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1 **A view of extraterrestrial soils**

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8

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10 **Summary**

11 The nature of soils on celestial bodies other than Earth is a growing area of research in
12 planetary geology. However, disagreement over the significance of these deposits arises in
13 part due to the lack of a unified concept and definition of soil in the literature. The pragmatic
14 definition “medium for plant growth” is taken by some to imply the necessity of biota for soil
15 to exist, and has been commonly adopted in the planetary science community. In contrast, a
16 more complex and informative definition bases on scientific theory: soil is the
17 (bio)geochemically/physically altered material at the surface of a planetary body that
18 encompasses surficial extraterrestrial telluric deposits. This definition emphasizes that soil is a
19 body that retains information about its environmental history and that does not need the
20 presence of life to form. Four decades of missions have gathered geochemical information of
21 the surface of planets and bodies within the Solar System, and more information is quickly
22 increasing. Reviewing the current knowledge on properties of extraterrestrial regoliths, we
23 conclude that the surficial deposits of Venus, Mars, and our moon should be considered soils
24 in a pedological sense, and that Mercury and some large asteroids are mantled by possible soil
25 candidates. A key environmental distinction between Earth and other Solar System bodies is
26 the presence of life, and due to this dissimilarity in soil forming processes, it is plausible to
27 distinguish these (presently) abiotic soils as Astrosols. Attempts to provide detailed
28 classifications of extraterrestrial soils are premature given our poor current knowledge of the
29 Universe, but they highlight the fact that Earth possesses nearly abiotic environments that
30 lend themselves to understanding more about telluric bodies of the Solar System.

31

32 *He found himself in the neighbourhood of the asteroids 325, 326, 327, 328, 329, and 330. He*
33 *began, therefore, by visiting them, in order to add to his knowledge.*

34 (Excerpted from the “The Little Prince” by Antoine de Saint-Exupéry)

35

36

37 **Introduction**

38 At 22,17 on July 20, 1969 Neil Armstrong set foot on the Moon (Figure 1) and declared:

39 «One small step for man, one giant leap for mankind». Since then, the “lunar regolith” has

40 been studied in detail on samples collected during that first landing, and from samples

41 retrieved on subsequent manned or unmanned missions. A comparable database is

42 accumulating for the Martian regolith, and lesser amounts of information exist for the surface

43 of other bodies in Solar System.

44 The four inner planets, including Earth, are telluric (rocky) planets depleted in volatile

45 elements. There is a broad similarity in their lithologies, along with enormous differences in

46 atmospheric chemistry and surface temperatures. While the regolith on the Moon and Mars

47 has been referred to as soil, the definition applied to these materials indirectly implies a

48 distinction from soil in the earth sense: “The term soil is used here to denote any loose,

49 unconsolidated materials that can be distinguished from rocks, bedrock, or strongly cohesive

50 sediments. No implication for the presence or absence of organic materials or living matter is

51 intended” (Soderblom *et al.*, 2004). Here, we argue that this definition is inconsistent with a

52 scientific definition of soil that most earth scientists use.

53 The surfaces of celestial bodies are strikingly inhospitable to the forms of life we know on

54 Earth (*e.g.* Hornek, 2008; Weber & Greenberg, 1985). Therefore, does the presence of life

55 represent a distinguishing *condicio sine qua non* between terrestrial and extraterrestrial soils?

56 In this paper, we discuss the definition of soil, and review the soil forming environments
57 on rocky bodies of the Solar System in order to consider the distribution of soil types on such
58 bodies.

59

60 **Definition of soil**

61 The definition of soil hinges on human perception and concepts, and it has been stated “soil
62 can be what you want it to be” (Arnold, 2006, p. 2). While that view is applicable to non-
63 scientists, the scientific definition of soil is generally agreed upon and is in wide use. Soil is a
64 natural, historical body at a planet’s surface that is a partial record of the environmental
65 conditions that have existed at that location. The Soil Taxonomy (Soil Survey Staff, 2006, p.
66 1) defines soil as “a natural body comprised of solids (minerals and organic matter), liquid,
67 and gases that occurs on the land surface, occupies space, and is characterised by one or both
68 of the following: horizons, or layers, that are distinguishable from the initial material as a
69 result of additions, losses, transfers, and transformations of energy and matter *or* the ability to
70 support rooted plants in a natural environment”. This definition clearly illustrates that while
71 soils *may* grow plants, they do *not* need plants, or processes driven by plants, to be soils. This
72 is particularly important on Earth, in regions such as Antarctica and Chile, where ancient soils
73 have formed entirely without the presence of higher plants due to cold and/or aridity. While it
74 has been demonstrated that some extraterrestrial materials are able to sustain plant growth on
75 the Earth (Mautner, 1997), soil is the *in situ* veneer of a planetary surface – not a potting
76 mixture or other horticultural materials. Soils are historical entities that retain information on
77 their climatic and geochemical history.

78 Soils form in response to the well known soil forming factors. How will these factors
79 differ in extraterrestrial settings? Based on our Earth perspective, rocky or solid parent
80 materials are required as a substrate. Climates, e.g. the environmental conditions of a

81 planetary surface, will be far different, and drive different chemical and physical processes,
82 than on Earth. The near absence of O₂, the lack of an ozone layer and/or atmospheres, will all
83 greatly change the expected nature of soil processes and alteration products. Additionally, in
84 tectonically inactive and stable surfaces, the amount of time available for soil processes may
85 be orders of magnitude longer than on Earth. Finally, based on our present knowledge, all
86 extraterrestrial soils will be abiotic, but the necessity of biota for soils is debatable (*e.g.*
87 Markevitz, 1997). While some authors have strictly associated soil with biological activity
88 (*e.g.* Richter & Markevitz, 1995), this restrictive view, of course, excludes important parts of
89 our own planet from pedological study – *e.g.* the Dry Valleys of Antarctica (Ugolini &
90 Anderson, 1973) or the Atacama Desert of Chile (Ewing *et al.*, 2006; Navarro-González *et al.*,
91 2008) – regions (Figure 2) that have virtually life-free soils with advanced horizonation.
92 Additionally, very young deposits can lack both plants and horizon differentiation; however,
93 they are soils that are simply very young (*e.g.* Ugolini and Edmonds, 1983; Amundson,
94 2006). Therefore, the USDA Soil Taxonomy definition, quoted above, includes these types of
95 soils on Earth, and serves as a template for the consideration of soils on other planetary
96 bodies. Soil is the skin of Earth, a skin weathered by contact with the atmosphere. Planetary
97 bodies have a chemical nature and atmospheric conditions that can be similar or very
98 dissimilar to those on Earth. Below, we examine these in more detail.

