Icarus 394 (2023) 115436

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Petrogypsic paleosols on Mars

Gregory J. Retallack *, Shane Jepson, Adrian Broz

Department of Earth Sciences, University of Oregon Eugene, Oregon 97403-1272, United States

A R T I C L E I N F O

Keywords:
Candor Chasma
Paleosol
Gypsid
Paleoclimate

A B S T R A C T

Unlike the water planet Earth, or furnace planet Venus, Mars is a frigid soil planet, most like the Dry Valleys of Antarctica, which also has paleosols revealing a different past. This study examined rocks in early Amazonian (3000 Ma) sequences of western Candor Chasma, cemented by sulfates and iron oxides. Mars Reconnaissance Orbiter data were used to quantify elevations, and the gypsic bands proved to follow ancient dune surfaces, like petrogypsic horizons of soils. Hesperian-early Amazonian (3700-3000 Ma) gypsic paleosols are widespread on Mars, which also has Noachian (3800-4000 Ma) deeply weathered, kaolinitic paleosols. The Archean (3700-3000 Ma) Earth was similar with both gypsic and deeply weathered profiles. Archean fossil microbes and soils on Earth include acid sulfate and deeply weathered soils, but both life and soil diversified afterward on Earth. There is not yet a fossil record on Mars, but the red planet does have acid sulfate and deeply weathered paleosols of geological ages equivalent to Archean on Earth. Unlike Earth however, there is little evidence of later significant soil formation on Mars.

1. Introduction

Multiple active rovers on Mars have revealed pedogenic alteration and diversity across much of the planet (Certini et al., 2020). Astropedology, or the study of soil formation on the early Earth and other planets, now has an increasingly diverse set of materials to explore the role of soils in the origin and sustenance of life, and reveals a trajectory of soil evolution on Mars very different from on Earth (Retallack, 2016). This study evaluates weather-resistant gypsum bands on Mars within layered deposits of Candor Chasma, a branch of Valles Marineris (Fig. 1a-b), as clues to past climates and surface environments on Mars.

2. Materials and methods

Transects and topography for Mars (Fig. 2) were obtained from the Digital Terrain Model on the University of Arizona's HighRISE website (https://www.uahirise.org/dtm/PSP_001918_1735), using the ArcGIS Pro program. HighRISE elevation data typically has an error or ±0.3 m (Schmidt et al., 2018). In our graphical presentation of elevations (Fig. 2B-D) we chose a line thickness corresponding to at least twice this thickness. Overlaying the ORTHO image on top of the Digital Terrain Model allows line tracing of specific profiles beds. This gives an accurate view of the specific bands for line tracing of elevations into a table exported to Excel for plotting. Comparable transects were also derived for topography and beds in eastern Washington from digital terrain models of the Washington State Department of Natural Recourse's LiDAR portal website (https://lidarportal.dnr.wa.gov).

3. Hypotheses for Martian layered terrains

Layered sedimentary deposits on the floor of Candor Chasma have long attracted attention for their striking topography and patterns (Figs. 1C, 2A). Early speculation on the nature of the light and dark banding as volcanic tuffs (Lucchitta, 1990), subice intrusions (Komatsu et al., 2004), or hydrothermal layering (Geissler et al., 1993) was falsified by OMEGA spectral data (Mangold et al., 2008), and ongoing investigation by the CRISM (Compact Reconnaissance Spectrometer at Mars) instrument onboard MRO (Mars Reconnaissance Orbiter: Murchie et al., 2009), revealed that ridge-forming, light-colored layers were not silicates, but sulfates, mainly kieserite ($MgSO_4 \cdot H_2O$). Dark recessive layers between the white bands had indeterminate polyhydrated Ca-, Na-, Fe-, or Mg-sulfates, as well as pyroxene and ferric oxides, including hematite (Fe_2O_3).

