Paleosols and paleoenvironments of early Mars

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ABSTRACT

Fluviolacustrine sediments filling Gale Crater on Mars show two levels of former exposure and weathering that provide new insights into late Noachian (3.7 ± 0.3 Ga) paleoenvironments of Mars. Diagnostic features of the two successive paleosols in the Sheepbed member include complex cracking patterns of surface dilation (peds and cutans), a clayey surface (A horizon), deep sand-filled cracks with vertical lamination (sand wedges), and replacive sulfate nodules aggregated into distinct bands (gypsic By horizon) above bedded sandy layers (sedimentary C horizon). Shallow gypsic horizon, periglacial sand wedges, and limited chemical weathering are evidence of a hyperarid frigid paleoclimate, and this alternated with wetter conditions for the lacustrine parent materials in Gale Crater during the late Noachian. Depletion of phosphorus, vesicular structure, and replacive gypsic horizons of these Martian paleosols are features of habitable microbial earth soils on Earth, and encourage further search for definitive evidence of early life on Mars.

INTRODUCTION

Based on an unprecedented stream of scientific information from two active rovers on Mars (Arvidson et al., 2014; Grotzinger et al., 2014), this paper advances a new interpretation that Martian outcrops include fossil soils; this has novel implications for past Martian habitability. Soils are sometimes defined by biological activity, but an alternative definition also has a following, i.e., soils as planetary surfaces altered in place by biological, chemical, or physical processes (Retallack 2001; Amundson et al., 2008). By this definition, the question is not whether the surface of Mars has soil, but whether Martian soil is or was alive. There is no current indication of life on Mars, and surface soil profiles at Chryse and Utopia Planitiae explored by the Viking missions are too clayey for current hyperarid and hyperfrigid Mars surface conditions (Amundson et al., 2008), so were relict paleosols (Retallack, 2001). Nevertheless, Chryse and Utopia Planitiae paleosols reveal much about early (3.5 ± 0.5 Ga; Hartmann and Neukum, 2001) and late Hesperian (3.2 ± 0.6 Ga; Thomson and Schultz, 2007), respectively, surface conditions on Mars. New documentation of late Noachian (3.7 ± 0.3 Ga) fluviolacustrine rocks (Thomson et al., 2011) of the Sheepbed member of the Yellowknife Bay formation within Gale Crater (Grotzinger et al., 2014) now reveal geochemical (McLennan et al., 2014) and petrographic (Vaniman et al., 2014) details of possible buried paleosols on Mars (Figs. 1 and 2), previously inferred only from remote sensing (Horgan et al., 2012). These paleosols are a new line of evidence for late Noachian paleoclimate and habitability of Mars.

METHODS

Chemical data to a depth of 25 cm below the Viking 1 lander on Chryse Planitia (McSween and Keil, 2000) are plotted in Figure 3; the Shergotty meteorite is also plotted as a likely basaltic parent composition (Varnes et al., 2003). Viking 1 analyses have such poor analytical precision that they do not reveal significant weathering after Gaussian error propagation for molecular weathering ratios (see Table DR1 [transfer functions] in the GSA Data Repository[1]). Stratigraphic levels of analyses and their order

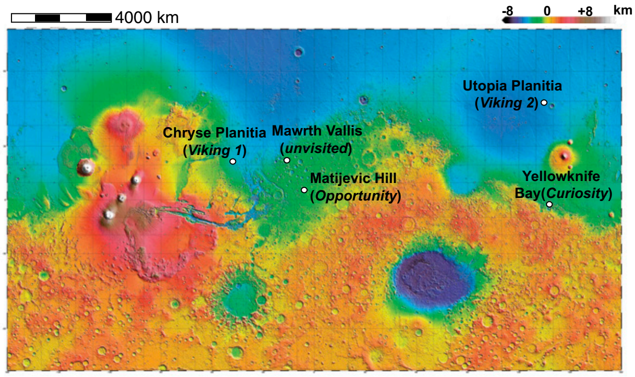

Figure 1. Widely separated sites of similar paleosols on Mars, such as Yila pedotypes at Matijevic Hill and Yellowknife Bay, and Spender pedotypes at Chryse and Utopia Planitiae. Base map is Mars Orbiter Laser Altimeter (MOLA) global topographic map of Mars; names of spacecraft or rovers are in italics.

