COULD EROSION OF MERIDIANI PLANUM REPRESENT A SIGNIFICANT CONTRIBUTOR TO GLOBAL SULFATE-RICH MARTIAN SOILS?

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Introduction: Among the significant findings of the Viking landers was the observation that soils on Mars are highly enriched in sulfur, most likely in the form of sulfate salts. Viking results indicated that SO_3 constitutes ~7-9 wt% of Martian soils [1,2]. Subsequent analyses of soils at other locations, including the Pathfinder [3] and Mars Exploration Rover (MER) [4] landing sites, have yielded similar results (Table 1). The uniformity of the soil compositions at the distally located landing sites lends strong credibility to the proposal that the soils have been globally homogenized by wind transport [2,5,6].

Explanations that have been proposed to account for the sulfate-rich nature of the soils include: (1) aqueous weathering of basaltic rocks on a warm, wet early Mars [2,7], (2) reaction of volcanic rocks with sulfuric acid aerosols produced by volcanic emissions (the so-called "acid-fog" model) [8,9], (3) hydrothermal alteration of igneous rocks [10,11], and (4) evaporation of sulfate-bearing groundwater [12,13]. Here, we suggest an alternative model to explain the enrichment of sulfur the martian soils; namely that sulfate-rich bedrocks from Meridiani Planum and elsewhere have been physically eroded and redistributed globally on Mars.

The MER Opportunity has documented exposures of layered, sulfate-rich bedrock on Meridiani Planum [14,15], and these deposits extend hundreds to thousands of kilometers to the east, north and west [16]. The stack of layered deposits on which Opportunity is operating is extensive, covering an area of at least 10^5 km^2 with a depth of up to 800 m. Furthermore, mapping of Meridiani Planum indicates that the unit was initially much more widespread, and has been extensively eroded during its history [17]. Spacecraft observations indicate the sulfate-rich bedrock is not limited to the surface layers being observed by Opportunity, but extends below the surface and probably throughout the entire depth of the unit [17,18,19].

The apparent erosion of extensive amounts of sulfate minerals from Meridiani Planum begs the question of whether these materials could represent a significant fraction of the sulfur found in global surface soil deposits on Mars. In order to test this possibility, we present some first-order calculations of the likely amount of material removed from in and around Meridiani, and determine the contribution that would be made to martian soils by global redistribution of this material. Our results suggest that past erosion from the Meridiani region could account for a significant fraction of the sulfur enrichments observed in surface soils at landing sites and inferred globally on Mars.

Estimates of Sulfur Erosion From Terra Meridiani and Global Redistribution: Mapping of Meridiani indicates that the initial deposits had an areal extent of ~1.75×10^5 km^2 and the thickness of the deposits is 500-800 m [17]. Erosion of the original deposit has been variable. If the hematite nodules that appear to cover the unit is a lag deposit and the density of hematite nodules in the bedrock at the MER landing site is representative, only a couple of meters of erosion above the current surface may be required [14]. However, over large areas, the entire hematite-bearing horizon has eroded away, exposing the underlying rocks [17,18]. To make an initial estimate of the amount of material eroded from Meridiani, we employed a volume analysis tool in ArcGIS© by utilizing Mars Orbiting Laser Altimeter (MOLA) track data and the geologic map of Hynek et al. [17]. We assumed that the original surface of the unit was planar, with the hematite-bearing Meridiani plain representing the top of the unit. We calculated the amount of material removed in adjacent exposures that were clearly stratigraphically lower as the difference between the present surface and the surface representing extension of the hematite-bearing unit. The results suggest an average of ~160 m of material has been eroded, which yields an estimate of 2.8×10^4 km^3 for the total volume of material removed from Meridiani region. Data from Opportunity indicate that exposed bedrock in the vicinity of the landing site contains 17-25 wt% SO_3 [15]. Taking 20 wt% SO_3 as a representative average value and assuming the eroded material had the same composition and a density of 2.5 g/cm^3, this is equivalent to 1.4×10^{16} kg SO_3 in the form of sulfate minerals eroded from Meridiani.

Global redistribution of these solid materials would represent a layer of sediments ~7 cm thick. If this material is ~20 wt% SO_3 on average, mixing with other components to reach the soil composition of 7-9 wt% SO_3 indicates that erosion of sulfate-rich Meridiani deposits could account for the amount of S in the first 20 cm or so of martian soil if distributed uniformly over the planet.

Discussion: Martian surface soils are largely composed of a mixture of mineral clasts (olivine, pyroxene, etc.), Fe-oxides, and sulfate-rich material, presumably in the form of salts [6]. Currently available data do not constrain the depth of the regolith, but it is likely to be highly variable spatially, ranging from essentially zero in bare rocks exposures to >100 m over much of the northern plains [20]. In addition, since landers have so far only measured the composition of the top few centimeters of soil, it is not yet known whether the sulfate-rich compositions measured at the surface extend into deeper parts of the soil. However, present observations suggest that sulfate salts may be concentrated in cm-scale duricrusts at the surface [e.g., 21]. If confined to the upper layer of the martian regolith, the sulfate minerals eroded from Terra Meridiani could account for most or all of the sulfur enrichment observed in global surface soil deposits.

Surface composition mapping by OMEGA indicates that layered sulfate-rich deposits are not unique to Terra Meridiani, but also occur elsewhere such as in Candor Chasma in Valles Marineris [19]. These other deposits are also extensively eroded, which could contribute additional sulfate to global soils. Furthermore, the lack of small impact craters at Meridiani and Candor Chasma [22] indicate these deposits are undergoing active erosion, perhaps contributing to ongoing global transport and sedimentation. Consideration of these multiple sources together further supports the possibility that weathering and redistribution of sulfate minerals from layered sulfate deposits might be the predominant source of S in martian surface soils.

We therefore propose the following scenario as a model for the formation of martian surface soils. Sulfate minerals and other materials are abraded from Meridiani and other layered deposits and transported by wind to locations around the globe. During transport, the sulfates mix with igneous mineral and glass fragments abraded from basalt exposures elsewhere on the planet and, perhaps, iron oxides and other minerals representing weathering products of igneous rocks. Following deposition, interaction of the sulfate minerals with water vapor or transient liquid water would result in recrystallization and cementation of the deposits, forming the duricrusts commonly observed in the surface soils at landing sites. In this scenario, other proposed sources for in situ generation of sulfate salts (acid-fog alteration, groundwater evaporation, hydrothermal alteration, etc.) may be only minor contributors.

This interpretation would have significant implications beyond understanding the composition of martian soils. For instance, the sulfur-rich nature of the soils has led to suggestions that the crust of Mars may be significantly enriched in sulfur relative to basalts elsewhere in the solar system [e.g., 23,24]. However, if the acid-fog and/or sulfate-rich groundwater models are not required to explain the soil composition, there may be no need to invoke a sulfur-rich crust or early SO_2-rich atmosphere to account for soil compositions.

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Table 1. Elemental compositition (in wt% oxides) of representative martian soils.

Component	Chryse[a]	Pathfinder average[b]	Gusev average[c]
SiO_2	43	42.3	45.8
Al_2O_3	7.5	8.0	10.0
Fe_2O_3	17.6	22.3	15.8*
MgO	6	8.7	9.3
CaO	6	6.5	6.1
K_2O	0	0.6	0.4
Na_2O	-	1.1	3.3
TiO_2	0.65	1.0	0.8
SO_3	7	6.8	5.8
Cl	0.7	0.5	0.5

[a]Sample C-1, Clark et al. [1]. [b]Wänke et al. [3]. [c]Gellert et al. [4]. *Iron reported as FeO.