

EVALUATION OF WATER ACTIVITY TIMESCALES ON MARS USING QUANTITIES OF SULFATE MINERALS DEPOSITED IN MERIDIANI PLANUM, VALLES MARINERIS, AND NORTH POLAR DUNES. A. Szykiewicz, R. D. Moore, University of Tennessee, Knoxville (aszynkie@utk.edu).

Introduction: Mars has extensive sulfate-rich sedimentary deposits in multiple locations [1-3]. Generally, it is accepted that water played a key role in the formation of the sulfate minerals in the martian sediments but the sulfur (S) sources for aqueous sulfate (SO_4^{2-}) remain poorly understood. Previous studies have usually considered one sole S source for sulfate mineral deposition (i.e., groundwater, surface runoff, or atmospheric deposition). However, the sheer volume of sulfate present in surface deposits on Mars suggests that sulfate deposition would have operated under a complex hydrological system [4-5] with active regional recharge influencing surface water and groundwater flows. Based on knowledge from terrestrial analogs [4], it can be expected that in addition to direct atmospheric deposition, an important source of aqueous SO_4^{2-} might have been a hydrological system interacting with S-rich bedrock and/or hydrothermal S gases leading to the precipitation of sulfate minerals in surface deposits on Mars.

A recent study in terrestrial watersheds by our group [5] have shown that primarily, climate controls SO_4^{2-} fluxes (contributions) in surface water and groundwater, as this influences the amount of water available for leaching and transport of dissolved SO_4^{2-} out of the catchment to the final depositional environment. Catchments that receive more precipitation consistently have greater SO_4^{2-} fluxes. The aqueous SO_4^{2-} flux is also controlled secondarily by volcanic activity and weathering of bedrock S mineralization, as the distribution of hydrothermal activity and enrichment in bedrock S minerals increase the dissolved SO_4^{2-} concentrations in the hydrological system. Our results also show that even when SO_4^{2-} concentrations are elevated from volcanic activity and/or chemical weathering of bedrock S mineral, but climatic conditions are dry, the resulting SO_4^{2-} flux is smaller due to less removal and leaching of S by aqueous activity via surface runoff and/or groundwater flow. Therefore, climate appears to be the dominant factor controlling SO_4^{2-} flux in terrestrial volcanic/basaltic catchments.

Because the amount of SO_4^{2-} in aqueous system (e.g., SO_4^{2-} flux) appears to correspond to climate and timescales of water activity on Earth [5], the amount (mass) of sulfate minerals in surface deposits on Mars can be used to evaluate the duration of main aqueous processes. For example, our initial estimates of timescales for water activity in the Meridiani Planum watershed suggest that ~30-60 Ma of active hydrological cycle under intermittent wet and dry conditions would be needed to account for the SO_4^{2-} mass currently deposited in the Meridiani sediments [5].

Study Goals: Further understanding and quantification of the timescales of water activity in other locations with sulfate-rich deposits on Mars is important because it can help better constrain hydrological and climatic conditions on Mars when liquid water was still active on its surface.

The main goal of this study was, therefore, to use the mass of sulfate minerals deposited in the surficial sediments of Valles Marineris and North Polar dunes to estimate possible timescales of water activity accompanying their formation. Six different Mars analog environments with different climates and primary S reservoirs were used: three volcanically active terrains of the Island of Hawai'i (tropical), Iceland (polar) and Valles Caldera in New Mexico (semi-arid) and three non-volcanically active terrains of Kauai/Hawaii (tropical), Svalbard Archipelago (polar) and Rio Puerco watershed in New Mexico (semi-arid). In the end, the obtained results were compared to the recently published data for Meridiani Planum [5] in order to evaluate the possible timescales of water activity on Mars when main sulfate-rich deposits were formed.

Methods: The mass of sulfate minerals deposited in the surficial deposits of Valles Marineris (mainly kieserite) and North Polar dunes (mainly gypsum) was calculated by multiplying the surface area of these sulfates by their thickness and by their density:

$$\text{Mass [kg]} = \text{surface area [m}^2\text{]} \times \text{thickness [m]} \times \text{density [kg/m}^3\text{]}$$

In Valles Marineris, the kieserite-rich surface sediments are mainly correlated with the bright interior layered deposits resembling terrestrial pseudo-layering with sulfate coatings along horizontal fractures [6]. Consequently, we assumed a thickness of 1 cm and the absence of internal bedrock layers with sulfate minerals. In contrast, dark albedo circumpolar dunes show a minimum 5% of gypsum based on orbital spectral measurements [7], thus we assumed the thickness of 0.05 cm in surface sediments of the North Polar dune fields containing gypsum. Afterward, the timescales of aqueous activity needed to transport the equivalent mass of SO_4^{2-} observed in Valles Marineris and North Polar dunes was determined as follows [5]:

$$\text{Timescale (years)} = [\text{SO}_4^{2-} \text{ mass (tons)}] / [\text{SO}_4^{2-} \text{ load (tons/year/km}^2\text{)} \times \text{catchment area (km}^2\text{)}]$$

where SO_4^{2-} load (e.g., SO_4^{2-} flux per km^2) is based on the aqueous SO_4^{2-} fluxes previously reported for the six terrestrial analogs with different climates and S reservoirs [5] used in our study.