99

100 **Soil processes on other planets**

101 Because of the enormous difference in atmospheres on the inner planets and moons, the
102 processes that modify the planetary surfaces can vary greatly from what we are familiar with
103 on Earth. Foremost, chemical and physical processes on most extraterrestrial bodies in the
104 Solar System are limited by the lack of water. However, there are several polar solvents that
105 could replace water, such as sulphuric, hydrofluoric, and hydrocyanic acids, and ammonia,

106 methanol, and hydrazine (Schulze-Makuch & Irwin, 2006). Secondly, the most powerful
107 proton acceptor on Earth, oxygen, is not present as free O₂ on nearby planetary bodies, but
108 can be available in ozone (O₃) and CO₂. On rocky bodies, oxygen is abundant in tightly bound
109 oxides such as SiO₂, Fe₂O₃, MgO, and Al₂O₃, but these require very high-energy processes to
110 reduce. Even without water and molecular O, a variety of energy sources drive chemical
111 reactions: thermal, osmotic, and ionic gradients, solar wind, magnetospheric energy, and
112 radioactivity are among the most important (Schulze-Makuch & Irwin, 2006). Volcanic
113 activity and meteorites supply both energy and material to planetary bodies.

114 Solar wind is a stream of high-energy electrons and protons that are able to escape star's
115 gravity and, eventually settle on the surface of planetary bodies. Mineral grains interact with
116 the atoms accelerated and ionised by shock waves. The energies of these ions, which depend
117 on the shock velocity, are of the order of keV. Chemical changes were observed in the
118 composition of olivine irradiated with relatively few keV H⁺ and He⁺ ions (Dukes *et al.*
119 1999). Demyk *et al.* (2001) caused the amorphisation of crystalline olivine, and its changes
120 toward a pyroxene-type composition through selective loss in O and Mg, by irradiating dust
121 with He⁺ ions at energies of 4 and 10 keV and fluxes varying from 5 10¹⁶ to 10¹⁸ ions cm⁻².
122 The thickness of the amorphised region was 40±15 nm and 90±10 nm for the 4 keV and 10
123 keV experiments, respectively. The amorphisation of the olivine also implied a porosity
124 increase due to the formation of bubbles.

125 Meteorite impacts can liberate enough energy to destroy not only the meteorite, but part of
126 the planetary surface, converting rock and minerals into gas at temperatures of several
127 thousand kelvin. Some of the gas condenses to form tiny metal spheres surrounding the
128 impact crater. The ejecta that falls back around the crater forms a rim that rises several metres
129 above the surrounding plain and, depending on the size of the impact, up to around ten

130 kilometres away. The rocks in the centre of the crater are intensely crushed and
131 metamorphosed, often leading to formation of new “shocked” minerals.

132 Volcanic activity is an internal weathering force that supplies fresh minerals as either
133 airborne solid ejecta or lava flows. However, all magmas release dissolved gases during
134 eruptive episodes and/or between them, and these gases can then form acids that weather local
135 or regional surficial deposits. Energy is released as explosions and tremors, which break rocks
136 and alters minerals through heating.

137 The rest of this paper will examine what is known of extraterrestrial regoliths and the
138 nature of their soils.

139

140 **Nature of planetary parent materials and bodies**

141 Soil, as we conceive it based on our experience on Earth, requires a solid parent material,
142 which in the Solar System occurs only on the four inner planets: Mercury, Venus, Earth, and
143 Mars. All of these have roughly the same structure: a central metallic core, mostly iron, with a
144 surrounding silicate mantle. Telluric planets have canyons, craters, mountains, and volcanoes
145 (Baker, 2008), and possess secondary atmospheres (generated through internal volcanism or
146 comet impacts). Moons and asteroids are solid and have a silicate or a carbonaceous
147 composition, but they lack both an iron core and an atmosphere. Telluric planets, some
148 moons, asteroids, and transient comets of the Solar System are the only space bodies that we
149 have direct observations from manned or unmanned landings.

150

151 *Mercury*

152 Mercury, the closest planet to the Sun, was first orbited by the NASA Mariner 10, in 1974,
153 which obtained about 10,000 images, about 57% of the planet’s surface. In January 2008, the

154 NASA Messenger began sending bright, detailed images of Mercury's cratered surface,
155 included the hemisphere that Mariner 10 did not succeed in imaging.

156 The surface of Mercury is characterised by a variety of terrains ranging from heavily
157 cratered to nearly crater free (Figure 3). Although volcanoes have not been yet identified, the
158 smooth plains on Mercury indicate that molten material in the past filled low-lying areas.
159 Mercury almost completely lacks an atmosphere that protects it from meteorites and solar
160 wind. The surface temperature ranges between 100 and 740 K. The regoliths of Mercury are
161 very dark, chiefly formed from anorthosite probably high in iron (McCord & Clark, 1979),
162 finely dispersed products of impact crushing and thermoclastism. Microscopic processes of
163 nanophase iron particle formation possibly can take place through repetitive dust impacts or
164 through Ostwald ripening. The latter is a thermodynamically-driven process that occurs when
165 a secondary phase precipitates out of a solid, and energetic factors cause the larger
166 precipitates to grow, drawing material from the smaller precipitates, which consequently
167 shrink (Sasaki & Kurahashi, 2004). The formation of glassy agglutinates due to meteorite
168 impacts is also probable. Hapke (2001) identified solar wind sputtering and presence of
169 submicroscopic metallic iron by deposition of vapours created by micrometeorite impact and
170 vaporization as the main causes of surface weathering on Mercury. Loeffler *et al.* (2008)
171 observed that olivine deposits produced reddening and darkening due to the production of
172 nanoparticles of metallic iron. Coarse-grained regoliths are generally much less affected by
173 many processes than fine-grained ones because space weathering is mostly a particle surface
174 phenomenon that extends less than 1 μm into the exposed faces.

