SULFUR CYCLING ON MARS FROM A PERSPECTIVE OF SULFUR-RICH TERRESTRIAL ANALOGS.

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Introduction: The geochemical sulfur (S) cycle appears to be extremely important on Mars and dominates many geological processes [1]. The monohydrated sulfate mineral kieserite ($MgSO_4 \cdot H_2O$), the fully-hydrated Ca sulfate mineral gypsum ($CaSO_4 \cdot 2H_2O$), and poly-hydrated sulfate minerals (for example, Mg-, Ca-, Na-, or Fe- $SO_4 \cdot nH_2O$) have been identified by rovers and orbital spectrometers in various locations of Mars [2-3]. However, many competing hypotheses for the origin of sulfates exist in the literature. These include deposition of sulfates via volcanic S-rich emission and ice-rock interaction [4-6], hydrothermal activity [7-8], deep groundwater discharge [9-10], and/or sulfide weathering [11-14]. While volcanic models provide good constraints on deposition of Fe-sulfates, including jarosite, in some locations (e.g., Meridiani Planum), they cannot satisfactory explain the widespread distributions of Mg-Ca-Na sulfates in other locations (e.g., Valles Marineris, North Pole) for which some combination of subsequent aqueous, sedimentary, and eolian processes appear to be important. Also, deep groundwater as a major source of sulfates is often inconsistent with the suggested short-term water conditions and dominance of episodic surface run-off on Mars [15].

Overall, each model provides some information about plausible individual S sources but is incomplete when it comes to describing aqueous S transport to its depositional environments and climate conditions.

Goals: Our goal is to use representative terrestrial S-rich analogs from arid and volcanic settings [14, 16-18] to summarize our knowledge about terrestrial S cycle and compare it to observed S deposition on Mars as a function of S source, sediment cycling, and climate condition.

Terrestrial Analog Settings - Results: We have selected three sites located in New Mexico, USA for this comparison:

Site 1. Sulfate-rich surface accumulations of the semi-arid Rio Puerco watershed – composed of Mg-sulfates, Ca-sulfates, Na-sulfates, Mg-Na-sulfates, and rare jarosite found on erosional hill slopes (Fig. 1), steep and fractured canyon walls, on mounds and topographic depressions of valley floors, in bedrock fractures, and in pseudo-layers precipitating at shallow groundwater discharge points in the lower slopes of mesas [16]. Surface occurrences are similar to the hydrated sulfates in Valles Marineris on Mars. An ephemeral arid hydrological cycle that mobilizes S present in the bedrock as sulfides, evaporite minerals, and dry/wet atmospheric deposition contribute to widespread surface accumulations of hydrated sulfate efflorescences. Prevailing dry conditions and repeating cycles of salt dissolution and reprecipitation appear to be major processes that migrate sulfate efflorescences to sites of surface deposition and ultimately increase the aqueous SO_4^{2-} flux along the watershed. Notably, these processes do not involve deep groundwater flows [16].

Site 2. High altitude volcanic system of Valles Caldera – surface oxidation of modern volcanic H_2S emission locally significantly increases SO_4 concentrations in hydrological system and accumulates Ca-sulfates, elemental S, and sulfides close to hydrothermal/fumarole vents [18]. However, in the total hydrological S budget the volcanic S contributions are considerably smaller (5-13%) compared to the bedrock S fluxes from water-rock interaction (87-95%). Volcanic atmospheric S deposition in active fumarole sites appears to be slightly smaller (~0.66 mg/L of SO_4 in snow) compared to non-volcanic sites (~0.94 mg/L of SO_4 in snow). Most likely, this results from quick dilution of volcanic gases in the atmosphere and minor incorporation into wet precipitation (snow). Overall, prevailing wet conditions and open drainage systems lead to limited sulfate deposition on the surface.