Candor Chasma itself formed as a graben during the early Hesperian (3700 Ma), Crater counts and other considerations suggest that the exposed sedimentary fill is early Amazonian, or roughly 3000 Ma (Schultz, 1991). The bright, thin, sulfate layers are distinct in thickness and brightness from the coarse layering of Candor Chasma walls

* Corresponding author.
E-mail address: gregr@uoregon.edu (G.J. Retallack).

https://doi.org/10.1016/j.icarus.2023.115436
Received 31 August 2022; Received in revised form 8 November 2022; Accepted 9 January 2023
Available online 13 January 2023

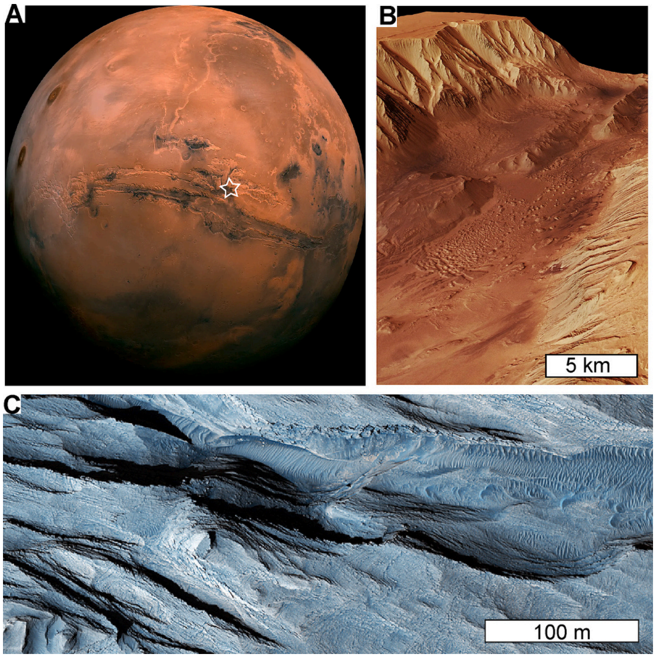

Fig. 1. Valles Marineris and Candor Chasma at star (A), dunes (B) and sulfate layers (C), Mars: A, July 9, 2013 Mars planetary mosaic 102 from Viking Orbiter (JPL-Caltech-NASA); B, July 6, 2006 Mars Express orbit 3195 perspective view of dunes in norther Candor Chasma (EES/DLR/FU Berlin by G. Neukum CC BY-SA 3.01GO by permission); C, sulfates (white layers) and hematite (blue background) in northwest Candor Chasma (Arizona State University LPL HiRISE image ESP-013350-1745).

(Mangold et al., 2008; Murchie et al., 2009). The sulfate-rich bands are not silicic volcanic tephra from subaerial eruptions (Lucchitta, 1990), nor sub-ice igneous eruptions and intrusions (Komatsu et al., 2004). Alternative views of Martian sulfate layers are as (1) playa lake evaporite sediments (Mangold et al., 2008), (2) evaporites from groundwater cementing sediments (Murchie et al., 2009), (3) aridland soil horizons (Retallack, 2014), (4) late diagenetic cements at disconformities (Yen et al., 2017), or (5) hydrothermally altered beds (Geissler et al., 1993), and their current landforms have been interpreted as (A) exhumed folds and fault blocks (Okubo, 2010), (B) yardangs (wind-sculpted rock: Liu et al., 2020), and (C) dunes (Peterson, 1982). Hypotheses 1-2 entail flat-lying lacustrine or marine basins in which evaporite minerals are deposited (1) or precipitated by evaporation from surface or groundwater (2), essentially sedimentological processes. Hypothesis 3 includes precipitation of salts from either meteoric or groundwater in flat or undulating topography, essentially pedological processes. Hypotheses 4 and 5 involve precipitation of salts from subsurface brines that are either cool or hot, and follow dikes, aquifers, or undulating disconformities, essentially geological processes. This study tests these alternatives with topographic profiles of erosion-resistant ribs of sulfate within topographic profiles of nearby hills in western Candor Chasma, Mars (Fig. 2).

4. Testing the hypotheses

Different alternatives to the relationship of topography with internal layers are shown schematically in Fig. 3. The differences shown are not dependent on absolute elevation, but on whether the lines are parallel or not. If the landforms were yardangs exposing horizontally bedded lacustrine evaporites, evaporative precipitates, or playa lake soils (Liu et al., 2020) the layering should be parallel (Fig. 3D). If the landforms were yardangs exposing folded or faulted sequences (Okubo, 2010), the layers within should also be folded or faulted and parallel (Figs. 3B-C). Other possibilities are that dunes were stabilized by pedogenic gypsic horizons and then overridden by additional dunes (Peterson, 1982), late diagenetic cements at unconformities (Yen et al., 2017), or hydrothermal alteration zones (Geissler et al., 1993), so that internal layers would not be parallel (Fig. 3B).

