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Short Communication

Do soils exist outside Earth?

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ABSTRACT

On Earth, soils form thanks to the combined action of at least five factors: parent rock, climate, topography, biota, and time. However, the necessity of biota as unavoidable soil forming factor is debated, as important parts of our planet experiencing extreme climates host virtually life-free soils with advanced horizonation. Now that space exploration has greatly expanded our understanding of the Solar System, providing consistent evidences that the loose, unconsolidated ''skin'' of some nearby rocky bodies is lifeless, it is time to establish if the latter can be considered to be soil in a pedological sense. Our feeling is that, since the concept of soil chiefly bases on the occurrence of weathering and internal differentiation – both induced by biotic and/or abiotic processes – in an incoherent mass of mineral matter, the clearly altered surfaces of Venus, Mars, and our moon deserve the rank of soils. In case of farming in planetary bases, the soils of Mars seem to have the potential to be fertile substrata, eventually only requiring to be designed in terms of pore-size distribution and pore connectivity and to be freed from excess salts and toxic compounds.

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Four decades ago, the Apollo missions scraped the surface of the Moon and analyzed the retrieved samples, providing our first direct glimpse of the nature of a soil mantle different from those on Earth. In 2008, the first soil profile – a vertical section of soil – outside Earth was pictured by the Phoenix lander on Mars (Fig. 1a). These events are milestones for pedology, the discipline born at the end of 19th century that studies soils on Earth as they are in nature, their genesis, their relations with the environment, and their spatial distribution. However, within the pedology community there is considerable debate as to the meaning and significance of the investigated loose covers of rocky planets (Banin, 2005). Are they really soils? Since Cameron (1963) wrote his incitement on the role of soil science in space exploration, the latter greatly expanded our understanding of the Solar System, and it is now appropriate for pedologists to vet the set of known superficial properties of near solid space bodies in order to finally make decisions on the occurrence of extraterrestrial soils (Certini et al., 2009). The starting point to do it is choosing a scientifically sound concept of soil. Generally, in geology and planetary science, the term soil gets used for surface material that has changed a lot from the deeper rock and the term regolith is used for less changed material that has experienced mostly mechanical damage. Pedologists advanced encyclopaedic definitions of soil, but none of them is exhaustive and universally accepted. Most of the definitions emphasise that soil is mainly a medium for plant growth. However, a broader, updated, scientific definition considers soil to be any *in situ* weathered veneer of a planetary surface that retains information on its climatic and geochemical history. Weathering is therefore the pivot of pedogenesis. On Earth, soil forms thanks to the combined action of at least five factors: parent rock, climate, topography, biota, and time. The necessity of biota as unavoidable soil forming factor is debated (Markevitz, 1997; Certini and Scalenghe, 2006). In fact, important parts of Earth host virtually life-free soils with advanced horizonation (Ugolini and Anderson, 1973; Ewing et al., 2006) and some young, slightly pedogenized, undifferentiated surfaces do not appear much different from extraterrestrial analogs, despite they sustain the growth of vascular plants (Fig. 1b).

Another open question is the necessity of liquid water for weathering. On Earth, liquid water is the medium where most of soil reactions happen and which drives translocations of matter and energy within soil. Outside Earth, water eventually occurs as ice and, as such, does not play any major role as weathering agent and carrier. However, there are several polar solvents that could replace liquid water, such as sulphuric, hydrofluoric and hydrocyanic acids, ammonia, methanol and hydrazine. The most powerful electron acceptor on Earth, oxygen, is not present as free O_2 on nearby planetary bodies, but ozone (O_3) and weaker oxidants may substitute molecular O, as they do in anaerobic environments on Earth. Several energy sources drive chemical reactions in space: thermal, osmotic and ionic gradients, solar wind, magnetic attraction, radioactivity, and, last but not least, volcanic activity and meteorite impacts.

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Fig. 1. Centimetric soil profiles at (a) 68°N in the Martian arctic plain and (b) at 37°N in the Pantelleria Island, Italy. Why does this slightly weathered, undifferentiated volcanic tephra deposit on Earth undoubtedly deserves the rank of soil, and should be not the same for the reddened and internally variegated cover of Mars? Perhaps because of the exclusive biotic colonisation by caper (*Capparis spinosa* L.) or, more plausibly, is the in situ mineral weathering sufficient *per se* to give the dignity of soils to both terrestrial and extraterrestrial earthy deposits? [Picture on the left courtesy of NASA/JPLCaltech/University of Arizona/Texas A&M University].

