Title:

Pedogenic processes and the drying of Mars

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Abstract:

New insights from Mars suggest crustal hydration contributed to the long-term drying of the planet. Three to four billion years ago, hydration of the Martian crust could have resulted from precipitation-driven surface weathering of mafic sediments, which on Earth leads to pedogenesis, i.e., the formation of soil. 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. Using a recently updated definition of soil as leverage, we argue that pedogenic processes could have consumed large amounts of Mars' exchangeable liquid water. Since there is no evidence of plate tectonics to liberate and recycle water from hydrated pedogenic 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:

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

Main Text:

Three to four billion year old sedimentary rocks on Mars may contain between 30 and 99% of the planet's ancient water - once liquid, now locked within hydrated minerals formed during weathering of the 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. 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" [5]. However, recent findings of what appear to be widespread pedogenesis on Mars during the Noachian period [2,3,6] warrant a new definition of soil.

On Earth, biological weathering speeds up the formation of soil by the secretion of organic acids [7], but abiotic chemical weathering with liquid water in surface environments also forms soil [8]. A new definition of soil would unite principles used to understand planetary formation of Earth and Mars, twin worlds which Carl Sagan in 1985 determined be *"a classic case of experiment and control"* to study the origins of life. Building on that analogy we see value defining soils as materials altered in place by chemical, physical and/or biological processes[9], a definition which can serve as a bridge between scientific communities and planets.

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" [5]. 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 extraterrestrial Planetary Science, as exemplified by new findings from Mars, one in which crustal hydration, which includes abiotic pedogenesis, may have led to the drying of Mars.

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 - 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) that are rich in hydrated minerals such as smectite and amorphous silica[10–12]. Hydrated minerals within paleosols may be a sink for water, but on Earth these ancient land surfaces are inevitably recycled by plate tectonics. Those that do survive are tortured by diagenesis and metamorphism[13,14] which releases volatiles like water back to the atmosphere. 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 [15]. Unlike Earth, Mars 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].

Perhaps what appear to be ancient, buried soils on Mars (Fig. 1) - as inferred from pedogenic features such as dioctahedral clay mineralogy, meter-scale horizonation, alumina enrichment, and accumulation of silica and iron oxides [6,16] – could have been formed by abiotic pedogenic weathering [17]. Perhaps the dioctahedral clay minerals in the eolian, fluvial and lacustrine sedimentary rocks at Gale crater could have been sourced from Noachian-age soils, or formed in-place during periods of subaerial exposure[18,19] The possibility of paleosols (also called weathering profiles) at Gale crater has also been hypothesized [20]. Intense subaerial weathering of eolian sediments in the Stimson and Murray formations could have resulted from pedogenic-like alteration by acidic and reducing fluids, followed by burial. Elsewhere on Mars, some Noachian layered sedimentary rocks containing hydrated minerals resemble Andisols (volcanic soils), Aridisols (desert soils), and Oxisols (tropical soils)[16,21], though differences in the nature of weathering on Earth and Mars (e.g., atmospheric composition) present challenges for paleoclimate interpretation.

In any case, global soil formation could have increased the aridity of Mars by removing exchangeable water from the atmosphere and locking it inside hydrated pedogenic minerals where it has remained for three to four billion years. Thus, the formation of soil on Mars coupled with the apparent lack of plate tectonics could have contributed to the irreversible drying of the planet. Disentangling soil formation from biological processes is a new direction that is driven by the growing evidence of pedogenic processes on Mars, where there is no conclusive evidence of life. The recently updated definition of soil should serve as a literal and metaphorical bridge between worlds to unravel the factors contributing to the habitability and planetary evolution of Mars.

