Title:

Pedogenic processes and the drying of Mars

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Abstract:

What exactly caused Mars to lose its liquid water billions of years ago remains as one of the most enduring questions in planetary science. New insights from Mars suggest that crustal hydration – the formation of hydrated minerals during aqueous alteration of the crust – contributed to the long-term drying of the planet. Here, we advance the hypothesis that hydration of the Martian crust could have resulted in part from precipitation-driven surface weathering of mafic sediments, which on Earth leads to pedogenesis, i.e., the formation of soil. Over the past decade, features resembling buried soils have been detected in thousands of locations across the ancient surface of Mars. Although soil has been traditionally defined by its biological component, growing evidence of global scale soil formation on a presumably lifeless Mars suggests abiotic pedogenesis was a critical process early in the planet's history. Here we argue that pedogenic processes could have consumed large amounts of Mars' exchangeable liquid water via the formation of hydrated pedogenic minerals. Since there is no evidence of plate tectonics to liberate and recycle water from hydrated minerals on Mars, the global formation of soil billions of years ago could have contributed to the irreversible desiccation of the planet.

One-Sentence Summary:

Pedogenic processes on Mars several billion years ago may have contributed to the irreversible drying of the planet.

Main Text:

Thick vertical stacks (> 5 km) of three-to-four-billion-year-old sedimentary rocks on Mars may contain between 30 and 99% of the planet's ancient water - water that was once liquid, now locked within hydrated minerals formed during weathering of the martian crust by ocean-scale volumes of liquid water[1]. Many of these hydrated minerals appear to have formed from surface weathering of mafic sediments such as volcanic ash with liquid water[2], which on Earth leads to pedogenesis, i.e., the formation of soil. Layered sedimentary rocks on Mars resembling ancient, buried soils (paleosols) are distributed globally across Noachian-age (4.1-3.7 billion year old) terrains (Fig. 1), and like other rocks on Mars, do not appear to be severely altered [3,4]. Critically, this implies a lack of plate tectonics to recycle water from the hydrated crust back to the atmosphere.

In their recent *Science* paper, Scheller et al[1] argue that global-scale crustal hydration was a critical process that increased the aridity of Mars. The geological evidence for crustal hydration – layered sedimentary rocks rich in hydrated minerals that compose thousands of meters of vertical stratigraphy - is the same evidence other researchers have been using to understand pedogenesis and past climates on Mars, primarily from the study of paleosols from Earth (Fig. 1) especially those rich in hydrated minerals such as smectite, amorphous silica, and gypsum[5–7].

Hydrated minerals within paleosols may be a sink for water, but on Earth these ancient land surfaces are inevitably recycled by plate tectonics. Plate tectonics on Earth may contribute to the sustainability of our hydrosphere over geological time scales because the hydrated crust releases volatiles like water back to the atmosphere during volcanic eruptions with mantle sources [8]. Unlike Earth, Mars apparently lacks plate tectonics and therefore had no mechanism to recycle water back to the atmosphere through degassing of subducted hydrated crust, and thus what appears to be an unsustainable hydrosphere [1]. In other words, the more that it weathered, the drier that it got.

Perhaps what appear to be ancient, buried soils on Mars (Fig. 1) - which have pedogenic features such as dioctahedral clay mineralogy, meter-scale horizonation, alumina enrichment, and accumulation of silica and iron oxides [9,10] – could have been formed by pedogenic weathering [11]. Perhaps the dioctahedral clay minerals in eolian, fluvial and lacustrine sedimentary rocks at Gale crater could have been sourced from Noachian paleosols, or formed in-place during periods of subaerial exposure[12,13]. The possibility of paleosols (also called weathering profiles) at Gale crater has also been hypothesized [14,15]. Here, intense subaerial weathering of eolian or lacustrine sediments could have resulted from pedogenic alteration with acidic and reducing fluids. Elsewhere on Mars, Noachian layered sedimentary rocks containing hydrated minerals resemble terrestrial Andisols (volcanic soils), Aridisols (desert soils), and Oxisols (deeply weathered tropical soils)[10,16], though differences in the nature of weathering on Earth and Mars (e.g., atmospheric composition) present challenges for direct comparisons.

Crustal hydration via pedogenesis could have contributed to the drying of early Mars, but a decades-old debate about the definition of "soil" poses challenges for testing this hypothesis on Mars, where there is no conclusive evidence of life. A key point of controversy is whether life was involved in pedogenic weathering processes on Mars, and therefore whether these materials on Mars can be called "soils". For example, a classic definition of soil is "The unconsolidated mineral or organic material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants" [17]. On Earth, biological weathering speeds up the formation of soil by the secretion of organic acids [18], but abiotic chemical weathering with liquid water in surface environments also forms soil [19].

