

1 **Planetary pedology: Expanding soil science horizons for lunar resource mapping**
2 **horizons for lunar soil science in space resource mapping**

4 **Abstract**

5 Space agencies, private organizations, and advocacy groups aim to establish a sustainable
6 human presence on the Moon and Mars in the coming decades, which necessitates in situ
7 resource utilization. Regolith, the most accessible resource, presents opportunities to extract
8 rare elements and produce high-strength structural materials for habitats. It could also serve as
9 a substrate for food production, functioning similarly to soil on Earth, which is crucial for
10 establishing future extraterrestrial human settlements. ~~Similar to~~ Like the Industrial Revolution
11 on Earth, the demand for resources requires detailed mapping of the surfaces of the Moon and
12 Mars, raising questions about suitable mapping methods and the classification of incoherent
13 materials. We propose that lunar regolith ~~qualifies as actual~~ can be classified as soil and
14 ~~investigate-assess the feasibility-applicability of applying long-~~ established terrestrial soil
15 ~~science~~ nomenclatures, such as the World Reference Base for Soil Resources and the U.S. Soil
16 Taxonomy, for its classification. We conclude that these systems are not inherently applicable
17 and would require substantial modifications and/or additions to account for the unique
18 characteristics encountered. Consequentially, we advance a new nomenclature for lunar soils
19 that highlights differences in pedogenic processes on the Moon, compared to those on Earth.

21 *Key Words:* astropedology; ISRU; regolith; soil horizon; soil classification; ~~Soil Taxonomy~~
22 ~~(ST)~~; space weathering; Soil Taxonomy; World Reference Base for Soil Resources; ~~(WRB)~~;

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25 Mapping extraterrestrial soils, a necessary step for space resources utilization

26 Since the 2010s, various space agencies and commercial entities have renewed their interest in
27 the Moon, viewing it as a platform for economic development beyond Earth and as a stepping
28 stone for missions to Mars and beyond. Establishing human settlements on the Moon and Mars
29 is becoming increasingly plausible, although current technology is not yet fully reliable
30 (Jakosky and Edwards, 2018). A sustainable human presence on these celestial bodies will
31 depend on ~~the~~ in-situ resources utilisation use of available resources (ISRU), which
32 involvmplies extraction and processing of materials for fuel, life support, and manufacturing.
33 The first step of ISRU involves detecting and assessing potentially useful materials, including
34 mapping ~~to for a~~ better understanding ~~ing of~~ of geographical variabilities in the composition, quantity,
35 and quality of rocks and regolith or soil. This advanced development has sparked a new field of
36 study, known asealled “planetary pedology”, which encompasses ing the study of both
37 paleosols and contemporary extraterrestrial soils (Retallack, 2016).

38 On Earth, the Industrial Revolution ~~of the 19th century~~ spurred societies to develop
39 standardized methods for exploring mineral resources. This period led to the establishment of
40 sState gGeological sSurveys in Western countries, initially tasked with mapping mineral
41 resources, and later expanding to include soil mapping. This integration of geological and
42 pedological mapping not only facilitated resource classification but also significantly enhanced
43 scientific understanding of Earth's surface.

44 With interplanetary exploration gaining momentum in recent years due to scientific and
45 economic interests (Elvis, 2012), the Moon and Mars have become ~~re~~ prime targets for future
46 missions. The search for in-situ resources to support these activities is a top priority for both
47 crewed and unmanned missions. The prospect of human presence on the Moon even suggests
48 the onset of a new geological era —, the Lunar Anthropocene (Holcomb et al., 2023) —, akin
49 to Earth's Anthropocene, where human activities “shape” the planet.

50 Like the 19th-century rush for mineral resources, the groundwork for human settlement on the
51 Moon involves active mapping efforts to locate resources (Ming & Henninger, 1994). This
52 raises fundamental questions about the surface types of rocky planetary bodies in our Solar
53 System, and ~~the~~ how to best methods to classify and map them.

54 Regolith is a term commonly used in planetary sciences for referring to the layer of fragmental,
55 unconsolidated rock material—whether residual or transported—that covers the surface of
56 nearly all celestial bodies (Lucey et al., 2006). However, ~~T~~he concept of soil is increasingly
57 compatible with extraterrestrial environments because several recent definitions of soil no
58 longer claim the occurrence of life but only the evidence of mineral weathering (e.g., Johnson,
59 1998; Banin, 2005; Certini and Ugolini, 2013). In ~~dealing with~~ Mars, Soderblom et al. (2004)
60 consider any loose, unconsolidated materials distinct from rocks or cohesive sediments to be
61 soil, without implying the presence of organic matter, ~~presence of,~~ while McKay et al. (1991)
62 and Banin (2005) argued that Martian soil is what it is by virtue of attributes that regolith does
63 not have. In this context, using the term soil in place of regolith is becoming more accepted
64 (Huggett, 2023). The soils of extraterrestrial bodies exhibit unique properties due to peculiar
65 physical and chemical forming processes, such as space weathering and repeated meteorite
66 impacts (Certini et al., 2009).

