DISAMBIGUATING THE SOILS OF MARS

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Abstract

Anticipated human missions to Mars require a methodical understanding of the unconsolidated bulk sediment that mantles its surface, given its role as an accessible resource for water and as a probable substrate for food production. However, classifying martian sediment as soil has been pursued in an ad-hoc fashion, despite emerging evidence from *in situ* missions for current and paleo-pedological processes. Here we find that *in situ* sediment at Gusev, Meridiani and Gale are consistent with pedogenesis related to comminuted basalts mixing with older phyllosilicates – perhaps of pluvial origin -- and sulfates. Furthermore, a notable presence of hydrated amorphous phases indicates significant chemical weathering that mirrors pedogenesis at extreme environments on Earth. Effects of radiation and reactive oxygen species are also reminiscent of such soils at Atacama and Mojave. Some related phases, like perchlorates and Fe-sulfates, may sustain brine-driven weathering in modern martian soils. Meanwhile, chemical diversity across in situ and regional soils suggests many different soil types and processes. But the two main soil classification systems –the World Reference Base (WRB) and the U.S. Soil Taxonomy – only inadequately account for such variability. While WRB provides more process insight, it needs refinement to represent variability of martian soils even at the first level of categorical detail. That will provide a necessary reference for future missions when identifying optimal pedological protocols to systematically survey martian soil. Updating Earth-based soil classification systems for this purpose will also advance soil taxonomy as a research field.

Keywords: Cryosols; Gelisols; mineral weathering; regolith; Soil Taxonomy; WRB.

1. Introduction

The martian surface holds such broad appeal as to even feature in popular culture. For example, Ridley Scott's 2015 film "The Martian", captured public interest in the context of martian soil, with more than $500M in box office profits. Despite such public visibility, a basic question continues to challenge planetary scientists: does the martian surface bear soil that can be interpreted in ways that mirror soil taxonomy on Earth? Even thirty years ago, "the top unconsolidated layer of weathered and partly weathered rocks of the martian lithosphere that is or was exposed to atmospheric effects" was already considered as soil (Banin, 1988). A plethora of subsequent remote sensing observations and NASA's landers/rovers Viking, Pathfinder, Spirit, Opportunity, Phoenix and Curiosity have amassed information that motivates direct comparisons with Earth. Martian soil has underpinned topical discourse across fields as diverse as modal mineralogy (e.g., McSween et al., 2010), habitability (e.g., Retallack, 2014; Edwards and Piqueux, 2016), *in situ* resources (e.g., Kumarathilaka et al., 2016; Chow et al., 2017; Scott et al., 2017), and lithification (e.g., Bridges and Muhs, 2012). However, a counterpart to terrestrial pedology is yet to emerge, creating a strategic knowledge gap between the terrestrial and planetary soil research communities.

Critically, inconsistent use of pedological terms would sow confusion and slow the progress of comparative pedology between Earth and Mars even as planetary soil sampling becomes more extensive in the coming years. While the promise and necessity of such effort has been highlighted by terrestrial soil scientists (e.g., Lin, 2005), a perspective review of the topical area remains lacking. A review of recent literature highlights the necessity of a coordinated and methodical soil characterization given the often *ad hoc* terminology, such as: regolith, (aeolian or fluvial) deposit, sediment, dust, and soil (e.g., Bish et al., 2013; Blake et al., 2013; Leshin et al., 2013; Meslin et al., 2013; Cousin et al., 2015; Grotzinger et al., 2015;

Martín-Torres et al., 2015; Szabó et al., 2015; Berger et al., 2016). Neologisms have also been used for martian sediment (Targulian et al., 2017), but these have resulted from specific research needs, not taxonomic consensus, rendering them ineffective as a common lexicon. Regolith, deposit, sediment, and dust all loosely refer to a layer of unconsolidated clasts and minerals covering bedrock, without conceptual connectivity to the nature of processes involved in pedogenesis.

For the moment, the greatest interest regarding the soils of Mars is for their suitability to physically support the landing of a possible spacecraft and related reconnoitring (Demidov et al., 2015; Golombek et al., 2012; Vago et al., 2015a). However, if or when any human missions reach that planet, the need to have a much deeper knowledge of its soils will increase abruptly. In fact, martian soils will then be used as a resource, e.g. to build shelters, extract water, and to grow plants (Certini and Scalenghe, 2010; Chow et al., 2017; Vithanage et al., 2019; Wamelink et al., 2014). The lack of liquid water and free oxygen on Mars and other planets makes the pathway of pedogenesis outside Earth quite different from those soil scientists usually encounter. Particularly, a range of alternative weathering mediators such as low pH brines, radiation, and micrometeor impacts (Certini et al., 2009; Schulze-Makuch and Irwin, 2006) need to be considered.

In this work, we review several fundamental perspectives of pedology in the planetary context, beginning with the possibility of extra-terrestrial soil, followed by a compositional overview of martian soils. Next, we consider reactive oxygen species (ROS) in martian soils; the roles of biology and water; pedogenic, mixing and transport processes on Mars; martian landscapes analogous to terrestrial soil settings; and the martian soils from a taxonomic perspective. Collectively, our discussion aims to emphasize that while the martian “soils” are indeed soils, current classifications based on terrestrial soils need to be adapted to adequately account for their most functional properties and their variability within broader taxonomic groups.

2. The possibility of extra-terrestrial soil

Although data are not yet exhaustive, we suggest that unconsolidated planetary sediment should be called soil in the technical sense of terrestrial pedology. The most compelling reason to place them in a pedological framework is the presence of chemically weathered fine-grained components and intermixed rock fragments, which is the key soil-forming pathway regardless of the planet (Certini and Scalenghe, 2010; Certini et al., 2013). Traditionally, according to the basic Hans Jenny's model, soil has long been believed to be the result of at least five forming factors: parent material, climate, organisms, topography, and time (Jenny, 1941). One of the limits of such a model is that it does not account for some terrestrial soils that form in virtually abiotic environments (Ewing et al., 2006; Sutter et al., 2007), and is even less open to including possible soils beyond Earth. Not contemplative of the possibility of extra-terrestrial soils are also the various definitions of soil coined over time, which are all focused on i) soil-forming factors, ii) the ability to sustain plant growth, or iii) a clear organization into horizontal layers (*soil horizon*).