175 In the first of its three encounters with Mercury before settling into orbit around the planet
176 in 2011, Messenger has captured a plethora of images of the surface that reveal that it has
177 been greatly weathered by the impacts and solar bombardment (Solomon *et al.*, 2008). There
178 is evidence of regolith maturation of Mercury's surface, the most important being the

179 occurrence of iron as nanoscale metal or oxide grains (McClintock *et al.*, 2008; Robinson *et*
180 *al.*, 2008). Areas of intense reflectivity near vents seem to be pyroclastic deposits. Preliminary
181 spectroscopic studies suggest a strange lack of ferrous iron from Mercury's crust and the
182 probable presence of opaque minerals, one of which could be the secondary iron titanium
183 oxide ilmenite (Melosh, 2008). Because the evidence available suggests that the Mercury
184 surface is both physically and chemically altered, it would seem plausible to suggest that it
185 possesses a soil mantle, one that has formed under conditions highly dissimilar to that on
186 Earth.

187

188 *Venus*

189 Venus is sometimes called "Earth's sister planet" because of its similarity in both size and
190 bulk composition. However, Venus' surface temperature is about 750 K, with small diurnal
191 temperature fluctuations. This stable climate is caused by Venus' atmosphere, the densest of
192 the four telluric planets, which imposes an atmospheric pressure 91 times that of sea level on
193 Earth. Such a dense atmosphere suggests that the surface is protected from erosion by small
194 cosmic particles. Venus' atmosphere consists mostly of carbon dioxide and sulphuric acid
195 droplets, with traces of water and oxygen. Despite the occurrence of clouds, there is no
196 precipitation. The planetary surface is characterised by mountains and highland areas
197 surrounded by large, flat stony deserts (Figure 4). In 1975, the Russian probes Venera sent
198 back the first close-up photographs of the planet's surface, which in places appeared covered
199 with sharp-edged rocks or fine-grained dust. The flat stones, several tens of cm in size,
200 seemed formed from outcrops as a consequence of thermal processes or corrosion carried out
201 by the atmosphere. Other mechanisms considered capable of causing physical weathering
202 include volcanic eruptions (some volcanoes may still be active today), impacts of large
203 meteorites, and wind erosion (Surkov *et al.*, 1984). In 1982, Venera 13 landed on Venus,

204 returning the first colour images and carrying out chemical analyses of the regolith. The
205 sample analysed was found to contain Ca, Na, Si, Fe, Mg and K. It is hypothesised that the
206 extremely acid atmosphere is effective at degrading rocks into secondary weathering
207 products. The weathering of rocks on Venus should produce the end-products magnetite and
208 anhydrite, given the environmental boundary conditions (Barsukov *et al.*, 1986), eventually
209 making the soil on Venus unique in the Solar System.

210

211 *Earth's Moon*

212 The nearest and most studied extraterrestrial body is our moon. Moon is mantled by a layer of
213 loose, heterogeneous fragmental debris that overlies solid rock. The Lunar regolith is
214 unevenly distributed, varying in thickness from 3-5 meters on plains called “maria” (Latin for
215 seas), to 10-20 meters in the highlands. Maria, which cover 85% of the total surface, are
216 basalts, while the highland bedrocks are mostly composed of anorthosite. Since the end of the
217 volcanic era, about 3 billion years ago, the lunar regolith has experienced the action of several
218 weathering processes which include: physical reworking by meteorite impacts, deposition and
219 chemical interactions of impact-generated and sputtered ions, irradiation by solar wind. As a
220 result of these processes, lunar regolith shows horizonation, and several categories of
221 centimetric and millimetric strata have been identified (Duke & Nagle, 1975). Some
222 millimetric laminae are probably debris shed from adjacent rock fragments. Other dark, fine-
223 grained, well-sorted thin laminae appear to be superficial zones reworked by micrometeorites.
224 Rock fragments and large spatter agglutinates are commonly found in their original
225 depositional orientation, or were reworked from the underlying units.

226 The NASA Apollo Programme enabled 12 astronauts to sample the Moon between 1969
227 and 1972 (Figure 5). From six landing sites almost 400 kg of rock fragments and fine earth
228 were returned to Earth. The main observable chemical effect on the Lunar regolith is the

229 formation of a 50-200 nm thick rim of weathering on grains. This rim differs from the core of
230 grains, primarily in the relative proportions and oxidation states of the elements (Keller &
231 McKay, 1997). For example olivine and pyroxenes have suffered significant loss of Mg,
232 transformation of Fe^{2+} to nanophase Fe metal, and preferential sputtering of Ca and Al
233 relative to Si and O. Rims on ilmenite grains are not amorphous as they are elsewhere, but are
234 microcrystalline as a consequence of the preferential removal of Fe and O, along with a
235 reduction of Fe^{2+} to Fe^0 and Ti^{4+} to Ti^{3+} .

236 The solar wind hits the surface of the Moon unimpeded by magnetic fields or
237 atmospheres. This wind darkens and reddens loose powders on the lunar surface in proportion
238 to their Fe content (Hapke, 2001). Starukhina *et al.* (1999) estimated that condensation
239 products of the clouds generated by sputtering and impacts should be distributed within a
240 layer of regolith whose thickness is several times the diameter of the impactor. During
241 thermal evaporation the rock-forming oxides are partially dissociated and the molecular
242 oxygen is selectively lost due to its high volatility (Hapke *et al.*, 1975). Fractionation
243 processes lead to formation of O-depleted, Fe-enriched films where the missing oxygen is
244 compensated for by the reduction of the oxides with the lowest binding energy. It has been
245 estimated that 30% of the metallic Fe is native to the lunar rocks, 30% is meteoritic in origin,
246 and the remaining 40% is the result of reduction of FeO by space weathering (Morris, 1980).