Our tracing of elevations of resistant bands in West Candor Chasma are not flat, nor parallel so falsify hypotheses of evaporitic deposits, precipitates, or lake-basin soils exposed in yardangs or tectonically folded sequences (Fig. 3). Diagenetic and hydrothermal sulfate ores ponding against an unconformity would show local thickening to several meters, and also thick cross-cutting feeder dikes, not seen in the images (Fig. 1C, 2). Thus we regard the continuous bands that we traced as aridland petrogypsic horizons stabilizing pre-existing dunes. This is not to say that sulfate springs, ores, deformed or planar bedded materials are found nowhere on Mars, just that the examples we have examined are most like dunes stabilized by petrogypsic paleosol horizons, cemented with gypsum, clay, and non-crystalline colloids. This implies precipitation of sulfate cements from both meteoric and groundwater within a hydrologically active surface layer of alteration, or soil, some 3000 Ma, like some other Martian sulfates (Amundson et al., 2008; Retallack, 2014; Amundson, 2018).

5. Analogous dune-binding paleosols on Earth

Instructive analogs on Earth for the complex interaction of eolian dune formation and aridland soil cements are found in the Pleistocene Palouse Loess of Washington, USA (Fig. 4). Eolian dunes from the last glacial maximum have been stabilized by post glacial grassland and Mollisol soils, but preserve interglacial aridland petrocalcic horizons of the Washtucna and Old Maid Coulee paleosols within the dunes (McDonald and Busacca, 1990). The complex stratigraphy of Calcid paleosols representing glacial aridity and Mollisol paleosols representing interglacial warmth and humidity (Retallack, 2007) can be observed within roadcuts through the dunes (Fig. 4B-C). Weather-resistant petrocalcic ribs are clear in the field (arrows in Fig. 5A) and on LIDAR images of eastern Washington (Fig. 5B-C), comparable with dunes and flanking weather-resistant ribs on Mars (Fig. 1C, 2A). We used LIDAR elevations compared with nearby dune relief to graphically represent paleorelief on buried petrocalcic surfaces (Fig 5B-C), in the same way as for images of western Candor Chasma (Fig. 2B-D). This idea of paleosol stabilization alternating with dune migration may reflect Milankovitch paleoclimatic fluctuation on Earth (McDonald and Busacca, 1990; Retallack, 2007). Comparable paleoclimatic fluctuation on Mars has been inferred from anomalies in its orbit and fluctuations in area and thickness of polar ice (Smith et al., 2016).

6. Paleosol record on Mars vs. Earth

Gypsic paleosol horizons have been recorded elsewhere on Mars. Kieserite ($MgSO_4 \cdot H_2O$) was identified at Viking lander sites, in surface soils on impact ejecta ca 3500 Ma on Chryse Planitia (Liu et al., 2021) and ca 3200 Ma on Utopia Planitiae (Hartmann and Neukum, 2001; Retallack, 2014), and on ca 3200 Ma sedimentary rocks on Meridiani Planum (Thomson and Schultz, 2007). Although at the surface, these Viking profiles are so old that they are paleosols in the sense that they are probably relict: no longer forming under current conditions on Mars (Retallack, 2007). Buried profiles some 3700 Ma in Gale Crater also were interpreted as Gypsid paleosols (Retallack, 2014) with nodules of bassanite ($2CaSO_4 \cdot H_2O$) and complex soil cracking developed on playa lake deposits (Grotzinger et al., 2014). Other potential petrogypsic horizons identified as "diagenesis at the unconformity" are below the basal Stimson formation at Greenheugh Pediment, and both Naukluft and Emerson Plateaus in Gale Crater (Rapin et al., 2019; Bedford et al., 2020, 2022). These consist of sulfate nodules, veins and pervasive cementation of the uppermost Carolyn Shoemaker and Murray formations that are largely truncated at the undulating unconformably overlying Stimson formation as would be expected of a truncated petrogypsic paleosol, but gypsic dikes with alteration haloes through the unconformity open the