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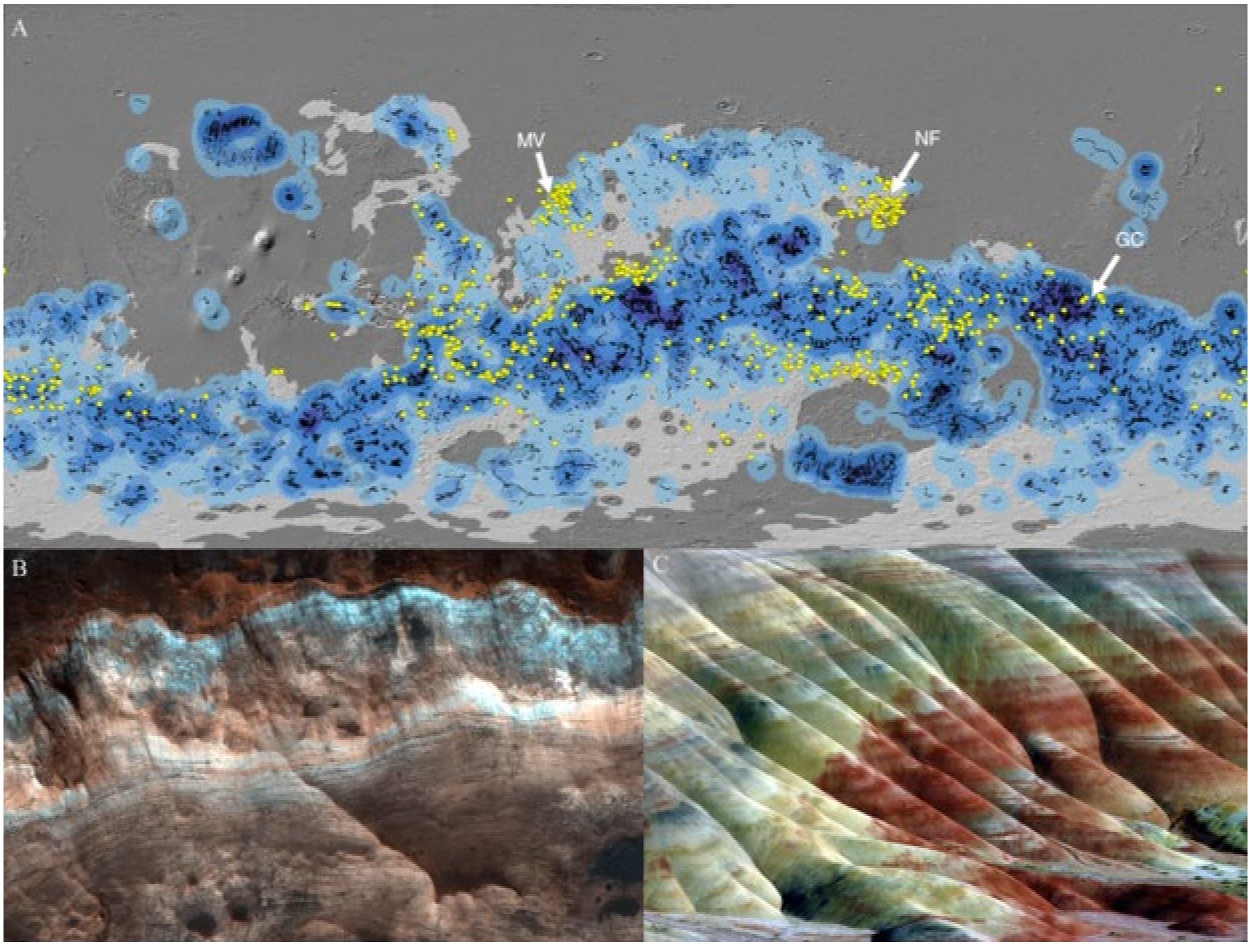

Fig. 1. **(A)** Global distribution of dioctahedral smectite clay minerals (yellow circles) across Noachian-age terrains on Mars (white) which contain the most occurrences of valley networks (blue tones). Locations of Mawrth Vallis (MV), Nili Fossae (NF) and Gale Crater (GC) are noted with white arrows (Adapted from[17]). **(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.