247 A renewed interest in the Moon has led the NASA to schedule unmanned missions
248 between 2008 and 2011 to map out landing sites and to find a spot for a permanent base
249 (NASA, 2009a). Other agencies are planning missions explicitly focused to study the nature
250 of the Lunar soils.

251

252 *Mars*

253 The remaining telluric planet, and the one that is farthest from the Sun, is Mars. Mars does not
254 show any evidence of plate tectonics and active volcanism, hence its surface is relatively
255 stable. However, a great difference in temperature between its two hemispheres induces
256 strong winds, up to 400 km h^{-1} , which are able to carry powders from one side of the planet to
257 the opposite one. The atmosphere is highly rarefied (average surface pressure is 1 Pa),
258 consisting mostly (95%) of carbon dioxide and molecular nitrogen.

259 Even with the naked eye, the Fe oxide rich regolith of Mars is visible from Earth. Our
260 knowledge of it has grown immeasurably due to 6 successful landing missions, all equipped
261 with varying payloads of imaging, spectroscopic, and chemical instrumentation (Figure 6).
262 The Martian regolith is a complex and spatially heterogeneous mixture of locally-derived
263 volcanic rocks of basaltic composition partly pulverised by impacts, a variety of fluvial
264 deposits, thick sequences of silicate and sulphate rich sedimentary rocks of possible marine
265 origin, and a variety of aeolian features (*e.g.* Herkenhoff *et al.*, 2004; Grant *et al.*, 2004;
266 Greeley *et al.*, 2004). The spacecrafts Viking 1 and 2 estimated that the Martian dust has bulk
267 densities of $1.0\text{-}1.6 \text{ Mg m}^{-3}$ and can comprise 70% of less than 2 mm particles at the
268 immediate surface, most of which is less than $100 \mu\text{m}$ (Cherkasov & Shvarev, 1978).

269 The presence of olivine, which is an easily weatherable primary mineral, has been
270 interpreted to mean that physical rather than chemical weathering processes currently
271 dominate on Mars (Morris *et al.*, 2004). Extreme thermal oscillations are among the physical
272 weathering processes. For example, the daytime surface temperature in equatorial regions of
273 Mars reaches 300 K, but at night it drops to 180 K.

274 Mars has no sea, but has water in the form of ice close to the surface and adjacent to the
275 permanently frozen poles, as revealed by NASA's Odyssey spacecraft and the Phoenix lander.
276 The Martian landscape at high latitudes bears the imprint of particle sorting and surface
277 patterns (Figure 6b) that are morphologically similar to patterned ground described on

278 periglacial regions of Earth (*e.g.* Ugolini & Bockheim, 2008). A 4-centimeter deep “profile”
279 (Figure 7), examined on June 1st, 2008 by the Phoenix lander, on the northern hemisphere of
280 Mars at 68°, revealed evidence of subsurface ice. Water contents of Martian regolith range
281 from <2% by weight to more than 60% (Mitrofanov *et al.*, 2002; Horneck, 2008). There is
282 abundance of geomorphic and chemical evidence that liquid water was once active on Mars
283 (*e.g.* Squyres *et al.*, 2008). Delta deposits, river terraces, thick sequences of sedimentary
284 deposits rich in sulphates, and the growing identification of secondary phyllosilicates and
285 hydrated secondary minerals all point to previous, and possibly periodic, aqueous chemical
286 alteration of the planetary surface. Grey hematite, for example, is an iron-oxide indicative of
287 past water, although it is not always associated with water. The reddish hue of Martian
288 regolith is due to rusting iron minerals presumably formed a few billion years ago when Mars
289 was warm and wet, but now that Mars is cold and dry, modern rusting may be due to a
290 superoxide that forms on minerals exposed to ultraviolet rays in sunlight (Yen *et al.*, 2000).
291 The NASA rover Opportunity, which landed on 2006 on Meridiani Planum, found hematite in
292 concretions that formed in salt-laden deposits laid down via wind and/or water (Kerr, 2004).
293 At “Hematite Slope”, Opportunity opened trenches about 50 centimetres long and 10
294 centimetres deep, discovering shiny round pebbles (“blueberries”) in fine-grained matrix. In
295 the Martian regolith it was observed that “what's underneath is different than what's at the
296 immediate surface” (Yen *et al.*, 2000), which is suggestive of soil horizonation.

297 Sulphates such as jarosite (potassium iron hydroxy sulphate) and kieserite (magnesium
298 sulphate) appear to occur in many geological settings on the planet. Barrón *et al.* (2006)
299 assessed that jarosite can transform directly to hematite in simulated Martian brines. Thick
300 sedimentary sequences of salts have been identified, which on Earth form in standing water,
301 possibly during evaporation (Vaniman *et al.*, 2004). However, sulphate and other salts are

302 found intermingled with siliceous surficial deposits at multiple locations (Viking 1, Viking 2,
303 Pathfinder, Spirit), associations that on Earth occur in hyperarid environments.

304 Burns (1987) proposed that on the young, volcanically active Mars, sulphuric acid derived
305 from volcanic emissions would have mixed with any water and chemically eroded rock to
306 produce a variety of sulphates, and would have contributed to pedogenesis. Other evidence
307 that indicates the rocks have experienced aqueous alteration is the migration of chlorine and
308 bromine into cracks and fissures on the surface of the rocks.

309 Clay minerals had been recently identified on Mars by orbiter-based spectroscopic
310 analyses (Chevrier *et al.*, 2007). In particular, the OMEGA instrument onboard the ESA's
311 Mars Express detected the presence of smectites (montmorillonite and nontronite) and
312 chamosite (a member of the chlorite group) in various locations by visible-near-infrared
313 hyperspectral reflectance imagery (Bibring *et al.*, 2005; Poulet *et al.*, 2005). Their presence
314 indicates chemical weathering combined with leaching. Fe-rich phyllosilicates probably
315 precipitated under weakly acidic to alkaline pH. It has been speculated that this process
316 occurred early in Martian history, and was later followed by strongly acid weathering that led
317 to sulphate deposits (Bibring *et al.*, 2006).