More inclusive concepts and definitions of soil have emerged over time, which essentially point out some chemical weathering as a necessary and sufficient condition for the loose rock material to be considered soil, regardless of whether or not it is due to biota-induced reactions. Hence, Johnson (1998) stated that "soil is organic or lithic material at the surface of planets and similar bodies altered by biological, chemical, and/or physical agents", and then Certini and Ugolini (2013) proposed that the soil should be seen as "a centimetric or thicker unconsolidated layer of fine-grained mineral and/or organic material, with or without coarse elements and cemented portions, lying at or near the surface of planets, moons, and asteroids, which shows clear evidence of chemical weathering". In 2017, the Soil Science Society of

America Board approved a new definition, implicitly acknowledging the existence of soils on Mars: soil is “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” (van Es, 2017). Accordingly, water, life, and organic compounds are not essential for a soil on planet Earth or elsewhere.

The emerging formalism may not directly suggest that chemically altered materials transported by aeolian, fluvial, or lacustrine processes create a soil once redeposited, which is a common situation on Mars. However, it does not exclude such a possibility. For example, on Earth there are numerous areas where present-day soil development is affected by major contributions of materials transported from elsewhere and at different stages of weathering (Ugolini et al., 2008; Martignier et al., 2013). Even the main soil classification systems consider categories of soils where little or nothing in terms of *in situ* alteration is required. For example, in the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2015) – the international soil classification system endorsed by the International Union of Soil Sciences (IUSS) and meant for correlation of national and local systems – Arenosols are coarse textured soils with little profile differentiation; Fluvisols are basically stratified fluviatile, marine and lacustrine sediments; while Regosols are soils without significant profile development. Produced elsewhere and transported by various methods, those are all effectively allochthonous (cf., Neuendorf et al., 2011). Psamments, Fluvents, and Orthents are approximately the equivalents of Arenosols, Fluvisols, and Regosols in the U.S. Soil Taxonomy (Soil Survey Staff, 2014).

3. Compositional overview and implications of martian soils

3.1 General overview

For the general compositional context of martian soils, we tabulate a few representatives *in situ* and regional soils based on past and ongoing works in Table 1. Fig. 1 shows the regional extent of the martian landscape, especially the Southern Highlands, where soils, possibly quite weathered like those observed within excavations at Gusev (Haskin et al., 2005; Yen et al., 2015), may be common to decimetre depth scales (Hood et al., 2019).

Among the sites where martian soil has been characterized *in situ*, Gusev, Meridiani, and Gale have been examined more comprehensively, including in the context of chemical weathering (e.g., Amundson et al., 2018; Meslin et al., 2013; Yen et al., 2005). The data collected at Gusev Crater and Meridiani Planum led McGlynn et al. (2012) to conclude that the chemical composition of the soil at both sites mostly overlaps with the basaltic bedrock. That soil may have arisen as mixtures of comminuted basalts with older phyllosilicates and sulfates not significantly altered by chemical weathering after formation. The possibility of serpentine-rich soil has also been considered on Mars (Kumarathilaka et al., 2016; Vithanage et al., 2019), given the mostly mafic chemistry at regional scales (e.g., Taylor, 2013), the likelihood of serpentinization (Oze et al., 2005; Etiope et al., 2013), and the detection of serpentine minerals in some outcrops (e.g., Ehlmann et al., 2010). Observations by Curiosity of the Rocknest target at Gale Crater refined that view.

3.2 Mars soil as seen at Gale Crater

Rocknest chemically resembles aeolian features analyzed by Spirit and Opportunity at other sites (Blake et al., 2013), but ChemCam data indicate that fine-grained soils at Gale, depleted in SiO_2, differ chemically from the bedrock analysed so far (Meslin et al., 2013; Cousin et al., 2015). Specifically, they contain a large fraction of volatile-rich, Si-poor amorphous components as determined from X-ray diffraction data from the CheMin instrument (e.g., Achilles et al., 2017; Smith et al., 2018). Therefore, although soil bulk composition may fall in the "basaltic" range of composition in a total alkali vs. silica (TAS) diagram, salts such as sulfates may be as high as 11% with regional SO3-equivalent abundance ~5% (Table 1). CheMin data also suggested that the mineralogy of crystalline phases found in Rocknest resembles the normative mineralogy of other basaltic rocks on Mars (Bish et al., 2013). The fraction of sand <150 μm in size contains ~55 wt% crystalline material consistent with a basaltic provenance, along with ~45 wt% x-ray amorphous material. Furthermore, soils throughout the Curiosity traverse at Gale Crater contain amorphous phases as a constituent in mass fractions (wt%) ranging from 15 to 70, suggesting a significant role to underlying processes at least within Gale Crater if not more broadly across the planet (e.g., Smith et al., 2018). While those processes remain mostly unconstrained, processes where phases form too rapidly for effective mineralization, such as sudden precipitation or quenching at magma-ground water contact may be at play (e.g., Smith et al., 2018).

The amorphous component of Rocknest is iron-rich and is the host of volatiles, such as H_2O, S, C, P and halogens (Blake et al., 2013; Leshin et al., 2013; Meslin et al., 2013), present at least partly as sulfates, carbonates and oxychloride compounds (e.g., chlorates and perchlorates) (Leshin et al., 2013). Oxychlorides are possibly produced by gas phase photochemistry and oxidation of chlorine volatiles, resembling arid environments like the Atacama desert on Earth (Catling et al., 2010). The amorphous component may also include fine-grained nanophase oxide (npOx), an amorphous or short-range ordered phase considered the product of oxidative alteration or weathering and where Fe^{3+} is octahedrally coordinated. Dehouck et al. (2014) found that the amorphous components of Rocknest soil and the Sheepbed mudstone are chemically similar including volcanic (or impact) glass, hisingerite (or silica + ferrihydrite), amorphous sulfates (or adsorbed SO_4^{2-}), and nanophase ferric oxides. Furthermore, amorphous components were found to hold ~5 to 9 wt% of H_2O (Leshin et al., 2013; Meslin et al., 2013); their metastable chemistry can lead to brine formation and associated chemical weathering.

The D/H isotope ratio of Rocknest samples suggests interaction with “current” atmospheric water vapour (Leshin et al., 2013), possibly from repeated contact with frost, a likely alteration agent under modern atmospheric conditions. Gale soils contain so much phosphorus, i.e. 0.8 wt% P_2O_5, that the apparent stability of the found amorphous component(s) – which are usually unstable – may result from the sorption of phosphates (Meslin et al., 2013), whose presence is known to inhibit the transformation of ferrihydrite to more crystalline goethite and hematite (Shoji et al., 1993; Galvez et al., 1999). Such observations collectively support past and present interaction with water, the possibility that some fraction of the soil is authigenic, and the likelihood of secondary mineralogy associated with pedogenesis.