In response to mounting evidence of soil-like materials across the surface of Mars, the Soil Science Society of America in 2017 redefined soil as "The layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at or near the planetary surface and usually hold liquids, gases, and biota and support plants" [17]. Not defining soils by their biological component now acknowledges the fundamental role of abiotic pedogenesis in the planetary evolution of a presumably lifeless Mars. This new definition should serve as a bridge between two worlds, those of Earth System Science and Planetary Science, one in which crustal hydration, which includes processes such as abiotic pedogenesis, may have led to the irreversible drying of Mars. Future tests of this hypothesis should consider the global extent of martian weathering profiles[3,20] to model the volume of atmospheric water consumption during pedogenic weathering of volcanic ash and tuff as a diffuse process that scales with space and time[21].

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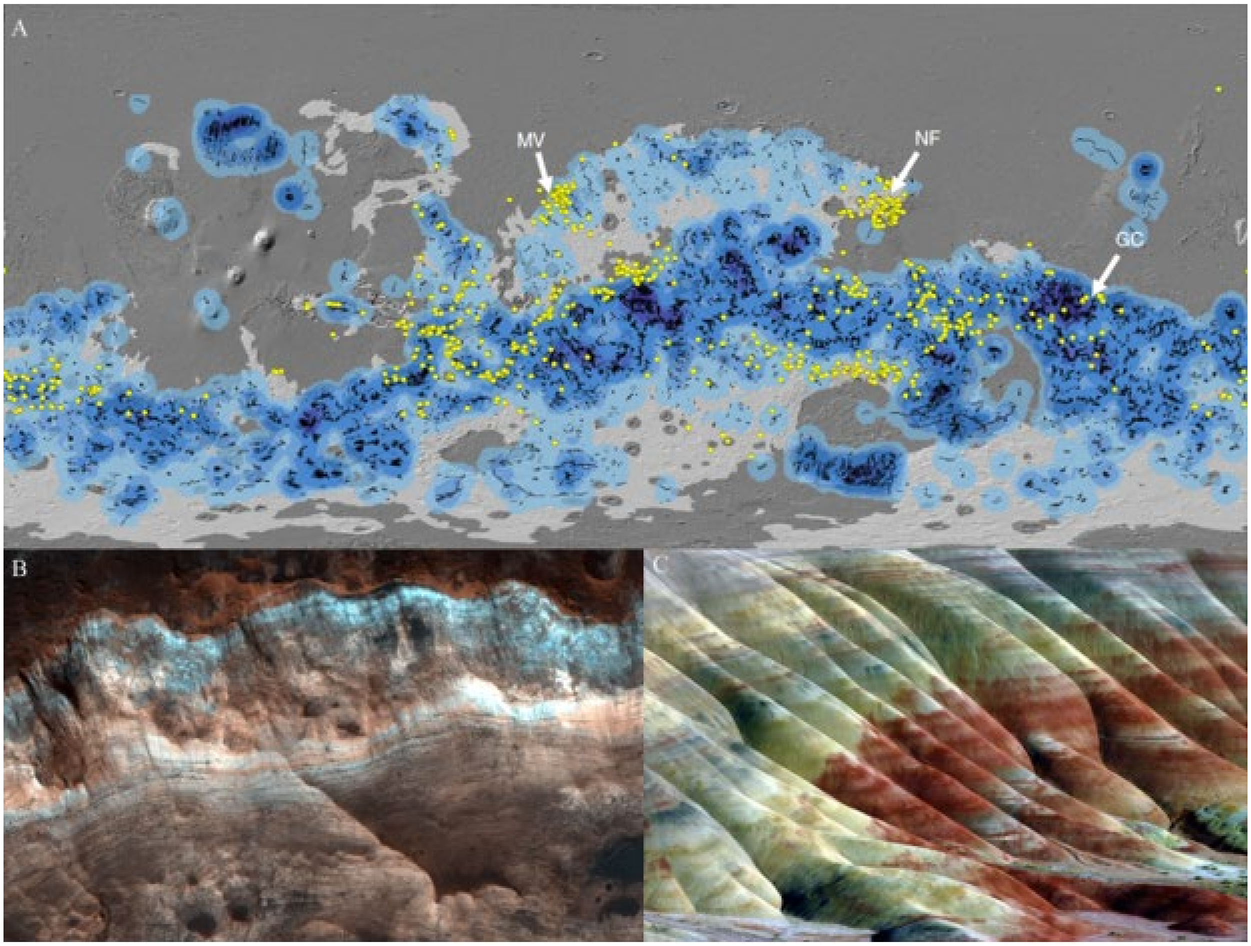

Fig. 1. **(A)** Global distribution of dioctahedral smectite clay minerals (yellow circles) across Noachian-age terrains on Mars (white) which contain the most occurrences of valley networks (blue tones). Locations of Mawrth Vallis (MV), Nili Fossae (NF) and Gale Crater (GC) are noted with white arrows (Adapted from[11]). **(B)** Noachian-age layered sedimentary rocks exposed in a crater rim at Mawrth Vallis on Mars which resemble ancient soils, and **(C)** 33-million-year-old paleosols from Earth at the Painted Hills Unit of the John Day Fossil Beds National Monument in eastern Oregon, an established Mars-analog site.