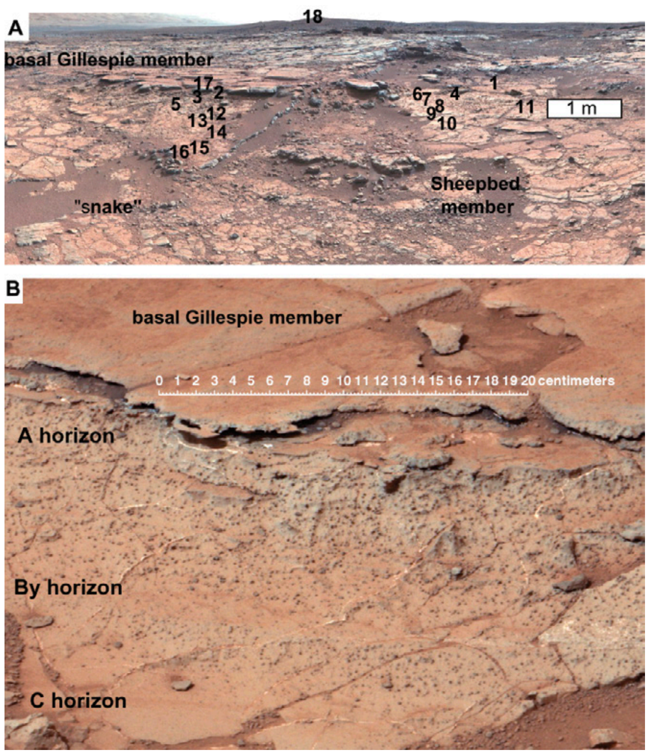

Figure 2. Paleosols of the Sheepbed member, Yellowknife formation, Gale Crater, Mars. A: Analytical stations and their stratigraphic order (McLennan et al., 2014): 1—Cumberland Brush, 2—Mavor, 3—Persillon, 4—Brock Inlier, 5—Nastapoka, 6—Drill RP, 7—Drillhole R4, 8—McGrath R3, 9—Wernecke Brush, 10—Divot 2, 11—Sayunei C, 12—Bonnet Plume, 13—Hudson Bay, 14—Hay Creek, 15—Ekwir 1 Brush, 16—Grit (1–16 are Sheepbed member), 17—Ungava (in overlying Gillespie member), 18—Rocknest (Glenelg member in distance). Note prominent rock rib ("snake") of basaltic sand. B: Interpreted soil horizons. Lenticular regions of low nodule density in horizon By are considered parent material irregularities.

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[1]GSA Data Repository item 2014275, Table DR1, transfer functions and error propagation, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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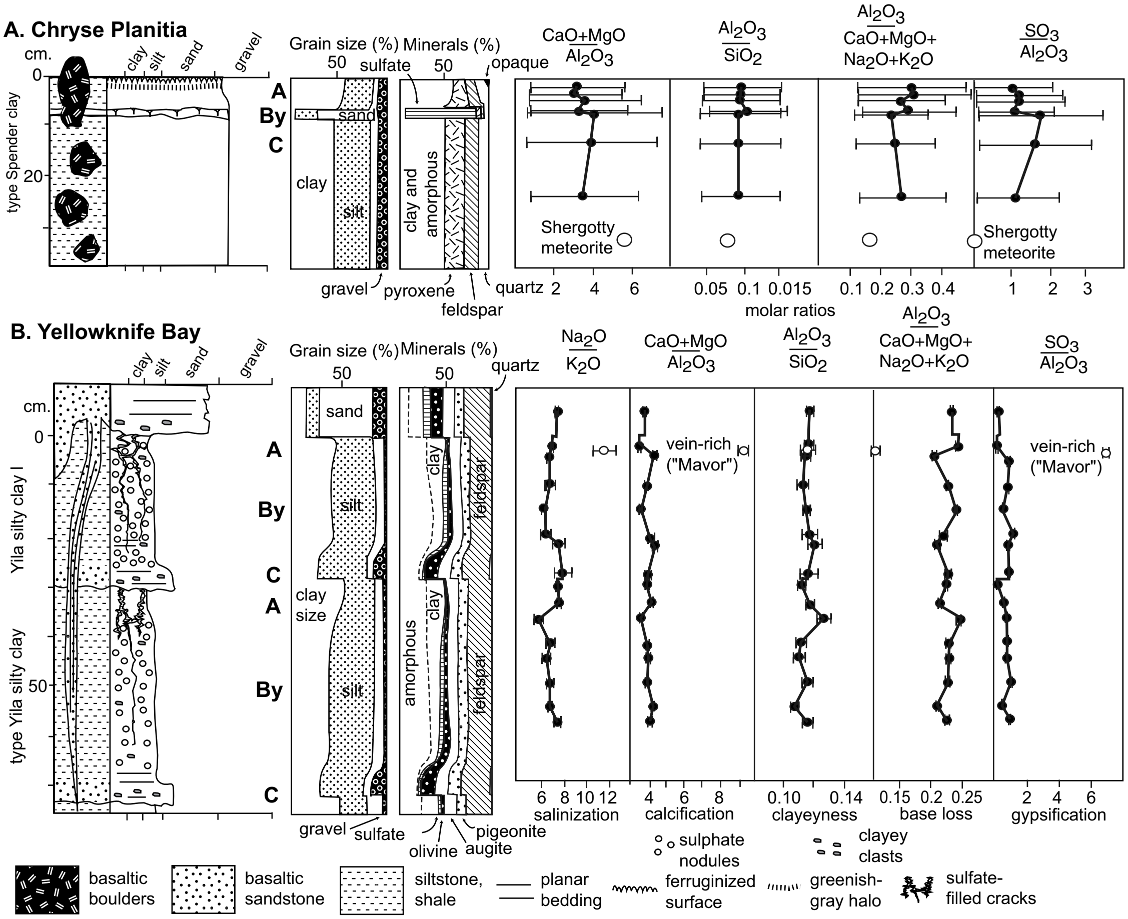