318 Amundson *et al.* (2008), based on comparisons to ancient soils in hyperarid regions of
319 Earth, argued that soil at the Spirit and Pathfinder landing sites bear evidence of early stage
320 chemical weathering and loss of major rock forming elements, and show a late stage addition
321 of sulphate, chloride, and associated cations. This interpretation implies the accumulation of
322 weathering products at depths below the Martian surface during time periods commonly
323 considered being too dry for aqueous weathering.

324 Weathering products are found also on Martian meteorites that have been deposited on
325 Earth. Taylor *et al.* (2002) attributed a round patch of smectite in the Martian meteorite
326 Dhofar 019 to aqueous alteration on Mars. Similarly, Treiman *et al.* (1993) argued that the

327 iddingsite (a fine-grained intergrowth of smectite clay, ferrihydrite and ionic salt) present in
328 the Martian meteorite Lafayette might be a product of pre-terrestrial alteration. Equally
329 important, Martian meteorites contain sulphates and carbonates with unique O isotope
330 compositions that imply they were formed by oxidation in the Martian atmosphere (Farquhar
331 & Thiemens, 2000) and were subsequently transported by aqueous carriers into the Martian
332 regolith, prior to being ejected by a meteor impact.

333 In summary, the strong likelihood of an early wetter and warmer Mars, the evidence of
334 depth related chemical features, and the evidence of recent or even on-going cryoturbation, all
335 are indicative of a variety of soil types on Mars that likely have close Earth analogues.

336 Phobos and Deimos, the two small moons of Mars, were first visited in the 1970's by
337 Mariner 9 and the two Vikings. Their importance in terms of human colonisation of space
338 could be much greater than their size because they have been considered as potential staging
339 areas for human colonies on Mars (Mautner, 1997; Veverka & Burns, 1980). Phobos and
340 Deimos contain carbon-rich rock, but their low bulk densities imply they consist of a mixture
341 of rock and ice. Both are heavily cratered. Phobos (Figure 8) is covered with a layer of fine
342 dust about a meter thick, similar to the regolith on the Earth's Moon. Less is known about
343 Deimos, but it is probable that it does not differ much from Phobos. Despite the parent rock
344 composition of Phobos and Deimos is one of the best candidate to allow formation of Earth-
345 like soils, at the present stage of knowledge it is impossible to speculate about the occurrence
346 of soils on these moons.

347

348 *Between Mars and the edge of the Solar System*

349 Direct observations for the celestial bodies currently orbiting outside of Mars' orbit have
350 not been made.

351 More than 100,000 asteroids lie in a belt between Mars and Jupiter. Asteroids are rocky
352 bodies that are believed to be left over from the beginning of the Solar System. They have
353 round or irregular shapes up to several hundred km across, but often are much smaller. Their
354 small size deprives them of any internal heat and, hence, tectonics that could rejuvenate their
355 surface. More than 75% of asteroids are C-type, namely they have a composition that is
356 largely carbon-based and lacks hydrogen, helium and other gases. Analysis of density trends
357 suggests that asteroids are divided into three general groups: asteroids that are essentially
358 solid objects, asteroids with macroporosities around 20% that are probably heavily fractured,
359 and asteroids with macroporosities over 30% that are loosely consolidated “rubble pile”
360 structures (Britt *et al.*, 2002). While small asteroids have bare rock surfaces, the larger ones
361 possess a sufficient gravitational force to allow the accumulation of regoliths, including a
362 fraction of finer particles (Matson *et al.*, 1977). For example, the asteroid Vesta, ~500-600 km
363 in diameter, has a gravity such that more than 95% of the ejecta from a meteoric impact falls
364 back onto its surface. By scaling for differences in gravity, the regolith of the larger asteroids
365 should resemble that of the Moon.

366 NEAR Shoemaker, the first spacecraft to soft-land on an asteroid, rendezvoused asteroid
367 433 Eros in 2001. Eros is approximately 13x13x33 km in size, the second largest near-Earth
368 asteroid. NEAR Shoemaker was not designed as a lander and was deactivated after it arrived;
369 hence, the last of a plethora of images of 433 Eros was taken from a range of 120 meters as
370 the craft collided with the body. Eros' surface is dominated by a blanket of regolith littered by
371 craters and boulders ranging in size from nearly 100 meters down to 8 meters. The regolith
372 seems to have been darkened and reddened by the solar wind and micrometeorite impacts,
373 while apparently fresh, bright material is confined to patches of fines set on a background of
374 older fragmental debris (Trombka *et al.*, 2000). Most of the large boulders look relatively
375 altered, or perhaps are stained by an adhering film of regolith particles.

376 The Japanese spacecraft Hayabusa was the first to take samples from an asteroid, the 535-
377 m-long 25143 Itokawa, in 2005. The surface of 25143 Itokawa photographed by Hayabusa
378 (Figure 9) appears bumpy, with knots of hard matter looking like lumps and only small
379 amounts of powdery regolith. Data shows that the asteroid's density is very low ($\sim 1.9 \text{ Mg m}^{-3}$),
380 suggesting Itokawa may be composed of small rocks held together by gravity (Abe *et al.*,
381 2006; Fujiwara *et al.*, 2006). Hayabusa did not land on the asteroid, but used a cone-shaped
382 device that captured materials ejected by the impact of a metal pellet fired onto the surface
383 (Okada *et al.*, 2006). Sample return is scheduled for 2010.

384 Io, the only telluric moon of Jupiter, was orbited by NASA Galileo spacecraft during the
385 period 1996-2003. Io is heated by tidal forcing – exerted by the gravitational fields of Jupiter
386 and two other moons, Europa and Ganymede – that causes volcanism. There is the possibility
387 that Io started out similar in character to the other icy moons of Jupiter and lost its icy mantle
388 over time due to tidal forcing. Most of Io's surface is 120 K or colder, despite the presence of
389 volcanoes. The volcanism continuously reworks the ferric-sulphuric-silicatic crust (Simonelli
390 *et al.*, 1997), thus reducing the time available for any pedogenic processes. However, the
391 residence time of this crust, and the possible assortment of pedogenic processes operable, is
392 unknown.