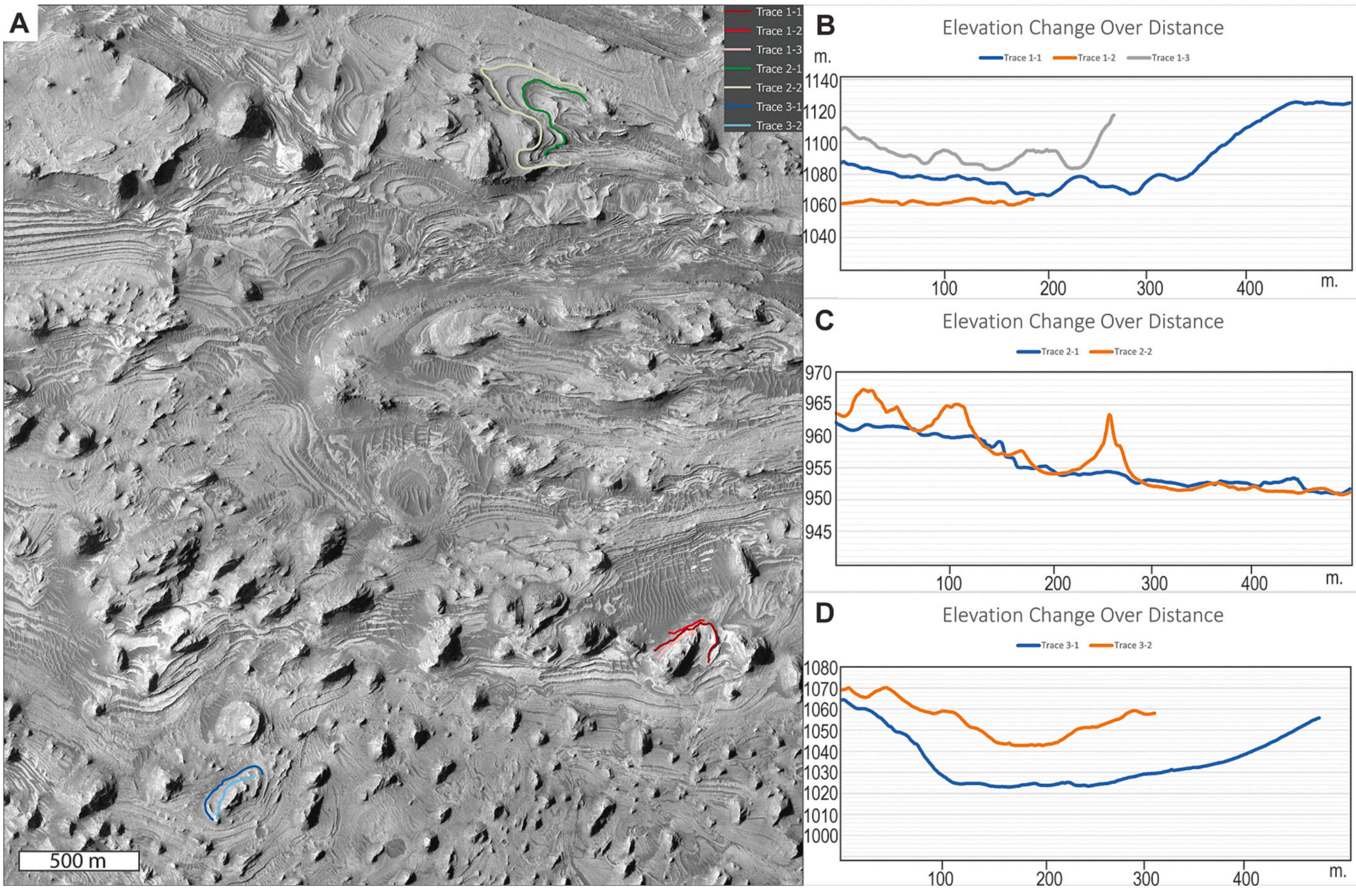

Fig. 2. Bed and landform tracing at three locations in southwest Candor Chasma, Mars. Bottom left-hand corner of image A is at latitude -6.49 longitude 283.17, from the HiRiSe Instrument onboard Mars Reconnaissance Orbiter (Arizona State University/ LPL HiRISE image ESP-013350-1745). All elevations and horizontal distances are in meters, and the uppermost trace is the nearest high ground.