3.3 Secondary minerals

Several studies clarify the occurrence of secondary pedogenic minerals on Mars. Iron- and magnesium-rich clays could form by precipitation from residual, water-rich magma-derived fluids (Meunier et al., 2012; Berger et al., 2014) instead of weathering associated with pedogenesis. However, Hurowitz and McLennan’s (2007) analyses suggest that the martian surface was long dominated by a low-pH, sulfuric acid-rich weathering environment in which the dissolution of the labile mineral phases olivine and apatite was promoted. The soil chemistry would differ from Earth’s since, under such low water activity, silicate mineral phases with slower dissolution rates (e.g., plagioclase and pyroxene) would contribute less to the secondary mineral budget, in turn limiting the formation of significant Al-bearing secondary phases (e.g., Al-clay minerals, Al-hydroxides, Al-sulfates). Impact-induced hydrothermalism can also locally favour leaching as a contributor to soil chemistry, as evidenced by Al-, Si- and Ge-enrichments observed in breccia clasts filling a fracture in the

Marathon Valley cross-cutting the rim of Endeavour Crater (Arvidson, 2016; Mittlefehldt et al., 2016).

4. Effects of radiation and reactive oxygen species (ROS) in martian soils

One of the distinctive characteristics of martian soil is the ubiquitous presence of oxidizing reagents on the surface layer. Presence of reactive oxygen species (ROS) in martian soils has been suggested since the Viking era, such as hydrogen peroxide (H_2O_2) and superoxide (O_2^-) (Hunten, 1979; Zent and McKay, 1994; Yen et al., 2000; Zent et al., 2008; Lasne et al., 2016), accounting for martian soil reactivity. Possible pathways for hydrogen peroxide production are electric discharges (Atreya et al., 2006) and interaction with frost (Huguenin et al., 1979). Later, oxychlorine species (perchlorate or chlorate) were detected at the Phoenix landing site (Hecht et al., 2009) and Gale crater (Leshin et al., 2013; Ming et al., 2013; Sutter et al., 2017), indicating possible redox pathways of surface materials involving oxychlorine species (e.g., Brundrett et al., 2019). The oxychlorine species have been proposed to form via several pathways on Mars, including photochemical-related processes (Catling et al., 2010; Schuttlefield et al., 2011; Carrier and Kounaves, 2015; Zhao et al., 2018), aeolian processes like dust storms or dust devils (Tennakone, 2016; Wu et al., 2018), or radiolysis of chlorine species (Wilson et al., 2016).

On Earth, ROS is notable in terrestrial topsoils of Atacama and Mojave deserts (Georgiou et al., 2015) and oxychlorine species are also detected in similar arid or semi-arid settings like Atacama, southwestern United States, and Dry Valley of Antarctica (Jackson et al., 2015), suggesting analogous alteration reactions across planetary bodies (Catling et al., 2010). Such reactive chemical species can induce chemical weathering of the surface materials. For example, Mars is known to have a reddish colour due to oxidation of its surface (Lasne et al., 2016), independent of oxidation in underlying sedimentary units as revealed by drilling at Gale by Curiosity (Grotzinger et al., 2014).

At a larger scale, impact gardening can also expedite soil formation by increasing the porosity and surface area for chemical weathering, even though it can simultaneously disrupt existing soils (cf., Hartmann et al., 2001; McGlynn et al., 2011). The chemical reactivity induced by space weathering is likely to be preserved until the soil particles are exposed to water and oxygen (Loftus et al., 2010). Therefore, with less water activity than terrestrial deserts and less atmospheric and magnetic protection to radiation compared to Earth, Mars may represent an extreme example of terrestrial soil ROS build-up (Georgiou et al., 2015).

Radiation is a major cause of chemical and optical property changes in planetary surface materials. The role of radiation-induced weathering processes of martian soil has not yet been considered extensively (Gurtner et al., 2005; Quinn et al., 2013; Yen et al., 2000), but its intensity is likely to be secondary to chemical weathering processes, unlike space weathering on the Moon and other bodies that are relatively devoid of atmospheres (Pieters and Noble, 2016). For example, while galactic and solar ionizing and non-ionizing flux (e.g., protons, secondary neutrons and gamma photons) interacts with soil at the atomic level to produce gamma spectra with enough intensity to discern regional geochemistry (e.g., Boynton et al., 2007; Karunatillake et al., 2007), bulk chemistry of soils and *in situ* observed alteration rinds are considered to be primarily the products of chemical processes.

The radiation exposure on the surface of Mars, previously estimated and modelled, was first measured at Gale crater by the Radiation Assessment Detector (RAD) on the Curiosity rover on 7 August 2012. The radiation dose rate during the first 300 sols on Mars varied between 180 and 225 microgray (μGy)/day, owing to the combined effects of diurnal variations from atmospheric pressure changes, Mars seasonal variations at Gale crater, and heliospheric structure variability due to solar activity and rotation (Hassler et al., 2014). Such a dose of ionizing radiation has fatal effects on unprotected living beings and, on the long term, may even induce space weathering (Pieters and Noble, 2016). Nevertheless, the time scale of the reworking for the upper layer of the martian surface may be much shorter than space weathering rates, obscuring the chemical signatures of the latter.

5. Role of biology and water in the context of planetary soil formation

That terrestrial soils are typically hydrated and rich in biota motivated Meslin et al. (2013) to refer to Gale Crater ChemCam soil targets as "loose, unconsolidated material that can be distinguished from rocks, bedrock, or strongly cohesive sediments, without any implication on the genesis and the presence or absence of organic materials or living matter". Bish et al. (2013) had a similar definition for the soils analysed by the CheMin instrument onboard Curiosity. Later, Grotzinger et al. (2015) noted that "on Mars, the term soil implies no biogenic component, as it does on Earth. It includes surficial deposits such as windblown dust and sand that may locally form small drifts or dunes, in addition to fragmented bedrock". On Earth, in many cases chemical weathering is promoted and even mediated by the biota, but such alteration can occur in the absence of life (e.g., Lin, 2004).

While limited, martian unconsolidated sediment shows mineralogy broadly consistent with geologically sustained chemical weathering as discussed by McSween et al. (2010). Weathered sediment may even arise on bodies with negligible atmospheres, such as the Moon, caused by space weathering via continuous irradiation and micrometeor impact (e.g., Pieters et al., 2000). Organics such as amino acids were detected in Apollo samples and, although bearing certain degree of terrestrial contamination, some of them were considered autogenetic, implanted by solar wind and meteor impact into the lunar surface (e.g., Elsila et al., 2016; Thomas-Keprta et al., 2014). Contribution of carbonaceous chondrites to lunar soils were estimated at 1-4% (Haskin and Warren, 1991). Similarly, average meteoritic material contribution to the martian soil was estimated to be 1-3% (Yen et al., 2006). Organics may be present in martian soil, as found in the Yellowknife Bay, a lake deposit in the Gale crater floor sediment (Freissinet et al., 2015). However, convincing traces of past or current life are generally inevident (Sephton and Carter, 2015; Levin and Straat, 2016), perhaps related to low sensitivity of rovers' instrument suites to a sufficiently broad suite of biosignatures (ten Kate, 2010; Ferralis et al., 2016; Cabrol, 2018). Relaxing biotic activity as a precondition for pedogenesis helps circumvent such uncertainties (Certini and Ugolini, 2013).