67 Our Moon is the initial target for ISRU mapping; ~~therefore, L~~unar soils are ~~the~~ under focus.
68 ~~They are~~ layered, poorly sorted, and fine-grained (Heiken et al., 1973; Duke and Nagle, 1975;
69 Lindsay, 1976) (Fig. 1). The bulk of lunar soils consists of particles <1 cm in size, with cobbles
70 and boulders, some as large ~~much~~ as several meters across. While sand and silt dominate ~~in~~ the
71 fine fraction (Kiely et al., 2011), recent findings from the Chinese Chang'E-5 mission have
72 identified clay-sized particles (<2 μm) as well (Li et al., 2022). Lunar soils reflect the
73 mineralogy of crystalline bedrocks, mixed with secondary particles from meteorite impacts.
74 However, ~~although~~ they undergo continuous evolution, known as *gardening*, involving

75 comminution and agglutination of particles (Heiken et al, 1973; Butler and King, 1974). Finer
76 textured soils often ~~exhibit better~~^{show higher} sorting and contain more agglutinates. These are
77 rounded particles composed of dark brown to black glass and mineral grains, with chemical
78 compositions ~~similar to that of~~^{like} the bedrock. Lindsay (1976) described three stages of
79 textural maturity: comminution-dominated, agglutination-dominated, and steady state, ~~all~~
80 influenced by impacts that can disrupt agglutinate populations. Equilibrium soils result from
81 repeated exposure to lunar weathering and micrometeoroid impacts, ~~which maintain~~^{ing} stable
82 grain sizes. Lunar soils originate from billions of years of continuous bombardment by
83 meteorites, galactic high-energy particles, and the solar wind, which break down and mix initial
84 rocks and their fragments. This comminution process, along with erosion, deposition, and the
85 embedding of solar wind gases, transforms regolith into soil rather than just crushed rock. Soil
86 maturity on the Moon is indicated by particle size distribution and the abundance of
87 agglutinates (finer soils richer in agglutinates are more mature).

88

89 [Insert Figure 1 here.]

90

91 The final product of lunar soil evolution, termed steady-state soil, balances the pulverization
92 by micrometeorites with processes of agglutination and replenishment of coarser particles
93 (~~McKay~~^{Me Kay} et al., 1974). Planetary scientists evaluate the maturity of the lunar surface
94 based on variables such as the percentage of agglutinates and the ~~I_s/I_o~~ ^{I_s/FeO} ratio, i.e., the amount
95 of iron ~~that is~~^{in the nanophase state} ~~—that is, with a grain size on the order of nanometers and~~
96 ~~exceptional tensile strength~~ because of space weathering, relative to total iron (~~Morris, 1976~~);
97 ~~—~~This ratio categorizes lunar soils into immature (I_s/FeO 0-30), submature (I_s/FeO 30-60),
98 and mature (I_s/FeO >60), providing a framework for understanding evolution despite

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99 occasional disturbances, such as like meteorite impacts, that can disrupt mature soils and create
100 new deposits (Fig. 2).

101

102 [Insert Figure 2 here.]

103

104 In regions with relatively few impact craters, the abundance of agglutinates is believed to
105 increase as lunar soil undergoes prolonged exposure to space weathering, which underscores
106 the utility of the I_{4s}/FeO ratio as a “Maturity index”.

107 Fryxell et al. (1970) proposed the following equation for ~~the~~ lunar soils: $R = f(c_l, p, r, t, a, b,$
108 $\dots)$, where R is regolith, c_l is climate, p is the protolith, r is relief, t is time, and while including
109 new variables, accumulation (a) and bombardment (b), were included. SinceAs we could
110 consider climate (c_l) is likely irrelevant in the lunar context and based on our considerations
111 that those on the Moon are soils, we suggest that the equation could be modified into: $S_{Moon} =$
112 $f(p, r, t, a, b, \dots)$, where S stands for soil.