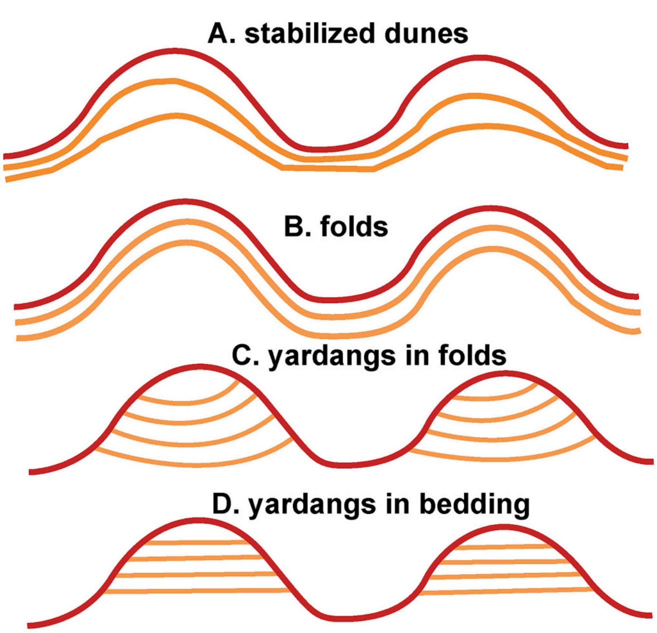

Fig. 3. Alternative interpretations of stratification in Candor Chasma, Mars, showing weather- resistant bands (orange) below the surface (red). Our data support option A.

possibility of deep burial groundwater alteration at that unconformity (Yen et al., 2017).

Comparable cold hyperarid soils of Chile (Amundson et al., 2008, 2012; Amundson, 2018; Ritter et al., 2022) and Antarctica (Campbell and Claridge, 1987), include thick gypsum cemented horizons that follow bedrock topography, but not dunes. Like these relict paleosols as old as Miocene (23 Ma) on Earth, Martian paleosols of Candor Chasma are evidence of cold, hyperarid paleoclimates on eolian dunes of 3000 Ma.

Hesperian and early Amazonian (3700–3000 Ma) gypsic Aridisols are surprisingly diverse and widespread on Mars (Amundson et al., 2008; Retallack, 2014; Amundson, 2018; Liu et al., 2020), which also has deeply weathered, kaolinitic Noachian (3800–4000 Ma) paleosols in Mawrth Vallis (Poulet et al., 2020; Liu et al., 2021). This array of paleosols is similar to paleosols of the same age on Earth, which includes widespread gypsic and baritic Archean Aridisols as old as 3700 Ma (Retallack, 2022), as well as deeply weathered paleosols (Oxisols?) on major geological unconformities as old as 3500 Ma (Retallack, 2010). On Earth there is evidence of life in Archean paleosols from phosphorus depletion, stable isotopic compositions, and permineralized microfossils (Retallack et al., 2021; Retallack, 2022), but evidence for life in Martian Hesperian paleosols is inconclusive (Retallack, 2014). Another difference between Earth and Mars is that Aridisols and Oxisols continued to form through to the present day amid a diversifying array of soils and ecosystems (Retallack, 2022). In contrast, the Martian soil record literally dries up after about 3000 Ma: although there are claims of continuing local gypsic soil formation (Liu et al., 2022). Soils have persisted on Martian landforms for that long without significant further alteration (Retallack, 2014), so are paleosols in the sense of relict soils

