, 2001). This sulfate (as well as Cl) must have been dispersed all over Mars by over 4 billion years of impacts. All this bears no relation whatever to the MER team scenario that invokes large-scale eolian redeposition of salts and muds from utterly vanished playa lakes (Grotzinger et al., 2005).

The deposits observed by Opportunity extend over hundreds of thousands of square km and are up to ~800 m in thickness[12-15]. Knauth et al.[1] argue that the source may have been the Schiaparelli impact basin, located more than 1100 km (~4. 8 crater radii) to the east. However, the age of the deposits is inconsistent with such a relationship to Schiaparelli, and indeed to the vast majority of craters in the Noachian cratered terrain. Specifically, the deposits disconformably overlie the dissected cratered terrain and associated large craters[13,16]. The deposits are therefore younger than the craters that would have produced the ejecta invoked by Knauth et al.[1].

The most recent and comprehensive consideration of the regional geology (Edgett, 2005) indicates that the age of the Meridiani deposit relative to most of the surrounding cratered terranes is highly ambiguous, especially in the areas to the north, east, and west of the

MER-B landing site. The 800 m accumulation is made up of at least 4 major units of unknown lithologies and is interbedded with numerous large impacts of various ages. Edgett (2005) even illustrates the possibility that Meridiani is older than the cratered terrains. A base surge deposit up to 5 m thick is preserved at 4.7 crater radii from the Chicxculub impact (Pope et al. 2004). If the deposits at Burns Cliff represent only one impact event, the much larger Schiaparelli event is a possible candidate. We have no position regarding the likelihood of this. Numerous other candidates are available if Meridiani is made up of interlaced, interbedded surges from smaller impacts (including secondaries). Every impact on Mars may have produced a surge deposit because Mars has an atmosphere. Those encountering larger amounts of subsurface ice and/or brine probably account for many of the rampart craters (Wohletz and Sheridan, 1983). In any case, we contend that Opportunity possibly landed on a surge deposit or sequence of surge deposits at least the thickness of Burns Cliff plus any overlying thickness traversed to date.

Finally, Knauth et al.[1] argue against our interpretation of the Meridiani deposits on the basis of the observed mixture of salts of variable solubility. However, our observations clearly show that the materials investigated by Opportunity have been thoroughly reworked by eolian and aqueous processes[3,10], so such mixing is expected.

Aqueous evaporation cannot yield deposits composed of the most soluble and least soluble salts as originally published (Squyres et al., 2004) for the reasons stated in our paper. The new eolian redeposition of playa muds hypothesis (Grotzinger et al., 2005) can mix salts under dry conditions, but the amount and role of water invoked during transport and deposition in the new interpretation almost certainly precludes eolian in-mixing of highly soluble Br observed in the rocks. The hypothesized 4-fold rise and fall of the subsequent "yo-yo" aquifer would have preferentially removed the more soluble components unless the aquifer somehow stayed at saturation with respect to the salt phases, even during times when the larger crystals dissolved to form vugs and during the "fresh water recharge" invoked to convert jarosite to hematite" (McLennan et al., 2005; Tosca et al., 2005). The unstated but required physical mixing of less dense fresh water with dense brine throughout the stratigraphy to produce the uniform spherule population cannot occur in aquifers at the low water/rock ratios modeled by Tosca et al. (2005) and instead requires an enormous flux of fresh water (Domenico and Robbins, 1985). Such a vast flux of fresh water would remove the soluble salts. Furthermore, saturation with respect to Br in the aquifer is not reasonable, so its retention in the rocks requires a further, challenging modification to this already "remarkably complex" (McLennan et al., 2005) diagenetic history. The new scenario also requires maintenance of a highly acidic aquifer in rocks containing basaltic materials. Zolotov et al. (2004) have shown that this is not reasonable. The mixed salts therefore constitute at least as large a problem for the new scenario as they did for the old.

In the inevitable absence of definitive mineral identifications and any petrographic analyses together with the usual difficulty of interpreting ancient sedimentary events, we disagree that any interpretation has been "clearly shown" and recommend that, for the present, multiple hypotheses remain in play. Impact surge easily explains the mixed salts, including Br. This, followed by 4 billion of years of cold, arid-region martian weathering is a simple explanation for all the observed features at Meridiani.

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