On Earth, chemical weathering needed for pedogenesis is often mediated by water. There is an abundance of geomorphic and mineralogical clues that liquid water once flowed on Mars (Baker, 2001; Squyres et al., 2008; Carr and Head, 2010; Grotzinger et al., 2014; Bhardwaj et al., 2017; Goudge et al., 2015): delta deposits, river terraces, outflow channels, phyllosilicates, carbonates and hydrated secondary minerals all point to previous, and possibly periodic, aqueous chemical alteration of the planetary surface. The orbital detection of hydrous minerals, such as exposed phyllosilicate-rich outcrops, with Al-phyllosilicate-rich layers overlying Fe/Mg phyllosilicate-rich layers, as observed in the Noachian terrains (Le Deit et al., 2012; Loizeau et al., 2012; Ehlmann et al., 2013; Carter et al., 2015), reveals that early aqueous environments altered the basaltic crust of Mars (e.g, Carter et al., 2013). Specifically, such exposed phyllosilicate-rich outcrops, with Al-phyllosilicate-rich layers overlying Fe/Mg phyllosilicate-rich layers, were interpreted as a result of the leaching of the superficial soil horizons by percolating surface water, i.e., as a result of pedogenic processes. Water ice still exists in the shallow subsurface, as first directly assessed by the Phoenix lander in a 4-cm deep trench examined on 1st June 2008 at 68° North latitude (Smith et al., 2009), confirming orbital inference by gamma and neutron spectroscopy of an ice-rich permafrost at high latitudes (Feldman et al., 2004; Boynton, et al., 2007). Buried water ice may even exist close to Mars' equator, where Western lobes of the Medusae Fossae Formation have been suggested to contain up to 40 wt% of stoichiometric H_2O (Wilson et al., 2018). Meanwhile, a convergence of radar sounding and mineralogic characterization of exposed stratigraphy has suggested currently receding buried glaciers of Amazonian provenance (Dundas et al., 2018).

Despite the shallow-crustal presence of H_2O on modern Mars, liquid H_2O is generally unstable to sublimation. While that may reduce its potential to promote chemical weathering (Massé et al., 2016), there is also some evidence that deliquescence of certain salts, such as perchlorate or chlorate, may form stable liquid brines for short periods of time (Chevrier et al., 2009; Rennó et al., 2009; Liu et al., 2018; Toner and Catling, 2018). Furthermore, orbital gamma and neutron spectroscopy suggests chemically bound H_2O hydrating bulk unconsolidated sediment at decimeter depths in the 1-8% mass fraction range throughout the ±45° latitudinal range (Karunatillake et al., 2014, 2016), as corroborated by *in situ* observations (Campbell et al., 2008; Archer et al., 2014; McAdam et al., 2014; Sutter et al., 2017). The regional H_2O signature can be related to the presence in soils of hydrous sulfates (Karunatillake et al., 2014) and, from *in situ* observations at Gale crater, a hydrated amorphous component (Blake et al., 2013; Leshin et al., 2013; Meslin et al., 2013), as well as some water adsorbed to the fine-grained soil component (Sutter et al., 2017) – all of which may enable brines to form via a combination of deliquescence and eutectic melting.

Chemical weathering may occur even in the absence of abundant liquid water or brine. For example, a few molecules thick film of unfrozen water can bathe minerals causing high dissociation constants in frozen terrestrial soil (Ugolini and Anderson, 1973), which has also been proposed for Mars.

6. Pedogenic, mixing, and transport processes on Mars

Mixing processes have been suggested for unconsolidated sediment on Mars, albeit less notably than on Earth. Yen et al. (2005) underlined the similarity in composition of the fine-grained material from Gusev crater and Meridiani Planum, respectively landing sites of the Mars Exploration Rovers (MERs) Spirit and Opportunity, hypothesizing aeolian global mixing. Sedimentology of *in situ* compositional variations by grain size suggests the possibility of hydrodynamic sorting (Karunatillake et al., 2010; McGlynn et al., 2012), further boosting the likelihood of a globally mixed component. Such a hypothesis is supported by data obtained by the ChemCam instrument onboard the Curiosity rover, which first enabled a chemical study of martian sediments at sub-millimeter resolution (Cousin et al., 2017).

Analysis of ChemCam spectra not only provided information in favor of a strong chemical variability in grains of different sizes, but also showed that the fine-grained component was chemically homogeneous at this scale, while different from the composition of local rocks, unlike pebbles and cobbles which showed evidence for local provenance (Meslin et al., 2013; Cousin et al., 2015). That suggests that martian soil contains a fine-grained, well-mixed component probably of regional to global origin (Cousin et al., 2015), reminiscent of aeolian sediment dispersal on Earth (Vandenberghe et al., 2018).

Soil-mixing on Mars may occur even in the absence of terrestrial analog settings or liquid water. In addition to aeolian processes (Fig. 2), other reworking factors may exist in the current climatic regime. For example, to explain morphological changes of the martian landscape, Massé et al. (2016) proposed a hybrid flow mechanism involving both wet and dry processes, where metastable water boils as it percolates into the sediment, so inducing grain saltation and leading to massive slope destabilization. Likewise, dry granular flows may occur seasonally on Mars because of CO_2(s) sublimation-deposition cycles (Pilorget and Forget, 2016; Dundas et al., 2017).

As considered in Section 2, sediment deposited by aeolian, fluvial, or lacustrine processes – even if weathered elsewhere – do constitute soils on Earth. *Authigenic* processes, leading to *in situ* formation of secondary minerals or vertical translocation, are not necessarily needed and, may be very much slower on Mars than on Earth. For example, in their "integrated view of the chemistry and mineralogy of martian soils", Yen et al. (2005) observed only minor oxidative weathering of the sediments, suggesting rather limited interactions of particles with liquid films of water. Furthermore, the well-preserved stony meteorites found at the Meridiani Planum landing site (Schröder et al., 2010), whose exposure age may range from ~1 to ~50 Ma (Schröder et al., 2016), would be consistent with one to four orders of magnitude lower weathering rates and extreme aridity even compared to Earth's Antarctic surface conditions (Schröder et al., 2016).