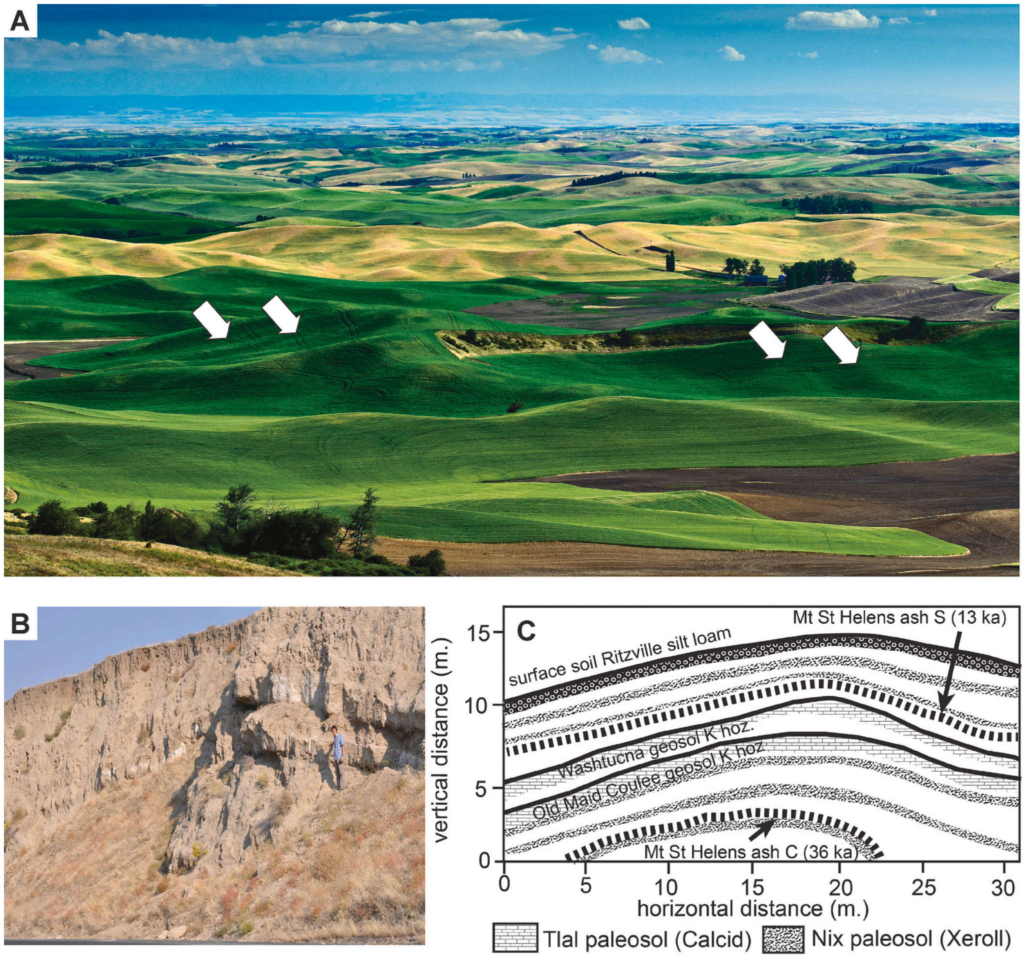

Fig. 4. Comparable bedforms near Steptoe Butte (A) and Clyde (B-C) Washington, USA: A, view southeast from top of Steptoe Butte, Washington, with resistant bands of pedogenic carbonate at arrows (N47.032372 W117.296865; photo courtesy of Ellen Bishop); B-C, photo and interpretation of cross-section of paleosols (McDonald and Busacca, 1990; Retallack, 2007) within dune on road north of Clyde, Washington (N46.433759 W118.460401).

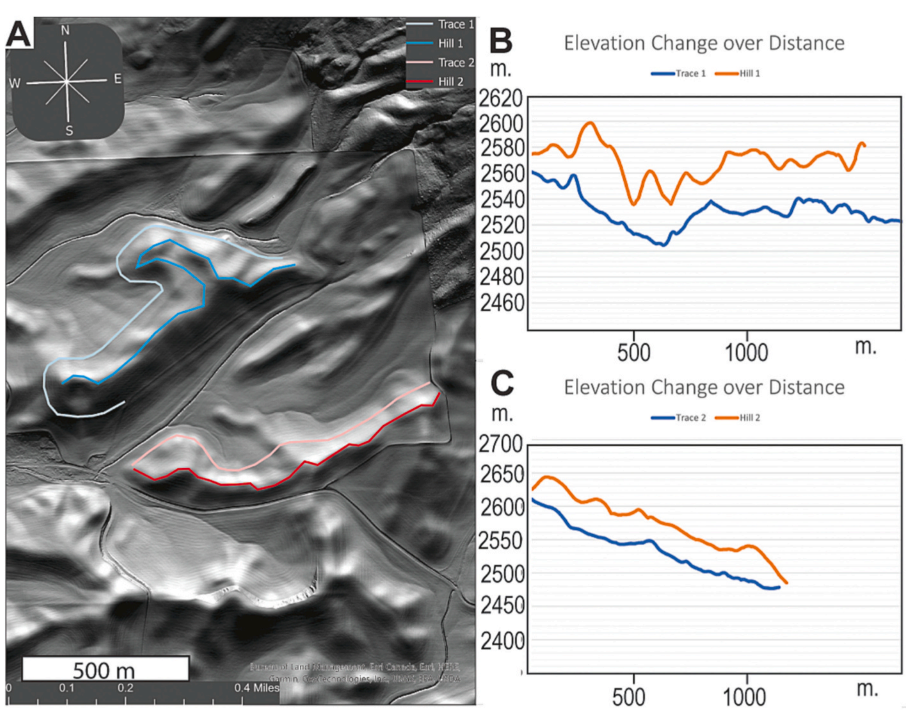

Fig. 5. Comparable bedforms (A) and transects (B-C) from LIDAR data near Steptoe Butte Washington USA. Transect B is at N47.019419 W117.315788. Elevations and horizontal distances are in meters, and the uppermost trace is the nearest high ground.

that formed under conditions unlike those currently prevailing. Crater counting studies have shown that Martian surfaces are generally billions of years older than soil mantled landforms on Earth (Hartmann and Neukum, 2001).