393 Titan (Figure 10a), the largest moon of Saturn, is so large that its gravity slightly
394 compresses its interior. Titan is about half water ice and half rocky material, but is probably
395 differentiated into several layers with a 3400 km rocky centre surrounded by several layers
396 composed of different crystal forms of ice. Titan's atmosphere is composed primarily of
397 molecular nitrogen with 6% argon, a few percent methane, and trace amounts of at least a
398 dozen of other organic compounds (i.e. ethane, hydrogen cyanide, carbon dioxide) and water.
399 Titan possesses rivers and, apart from our planet, it is the only body known to possess lakes.
400 However, the fluid is not water but methane and other liquefied hydrocarbons (Mitri *et al.*,

401 2007). A geologically varied surface, apparently modified by a mix of processes including
402 strong fluvial erosion, impacts, and cryovolcanism was revealed by the NASA Cassini orbiter
403 and the ESA Huygens probe that landed on Titan in 2005 (Elachi *et al.*, 2005). Cassini
404 RADAR images show widespread plains covered by sand dunes probably composed of
405 organic solids and water ice (Lorenz *et al.*, 2006).

406 Iapetus (Figure 10b) is the Saturn's third-largest moon. The most enigmatic feature of
407 Iapetus is the roughly elliptical region centred on the leading side ("Cassini Region"), darker
408 by a factor of about 10 than parts of the surrounding areas (Porco *et al.*, 2005). Such a feature
409 and the Iapetus's asymmetry may perhaps be attributed to a thick primordial low-albedo
410 subsurface layer of organics exhumed by impact erosion (Wilson & Sagan, 1996). At the
411 current stage of knowledge, it is hard to hypothesise about the occurrence or nature of soils
412 here and on Titan.

413

414 *Comets and exoplanets*

415 Comets are assemblages of ice and dust that periodically pass through the centre of the Solar
416 System along highly elliptical orbits. When comets get close enough to the Sun, heat induces
417 their partial sublimation so that jets of gas and dust form long tails that can be seen from
418 Earth. Comets contain the most primitive material in the Solar System (*e.g.* Ishii *et al.*, 2008).

419 In 2005, the NASA Deep Impact space probe shot a projectile into comet Tempel 1 to
420 obtain material to analyse. The first results showed that cloud contained more minerals and
421 less ice than had been expected (OSIRIS Team, 2005). However, even if many comets do
422 contain rocky debris, the dynamic nature of comets likely precludes the formation of any type
423 of soil.

424 There is a rapidly growing number of stars in the universe that now have known planets
425 orbiting them (Cole, 2001), and it is speculated that the number of planets in the universe

426 exceeds the number of stars. These planets, called “exoplanets”, are being discovered
427 continually and as of May 2009, 347 candidates had been identified (URL exoplanet.eu).

428 Recently, using the ESO 3.6-m telescope in La Silla, Chile, an Earth-like exoplanet,
429 Gliese 581c, was discovered at 20.5 light years from the Earth, in the constellation of Libra
430 (Udry *et al.*, 2007). Under the assumption that it is a rocky planet, Gliese 581c has a radius at
431 least 50% larger than that of Earth, is about 5 times the mass of the Earth, and has a gravity
432 approximately 2.2 times as strong as on Earth. It appears to be in the habitable zone of space
433 surrounding the parent star red dwarf Gliese 581, where the surface temperatures might
434 maintain liquid water. Gliese 581c may be tidally locked to its parent star, with one
435 hemisphere always lit and the other always dark. Gliese 581c has a projected equilibrium
436 surface temperature 270–310 K. However, the actual temperature on the surface depends on
437 the planet's atmosphere, which remains unknown. In 2008, the NASA/ESA Hubble Space
438 Telescope captured the first optical image of an exoplanet, Fomalhaut b, which apparently is
439 mostly solid (Kalas *et al.*, 2008).

440 A few of the discovered exoplanets are solid. However, according to the law of large
441 numbers, many other telluric exoplanets are expected soon to be discovered from the Earth by
442 techniques such as coronagraphic imaging (*e.g.* Boccaletti *et al.*, 2005) and radial velocity
443 (“gravitational microlensing”), or by the on-going European mission COROT or NASA’s
444 Kepler (Sanderson, 2007). *In situ* investigation or study of exoplanets is not feasible due their
445 remoteness, and no inference about the occurrence of soils is obviously possible at present.

446

447 **Role of pedology in planetary science**

448 Our nearest planetary neighbours certainly possess complex physically and chemically altered
449 soil mantles. None of these bodies, however, bear (or bore) more resemblance to Earth than
450 does Mars. The periodic return of Martian soil chemical data since the Viking missions of the

451 1970's has subsequently sent planetary geologists to acid mine drainages, volcanic mountain
452 tops bathed in acid fog, or to the lab to find Earth analogues that could aid in the interpretation
453 of the Martian data. However, it is the widespread soils of Earth that may hold much insight
454 into the Martian soil history.

455 Maybe no area on Earth is more relevant to many recent Mars discoveries than the
456 Atacama Desert of northern Chile. The Atacama landscape has endured an exceptionally long
457 and protracted period of aridity (Hartley & Chong, 2002), allowing soils there to achieve ages
458 ($>10^7$ y) impossible on other parts of our otherwise dynamic planet. The soils here lie within a
459 nearly abiotic zone due aridity, providing insights into the protracted arid and presently
460 lifeless Martian history. Soil formation in humid climates is characterised by atmospheric
461 inputs of water and solutes, in-soil biogeochemical weathering processes, and downward
462 leaching of solutes into the underlying vadose zone and groundwater. Soils in hyperarid
463 regions like Chile retain virtually all incoming atmospheric dust and salt, and the infrequent
464 rainfall events that occur over millions of years chemically separate these salts vertically
465 based on solubility (Ewing *et al.*, 2006). This vertical distribution – sulphates over chlorides,
466 nitrates, and perchlorates (Ericksen, 1981) – combined with associated isotopic fractionation
467 during transport (Ewing *et al.*, 2008) – provide clear and unambiguous signals to the long-
468 term net direction of liquid water movement. In addition, oxygenated anions such as nitrate,
469 sulphate, and perchlorate, which are produced by atmospheric reactions with ozone, contain
470 unmistakable isotopic markers of their atmospheric origins. This “mass independent” O
471 isotope signal, well documented in salts found in the hyperarid soils of the Dry Valleys of
472 Antarctica (Bao *et al.*, 2000), has also been detected in sulphates derived from Martian
473 meteorites (Farquhar & Thiemens, 2000), clearly indicating that some similarity in sulphate
474 production mechanisms and transport through the soil zone has operated on both planets.
475 Although far less studied, the Atacama Desert and the Andean Altiplano contain some of the

476 world's largest sulphate and chloride-rich salt deposits, and the stratigraphy, near surface
477 geochemical profiles, and surface geomorphology of these deposits are untapped sources of
478 information for interpreting the post depositional weathering of salt-rich sedimentary deposits
479 that are now widely recognised on Mars.