113

114 **Moon soils from a taxonomic point of view**

115 *Testing Earth's soil classification for the Moon*

116 Classifying and mapping lunar soils will enable their optimized utilization in technology
117 design, building materials, agriculture, and mission planning, thereby ensuring efficient
118 resource exploitation. However, understanding lunar soil properties and their geographic
119 variability remains challenging due to resolution limitations of remote sensing instruments and
120 the scarcity of samples. For a comprehensive soil classification, detailed morphological data —
121 such as layering, colour, texture, and structure—, are essential. Such data can mainly be
122 obtained mainly through the collection of core samples, which are still few – primarily derived
123 from the Apollo missions – and represent an insignificant fraction of the potential lunar soils.

124 From the available cores (Fig. 1), NASA researchers identified millimetric-to-centimetric
125 layers formed by chemical and/or physical alteration, suggesting pedogenesis (Duke and Nagle,
126 1975; Lindsay, 1976).

127 The observed morphological diversity of lunar soils may raise questions about classification
128 and comparison with our terrestrial soils. Soil classification systems condense knowledge about
129 soils and their related characteristics into a specific name, which is essential for scientific
130 reporting. However, these Earth-based systems may not suit extraterrestrial soils because of
131 their different forming processes (Certini et al., 2020). ~~The recent update of the~~ World
132 Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2022) is more
133 inclusive after incorporating many revisions. However, it ~~but still begins by~~ starts with defining
134 soil as “a living, heterogeneous and dynamic system that includes physical, chemical,
135 biological components, and their interactions”, which excludes extraterrestrial soils from
136 classification. This definition although thus ~~curiously contradicting~~ the “abiotic” definition of
137 the classifiable materials: “any material within 2 m of the Earth’s surface that is in contact with
138 the atmosphere, excluding living organisms, continuous ice not covered by other material, and
139 water bodies deeper than 2 m”.

140 The ~~latestst, 13th~~ edition of the Keys to U.S. Soil Taxonomy (ST), the thirteenth (Soil Survey
141 Staff, 2022), does not address the classification of ~~ing~~ extraterrestrial mineral surfaces and
142 reiterates the concept of soil as “a natural body consisting of solids (minerals and organic
143 matter), liquids, and gases, occurring on the land surface and characterized by distinguishable
144 horizons or layers due to energy and matter transformations, or the ability to support rooted
145 plants”. This definition, which is inclusive of soils in Antarctica and other extreme
146 environments where pedogenesis occurs despite harsh climates. Given that many pedogenic
147 processes responsible for ~~justifying~~ soil horizonation, such as the transformation of carbonates,
148 anhydrite, gypsum, and the concentration of oxides and silicate clay, also occur on the

149 extraterrestrial environments, we ~~believe~~consider that this definition could be extended to
150 extraterrestrial soils as well.

151 On the Moon, the ~~obvious~~ absence of biodiversity and the uniform climate limit soil
152 differentiation on a regional scale. Instead, parent material, ~~the~~ duration of exposure to the
153 surface, and topography play crucial roles (Cameron, 1963). This challenges the classification
154 of extraterrestrial soils using Earth-based systems. A new, specific classification should
155 emphasize ~~the~~ soil-forming processes, mineralogy, and factors unique to extraterrestrial
156 environments. Separate systems might even be necessary for each rocky celestial body.

157 Regardless of pedogenesis signs, the first diagnostic horizon to classify Moon soil is the WRB's
158 Cryic horizon or its ST equivalent, permafrost. This requires recognizing at least 5 cm thick of
159 visible water ice for ≥ 2 consecutive years, or soil temperatures < 0 °C with insufficient water
160 to form visible ice crystals. Surficial water ice has been suggested to exist in the lunar polar
161 regions (Li et al, 2018); however, we still do not have visual confirmation of it, nor of any
162 regolith-ice mixture.

163 Since the Moon lacks atmospheric pressure, the temperature ~~needed~~required for ice crystals
164 formation is far below 0 °C. This compels us to disregard soil temperature ~~when~~to achieve
165 a meaningful classification of Moon soils using WRB and ST.

166 Given the widespread thinness of lunar soils and their abundance of rock fragments, common
167 WRB soil groups on the Moon could include Leptosols (shallow, <25 cm, and rocky soils) and
168 Regosols (immature soils from an Earth perspective). The presence of sandy, virtually stone-
169 free soils on the Moon is improbable and, if present, likely restricted to very small areas. In
170 such cases, Arenosols can be assumed. Pyroclastic deposits, which are a small proportion of
171 lunar volcanic material, were sampled during the Apollo program (Gaddis et al., 2000; Keske
172 et al., 2020). Being glass-rich, they could be described as Tephric material with Vitric
173 properties, akin to weakly weathered Andosols according to the WRB.