Martian pedogenesis, from ancient pluvial periods to more petrogypsic(-like) soils under hyperaridity has been examined using *in situ* data (Amundson et al., 2008; 2018). Amundson et al. (2008) reveal that exogeneous sources for the weathered Mars soil are possible based on available landscape features and soil profile chemistry. Nevertheless, their work across three geographically disparate sites – at Viking, Pathfinder, and Opportunity landings – with geochemical mass balance provided convincing clues to post-depositional, *in situ* pedogenesis, regardless of substratum (dust or basalt). In particular, such soils have lost significant quantities of major rock-forming elements and gained elements that are likely present as soluble ions, the latter corresponding to the hyperarid and more recent Amazonian eon, possibly driven by thin brine films. Furthermore, the chemical differences detected among the sites, along with regional differences in soil composition (Table 1) are suggestive of multiple soil types on Mars (cf., Amundson et al., 2008).

The nature of soil transport and possible maturation has been considered *in situ*, such as at Gusev Crater (e.g., Arvidson et al., 2006). For example, the similarity in soil chemistry across a considerable elevation difference of ~ 70 m and distance ~ 4 km within Gusev Crater is consistent with localized aeolian transport. Nevertheless, subsurface soil at the Paso Robles excavation, dominated by iron sulfates of hydrothermal or aqueous origin, raised the possibility of authigenic origin, given compositional similarities with local outcrops (Arvidson et al., 2006). Meanwhile, compositional differences between surficial and underlying sediment is in support of distinct soil units even in a shallow decimeter scale profile. Likewise, evidence of induration within subsurface soil and chemistry suggestive of cementing salts in associated excavations (Arvidson et al., 2006) generally converge with Amundson et al.'s (2008; 2018) pedogenic interpretations.

Reinforcing Viking era observations, measurements by the Spirit rover revealed the presence of vertically stratified soil at Gusev: Fe-sulfate-rich sands were found beneath unremarkable basaltic sediment compositionally similar across current landing sites (Yen et al., 2008). The compositional similarity of the observed Fe-sulfate-rich sands to weathered local outcrops further supports the possibility of pedogenesis here (Campbell et al., 2008; Arvidson, 2016). Nevertheless, the presence of olivine – a mineral that is notoriously prone to weathering – likely preserved over geologic time scales in martian soils and particularly in atmospherically suspended dust (Goetz et al., 2005), suggests pedogenesis constrained by limited water. The similarity of that dust mineralogy at both Gusev and Meridiani further reinforces the scarce exposure of the globally sourced dust to aqueous alteration. This is also consistent with low weathering rates in the Amazonian, a period on Mars characterized by low rates of meteorite and asteroid impacts and by cold, hyperarid conditions broadly resembling current conditions (cf., Schröder et al., 2016). Likewise, a comparison between the chemical composition of dust and soils at Gale indicated that dust is not the most altered component of the martian soil (Meslin et al., 2013; Lasue et al., 2018).

7. Martian landscapes analogous to terrestrial soil settings

Remote sensing and the most recent *in situ* investigations highlight aspects of the martian landscape that are also characteristic of some soil settings on Earth. One of them is *patterned* *ground* (Mangold, 2005; Feuillet et al., 2015), primarily in the form of circles, polygons (Fig. 3), irregular networks, or stripes. Another is *desert pavement*, present in hot and cold deserts on Earth, as exposed mosaics of closely packed, interlocking angular or rounded rock fragments of pebble and cobble size (Golombek et al., 2006; Ugolini et al., 2008). Indurated crusts are also evident, which could occur by the infilling of dust particles among the intergranular spaces of the sand grains. An alternative driving factor for such processes could be groundwater upwelling, followed by evaporation, which has been also invoked by Flahaut et al. (2017) to explain the sulfate flats detected in several regions on Mars (Fig. 5).

Terrestrial desert pavement has been proposed as due to deflation, up freezing, wet-dry cycles and weathering (Pelletier et al., 2007; Knight and Zerboni, 2018). On Mars, it is possible that similar processes are, or were, active. Cementation by the evaporation of thin brine films presents an additional pathway, sometimes considered as a mechanism that forms "dust stone" and duricrust on Mars (e.g., Putzig and Mellon, 2007; Grotzinger, 2013). The latter has also been considered in a pedogenic context as early as the Pathfinder and Viking observations (e.g., Kraft and Greely, 2000).

Desert pavement usually coincides with the varnishing of outcrop and exposed rock fragments. *Rock varnish* is a 50-100 μm thin patina of iron and manganese oxides, clay minerals, and other elements with shared properties across Mars and Earth (Fleischer et al., 2008; Ugolini et al., 2008). The presence of manganese-rich coatings at the surface of some rocks has also been identified in the Gale Crater on Mars (Lanza et al., 2015; 2016). Other coatings, such as opaline silica and sulfur-phases have also been considered *in situ* (e.g., Pathfinder landing site) and locally from remote sensing. That generally suggests that coatings, in the form of alteration rinds, are found at varying spatial scales from soil grains, to float rocks and outcrops (e.g., Bishop et al., 2002; Hurowitz et al., 2014; Kraft and Greeley, 2000).

Desert varnish and cementation point to surface chemical weathering (e.g., Bishop et al., 2002; Hurowitz et al., 2014), but terrestrial soils are often characterized by vertical differentiation, due to an alteration gradient or to some internal redistribution of substances. Compositional observations of the first soil excavation on Mars by Viking enabled Yen et al. (2000) to state that on Mars “what’s underneath is different than what’s at the immediate surface”, supported further by analyses at Gusev and Meridiani (Yen et al., 2005). McSween et al. (2010) also derived modal mineralogy related to pristine and altered chemistry of soil as excerpted in Table 1. Such consistent observations of Mars by spacecraft augured the variability in mineralogical composition of martian soil at depth, which is hardly explainable with just physical processes (Bibring et al., 2005, 2006; Loizeau et al., 2012). Depth variability of carbonates, phyllosilicates, and soluble salts suggest chemical alteration and differentiation, regardless of mediation by water.

8. Martian soils from a taxonomic perspective

As discussed in Sections 4, 5 and 6 physical and compositional properties of unconsolidated sediment on Mars, along with associated processes, are collectively consistent with terrestrial soil. Consequently, we may consider the efficacy of the general framework of the WRB or the U.S. Soil Taxonomy to classify them. However, WRB classification tends to lump martian soils into a broad category, associated Reference Soil Groups (RSG), and qualifiers with only limited informativeness of the range of already known soil processes on Mars. Meanwhile the U.S. Soil Taxonomy standards are even more restrictive, resulting in lower correspondence between processes and classification than WRB. We consider the limitations in detail first for WRB, then for the U.S. Soil Taxonomy.