Results: The estimated timescales of water activity for Valles Marineris and North Polar dunes using the mass of sulfate minerals greatly varied depending on the modelled hydrological and volcanic active and inactive conditions (Tab. 1). The shortest timescales of 3 and 4 Ma, respectively, were under tropical climate conditions of the youngest and volcanically active Island of Hawai'i. In contrast, the tropical climate conditions of inactive and oldest island of Kauai in Hawaii yielded larger timescales of 34 and 49 Ma, respectively. Interestingly, the timescales under polar climate conditions of volcanically active Iceland and inactive Svalbard were similar: 10-16 Ma in Valles Marineris and 15-23 Ma for the North Polar dunes. The largest timescales of 107-199 Ma and 154-285 Ma, respectively, were under semi-arid climate conditions of the terrestrial analogs located in northern New Mexico.

Generally, the modelled timescales under different climate conditions (tropical, polar, semi-arid) for Valles Marineris and North Polar dunes were similar to the previous estimates of water activity in the Meridiani Planum region [5] (Tab. 1).

Discussion & Initial Conclusions: While there is a general agreement that water played a key role in deposition of sulfate minerals on Mars [1, 3-4], the main questions remain about the duration of water activity and accompanying climate conditions. Geomorphological, mineralogical, and sedimentary evidence [1, 3, 7] suggest that these conditions were likely dry and cold throughout much of the martian geological history. If this was the case, our new results (Tab. 1) suggest that millions of years of water activity would be needed to account for the mass of sulfate minerals detected in various locations on Mars.

The sulfates detected in the studied regions of Meridiani Planum, Valles Marineris, and North Polar dunes are mainly associated with dry and/or eolian dep-

ositional environments that are typically accompanied by episodic water activity on Earth. Even under elevated S volcanic emission such as in Valles Caldera, the SO_4^{2-} loads in aquatic systems are relatively small under dry conditions (Tab. 1) and would require up to ~100-300 Ma of active water cycle to account for the mass of sulfate minerals currently present in the studied locations on Mars.

Some studies have suggested that a polar climate prevailed on Mars throughout most of its geological history [8]. Comparisons to the SO_4^{2-} loads in our polar analog sites yielded shorter timescales of water activity for the studied martian settings (6 to 23 Ma). However, it should be pointed out that these are based on SO_4^{2-} fluxes in glacial catchments with significant seasonal melting of large quantities of ice that is not apparent in Meridiani Planum, Valles Marineris, or the North Polar region. While polar conditions usually increase aqueous SO_4^{2-} fluxes from coupled physical-chemical weathering of S-rich bedrock (e.g., sulfide oxidation), the overall SO_4^{2-} loads would be small under limited water activity thus increasing the time needed for equivalent aqueous SO_4^{2-} transport to the depositional settings.

In summary, if Mars was dominated by cold but dry climate conditions in the past, it would have likely taken hundreds of millions of years to account for the amount of secondary sulfate minerals currently present in the surficial deposits of the studied settings.

References: [1] McLennan (2012) *Sed. Geol. of Mars*, 112, 119-138. [2] Gaillard et al., (2012) *Space Science Reviews*, 174, 251-300. [3] Arvidson (2016) *JGR-Planets*, 121, 1602-1626. [4] Moore and Szyrkiewicz (2022) *Icarus*, 376, 114880. [5] Moore and Szyrkiewicz (2023) *Icarus*, 391, 115342; [6] Szyrkiewicz et al. (2014) *EPSL*, 393, 14-25; [7] Horgan et al. (2009) *JGR-Planets*, 114, E01005. [8] Bishop et al. (2018) *Nature Astronomy*, 2, 206-213.

Table 1. *Left:* Representative SO_4^{2-} loads in aquatic systems of terrestrial analogs under different climate and volcanic conditions. *Right:* Estimated timescales of water activity in various settings on Mars using terrestrial SO_4^{2-} loads.

TERRESTRIAL ANALOGS		TIMESCALES OF WATER ACTIVITY		
Site - volcanic activity (climate)	SO_4^{2-} Load [tons/yr/km ²]	Meridiani Planum	Valles Marineris	North Polar Dunes
		[Ma]	[Ma]	[Ma]
Hawaii - active (tropical)	97.1	2	3	4
Iceland - active (polar)	17.4	10	16	23
Valles Caldera - active (semi-arid)	1.4	115	199	285
Hawaii - inactive (tropical)	8.2	20	34	49
Svalbard - inactive (polar)	27.5	6	10	15
Rio Puerco - inactive (semi-arid)	2.6	62	107	154