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Half a century after the first bootprint on the lunar surface: the ichnological side of the Moon

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Abstract

Humankind began with extra-planetary expeditions in the 1960s. To date, more than fifty manned and unmanned lunar missions have taken place. Maybe, the most iconic image of these campaigns is the bootprint left and photographed by the astronaut Edwin Aldrin. Nevertheless, there is also other evidence of human activities on the Moon, such as rover trails, drill holes, vehicles, and rubbish. For some researchers, ichnology only studies the traces made by one or several individuals with their own bodies, but other authors advocate that artefacts as well as traces made by these artefacts are also traces. In this context, the ichnology of the Moon allows both analysis of the traces left on the lunar surface themselves and discussion of the aim and scopes of ichnology. The Moon ichnology, which arises from the development of hominid ichnology, includes technical artefacts (called technofossils, e.g. Lunar Module, flag, religious text) and traces of technical artefacts (comprised in the new category technotraces, e.g. bootprints, drill holes) but not traces made by individuals with parts of their bodies. Although the lunar environment is very different from that of the Earth due to the absence of atmosphere, magnetic field, water, organic material and life, it is possible to propose three ichnological analogies between the Earth and its satellite. First of all, traces on the Moon surface are subjected to very slow sedimentation rates, similar to what occurs in abyssal bottoms or caves, among other environments. Moreover, physical and mechanical properties allow comparison with processes leading to the formation of traces in volcanic ash deposits with those acting on the soil and regolith of the Moon. Finally, cultural similarities have been identified between the traces left by humans on the Moon and comparable expeditions of humankind, such as Antarctica and the North Pole. The evolution of human technical artefacts has been used to help characterize the onset of the "Anthropocene". These artefacts can be included within the technosphere and can also be

thought to be phenotypic expressions of human genes. Therefore, the traces left on the Moon as well as others which are in other celestial bodies or even in the space, can be considered evidence of extended phenotype of *Homo sapiens* and the “Anthropocene” beyond the Earth.

Keywords: ichnology; technotrace; technofossil; lunar missions.

1. INTRODUCTION

On July 20th, 1969, at 20:17 UTC, Apollo 11 and part of its crew, the astronauts Neil Armstrong and Edwin “Buzz” Aldrin Jr., landed on the Earth’s Moon (hereafter, Moon) for the first time in the human history. Six hours and 39 minutes later, on July 21st, at 02:56 UTC, Armstrong got off the Lunar Module and, while registering his bootprints on the Moon surface, “spoke” the iconic sentence: “*One small step for a man, one giant leap for mankind.”* (see Barbree, 2014: p. 263). Aldrin joined him 19 minutes later. After the Apollo 11 spaceflight, ten astronauts walked on the Moon’s surface as part of five subsequent missions of the Apollo program, and more than forty unmanned lunar missions were performed (Gorman, 2016) (Fig. 1).

“*The surface is fine and powdery. I can pick it up loosely, with my toe. It does adhere in fine layers like powdered charcoal to the sole and sides of my boots. I only go in a small fraction of an inch. Maybe an eighth of an inch, but I can see the footprints of my boots and the treads in the fine sandy particles.*” (see Barbree, 2014: p. 264). These words, pronounced by Armstrong shortly after trampling the lunar soil, constitute the first report about the Moon surface and were the basis of many studies on lunar rheology, sedimentology, and mineralogy (e.g. McKay et al., 1991). Armstrong’s description is similar to those of people dealing with the study of trace fossils, especially in the field of tetrapod ichnology, in order to characterise trampled sediments by the observation and measurements of some features of the produced footprint. Classically, from an inclusive standpoint, ichnology studies the traces resulting from the vital activity of one or several organisms modifying a substrate (e.g. Bromley, 1996; Buatois et al., 2002; Bertling et al., 2006). A commonly shared, practical approach to the understanding of the dynamics of the registration process relates the final morphology of a trace to three main factors: organism morphology, organism behaviour and substrate properties (e.g. Padian and Olsen, 1984; Minter et al., 2007; Falkingham, 2014). The traces left on the Moon soil are unique for several reasons, namely, humans have been the only organisms trampling and interfering with the Moon's soil during an exploration campaign. In addition, the lunar substrate is quite different from the Earth's due to the absence of both atmosphere and magnetic field, the mineral composition and the lack of water and organic material or activities (e.g. Carrier et al., 1991; Schuerger et al., 2018).