8.1 WRB taxonomy

According to the WRB, martian soils are *Cryosols*, all showing in the top meter a *cryic horizon*, which is a layer, containing water or not, where the temperature has been continuously below 0 °C for at least 2 consecutive years (i.e., corresponding to 2 consecutive revolutions of a planet in its orbit). On Earth, Cryosols are also those soils with a cryic horizon starting between 100 and 200 cm from the soil surface associated with evidence of cryoturbation (frost heave, cryogenic sorting, thermal cracking, ice segregation, patterned ground, etc., i.e. all phenomena that involve the presence of water) in some layer within 100 cm from the soil surface, which actually seem to occur in some places on Mars. Cryosols are fourth in the Key to the thirty-two RSG, the first level of categorical detail in the WRB. The users of this soil classification system go through the Key systematically, excluding one by one all RSGs for which the soil in question does not meet the specified requirements and until the one for which the criteria are fulfilled.

The first RSG in the sequence is that of *Histosols*, followed by the *Anthrosols* first and then the *Technosols*. None of the three RSG can represent martian soils, *Histosols* being organic soils and the other two types of soils being significantly affected by human activity. As largely demonstrated for high-latitudes (Schorghofer and Aharonson, 2005; Aharonson and Schorghofer, 2006; Arvidson et al., 2009; Mellon et al., 2009; Vincendon et al., 2010) and inferred at mid-latitudes (Bramson et al., 2015), Mars currently has a subsurface ice-bearing layer (Piqueux et al., 2019).

More important for classification purposes, a cryic horizon is much more widespread on Mars than Earth, right from the surface. There are parts of the martian surface that for a few hours seasonally exceed 0 °C or even the triple point of water (Figs. 6 and 7, respectively), but the affected top layer is probably just a fraction of a centimeter. Furthermore, this layer is not really a melting layer, as ice would sublime instead of melting at surface pressure slightly lower than 611.7 Pa. Nevertheless, brines may form, as was suggested by mineralogical characterization of recurring slope lineae (Ojha et al., 2015).

The WRB can indicate the most significant soil properties by *principal qualifiers*, which are added before the name of the RSG. *Supplementary qualifiers* give some further details about the soil and are eventually added in brackets after the name of the RSG. The qualifiers available for use with a particular RSG are listed in the Key. The principal qualifiers are ranked and given in an order of importance; hence, the uppermost principal qualifier in the list is placed closest to the name of the RSG. The supplementary qualifiers are not ranked, but are used in alphabetical order.

Present and future missions (ExoMars, Mars2020 and HX-1) will continue to investigate martian soil, where there may be no life and organic matter and the processes of translocation of materials and energy within the profile if present are minimal. With our current knowledge, several WRB principle qualifiers can be plausibly used with Cryosols on Mars, such as in order: *Glacic* (having a layer ≥ 30 cm thick, and starting ≤ 100 cm from the soil surface, containing ≥ 75% ice by volume); *Relictiturbic* (having cryoturbation features within 100 cm of the soil surface, caused by frost action in the past); *Leptic* (having continuous rock or technic hard material starting ≤ 100 cm from the soil surface); *Protic* (showing no soil horizon development, with the exception of a cryic horizon, which may be present); *Salic* (having a *salic horizon*, i.e., an horizon with high amounts of readily soluble salts, starting ≤ 100 cm from the soil surface); *Skeletic* (having ≥ 40% (by volume) coarse fragments averaged over a depth of 100 cm from the soil surface or to continuous rock, whichever is shallower; or *Haplic* (having a typical expression of certain features – typical in the sense that there is no further or meaningful characterization – and only used if none of the preceding qualifiers applies). However, none of the available qualifiers can reflect the variations in mineralogy and underlying processes that have been identified in situ (e.g., McGlynn et al., 2012; Sullivan et al., 2008).

Among the supplementary qualifiers, the most plausible for martian Cryosols are *Abruptic* (having an abrupt textural difference within ≤ 100 cm of the mineral soil surface); one between *Alcalic/Dystric/Eutric* (which essentially refer to base saturation); one between *Arenic/Clayic/Loamic/Siltic* to indicate the soil texture class; and *Aridic* to indicate that the soil undergoes arid conditions. On this basis, a map unit on Mars could be named, for example, *Leptic Protic Cryosols (Aridic)* at the third map scale level. However, as with the principal qualifiers, none of the supplementary qualifiers are informative of the compositional variability and processes revealed by in situ and regional analyses of soil (cf., Cannon et al., 2019; Hood et al., 2019; Marlow et al., 2008; Meslin et al., 2013).

8.2 U.S. Soil Taxonomy

The U.S. Soil Taxonomy would frame all the martian soils in the *Gelisols* – the first of the twelve *Orders*, the highest category of this classification system – because of the occurrence of *permafrost* whether hydrous or not. That is the quasi-equivalent of the cryic horizon, and *gelic material*, related to cryoturbation, within the same limits set for their homologues in the WRB. Being a fully dichotomic key, the U.S. Soil Taxonomy allows fewer degrees of freedom than the WRB in the construction of the name of a soil once its Order has been identified. Hence, already at the second stage, the Suborder, the key forces to choose, by exclusion, between only three Suborders: *Histels* (rich in organic matter), *Turbels* (showing cryoturbation), and *Orthels* (other Gelisols). The above-mentioned hypothetical martian *Leptic Protic Cryosols (Aridic)* of the WRB, according to the Soil Taxonomy should be called *Lithic Anhyorthels* at the Subgroup categorical level (the fourth one), i.e., Gelisols that do not have any organic material and any evidence of cryoturbation, undergoes anhydrous conditions (*Anhy-*) and show a lithic contact within 50 cm of the mineral soil surface (*Lithic*). Even going down to the lowest categorical level, the Family, there is no possibility of highlighting the absence of horizonation. Maybe more than the WRB, the US Soil Taxonomy gives great importance to the presence of permafrost at shallow depth.

While effective on Earth, permafrost is sufficiently widespread on Mars that the variability of martian soils cannot appropriately be mapped on small scale. Permafrost-based classification would then obscure the importance of other perhaps more functional features for future in situ resource use, such as thickness, salinity, stoniness and texture. Consequently, adjusting the current terrestrial soil classification systems is needed to appropriately account for the variability of martian soils already at the first level of categorical detail (RSGs or Orders), e.g. releasing these extra-terrestrial soils from the too limiting initial permafrost-related criterion in the keys.