174 Under the ST classification system, hypothetical lunar soil Orders might include Entisols (soils
175 with minimal pedogenic development) and, less likely, Andisols (soils developed on volcanic
176 material with at least 30% ~~or more~~ of particles ~~between from~~ 0.02 ~~and to~~ 2.0 mm and ~~a~~ volcanic
177 glass content of 5% or more). ~~Less~~ ~~More~~ ~~un~~likely ~~still~~ ~~there~~ are Aridisols – characterized by an
178 arid soil moisture regime, which is evident on the Moon – in their version with one or more of
179 the following within 100 cm of the soil surface: a cambic horizon with a lower depth of 25 cm
180 or more; a cryic soil temperature regime and a cambic horizon; an anhydritic, calcic, gypsic,
181 petrocalcic, petrogypsic, or salic horizon; or a duripan.

182 On Earth, ongoing updates in soil classifications are driven by ~~a~~Anthropogenic soils, heavily
183 influenced by human activity (Capra et al., 2015), and the emerging concept of regolith
184 pedology (Juilleret et al., 2016; Huggett, 2023). Both aspects are of potential interest for
185 categorizing lunar soils. However, classifications still heavily rely on variables like temperature
186 and horizon thickness, which are irrelevant on the Moon. The lack of biota also complicates
187 ~~the~~ direct application of Earth-based soil classifications to lunar soils (Cannon, 2023).

188

189 *Proposal for a lunar soil horizon labelling system*

190 The available soil classifications are therefore poorly suited to the Moon. In them, soil horizons
191 are designated with capital letters (master symbols), ~~such as like~~ A for topsoil, B for subsoil,
192 and C for ~~transition to~~ geological substratum ~~R~~. Lowercase letters (suffixes) following the
193 master symbols denote specific properties, such as organic matter content or mineral
194 accumulations. For instance, a soil rich in organic matter in the topsoil and significant
195 secondary carbonate in the subsoil would be labelled Ah, Bk, C. ~~Horizons symbols serve fulfil~~
196 ~~a useful function in the labelling of soil horizons and facilitate discussion about them, which is~~
197 ~~helpful, both in the theoretical and practical aspects of soil science (Bridges, 1993). However,~~

198 soil horizons are artificial concepts, and in many soils, horizons are irregular,
199 fragmented~~broken~~, or have nearly invisible boundaries (Hartemink and Minasny, 2014).

200
201 As soil horizons are typically defined layers distinguishable from adjacent layers by a
202 distinctive set of properties produced by the soil-forming processes (Soil Survey Staff, 2017)

203 ~~For our proposal,~~ we consider the layers observed in the Apollo cores as soil horizons. To
204 distinguish these from terrestrial soil horizons and highlight the distinct processes influencing
205 their formation on the Moon, we propose using the degree symbol ° (Unicode U+00B0) as a
206 prefix for master horizons in lunar soil labelling (e.g., °A). We further suggest employing a

207 combination of ~~agglutinate~~the content of agglutinates (a diagnostic material) and the I_s/FeO
208 maturity index of Morris (1976) (a diagnostic property) to differentiate these master horizons,

209 reflecting the lunar soil's exposure time to weathering. In addition, we ~~propose~~suggest a
210 labelling system inspired by Earth's pedology but adapted to lunar conditions. We define four

211 ⁺master horizons (°A, °B, °C, °D), each characterized by varying agglutinate content, and
212 further differentiated with suffixes i, s, and m based on increasing values of the I_s/FeO maturity

213 index. This nomenclature allows for the definition of 12 reference soil horizons, as outlined in
214 Table 1.

215
216 Table 1. Proposed soil horizon designation for the Moon.

217 [Insert Table 1 here.]

218
219 Given the limited field data acquisition on the Moon and the consequent difficulty in

220 determining impossibility to infer what is the most meaningful thickness of diagnostic horizons,
221 we propose labelling the top meter of lunar surface by aggregating horizons in 25 cm

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222 ~~increments~~~~sequences~~ to define four diagnostic horizons. For instance, if the majority of the top
223 25 cm consists of °A horizon ~~material thickness~~ despite ~~the presence of~~ other horizons (°B, °C,
224 or °D), it will be classified as °A. We suggest naming ~~the~~ soil diagnostic horizons as follows:
225 “Agglutinic” for the °A horizon, i.e., the one with ~~the~~ highest content of agglutinates;
226 “Mutaric” (from Latin *Mutare*: to change) the °B horizon with intermediate content of
227 agglutinates;
228 and “Inceptic” (from Latin *Inceptum*: to initiate) and “Lapideic” (from Latin
228 *Lapis*: stone) the °C the °D horizons, ~~respectively~~, showing little and no weathering,
229 ~~respectively~~.