One of the main aims of the hominid ichnology, a term introduced by Lockley (1998), is the study of human traces. Human traces constitute a complex area of study in the field of ichnology, especially for inherent philosophical and gnoseological implications of the record in the light of hominid evolutionary trends (i.e. evolution of the human body and walking dynamics besides brain development). From the hominid steps in the Pleistocene of Laetoli to the human bootprints on the Moon surface (see Lockley, 1998, 1999; Lockley et al., 2016) hominid ichnology has increased the scope and possibilities beyond traditional approaches (e.g. Baucon et al., 2017). For instance, hominid ichnology studies the human traces themselves (e.g. footprints, coprolites) as well as the traces produced by hominid technology, like traces of artefacts (Hasiotis et al., 2007; Kim et al., 2008). An interesting and controversial proposal, partly related to the extended phenotype concept (Dawkins, 1982: p.199), is to include within ichnological studies the manufactured artefacts made by humans, such as cars, computers, and weapons (see Hasiotis et al., 2007; Kim et al., 2008; Ekdale, 2010; Astibia, 2012). Therefore, the scope of the Moon ichnology would not deal only with the bootprints of the astronauts, but also extend to the study of other traces, such as the lunar module impressions made during landing and taking off, rover trails, and drilling borings, as well as all the artefacts left on the Moon.

According to current data, the Moon ichnology constitutes an excellent opportunity both to analyse the traces left by humans and their technologies on the Moon soil and to discuss the scope of ichnology itself. Thus, after analysing the most representative information about Apollo missions, available from scientific literature, reports and graphic material retrieved from NASA archives, we discuss the implications of this new approach to hominid ichnology and, on the whole, within the theoretical and epistemological framework of ichnology. To do this, the lunar environment and its substrate properties, their possible analogues on the Earth, and the traces produced by humans on the Moon will also be discussed.

2. THE ICHNOLOGY AND THE MOON: AIM AND SCOPES

The humankind has started to leave traces on the Moon on 13rd September 1959, when the Soviet Cosmic Rocket "Luna 2" impacted the Moon surface, east of *Mare Imbrium* (Gorman and O'Leary, 2007) becoming the first human-made object to contact a celestial body.

The debate on the scope of hominid ichnology is booming. For instance, Lockley (1998) included within the hominid ichnology the footprints and cut traces in bones, as well as writing and art regardless of the use of technologies. Subsequently, Lockley and Meyer (2000) proposed that any technological creation or artefact is a modification of a natural object or substrate either done by human hands or tools, thus, in a very inclusive sense, it is a trace. On the other hand, Bertling et al. (2006) only considered as traces the evidence of hominid biology, such as footprints or faeces, and excluded the "signs of human technology" (like artefact marks -and artefacts itself-), although they included non-hominid tools. Hasiotis et al. (2007) classified hominid trace fossils as artefacts, biofacts, and features. According to these authors, the category artefacts include manufactured objects (e.g. lithics, ceramics, metallics, and organics), biofacts are the remains of plants or animals modified by hominid gnawing, trampling, butchering, gathering or digging, and features are the superficial physical and chemical traces (e.g. roads, buildings). Kim et al. (2008) divided hominid ichnology into four main categories: footprints, butchering and feeding traces, stone tools, and multimedia technology and art, including dwelling traces. Ekdale (2010: p.229), who highlighted the value of ichnology as a tool in the analysis of hominid evolutionary trends, proposed a suggestive concept: "*Paleoanthropologists and primate paleontologists necessarily base their phylogenetic interpretations of the hominid evolutionary tree on anatomical characters, and yet hominid trace fossils also play an important role in understanding hominid evolution*. (...) *It is the many kinds of artifacts created by the hands of our prehistoric ancestors that allow us to understand the evolution of human thought and creativity in the distant past. (I recognize that some of my colleagues do not like to include prehistoric artifacts under the broad rubric of ´trace fossils´, but in fact they clearly are the preserved evidence of activities of ancient organisms.)*". The same idea was conceived by Astibia (2012), who considered human-made objects as ichnofossils because they account for the activity and behaviour of the producers. Lockley et al. (2016) summarised that hominid traces also include, but are not limited to, tool marks, artefacts and various forms of painting and writing made by modifying (flaking, engraving, sculpting, excavating) a wide range of substrates (such as wood, bone, rock and soil). From a standpoint based on the "Anthropocene" concept, Zalasiewicz et al. (2014) pointed out that the artefacts made by humans are ichnofossils because they are biological innovations that reflect their own technology. The authors called these artefacts as technofossils to separate them from trace fossils in a traditional sense (galleries, footprints, among others), also underlining the potential of these objects (i.e. technofossils) as stratigraphic markers.