480 If the arid soil beneath our feet provides insight into interpreting available Martian
481 surficial geochemistry, it provides even more important guidance into developing novel
482 hypotheses and new methods for sampling the Martian surface on future missions. First, the
483 direction of water movement through the Martian soils remains, at this stage, a somewhat
484 contentious point of debate (Amundson *et al.*, 2008). Isotopic analyses of salts profiles could
485 address this question as well as provide new insights into the origin of salts. In addition, pH
486 should be more frequently measured on future missions. While jarosite is a mineral that
487 clearly requires acidic formation conditions, the presence or absence of many secondary
488 minerals is at best only weakly suggestive of pH. Geochemical profiles provide a key for
489 interpreting soil history (Ewing *et al.*, 2006; Quade *et al.*, 2007). On Mars, only the fortuitous
490 encounter of the rover Opportunity with Endurance Crater at Meridiani Planum has provided
491 a depth profile of sufficient magnitude required for unambiguous soil geochemical
492 interpretation. Pedological protocols and standardised guidelines for surveying soil are
493 inexpensive in comparison to the costs of a planetary mission. The resulting information
494 could render an unexpected and amplified insight into extraterrestrial soils.

495

496 **Conclusions**

497 The long term exposure of rocky planets, moons, and other objects within the Solar System
498 and outside to physical and chemical processes has undoubtedly created an array of soil types
499 grading from those impacted by radiation and meteorites to those of Mars which have
500 experienced, in their past, aqueous alteration and transport. On other planets, lacking liquid

501 water, the pace and nature of pedogenic processes is more removed from those we observe on
502 Earth, but these alterations are indeed consistent with a broad, although scientifically
503 constrained, definition of soil.

504 The growing data on rocky planets in the Solar System opens a window of opportunity for
505 serious discussions about planetary soil formation processes. In addition, some of the trillions
506 of planets that orbit the hundreds of billion stars in our galaxy more than likely possess soils,
507 though their nature may always elude us given the position of our isolated planet in the
508 universe. The consideration of extraterrestrial soils most importantly offers new opportunities
509 for earth scientists to provide quantitative models, data, and insights relevant to interpreting
510 their composition. On the other hand, the Earth is our most accessible natural laboratory, and
511 the full spectrum of its experimental results is required to understand the history of our
512 planetary neighbours.

513 While our understanding of extraterrestrial soils is very rudimentary, their diversity may
514 raise the question of how we might classify them, or formally compare them with our Earth-
515 based soils. One approach is to simply use our present soil classification schemes, in which
516 case many extraterrestrial soils would be Regosols in the World Reference Base for Soil
517 Resources (IUSS Working Group WRB, 2006) or Entisols in the US Soil Taxonomy (Soil
518 Survey Staff, 2006). On Mars, it is possible that Gelisols and Aridisols exist. However,
519 applying an Earth-based system to such dissimilar settings is debatable. Another option is to
520 distinguish the (largely) biotic Earth from the abiotic Solar System, and include all non-Earth
521 soils in a new Reference Group or Order, which might be tentatively called Astrosols. While
522 we emphasize that classifying extraterrestrial soils is, at this stage, not an important or
523 pressing pedological concern, the discussion helps focus our attention on environments or
524 conditions on Earth that are intergrades to the conditions of our nearby neighbours, and

525 positions pedology to provide increased scientific input towards future planetary missions and
526 data analysis.

527

528

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750 **FIGURE CAPTIONS**

751 **Figure 1.** The footprints left by the astronauts in the powdery Sea of Tranquillity are more
752 permanent than most solid structures on Earth. Barring a chance meteorite impact, these
753 impressions in the lunar soil will probably last for millions of years. [Courtesy of
754 NASA]

755 **Figure 2.** Terrestrial environments formed under virtually abiotical conditions: a) the Wright
756 Valley, McMurdo Dry Valleys System, Antarctica [courtesy of FC Ugolini], and b) the
757 Atacama Desert, northern Chile [photo by R Amundson].

758 **Figure 3.** Image of Mercury taken by the NASA's spacecraft Messenger, showing a variety of
759 surface textures, including smooth plains at the centre, numerous impact craters and
760 rough material that appears to have been ejected from the large crater to the lower right.
761 [Courtesy of NASA]

762 **Figure 4.** Venus' surface pictured by the Venera 13 lander (URL
763 nssdc.gsfc.nasa.gov/planetary/venera.html). [Courtesy of NASA]

764 **Figure 5.** Astronaut Alan Bean drives a soil core tube into the Lunar soil surface during the
765 Apollo 12 mission (photo #AS12-49-7286 from the Project Apollo Archive, URL
766 www.apolloarchive.com/apollo_gallery.html). [Courtesy of NASA History Office]

767 **Figure 6.** Mars: a) A portion of the "Presidential Panorama" of the Pathfinder landing site,
768 with light-toned sulphate rich outcrops in lower left and top, left/center (URL
769 mars.jpl.nasa.gov/MPF/ames/ames-pres.html); b) Patterned ground observed at the
770 Phoenix mission landing site. [Courtesy of NASA]

771 **Figure 7.** Martian soil profiles (a) and (b) exposed by NASA's Phoenix, and the Martian soil
772 lab (c) equipped with microscopy, electrochemistry, and gas analyzer. [Courtesy of
773 NASA/JPL-Caltech/University of Arizona/Texas A&M University/Max Planck
774 Institute]

775 **Figure 8.** The Mars' moon Phobos pictured on 2004 by the Mars Express spacecraft, from
776 some hundreds kilometers. [Courtesy of ESA/DLR/FU Berlin G. Neukum]

777 **Figure 9.** 25143 Itokawa. Lateral image, 0.5 by 0.3 by 0.2 kilometres. The asteroid is
778 composed of discrete rock fragments and fine earth held together by gravity. [Courtesy
779 of JAXA]

780 **Figure 10.** Saturn's moons Titan and Iapetus: a) Rivers on Titan's landscape; b) The white
781 frozen Iapetus spotted with carbonaceous dark areas pictured by the NASA Cassini
782 orbiter in 2007. [Courtesy of ESA/NASA/JPL/Space Science Institute/University of
783 Arizona]

Appendix. Main characteristics of telluric bodies in space.