230

231 **Topsoil mapping of the Apollo 17 site**

232 We ~~designated~~ 30 topsoils ~~in terms of~~ master horizons based on samples from the Apollo
233 17 mission, using data available ~~from~~ NASA’s Lunar Sample Compendium
234 (<https://curator.jsc.nasa.gov/lunar/lsc/>), excluding all material not related ~~to~~ soil (Table 2).
235 We focused on the upper sections of the cores because current remote sensing technologies
236 only allow ~~for~~ surface observations, and used high-resolution images from the Lunar
237 Reconnaissance Orbiter Narrow ~~A~~ngle Camera (LRO-NAC, spatial resolution ~~of~~ 50 cm) to
238 delineate the soil boundary units.

239

240 [Table 2. Attribution of each Apollo 17 mission topsoil sample to one of the horizons we](#)
241 [proposed for lunar soils \(Table 1\), based on data available from NASA’s Lunar Sample](#)
242 [Compendium.](#)

243 [Insert Table 2 here.]

244

245 Using this labelling, we have built a first, ~~preliminary rough~~ soil map of the Moon (Fig. 3). We
246 focused on the Taurus-Littrow (TL) ~~V~~alley, working at a scale of about 1:250,000, which, on

247 Earth₁ is generally used to represent ~~on a regional scale~~ the geometries of Soil Mapping Units
248 on a regional scale, defined according to criteria of pedogenesis and the functional properties
249 of the soil. The low resolution is due to~~because~~ the limitations of the available data. The
250 primary sources included soil samples collected during the Apollo missions and imagery from
251 NASA's LRO NAC images (50 cm spatial resolution). The lack of precise geographic
252 information of the samples introduces inherent positional uncertainties. Additionally, the
253 resolution of the orbital imagery is not sufficient for detailed mapping, further
254 limiting~~constraining~~ the map's precision. A greater level of detail is currently impossible on
255 the Moon, but future human or robotized soil surveys will allow it.

256 The mapping process was done using QGIS to integrate sample data ~~and~~ with orbital imagery.
257 Unfortunately, there is currently no more accurate data on other potential covariates that could
258 influence the properties of the lunar regolith. This limitation stems from the fact that past lunar
259 data acquisition efforts were not specifically designed to address the needs of planetary
260 pedology. As a result, key variables that might improve the precision of soil mapping are either
261 unavailable or insufficiently detailed. Nonetheless~~In any case~~, our approach reveals observable
262 spatial heterogeneity and provides a foundational tool for identifying patterns in lunar soil
263 distribution.

264 The TL valley is located a few tens of kilometres outside the southeastern edge of Mare
265 Serenitatis, a 740 km diameter mascon basin. The valley trends east-southeast ~~and~~ is bounded
266 by the North and South Massifs, ~~and~~ filled with approximately 1400 m of basaltic lava. The
267 subfloor basalt is overlain by deposits of unconsolidated material, which include ~~where the~~
268 major units, such as ~~are~~ a pyroclastic deposit of orange and black glass beads, impact-generated
269 regolith of ejecta from a cluster of craters on the valley floor, and ~~the~~ light mantle derived
270 from the South Massif. This site was chosen because it is the largest explored area ~~in any~~

271 Apollo mission, where a substantial number of soil cores were collected (Fig. 1), and, in a
272 single case, descriptive comments were made by a geologist.

273 The map reveals a high prominence of the mature °A horizon (°Am), ~~indicat~~ showing a long
274 history of exposure to space weathering in the TL ~~V~~ valley morphological unit. However, it is
275 interesting to observe that in the Sculptured Hills area, the agglutinates percentage is higher
276 (station 8) than in the North and South Massifs (Highlands) and the floor of the TL Valley. We
277 assume that samples taken from the Steno and Camelot craters ~~ar~~ to be representative of the
278 Crater Cluster unit. These samples are consistent with °A horizon material; however, their
279 agglutinate content is lower than that of samples taken from outside this region (i.e., the TL
280 Valley unit). This is coherent with the older age of the Crater Cluster ~~u~~ nit, ~~although~~ but the
281 TL Valley is even older. The Lara and Shorty craters exhibit much lower agglutinate content
282 and maturity index, reflecting their younger age and, consequently, lower exposure to space
283 weathering.