Figure 3. Molar weathering ratios of paleosols at Chryse Planitia (A) and Gale Crater (B), Mars. Viking 1 rover results for the late Hesperian (3.5 ± 0.5 Ga) Spender paleosols of Chryse Planitia are compromised by low analytical precision, but not results from late Noachian (3.7 ± 0.1 Ga) Yila paleosols analyzed by Curiosity rover in Gale Crater, where pedogenic clay formed largely at the expense of olivine, and sulfates accumulated. Mavor sample is plotted separately because it is vein rich.

in Yellowknife Bay are from McLennan et al. (2014) and Grotzinger et al. (2014). Mineral compositions were reconstructed by Vaniman et al. (2014) for the Sheepbed member in bores from Cumberland and John Klein localities, and for overlying Gillespie and Glenelg members from Rocknest outcrop. Drilling behavior at Yellowknife Bay suggested a bulk density comparable with Pliocene siltstone from California (USA) (Grotzinger et al., 2014). Paleosols at Yellowknife Bay may have been buried by as much as 5.2 km of overlying rocks on Mount Sharp (Thomson et al., 2011), and like other paleosols buried as deeply (Retallack, 2012), would have had a relatively uniform bulk density compared with original soil. The density for mass balance analysis (Brimhall et al., 1992) used here (Fig. 4) assumed a uniform bulk density for all samples of 2.33 g cm^{-3} from Pliocene Gelisols (Gypsic Anhyturbels) of Antarctica (Retallack et al., 2001).

PALEOSOL RECOGNITION

Fluviolacustrine sediments found by Grotzinger et al. (2014) at Yellowknife Bay in Gale Crater have the field appearance (Fig. 2) of a sequence of paleosols interrupted and terminated by deposition (Fig. 3). Paleosols have sharp tops, truncating downward gradational alteration (Retallack, 2001). Similarly, there is a sharp upper contact of the Sheepbed member overlain by the sandy Gillespie member, which shows scouring and bedding, incorporating likely clasts of the underlying Sheepbed member (Grotzinger et al., 2014). Bedding is strongly disrupted by a system of cracks and veins, widest at the top of the Sheepbed member, but also seen at other levels in the member where intervals of dilational deformation are overlain by thin beds of sandy sediment (Grotzinger et al., 2014). These dilational cracking systems have coatings of sulfate, comparable with soluans of desert soils on Earth (Amundson et al., 2008), and also define blocky angular ped structure of clayey surface (A) horizons (Retallack, 2001). Disruption of lacustrine lamination characteristic of soils includes abundant nodules of the Sheepbed member (Grotzinger et al., 2014). Hollow nodules may have been gas vesicles (Grotzinger et al., 2014), comparable with vesicular structure common in desert soils on Earth (McFadden et al., 1998). Nodule composition is similar to that of the matrix, but enriched in Fe, Ca, Cl, Br, Ni, and Ge, suggesting cements of iron oxyhydroxide (akaganeite) and sulfate (bassanite or anhydrite; Vaniman et al., 2014). The nodules are aggregated into patches within irregular horizons (Fig. 2B) that have less prominent cracking (ped structure) than the surface horizon, as in gypsic (By) horizons in soils on Earth (Retallack and Huang, 2010). A prominent rock rib ("snake", Fig. 2A) is basaltic sand with clasts of finer-grained sediment and vertical bedding, centered on an uparched arched surface of the Sheepbed member (Grotzinger et al., 2014). Uparching, taken as evidence of upward intrusion by Grotzinger et al. (2014), as well as other features of the "snake" are comparable with periglacial sand wedges on Earth (Williams, 1986).