At this point, we need to discuss the meaning of the term “artefact” from an ichnological and philosophical perspective. For instance, Brey (2005) mentioned that, from a realistic perspective, artefacts have inherent properties and agency can be attributed to them, whereas from a social constructivist perspective, artefacts do not have inherent properties and are only related with the attribution that derives from the interpretations and behaviour of individuals and social groups. There is a third proposal that is called a “hybrid perspective” (*sensu* Brey, 2005). From this point of view, artefacts and their properties should be analysed neither as objective facts nor as mere social constructions, but as both real and constructed (Brey, 2005). Thus, artefacts and their properties emerge as the result of their being embedded in a network of human and nonhuman entities (Brey, 2005). We follow this last proposal. All artefacts would be cultural entities, although with different characteristics. Borgo et al. (2014) differentiate between artefacts (or “simple artefacts” in this contribution) and technical artefacts. A simple artefact (e.g. “α”) *“is a physical object which an agent (or group of agents) creates by two, possibly concurrent, intentional acts: the selection of a material entity (as the only constituent of α) and the attribution to α of a quality”* (Borgo et al., 2014: p. 219). A technical artefact was also proposed by Borgo et al. (2014) after a seminal notion in Kitamura and Mizoguchi (2010: p. 221): “*A technical artifact α is a physical object created by an intentionally performed production process. The process is intentionally performed by one or more agents with the goal of producing the object α which is expected to realize intended behavior in some given generic technical situation, and the object α can realize to some extent that intended behavior and/or has a property which supports that behavior”*.

If we consider a trace as the result of the vital activity of one or several organisms modifying a substrate and the arguments discussed above, the category “trace” not only includes traces left without artefacts (e.g. footprints, faeces), but also those produced by artefacts (e.g. tool blows, boot tracks), and the artefacts themselves, both simple (e.g. a stone used by a squirrel to open a walnut) and technical (e.g. cars, computers), which clearly originated along evolutionary/cultural processes (Fig. 2). The modifications of the substrate could be thought to appertain to different orders. For example, extracting mud from the field is first order of the mud modification, making a ceramic component with this mud is second order, the use of this ceramic as components in an electronic circuit is third order, and so on. And even the redeposition of this material can be considered as the last order in substrate modification, being the last stage of a cycle of substrate modification.

The concept of technical artefact of Borgo et al. (2014) can be considered analogous with the term of technofossil of Zalasiewicz et al. (2014), which are technical components of the physical technosphere (Zalasiewicz et al., 2017) (Fig. 2). In this context, it is important to highlight that artefacts are not a human prerogative, seeing that other animals, like some birds, otters, and primates, make and use both technical and simple artefacts (e.g. Van Lawick-Goodall, 1970). For instance, the rock used by an otter to open a shell is a simple artefact because is an object used with a purpose (Fig. 2). By contrast, the flint used by a human individual to make an arrowhead is a technical artefact, as well as a mud nest of *Furnarius rufus* (rufous hornero bird), because both were produced with a purpose or further use after a specifical production process. Within technical artefacts or technofossils, multimedia technology, buildings, and art, among many others, are included.

Furthermore, the manipulation of the artefacts can produce other traces: bioturbation (e.g. boot tracks, furrow plow), bioerosion (e.g. drill holes, cut traces) or bioconstruction (e.g. rubbish bin). The traces made by simple artefacts are considered here as traces in a traditional sense. For the traces produced by the manipulation of technical artefacts we propose the name technotrace (Fig. 2), which sometimes are the only evidence of the objects from which they are derived in a particular place.