Declaration of Competing Interest

The authors of this manuscript do not have any known conflict of interest in this article.

Data availability

Data will be made available on request.

Acknowledgments

GJR acknowledges useful discussion and field guidance with Eric McDonald, Alan Busacca and Nathan Sheldon. GJR conceived the project and wrote the first and revised drafts, SJ and AB extracted and plotted data. The authors declare no competing interests.

References

Amundson, R., 2018. Meteoric water alteration of soil and landscapes at Meridiani Planum. Mars. Earth Planet. Sci. Lett. 488, 155–167.
Amundson, R., Ewing, S., Dietrich, W., Sutter, B., Owen, J., Chadwick, O., Nishiizumi, K., Walvoord, M., McKay, C., 2008. On the in situ aqueous alteration of soils on Mars. Geochim. Cosmochim. Acta 72, 3845–3864.
Amundson, R., Dietrich, W., Bellugi, D., Ewing, S., Nishiizumi, K., Chong, G., Owen, J., Finkel, R., Heimsath, A., Stewart, B., Caffee, M., 2012. Geomorphologic evidence for the late Pliocene onset of hyperaridity in the Atacama Desert. Geol. Soc. Am. Bull. 124, 1048–1070.
Bedford, C.C., Schwenzer, S.P., Bridges, J.C., Banham, S., Wiens, R.C., Gasnault, O., Rampe, E.B., Frydenvang, J., Gasda, P.J., 2020. Geochemical variation in the Stimson formation of Gale crater: Provenance, mineral sorting, and a comparison with modern Martian dunes. Icarus 341, 113622.
Bedford, C.C., Banham, S.G., Bridges, J.C., Forni, O., Cousin, A., Bowden, D., Turner, S. M., Wiens, R.C., Gasda, P.J., Frydenvang, J., Gasnault, O., 2022. An insight into ancient aeolian processes and post-Noachian aqueous alteration in Gale crater, Mars, using ChemCam geochemical data from the Greenheugh capping unit. J. Geophys. Res. Planets 2021JE007100.
Campbell, I.B., Claridge, G.G.C., 1987. Antarctica: soils, weathering processes and environment. Elsevier, Amsterdam.
Certini, G., Karunatillake, S., Zhao, Y.Y.S., Meslin, P.Y., Cousin, A., Hood, D.R., Scalenghe, R., 2020. Disambiguating the soils of Mars. Planet. Space Sci. 186, 104922.
Geissler, P.E., Singer, R.B., Komatsu, G., Murchie, S., Mustard, J., 1993. An unusual spectral unit in West Candor Chasma: Evidence for aqueous or hydrothermal alteration in the Martian canyons. Icarus 106, 380–391.
Grotzinger, J.P., Sumner, D.Y., Kah, L.C., Stack, K., Gupta, S., Edgar, L., Rubin, D., Lewis, K., Schieber, J., Mangold, N., Milliken, R., 2014. A habitable fluviolacustrine environment at Yellowknife Bay, Gale Crater. Mar. Sci. 343, 1242777.
Hartmann, W.K., Neukum, G., 2001. Cratering chronology and the evolution of Mars. Space Sci. Rev. 96, 165–194.
Komatsu, G., Ori, G.G., Ciarcelluti, P., Litasov, Y., 2004. Interior layered deposits of Valles Marineris, Mars: analogous subice volcanism related to Baikal Rifting, southern Siberia. Planet. Space Sci. 52, 167–187.
Liu, J., Di, K., Gou, S., Yue, Z., Liu, B., Xiao, J., Liu, Z., 2020. Mapping and spatial statistical analysis of Mars yardangs. Planet. Space Sci. 192, 105035.
Liu, J., Michalski, J.R., Tan, W., He, H., Ye, B., Xiao, L., 2021. Anoxic chemical weathering under a reducing greenhouse on early Mars. Nat. Astron. 5, 503–509.
Liu, Y., Wu, X., Zhao, Y.Y.S., Pan, L., Wang, C., Liu, J., Zhao, Z., Zhou, X., Zhang, C., Wu, Y., Wan, W., 2022. Zhurong reveals recent aqueous activities in Utopia Planitia, Mars. Science. Advances 8, eabn8555.
Lucchitta, B.K., 1990. Young volcanic deposits in the Valles Marineris, Mars? Icarus 86, 476–509.