Site 3. Semi-arid White Sands dunes – large eolian accumulation of gypsum sand resulted from deflation of playa sediments sourced by SO_4-rich groundwater [17]. Aerial photographs of the White Sands dust storm in 2012 (Fig. 2) suggest that gypsum can be transported over long distances (~600 km) as dust plumes. Moreover, a gypsum erosion experiment suggests that aeolian deposits such as the White Sands gypsum sand can be transported over great distances (~2000 km) by saltation without significant loss of mass [14]. Consequently, these results are consistent with a widespread distribution of gypsum around North Polar ice cap on Mars.
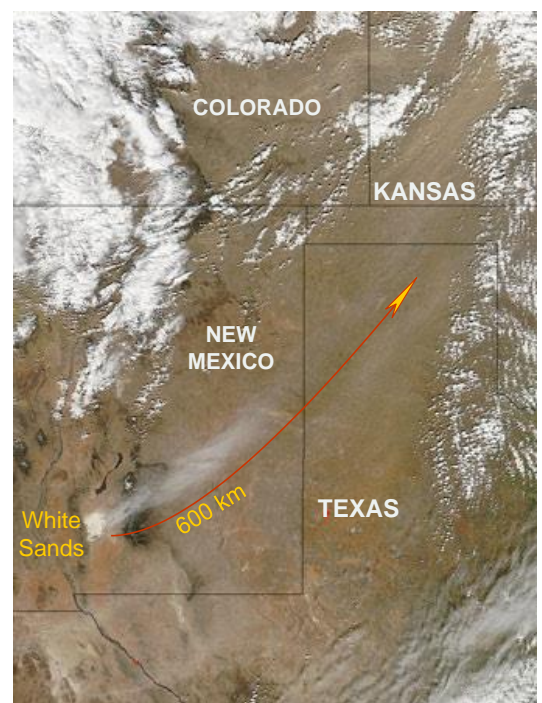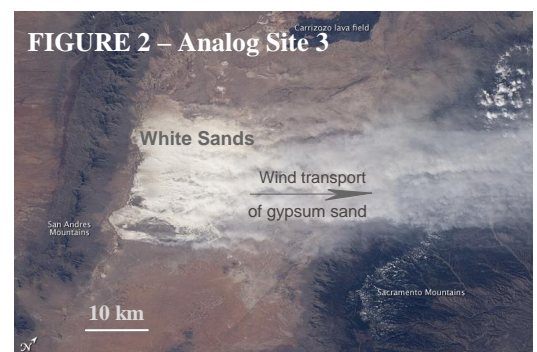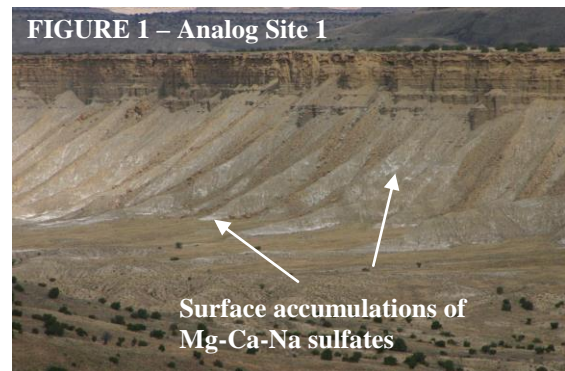
Discussion & Conclusions: The Mg-Ca-Na sulfates in Site 1 show very close resemblance to surface occurrences and mineralogy of hydrated sulfates in Valles Marineris [16]. Our calculations suggest that the mass of surface sulfates in Valles Marineris (135,370 km^2) is relatively small, equivalent to ~4-42% of the gypsum present in the gypsum dune field of White Sands in Analog Site 3 (710 km^2). Under similar semi-arid dry conditions as in Analog Site 1, it would take at least ~100 to 1,000 years to activate an equivalent flux of aqueous SO_4 to account for the current mass of hydrated sulfates in Valles Marineris [16].

While long-term volcanic S emission could account for some portion of sulfates deposited on Mars, our results from Analog Site 2 suggest that the bedrock-water interaction and subsequent oxidation/dissolution of S-bearing volcanic mineralization accounts for the majority of SO_4 aqueous flux in this volcanic system. Since sulfate occurrences on Mars appear to be locally distributed on the surface, the heterogeneity of bedrock S content on Mars is probably a first order factor leading to the sulfate occurrences in the restricted areas. If there were a global deposition of sulfates via volcanic processes, we would expect to see more homogenized sulfate distribution on the Martian surface. Instead sulfate appearance is apparently linked to geomorphic and sedimentary features such as the erosional canyon slopes of Valles Marineris [7-8] and sediment systems of Meridiani Planum and Olympia Undae [2-3, 9]. Similar to terrestrial crystalline and volcanic rocks, we expect that the primary source of bedrock sulfur on Mars is minor/trace sulfides and sulfates of magmatic/volcanic/hydrothermal origin. Therefore, we infer that physical erosion and bedrock disintegration into finer particles via sediment cycling in the surface environment were important factors in releasing the bedrock sulfur into an episodic hydrological cycle on Mars. For example, in aqueous terrestrial settings these processes are crucial in releasing sulfide-derived SO_4. This is in accord with rather minor/trace bedrock sulfide contents compared to concentrated gypsum/anhydrite accumulations in marine formations on Earth.

Generally, comparison with the terrestrial S cycle in our three analog sites suggests that the observed S cycle in various locations on Mars was operating under water-limited and prevailing dry conditions. Additionally, the observed resistance of White Sands gypsum to physical erosion [14] and vast distribution of gypsum in circumpolar dunes around Martian ice cap [12] highlights the importance of aeolian processes in the S cycle on Mars, which appears to be less important in terrestrial settings. On Earth, wetter conditions prevent gypsum from being transported for long distances; gypsum and other sulfate minerals are either dissolved quickly by meteoric waters as it is seen in Analog Site 2 or undergo quick deposition during fluctuation of a near-surface groundwater table, as seen in Analog Sites 1 and 3.

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FIGURE 1 – Analog Site 1

Surface accumulations of Mg-Ca-Na sulfates

FIGURE 2 – Analog Site 3

White Sands

Wind transport of gypsum sand

Carrizozo lava field

San Andres Mountains

Sacramento Mountains

10 km

COLORADO

KANSAS

NEW MEXICO

TEXAS

White Sands

600 km