284 While our map does not achieve high resolution, it represents an ~~important~~ step toward
285 understanding lunar soil variability and highlights the need for higher-resolution imagery and
286 an expanded network of geolocated samples. ~~The~~ Starting from general maps, like this one or
287 even on a smaller scale, the path forward could ~~be the one~~ follow ed in the ~~approach used~~ past
288 on Earth, where the costs ~~associated with~~ related to obtaining ~~highera~~ greater resolution led
289 to ~~pushed~~ investments ~~being~~ to be gradually focused on areas of ~~where there was~~ economic or
290 other interest.

291 The TL valley is located a few tens kilometres outside the southeastern edge of Mare
292 Serenitatis, a 740 km diameter mascon basin. The valley trends east-southeast, is bounded by
293 the North and South Massif and filled with approximately 1400 m of basaltic lava. The subfloor
294 basalt is overlain by deposits of unconsolidated material where the major units are a pyroclastic
295 deposit of orange and black glass beads, impact-generated regolith of ejecta from a cluster of

296 craters on the valley floor and the light mantle derived from the South Massif. This site was
297 chosen because it is the largest explored area on any Apollo mission, where a substantial
298 number of soil cores were collected (Fig. 1) and, in a single case, descriptive comments were
299 made by a geologist. All this had revealed great variability in soil composition.

300
301 [Insert Figure 3 here.]

302
303 The map reveals a high prominence of mature °A horizon (°Am) showing a long history of
304 exposure to space weathering in the TL valley morphological unit. However, it is interesting
305 to observe that in the Sculptured Hills area, the agglutinates percentage is higher (station 8)
306 than in the North and South Massifs (Highlands) and the floor of the TL Valley. We assume
307 samples taken from the Steno and Camelot craters to be representative of the Crater Cluster
308 unit. These samples are consistent with °A horizon material; however, their agglutinate content
309 is lower than that of samples taken from outside this region (i.e., the TL Valley unit). This is
310 coherent with the old age of the Crater Cluster Unit, but the TL Valley is even older. Lara and
311 Shorty craters exhibit much lower agglutinate content and maturity index, reflecting their
312 younger age and consequently lower exposure to space weathering.

314 Conclusions

315 ~~W~~In this article, we discuss the possibility of applying the nomenclature consolidated by
316 pedology for terrestrial soils to classify lunar soils as well. ~~We conclude that~~I to avoid
317 confusion with Earth's soil counterparts and emphasize the differences in pedogenic processes
318 operating on the Moon. ~~I~~It is convenient to resort to a specific labelling system for lunar soil
319 horizons and a distinct classification system for lunar soils, although largely inspired by Earth's
320 pedology. The labelling system to differentiate soil reference horizons is based on a

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321 combination of ~~agglutinate~~the content of ~~agglutinates~~ (diagnostic material) and the I_s/FeO
322 maturity index of Morris (diagnostic property), as these variables reflect the surface exposure
323 time of lunar soils to weathering. It includes four master horizons (°A, °B, °C, °D)~~based on~~
324 ~~the content of agglutinates~~, each defined by agglutinate content, and ~~them~~ further
325 differentiates~~ble them~~ with ~~the~~ three suffixes -i, s, and m according to ~~the~~ increasing values
326 of the I_s/FeO maturity index as follow: immature, submature and mature. Such nomenclature
327 allows defining twelve reference soil horizons. ~~Maps of lunar soil~~ maps could be drawn up
328 on this basis relying on accurate pedological surveys during future missions. ~~Here~~ and here, we
329 present a preview of one such map, created using ~~the~~ soils samples and the upper sections
330 of core samples from the Lunar Apollo Sample Compendium, along with ~~and~~ Lunar
331 Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images. The more
332 refined these maps become, the more useful they will be for future ~~coming soon~~ in-situ
333 resource utilization on the lunar surface ~~ground~~. Finally, by ~~through~~ the
334 establishing ~~establishment of~~ planetary pedology as a subfield ~~branch~~ of pedology, we aim to
335 stimulate discussions ~~among pedologists about~~ regarding their role in advancing scientific
336 exploration beyond Earth.