Paleosols were not recognized by Grotzinger et al. (2014) or Schieber et al. (2013), who regarded the outcrop as fluviolacustrine facies cracked by hydraulic fracturing or synaeresis, and infiltrated with diagenetic nodules. Diagenesis includes alteration after deposition as well as after burial, and it is only the latter that differs from the paleosol interpretation presented here. Nodules of the Sheepbed member are small, complex, and dispersed like soil nodules (Retallack and Huang, 2010), unlike burial diagenetic nodules that are large, rounded, and less stratigraphically restricted (Retallack, 2001). Hydraulic fracturing and synaeresis are unlikely, considering ptygmatic folding of a deep sulfate dike in the John Klein drill hole (Grotzinger et al., 2014) that indicates compaction of 76%, close to what can be calculated (74%) using a compaction equation for Aridisols (Sheldon and Retallack, 2001) on Earth buried by 5.2 km of overburden, as inferred for Gale Crater (Thom-

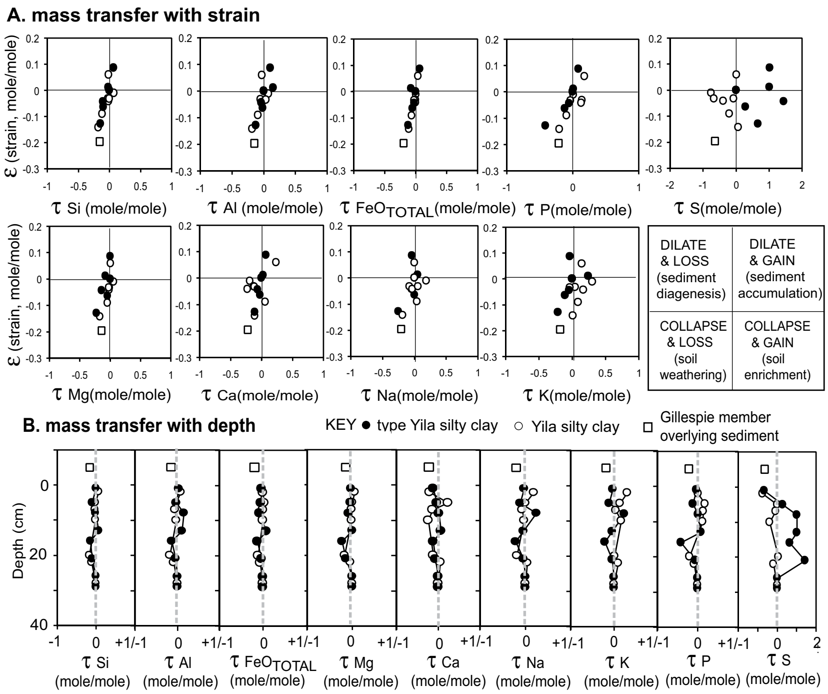

Figure 4. Geochemical mass balance of paleosols in the Sheepbed member, Gale Crater, Mars (determined using the methods of Brimhall et al., 1992; Amundson et al., 2008). Calculations assumed constant bulk density (Retallack, 2012) because of burial by 5.2 km of overburden (Thomson et al., 2011). Two successive late Noachian Yila paleosols show loss of volume and weatherable bases typical of hydrolytic weathering [compared with assumed parent materials of sample 15 "Ekwir Brush 1" (lower) and sample 8 "McGrath" (upper)]. Overlying sediments of the Gillespie member plot on the same weathering trend (with parent sample 8 McGrath). A: Degree of soil formation indicated by deviation from origin (interpretation of each quadrant of these diagrams is given at lower right). B: Degree of soil formation indicated by deviation from zero line of lowest sample. Mass transfer (τ) is mole fraction (mole/mole).