Perhaps the arising dilemma of this issue is related to the conceptions, or misconceptions, of modern technical artefacts as fossils, thus as technofossils. Therefore, is the nature of modern objects fundamentally different from the fossil concept? It may display an inherent weakness when is used from an inclusive point of view, and several caveats can be noted to assess a “global” definition (see Ritter and Pettersen, 2015). In this sense, an interesting definition was provided by Behrensmeyer et al. (2000). ‘‘*A fossil is any nonliving, biologically generated trace or material that paleontologists study as part of the record of past life*’’. We consider that artefacts are included within this definition because they are objects generated by organisms. Different artefacts may not satisfy all the requirements to be considered a fossil *sensu stricto*, although several features would allow their inclusion as fossils. Mainly, we can mention two key features: I- long durability of materials (see Andrady, 2003), and II- an accurate chronostratigraphical position after final burial based on inherent features (e.g. design patterns, used raw materials, fabrication information) (e.g. Astibia, 2012). The latter feature characterize technofossils as stratigraphic markers. We recognize that this issue is still in flux, and beyond the scope of this contribution, however we admit that these mentioned features of artefacts may correspond with a traditional conception of fossils. The inherent concept is that human-made objects have many “fossil” characteristics, in a traditional sense, after their construction.

Human traces clearly differ in several major respects from traditional ichnofossils, which are characterised by narrow morphological ranges predetermined by genetic control (Zalasiewicz et al., 2014). In the field of tetrapod palaeoichnology, Avanzini et al. (2001) have considered the extended phenotype as an expression of the anatomical and behavioural characters of an organism, as a resulted of evolutionary processes. Dawkins (1982: p. 199) pointed out: "*(...) an animal artifact, like any other phenotypic product whose variation is influenced by a gene, can be regarded as a phenotypic tool by which that gene could potentially lever itself into the next generation*". Therefore, animal artefacts, produced by both a single individual and/or different members of a kin group, can be thought to be part of the phenotypic expressions of genes, more precisely the part extending from them, assuming they varied under the control of genes evolving by Darwinian natural selection (Dawkins, 1982). Beaver dams, the spiderwebs, or the mound built by a colony of termites are examples of extended phenotypes. In the same way, pushing this concept 384.400 kilometres far away from the Earth, all the artefacts left on the Moon surface, including bootprints, traces of landing and take-off of the lunar modules, as well as rover trails, drilling borings, hammer marks, and traces of the crashed modules, which are undoubtedly components of the culture in its most inclusive meaning, can be regarded as an extended phenotype of *Homo sapiens.*

3. LUNAR ENVIRONMENT AND SUBSTRATE PROPERTIES

The environments on the Moon and Earth differ greatly from each other (see Benaroya, 2018, and references therein). The Moon's gravity at the equator equals to 1.62 m/s^2, day cycle is 29.53 Earth days in duration (Benaroya, 2018). The lunar surface experiences extremely harsh conditions with extreme wide temperature ranges (-171°C to 140° C), high doses of ultraviolet irradiation (26.8 W/m^2 UVC/UVB), high levels of ionizing radiation by solar wind particles, and low atmospheric pressure (10^{-10} Pa) (Schuerger et al., 2019). Moreover, the Moon lacks atmosphere, liquid water, and organic material (Carrier et al., 1991; Schuerger et al., 2019). All these factors endow the lunar substrate with a relatively narrow and well-defined range of physical properties (Carrier et al., 1991).