Since the dawn of pedology until now, scant taxonomic attention was paid to soils outside our planet, but this will become increasingly pressing as the first human missions to Mars draw closer. Relying on specific, peculiar martian soil classes to expand current soil classifications could be optimal. Qualifiers and descriptive terms should be added to include in martian soils names at the lower levels of categorical detail properties rarely considered for Earth's soils, such as, for example, the content of ROS, perchlorates, or specific sulfates. The utilitarian aspects of compressive lithification without calcination or additives (Chow et al., 2017) can supplement such classifications, perhaps with the longer-term rock cycle from sediment to sedimentary rocks in mind (McSween, 2015).

The concept of soil, on Mars, could even abstract from chemical weathering and target the interaction of the bedrock with fluids (not just water), and thus embrace unaltered mobile sediments as well. The flux of new results from rovers (e.g., grain size compositional sorting; volatile element variations laterally and vertically) and new investigative techniques {e.g., Mars 2020 ground penetrating radar (e.g., Hamran et al., 2015) revealing regolith stratification, Insight mission's characterization of seismic wave propagation (e.g., Clinton et al., 2018) and geothermal gradient (e.g., Morgan et al., 2017)} will deepen insight into martian soils, maybe revealing unique trends that motivate new names and pedological models.

Soil mapping on Mars is a critical near-future step, useful not only for future human colonists but also for comparative planetology for soil processes. Due efforts are required to survey the martian soil resources with adequate tools and *modus operandi*. For instance, the ESA ExoMars drill will deliver Z-profiles into soils over a 2 m depth (e.g., Vago et al., 2015b). A patchwork of different soil types is expected, possibly less diverse than on Earth, where the biotic factor exponentially increases soil variability. An inclusive description of martian soils will enable future comparative pedology across other solid celestial bodies (Amundson, 2018), which would follow the existing precedent from substantial work on the Moon (Cooper et al., 2015).

Earth provides a case study in how quickly robust soil taxonomy can arise. In 1899, a few years after the birth of pedology in Russia, the Bureau of Soils of the United States Department of Agriculture launched the first systematic soil survey, considering all properties that may influence plant growth (Simonson, 1989; Hartemink et al., 2013). One century later, all USA soils were mapped (https://www.nrcs.usda.gov/wps/portal/nrcs/soilsurvey/soils/survey/state/) and today even the most remote and unknown areas of Earth are undergoing soil mapping, based on both field sampling and statistical modelling (Barthold et al., 2013). Applying the lessons learned in that terrestrial endeavour may well ensure comprehensive mapping and classification of martian soils.

9. Conclusions

The human exploration of Mars is a decadal-scale goal for humankind. When that happens, it will have to rely on the accurate knowledge of the surface of the planet, acquired in the meantime through remote sensing observations and *in situ* investigations. Information will be collected subsequently through sampling campaigns and lab analyses. Humans will need *in situ* resources for colonizing Mars. That demands an understanding of the local unconsolidated bulk sediment, given its role as an accessible resource for water and probable substrate for food production. However, the classification of such sediment remains a work in progress, despite emerging evidence for its pedological nature. For the moment, too little of the entire martian "soil skin" is known to draw a sufficiently representative picture and more terrain must be explored, particularly in areas of the planet where the environmental conditions may induce more weathering. Meanwhile, it is appropriate to preferentially use the term soil for indicating unconsolidated sediment of Mars, also because it emphasizes the necessity of relying on pedologic protocols and standardized guidelines for surveying and sampling such material. Soil mapping of the entire planet is expected, but the permafrost-related criterion in the keys of the current Earth-based classification systems for the highest categorical level detail (RSGs or Orders) is too stringent for the martian soils, to the extent of preventing proper accounting for their variability. Hence, efforts should be made to adapt such systems for Mars and, possibly, other rocky bodies of the solar system.

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Tables

Table 1. Chemistry for several examples of in-situ and regional martian soil, with 1σ uncertainties in parentheses when available and all Fe presented as +2 oxidation (FeO). Mineralogy of three soils is also provided as a general reference to martian soil mineralogy. In each column, location and instrumental method are listed. Gale Dust is included as a general reference for martian dust composition. The columns for Gusev and Meridiani are representative of regolith (i.e. both rocks and soils), compared to the Gale column, which is exclusively soil analyses. Mars Odyssey Gamma-Ray Spectrometer (GRS) values are based on the currently available chemical maps (Si, Al, Fe, Ca, K, Th (not shown here) S, Cl, H_2O), some of which are not available in earlier data (e.g., Karunatillake et al., 2007). GRS provides regional (5°x5° resolution) chemical data for the shallow subsurface (upper 10s of cm) with coverage from ~55°S to 45°N (Fig. 1), and all oxides shown are calculated based on measured elemental composition, assuming typical oxidation states. The division between the northern lowlands and southern highlands used in the Southern Highlands Average and Northern Lowlands Average columns is shown in Fig. 1.

Oxide	Meridiani[a] (Opportunity APXS)	Meridiani[a] (GRS)	Gusev[a] (Spirit APXS)	Gusev[a] (GRS)	Gale Soil[b] (Curiosity APXS)	Aeolis Palus Soils[c] (Curiosity ChemCam)	Gale Dust[d] (Curiosity APXS)	Gale Dust[c] (Curiosity ChemCam)	Southern Highlands Average[e] (GRS)	Northern Lowlands Average[e] (GRS)	Average Martian Soil[f]	MGS-1 Simulant[g]
SiO_2	43.2 (1.3)	42.4 (1.1)	39.3 (1.1)	41.9 (1.1)	43.46 (0.83)	42.00	38.6 ± 4.0	44.00	42.22 (1.64)	43.25 (2.28)	45.41	48.3
TiO_2	1.129 (0.028)		0.984 (0.133)		1.05 (0.06)	0.86	1.05 ± 0.18	1.05			0.9	0.2
Al_2O_3	8.86 (0.43)		8.69 (0.57)		9.37 (0.56)	8.50	9.32 ± 0.77	8.70	9.18 (1.80)	6.61 (1.92)	9.71	9.5
FeO (T)	17.75 (.90)	19.81 (1.67)	15.18 (0.39)	20.20 (1.54)	18.73 (1.75)	18.40	21.6 ± 4.2	19.80	15.66 (1.40)	17.90 (1.52)	16.73	16.9
MgO	6.93 (0.22)		8.32 (0.40)		8.35 (0.51)	7.70	8.08 ± 0.53	7.70			8.35	12.1
CaO	6.34 (0.04)		5.69 (0.31)		7.02 (0.20)	7.30	7.13 ± 1.23	6.50	6.93 (1.06)	7.18 (1.15)	6.37	6.7
Na_2O	2.13 (0.07)		2.53 (0.22)		2.80 (0.16)	1.86	2.73 ± 0.37	2.01			2.73	2.6
K_2O	0.405 (0.019)	0.381 (0.028)	0.342 (0.017)	0.395 (0.024)	0.57 (0.14)	0.23	0.44 ± 0.25	0.39	0.413 (0.052)	0.458 (0.091)	0.44	0.1
Cr_2O_3	0.443 (.010)		0.336 (0.029)		0.43 (0.08)		-				0.36	0.1
MnO	0.035 (0.014)		0.307 (0.008)		0.40 (0.04)		0.46 ± 0.25				0.33	0.1
P_2O_5	0.73 (0.05)		1.12 (0.34)		0.93 (0.05)		-				0.83	0.2