son et al., 2011). Hydraulic factures are sinuous to straight, not ptygmatic (Cosgrove, 2001). The low water:rock ratios of observed alteration (McLennan et al., 2014) and a lack of hydrothermal chert or ore minerals (Vaniman et al., 2014) are also contrary to hydraulic fracturing.

QUANTIFYING CHEMICAL WEATHERING

Molecular weathering ratios reveal depletion of weatherable bases and subsurface enrichment in alkaline earths and sulfite in two successive paleosols at Yellowknife Bay (Fig. 3). Geochemical mass balance of changes in volume and chemical components compared with those observed in the parent material (see the origin in Fig. 4A, and the deepest sample in Fig. 4B) show both the volume and component loss expected during soil formation. Additions of material by sedimentation or cementation would plot in the upper right quadrant of Figure 4A and right of the center line in Figure 4B.

Mass balance depletion of weatherable bases on Mars is modest (little deviation to left of parent in Fig. 4) compared with soils and paleosols with similar nodule development on Earth (Retallack, 2012), and comparable with soils from extreme environments such as the Atacama Desert (Amundson et al., 2012) and the Antarctic Dry Valleys (Retallack et al., 2001). Chemical weathering and soil formation in paleosols of the Sheepbed member is little evolved from likely Martian bulk crustal composition (McLennan et al., 2014). Nevertheless, differences between soil and parent materials (Figs. 3 and 4) indicate hydrolytic weathering at low temperature and pressure to produce clay (saponite) and sulfates (bassanite, anhydrite), largely at the expense of olivine (forsterite). Pyroxene and plagioclase were less weathered (Fig. 3). Less can be said about Viking relict paleosols, because analyses are imprecise and their mafic mineralogy is not well known, but their gypsic horizons and clayey fines suggest comparable weathering trends (Amundson et al., 2008).

PALEOSOL NAMING

The two successive gypsiferous paleosols at Yellowknife Bay (Figs. 3 and 4) are here named the "type Yila silty clay" (lower) and "Yila silty clay" (upper), after the woman who dreamed of arriving astronauts in *The Martian Chronicles* (Bradbury, 1950). Buried Yila paleosols are very different from the Chryse Planitia relict paleosol, with shallow tabular gypsum stringers (Fig. 3) here named the "type Spender clay pedotype" after the archaeologist in Bradbury's (1950) novel. Yila paleosols are comparable with nodular silty clays on Matijevic Hill (Fig. 1), where exposure is incomplete and paleosols have not been previously noted (Arvidson et al., 2014). A Spender pedotype paleosol has also been documented from the Viking 2 site on Utopia Planitia (Retallack, 2001). Both Yila and Spender paleosols may be present at Mawrth Vallis, where geologically older, more clayey paleosols have also been inferred from remote sensing (Horgan et al., 2012).

PALEOENVIRONMENTAL IMPLICATIONS

The regolith of Mars includes sediments (Grotzinger et al., 2014), but its paleosols are also valuable guides to soil-forming factors of organisms, climate, time, parent material, and topographic relief (Amundson et al., 2008). The topographic relief of the Yila paleosols has been interpreted (Grotzinger et al., 2014) as a low-gradient playa lake, which is a desert lake that is often dry, sometimes for protracted periods, thus allowing formation of soils. Yila paleosols have been exhumed from cover and are exposed in a hilly landscape dated by Farley et al. (2014; from cosmic ray production of ^{3}He, ^{21}Ne, and ^{36}Ar) at 78 ± 30 Ma (late Amazonian, or Late Cretaceous in Earth time). The chemical composition of Yila parent siltstone is basaltic (McLennan et al., 2014). Spender paleosols, in contrast, formed on bouldery basaltic plains that have been eroded (Thomson and Schultz, 2007) back to an armoring gypsic horizon (Retallack, 2001).