Mangold, N., Gendrin, A., Gondet, B., LeMouelic, S., Quantin, C., Ansan, V., Bibring, J.P., Langevin, Y., Masson, P., Neukum, G., 2008. Spectral and geological study of the sulfate-rich region of West Candor Chasma, Mars. Icarus 194, 519–543.
McDonald, E.V., Busacca, A.J., 1990. Interaction between aggrading geomorphic surfaces and the formation of a Late Pleistocene paleosol in the Palouse loess of eastern Washington state. Geomorphology 3, 449–469.
Murchie, S., Roach, L., Seelos, F., Milliken, R., Mustard, J., Arvidson, R., Wiseman, S., Lichtenberg, K., Andrews-Hanna, J., Bishop, J., Bibring, J.P., 2009. Evidence for the origin of layered deposits in Candor Chasma, Mars, from mineral composition and hydrologic modeling. J. Geophys. Res. Planets 114, E00D05.
Okubo, C.H., 2010. Structural geology of Amazonian-aged layered sedimentary deposits in southwest Candor Chasma, Mars. Icarus 207, 210–225.
Peterson, C., 1982. A secondary origin for the central plateau of Hebes Chasma. Proc. Lunar Planet. Sci. Conf. 12, 1459–1471.
Poulet, F., Gross, C., Horgan, B., Loizeau, D., Bishop, J.L., Carter, J., Orgel, C., 2020. Mawrth Vallis, Mars: a fascinating place for future in situ exploration. Astrobiology 20, 199–234.
Rapin, W., Ehlmann, B.L., Dromart, G., Schieber, J., Thomas, N.H., Fischer, W.W., Fox, V. K., Stein, N.T., Nachon, M., Clark, B.C., Kah, L.C., 2019. An interval of high salinity in ancient Gale crater lake on Mars. Nat. Geosci. 12, 889–895.
Retallack, G.J., 2007. Soils and global change in the carbon cycle over geological time. In: Holland, H.D., Turekian, K.K. (Eds.), Treatise on geochemistry, 5. Pergamon Press, Oxford, pp. 581–605.
Retallack, G.J., 2010. Lateritization and bauxitization events. Econ. Geol. 105, 655–667.
Retallack, G.J., 2014. Paleosols and paleoenvironments of early Mars. Geology 42, 755–758.
Retallack, G.J., 2016. Astropedology: palaeosols and the origins of life. Geol. Today 32, 172–178.
Retallack, G.J., 2022. Soil salt and microbiome diversification over the past 3700 million years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 598 (111016), 1991.
Retallack, G.J., Chen, Z.Q., Huang, Y., Fang, Y., 2021. Oxidizing atmosphere and life on land during the late Paleoproterozoic outset of the "boring billion". Precambrian Res. 364, 106361.
Ritter, B., Diederich-Leicher, J.L., Binnie, S.A., Stuart, F.M., Wennrich, V., Bolten, A., Dunai, T.J., 2022. Impact of $CaSO_4$-rich soil on Miocene surface preservation and Quaternary sinuous to meandering channel forms in the hyperarid Atacama Desert. Sci. Rep. 12, 1–9.
Schmidt, G., Fueten, F., Stesky, R., Flahaut, J., Hauber, E., 2018. Geology of Hebes Chasma, Mars: 1. Structure, stratigraphy, and mineralogy of the interior layered deposits. J. Geophys. Res. Planets 123, 2893–2919.
Schultz, R.A., 1991. Structural development of Coprates Chasma and western Ophir Planum, Valles Marineris rift. Mars. J. Geophys. Res. Planets 96, 22777–22792.
Smith, I.B., Putzig, N.E., Holt, J.W., Phillips, R.J., 2016. An ice age recorded in the polar deposits of Mars. Science 352, 1075–1078.
Thomson, B.J., Schultz, P.H., 2007. The geology of the Viking Lander 2 site revisited. Icarus 191, 505–523.
Yen, A.S., Ming, D.W., Vaniman, D.T., Gellert, R., Blake, D.F., Morris, R.V., Morrison, S. M., Bristow, T.F., Chipera, S.J., Edgett, K.S., Treiman, A.H., 2017. Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater. Mars. Earth Planet. Sci. Lett. 471, 186–198.