337

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343

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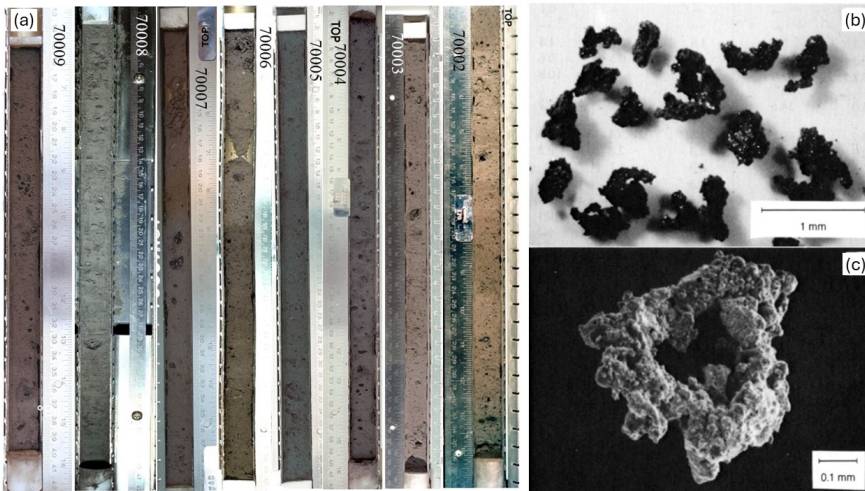
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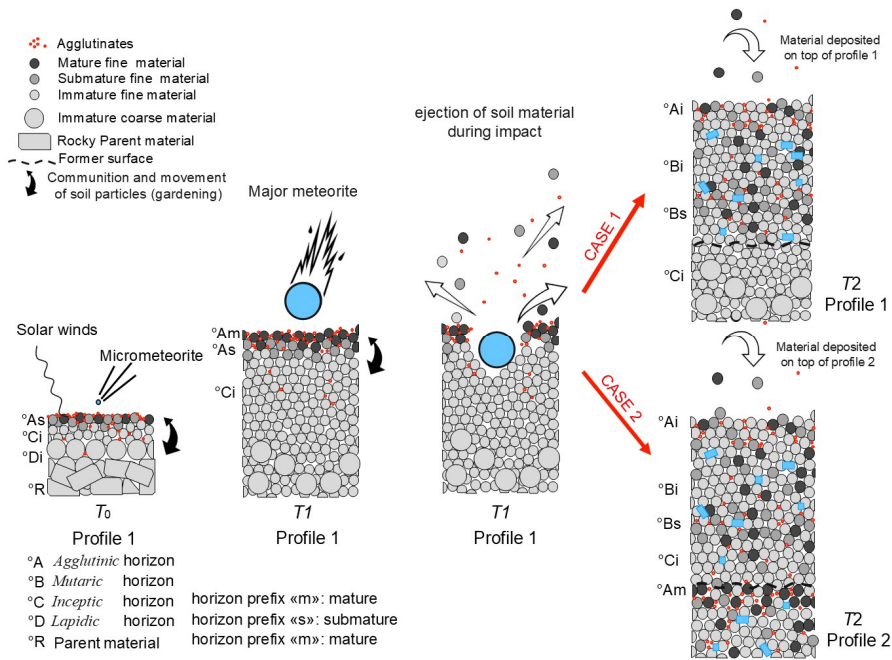


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418 Fig. 1 Evidence of pedogenesis on the Moon. a, Succession of Apollo 17 soil cores (70009 to
419 70002) showing variation in colour similar to earth soil horizons and layers. b, Typical
420 agglutinates separated from an Apollo 11 soil sample, and c, electron micrograph of an
421 individual agglutinate. Credit: NASA Lunar Sample and Photo Catalog
422 <https://curator.jsc.nasa.gov/lunar/samplecatalog/> (panel a), McKay et al (1991) (panels b and
423 c).