The paleoclimate of Yila paleosols was arid and frigid, on the basis of sulfate nodules and weak chemical differentiation (McLennan et al., 2014). On Earth, depth to gypsic horizon is a proxy for mean annual precipitation (Retallack and Huang, 2010); this cannot be used for the upper Yila silty clay, which shows clear surface erosion (Fig. 2A). However, the type Yila silty clay below has an ~6-cm-thick cracked (blocky peds) and low-sulfate (buried A) horizon. Correcting for known burial compaction of Aridisols (Sheldon and Retallack, 2001) under a maximum 5.2 km of overburden (Thomson et al., 2011), the depth of 8 cm is comparable with that in gypsic soils on Earth receiving 104 ± 129 mm mean annual precipitation (Retallack and Huang, 2010). A case of no burial, unlikely considering ptygmatic compaction of veins (Grotzinger et al., 2014), gives not much less, 100 ± 129 mm mean annual precipitation. Applying a transfer function based on tundra soils on basalt in Iceland (Óskarsson, et al., 2009) to Yila paleosols gives −1 °C mean annual temperature. The "snake" dike with vertical bedding (Fig. 2A) has the appearance of a periglacial sand wedge; these form in arid frigid continental environments on Earth (Williams, 1986), i.e., environments with a mean annual temperature of <–4 °C to <–8 °C, coldest-month mean temperature of <–25 °C to <–40 °C, warmest-month mean temperature of 10–20 °C, and mean annual precipitation of 50–500 mm. The "snake" dike originates at the top of the Yila silty clay, or perhaps a little above (Grotzinger et al., 2014), and so postdates the Yila silty clay. In view of these paleoclimatically significant features, Yila and Spender paleosols are Gelisols, comparable with Gypsic Anhyorthels, in the United States soil taxonomy (Soil Survey Staff, 2010).

The time required for formation of the paleosols can be inferred from the degree to which primary bedding is obscured by the growth of nodules. Sulfate (3.6%) in Yila paleosols, estimated from chemical modes of the John Klein drill core (Vaniman et al., 2014) and entered into a chronofunction for gypsic soils of the Sinai and Negev Deserts (Retallack, 2013), gives a duration of 20 ± 15 k.y. for the formation of the Yila silty clay paleosol. A better comparison may be with soils of Arena Valley, Antarctica (Retallack et al., 2001), where a weathering stage of 3.6, comparable with Yila paleosols, is seen after 1.3 ± 0.7 m.y. Amalgamation of nodules into solid horizons like that of the Spender paleosol takes a long time on Earth: a comparable weathering stage 6 of residual soils is seen after 1.7 ± 0.7 m.y. in Antarctica (Retallack et al., 2001).

LIFE ON MARS?

Spender and Yila paleosols are evidence of habitable environments, but have yielded no conclusive evidence of life. They appear habitable by the same criteria applied to their sedimentary paleoenvironment, i.e., circumneutral pH with buffering base-rich clays (Grotzinger et al., 2014). Additional aspects of Yila paleosols compatible with microbial life are phosphorus depletion (Neaman et al., 2005), vesicular structure (McFadden et al., 1998), nodularized rather than crystalline sulfate, and the spread of nodules though a substantial thickness of matrix (Retallack, 2013). On Earth, organic ligands produced by microbes are necessary to deplete phosphorus from primary minerals such as apatite (Neaman et al., 2005), although depletions observed in Yila paleosols are smaller than in soils (Amundson et al., 2012) and paleosols on Earth (Retallack, 2012, 2013). Vesicular structure is a characteristic but enigmatic feature of desert soils on Earth, perhaps formed by gas from by microbial population explosions following rare rains (McFadden et al., 1998). In Yila paleosols, pedogenic sulfate is in replacive scattered small nodules, unlike crystals of displacive sulfate in evaporates (Retallack et al., 2001; Retallack, 2012, 2013).

Indications of habitability outlined here decline dramatically from late Noachian Yila paleosols to Hesperian Spender paleosols, so earlier Noachian terrains are more promising prospects for clear evidence of life on Mars. These novel observations support the view that the Noachian-Hesperian transition at ca 3.6 Ga was a time of change from an early benign water cycle on Mars to the acidic and arid Mars of today (Grotzinger et al., 2014). Details of this planetary history will be gained by further discovery and interpretation of paleosols on Mars, now that a search image of their general appearance is available.

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