SO_3	5.24 (1.0)		8.5 (1.2)		5.96 (0.85)	8.01 ± 0.94		5.38 (0.59)	5.60 (0.79)	6.16	3.2
Cl	0.466 (0.006)	0.59 (0.06)	0.72 (0.07)	0.68 (0.06)	0.80 (0.14)	1.06 ± 0.27		0.466 (0.069)	0.497 (0.092)	0.68	0
H_2O	-	5.4 (0.6)	-	7.4 (0.6)	-	-		3.83 (1.02)	4.09 (0.97)	-	-

Soil Mineralogy

	Primary Minerals						*Secondary Minerals*					
	Olivine	Pyroxenes		Plagioclase	Magnetite + Chromite	Apatite	Nano-particle Oxide	Hematite	Sulfates	Chlorides	Silica	Clays
		High-Ca	Low-Ca									
Gusev[h]	14.0 - Fo51	0.9 - En26	17.7 - En53	34.3 - An39	2.0	1.8	3.2	0.1	11.3	2.7	8	4
eridiani[h]	14.3 - Fo37	2.7- En20	18.1 - En39	29.8 - An49	2.0	1.9	3	0.6	10.8	2	10	5
		Augite	Pigeonite		Magnetite							
Gale[i]	22.4 - Fo62	14.6	13.8	40.8 - An57	2.1	-	-	1.1	1.5	-	1.4	

Data sources: a: Table 3 “Opportunity” and “SpiritHW” (Karunatillake et al., 2007), b: Table 2 “Gale Soil” (O’Connell-Cooper et al., 2017), c: Table 1 “ChemCam eolian dust Sols 1-1,500” and “Aeolis Palus soils” (Lasue et al., 2018), f: Table 1 “O-tray Dust Sol 177” see source for details on uncertainty calculations (Berger et al., 2016), e: (Hood et al., 2019), f: (Taylor and McLennan, 2010), g: Table 2 “Calc. MGS-1” (Cannon et al., 2019), h: Model 1 data (McSween et al., 2010), i: Rocknest ChemMin crystalline soil component (Bish et al., 2013).

Figures

Fig. 1. Map of the martian surface showing the extent of coverage for the Mars Odyssey Gamma-Ray Spectrometer chemical data (solid black lines, from Hood et al., 2016) and the boundary between the northern lowlands and southern highlands region (black dotted line, from Tanaka et al., 2014). In addition to the topographic and age distinction across this boundary, there are geochemical distinctions that may be indicative of changes in soil alteration history, hence their separate consideration in Table 1. Background shows the map of Dust Cover Index (Red/solid white boundaries = high dust abundance, Blue/dashed white boundary = low dust abundance) (Ruff and Christensen, 2002).

Fig. 2. Panorama image taken on April 10, 2015 from the Mast Camera (Mastcam) instrument on NASA's Curiosity Mars Rover and showing diverse geological textures on Mount Sharp. Outcrops in the midfield are of two types: dust-covered, smooth bedrock that forms the base of the mountain, and sandstone ridges that shed boulders as they erode. The wind-induced sand ripples filling the foreground are typical of terrains that Curiosity traversed to reach Mount Sharp from its landing site. (Credit: NASA/JPL-Caltech/MSSS. URL https://mars.nasa.gov/resources/7404/curiosity-rovers-view-of-alluring-martian-geology-ahead/).

Fig. 3. The flat landscape of the northern polar region of Mars in one of the first images captured by NASA's Phoenix Mars Lander. Evident is the polygonal cracking, a pattern widespread in martian high latitudes and also observed in permafrost terrains on Earth, where it results from seasonal contraction and expansion of surface ice (Credit: Phoenix Mission Team, NASA, JPL-Caltech, Univ. Arizona. URL https://apod.nasa.gov/apod/image/0805/230118main_phoenix.jpg).

Fig. 4. View of the third (left) and fourth (right) trenches made by the 4-centimeter-wide scoop on NASA's Mars rover Curiosity in October 2012. The image was acquired by the

Mars Hand Lens Imager (MAHLI) on Sol 84 (Oct. 31, 2012) and shows some of the details regarding the properties of the "Rocknest" wind drift sand (Credit: NASA/JPL-Caltech/MSSS. URL http://mars.jpl.nasa.gov/msl/multimedia/images/?ImageID=4917).

Fig. 5. Sulfate salts (beige-coloured) covering the white-coloured aluminous clay-bearing material at Columbus Crater (28.79ºS/193.84ºE) within Terra Sirenum, southern martian hemisphere. Image taken by the Colour and Stereo Surface Imaging System (CaSSIS) onboard the ESA-Roscosmos ExoMars Trace Gas Orbiter on 15 January 2019 (Credit: ESA/Roscosmos/CaSSIS, ID: 418172. URL https://www.esa.int/spaceinimages/Images/2019/03/Salty_sulphates).

Fig. 6. Map of numbers of (Mars) hours per Mars year where the surface temperature is above T = 0 °C. A Mars hour is defined here as 1/24 of a martian solar day, or sol. It lasts 3699 seconds. This map was extracted from the Mars Climate Database (v4.3) for an average solar climatology (from Millour et al., 2008). Locations without colours are locations where T never exceeds 0 °C.

Fig. 7. Map of numbers of (Mars) hours per Mars year that the surface of Mars spends above the triple point of water (surface pressure > 611.7 Pa and surface temperature > 273.16 K). It does not imply, however, that liquid water is present. This map was created from the Mars Climate Database (v4.3) for an average solar climatology (from Millour et al., 2008). Locations without colours are locations where the triple point of water is never reached.