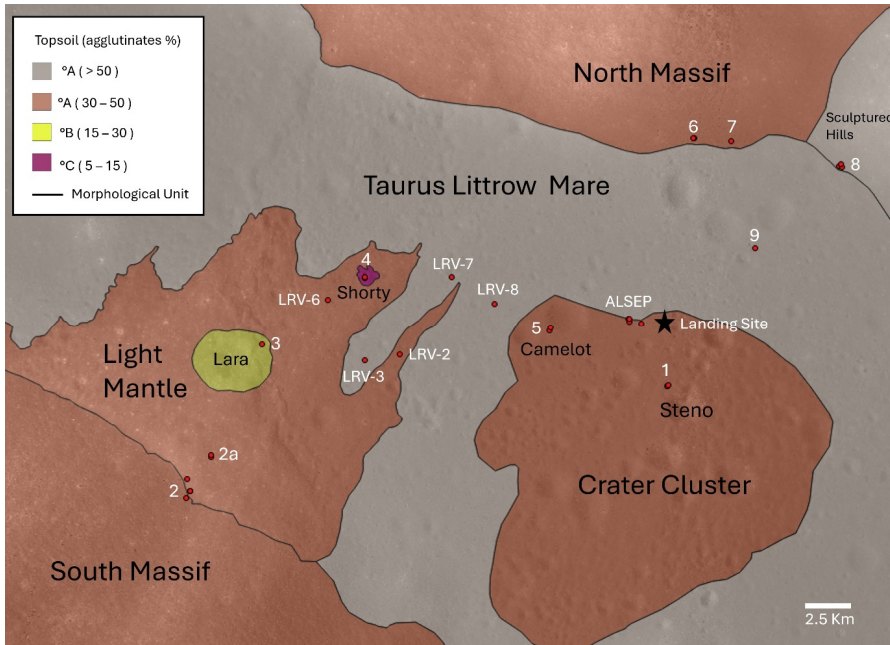
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427 Fig. 2 Soil formation processes according to time: Space weathering and soil gardening processes
 428 lead to different horizons by comminution and agglutination processes. Gardening is a
 429 permanent reworking promoted by meteorites. Sometimes, major meteorite disturbs the soil
 430 profile (Profile 1) leading to erosion before redeposition of the ejected soil material on the same
 431 place (Case 1). When the ejected material is deposited in a location not impacted by meteorites
 432 (Profile 2) then a buried surface is formed, and soil horizons mix (Case 2).



433
 434 Fig. 3 Topsoil horizon map of the Taurus-Littrow valley. The black points are locations of
 435 samples, in white the names of the sampling stations from Apollo 17.

436

437 Table 1. Proposed soil horizon designation for the Moon.

Agglutinates (%)	Master horizon	I _w /Fe (%)	Reference horizon
> 30	°A	> 60	°Am
		30 – 60	°As
		< 30	°Ai
15- 30	°B	> 60	°Bm
		30 – 60	°Bs
		< 30	°Bi
5 - 15	°C	> 60	°Cm
		30 – 60	°Cs
		< 30	°Ci
< 5	°D	> 60	°Dm
		30 – 60	°Ds
		< 30	°Di

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440 Table 2. Attribution of each Apollo 17 mission topsoil sample to one of the horizons we
 441 proposed for lunar soils (Table 1), based on data available from NASA's Lunar Sample
 442 Compendium.
 443

Sample	Agglutinates (%)	I/Fe index	Reference horizon	Master horizon	Location	Morphological units
7009	35	50	°A	°A	ALSEP	Crater Cluster
70161	34	46	°As	°A	ALSEP	Crater Cluster
70181	56	16	°Ai	°A	ALSEP	TL Valley
71041	27	29	°Bi	°B	Station 1	Crater Cluster
71061	9	14	°Ci	°C	Station 1	Crater Cluster
71501	35	35	°As	°A	Station 1	Crater Cluster
72321	45	73	°Am	°A	Station 2	Light Mantle
72441	42	68	°Am	°A	Station 2	Light Mantle
72461	43	71	°Am	°A	Station 2	Light Mantle
72501	48	81	°Am	°A	Station 2	South Massif
72150	53	82	°Am	°A	LRV-3	TL Valley
72141	51	81	°Am	°A	LRV-2	Light Mantle
72701	43	61	°Am	°A	Station 2	Light Mantle
73121	42	78	°Am	°A	Station 2a	Light Mantle
73141	32	48	°As	°A	Station 2a	Light Mantle
73221	26	43	°Bs	°B	Station 3	Lara Crater
74121	52	88	°Am	°A	LRV-6	Light Mantle
74220	2	1	°Di	°D	Station 4	Shorty crater
74002	13	3	°C	°C	Station 4	Shorty Crater
75111	52	58	°As	°A	LRV-7	TL Valley
75121	63	67	°Am	°A	LRV-8	TL Valley
75061	24	33	°Bs	°B	Station 5	Crater Cluster
75081	35	40	°As	°A	Station 5	Crater Cluster
76240	48	56	°As	°A	Station 6	North Massif
76501	47	48	°As	°A	Station 6	North Massif
77531	54	79	°Am	°A	Station 7	North Massif
78221	57	93	°Am	°A	Station 8	Sculptured Hills
78421	63	92	°Am	°A	Station 8	Sculptured Hills
78501	35	36	°As	°A	Station 8	Sculptured Hills
79221	44	81	°Am	°A	Station 9	TL Valley

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Tabella formattata