	Mercury	Venus	Earth	Moon	Mars	Phobos ¹	Deimos ¹	Asteroids ²	Io ³	Titan ⁴	Iapetus ⁴	Comets ⁵	Exoplanets ⁶	
Physical characteristics	^{b, d} diameter /km	~4900	~12100	~12700	~1700	~6800	~20	~10	1-1000	~3600	5600	~1600		
	^b md ¹⁰ /kg m ⁻³	5.4	5.2	5.5	3.3	3.9	1.9	2.2	^e 1.0-4.9	3.5	1.9	^p 1.1	? ?	
Detection [#]	≤	☑	☑	☑	☑	≤	≤	^h ☑, □, ≤	□	☑	☑	≤	≤	
Atmosphere	^b mst/ ^b MST ⁷ /K	100/740	750	180/310	40/400	150/310	230	230	200?	^u 80/140	90	100/130	? ?	
	thermal excursion ⁸	↓↑/↓↑	↓↑/↓↑	↓↑/↓↑	=/↓↑	↓↑/↓↑	=/↓↑	=/↓↑	?/?	=/↓↑	=/↓↑	=/↓↑	?/?	
	albedo	0.10	0.59	0.39	0.12	0.15	0.07	0.07	0.10-0.22	0.62	0.21	0.3-0.6	? ?	
	^s pressure /kPa	10 ⁻¹⁵	~9100	~100	10 ⁻¹³	~1	<10 ⁻¹⁵ ?	<10 ⁻¹⁵ ?		^u 10 ⁻⁹	^t 150	?		
	^{a, c} main components /%	He/H ₂ /O ₂	CO ₂ /N ₂ /O ₂	N ₂ /O ₂ /Ar	^e CH ₄ tr.	CO ₂ /N ₂ /Ar	?	?	?	SO ₂	N ₂ /Ar/CH ₄	?	?	?, ^r CH ₄
Hydrosphere [‡]		☂	☂	☂, *, ☂	-	*, ☂	*	(☂)	-	ⁱ *	(☂)	^q (*)	ⁿ (*)	(☂)
	^a liquid solvent	none	H ₂ O, H ₂ SO ₄	H ₂ O	none	H ₂ O	H ₂ O?	H ₂ O?	none	H ₂ S	^j CH ₄	^q NH ₃ , ?	none	?
Lithosphere	^{a, c} lithology ⁹	b, a	b, am	b, g, am	b, a	b, am	cc	cc	^f cc, s, m	s	?	^b cc (?)	^m s (?)	?
Pedosphere [‡]		✦, (*, ✦)	✦, (*)	✦	✦, (✦)	✦, (✦)	✦	✦	✦, ✦	✦	[✦]	[✦]	[✦]	✦
^b Biosphere [*]		☹	☹	☺	☹	☹	☹	☹	☹	☹	^k ☹	☹?	☹	☹?

¹Satellites of Mars.

²376,537 are registered as minor planets, their global mass is estimated to be about 3.0-3.6×10²¹ kg^d. Originally, only three types of asteroids were classified: C-type carbonaceous, (75% of known asteroids), S-type siliceous, (17%), L-type metallic, (8%). More recently 26 types have been defined^o.

³Satellite of Jupiter.

⁴Satellite of Saturn.

⁵According to the International Astronomical Union comets are designated by the year of their discovery followed by a letter indicating the half-month of the discovery and a number indicating the order of discovery.

⁶Planets beyond the Solar System.

[#]Detection: landing and collecting samples ☑, research with space probes, not collecting samples ☐, remote sensing only ☐

[‡]Hydrosphere: liquid water ♠, solid water ✱, vapor ☁, presence of liquid water (♠) or ice (✱) inferred.

[‡]Pedosphere: active pedogenesis and horizonation ✱, physical reworking only ✱, chemical weathering ✱, pedogenesis plausible ✱, pedogenesis improbable [✱].

[‡]Biosphere: active ☺, not detected but possible ☹, not likely to be present based on current knowledge ☹

⁷Atmosphere characteristics: Maximum Surface Temperature MST, minimum surface temperature mst.

⁸Thermal excursion (difference between the highest temperature and the lowest one in a given lapse of time): ↓↑ occurrence, = absence; the symbol on the left of the slash indicates diurnal thermal excursion, that on the right seasonal thermal excursion.

⁹Lithosphere: basalts b, granits g, anorthosite a, altered materials am, carbonaceous chondrites cc, silicates s, metallic m.

¹⁰Lithosphere: mean density md.

Sources: a) Schulze-Makuch *et al.* (2002); b) NASA (2009b); c) Wikipedia; d) Krasinsky *et al.* (2002); e) Stern (1999); f) Chapman *et al.* (1975); g) Britt *et al.* (2002); h) Okada *et al.* (2006) i) Douté *et al.* (2004); j) Mitri *et al.* (2007); k) Raulin & Owen (2002); l) Lortet *et al.* (1994); m) van Boekel *et al.* (2004); n) Sunshine *et al.* (2006); o) Bus & Binzel (2002); p) Thomas *et al.* (2007); q) Castillo-Rogez *et al.* (2007); r) Swain *et al.*, 2008, s) NASA (2009c); t) Fulchignoni *et al.* (2005); u) Lopes & Williams (2005).