What soil genesis cannot prescind from is a rocky parent material, which in the Solar System occurs just on the four inner planets—Mercury, Earth, Venus and Mars, a few planets' moons, and the largest asteroids. Some *exoplanets* – the planets orbiting other stars – are expected to be solid, but their direct observation is not feasible because of their remoteness. As a consequence, no inference about the occurrence of soils on them is possible.

The hot, close-to-sun *Mercury* has a dark surface of iron-rich anorthosite (McCord and Clark, 1979) greatly weathered by the impacts and solar bombardment and showing evidences of maturation, the most important being the occurrence of iron as nanoscale metal or oxide grains (Robinson et al., 2008). Opposite to Mercury, *Venus* has a dense atmosphere, mainly composed of carbon dioxide and sulphuric acid droplets, which protects the surface from erosion by cosmic particles, but is effective at degrading rocks into secondary weathering products (Barsukov et al., 1986). However, lava flows lacking surface weathering – hence suggesting ongoing resurfacing of the planet – have been detected (Smrekar et al., 2010). *Mars* is covered by a heterogeneous mixture of volcanic rocks partly pulverized by impacts and thermoclastism, fluvial deposits, thick sequences of silicate, and sulphate-rich sedimentary rocks of possible marine origin (Grant et al., 2004). The reddish hue of Martian landscape is symptomatic of intense weathering, which results from rusting iron minerals formed a few billion years ago when Mars was warm and wet. Now that Mars is cold and dry, modern rusting may result from a superoxide that forms on minerals exposed to ultraviolet rays in sunlight (Yen et al., 2000). The presence of clay minerals (Chevrier et al., 2007) and sulphates such as jarosite (Vaniman et al., 2004) suggests that chemical weathering combined with leaching occur(red) in many geological settings on Mars, possibly providing a variety of soil types on the planet. A layer of fine dust consisting of carbon-rich rocks and ice coats *Phobos* and *Deimos*, the two small moons of Mars (Veverka and Burns, 1980); at the present stage of deficient knowledge it is impossible to speculate whether it is soil or not. The *Earth's moon*, which is the nearest celestial body and the sole trod until now, has a mantle of loose, heterogeneous fragmental debris that overlies solid rock. Since the end of the volcanic era, lunar basalts have experienced the action of weathering processes including physical reworking by meteorite impacts, which exposed rocks rich in Fe-bearing alterable olivine (Yamamoto et al., 2010), and chemical interactions of impact-generated and sputtered ions or irradiation by solar wind, which darkened and reddened powders in proportion to their Fe content (Hapke, 2001). As a result, lunar surface shows thin rims of weathering on grains (Keller and McKay, 1997), and even horizonation (Duke and Nagle, 1975). Furthermore, opposite to what previously believed, a minor hydrated phase or hydration process occurs in the top millimetres of lunar soils (Pieters et al., 2009). *Io*, the only telluric moon of Jupiter, is heated by tidal forcing exerted by the gravitational fields of its reference planet and two other moons, *Europa* and *Ganymede*. The consequential volcanism continuously reworks the ferric-sulphuric-silicatic crust (Simonelli et al., 1997), thus reducing the time available for any pedogenic processes, whose rate is anyway low because Io's surface is perennially frozen. *Titan*, the largest moon of Saturn, is in all half water ice and half rocky material, but is probably differentiated into a rocky centre surrounded by several layers of ice of different crystal forms. The outer layer seems to consist of water ice contaminated with little amounts of dark materials, perhaps partly organic and partly mineral (McCord et al., 2006). Such a composition makes the occurrence of soils on Titan highly improbable. *Asteroids* are too small to have any internal heat able to induce volcanism and tectonics, which could rejuvenate their surface. The latter is hence currently reddened or darkened by the solar wind and micrometeorite (dust) impacts. Vernazza et al. (2009) demonstrated that most of the final colour of silicate-rich asteroids is acquired relatively shortly after their birth, within the first million years; this supports solar wind implantation as the main mechanism of surface weathering, since it is a more rapid process than micrometeorite impact and other phenomena. The enigma of unweathered, much older than 10^6 years asteroids often observed among those passed close to Earth in the last several thousand years has been solved by Binzel et al. (2010): tidal stresses cause profound turbation of surface material and exposure of unweathered grains in asteroids that pass within a few diameters of Earth. After taking close-up images of the asteroid *25143 Itokawa* and landing on it in November 2005 to capture some surface material (Yano et al., 2006), the Japanese spacecraft Hayabusa returned to Earth in June 2010. Hopefully, the sample Hayabusa succeeded in bringing will soon provide the first direct information on an asteroid's skin and its stage of alteration.

Summarising, our nearest planetary neighbours, Venus, Mars, and our moon, certainly possess weathered mantles that should be considered to be soils in a pedological sense, while Mercury

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