Lunar soil is used to describe the finer-grained, sub-centimetric fraction of the unconsolidated regolith (McKay et al., 1991). Individual lunar soil particles are mostly glassbonded aggregates (agglutinates), as well as various rock and mineral fragments (McKay et al., 1991). The soil composition ranges from basaltic to anorthositic, and it includes a small (<2%) meteoritic component (Houck, 1982a; McKay et al., 1991). Lunar soil grain size is controlled by three principal processes: commination (which reduces the grain size), agglutination (which increases the grain size), and mixing (McKay et al., 1991). Although the lunar soil chemical composition shows considerable variation, physical properties, such as grain size, density, packing, and compressibility, are rather uniform (McKay et al., 1991). The mean grain size of the analysed soil ranges from about 40 μm to about 800 μm and averages between 60 and 80 μm. The soil properties are different from place to place and depend on the mineralogy of the source rocks and the geologic processes that the rocks have undergone (Houck, 1982b; Horz et al., 1991; Taylor et al., 1991). Its origin is related to the continuous meteoroid impacts that have broken down the lunar rocks since ~4.5 billion years (Ga) ago (Zellner, 2017).

The physical and mechanical properties of the lunar soil have been studied in almost all lunar missions (e.g. Scott et al., 1970). Some factors have been measured *in situ* by astronauts (using both their own bootprints and specific tools) and robots, in the laboratory with lunar samples, and from the Earth's surface by remote sensing (Carrier et al., 1991). The main parameters analysed were: granulometric composition, density and porosity, cohesion and adhesion, angle of internal friction, shear strength of loose soil and regolith, deformation characteristics, the compressibility and bearing capacity (see Slyuta, 2014, for further details). Many of these parameters determine the final morphology of the traces (e.g. bootprint depth and shape).

The particles composing the lunar substrate are irregular and vary from spherical to very angular in shape (Carrier et al., 1991; Slyuta, 2014). The irregular shape increases the cohesive behaviour of the substrate, and this is why the astronauts' bootprints are practically a perfect copy of the sole of the boots, with very well preserved almost vertical walls (Carrier, 2005). On the other hand, the fine-grained material adhered to the astronauts' boots and space suits, the camera, and the rest of the elements (Scott et al., 1971). Thus, it is possible that a fine layer of the substrate has stuck to the boot sole and that layer is missing in the bootprint (Lee, 1995). Finally, the bootprint depth in the intercrater area was about 70 mm, while in the crater proximities was about 16 mm (Mitchell et al., 1974), thus the substrate in the intercrater is softer and less relative density than in the crater rims areas.

As commented before, the Moon lacks atmosphere and liquid water, which are the main erosive factors in the Earth, as well as bioerosion could affect the lunar surface. That is why it is believed that the traces of the Moon will be there almost 'forever', at least in terms of human generations. On the other hand, the lunar substrate is affected by the impact of sunlight, solar wind plasma, meteors (Mendillo, 2001), and neotectonics (Valantinas and Schultz, 2020). These factors are fewer than those present on the Earth. For instance, micrometeorites produce a minimum erosion rate of 0.2–0.4 mm per million years (Mendillo, 2001), and sunlight produces dust storms that could cover the astronaut's bootprints in at least 25,000 years (O'Brian and Hollick, 2015). Of course, the impact of meteors or tectonics in the area where the traces are preserved would destroy them immediately.

4. THE ICHNOLOGICAL RECORD OF THE MOON

The environment of the Moon does not allow human life without external protection, so astronauts must wear the spacesuit or inhabit the lunar module (Benaroya, 2018). Therefore, the whole ichnological record on the Moon is the reflection of human technology and is represented by traces of bioturbation, traces of bioerosion, and artefacts.

Bioturbation is considered as the process by which the primary consistency and structure of a sediment are modified by the activities of organisms (see Baucon et al., 2017:

table 3 for a complete review of ichnological concepts). Astronaut bootprints, lunar rover trails, traces of Lunar Module when landing and taking off the Moon, traces of transport and placement of scientific equipment (e.g. seismometers, Lunar Surface Experiments Package), surface sampling marks, among others, are included in this category (Fig. 3, 4). In fact, the bootprints are the impression of the overshoes, which were worn over the boots. The overshoes of all the Moon-landed Apollo missions had a similar design (parallel latero-medially ribs) but were manufactured in two different sizes (Mather, 2014): overshoes of 336 mm long, with eight ribs, called OMED, like the ones Armstrong wore; and overshoes of 368 mm long, with nine ribs, called OLGE, like the ones Aldrin wore. Apart from size and number of ribs, differences among bootprints depend on both the movement of the astronaut such as walking and jumping, and the physical properties of the substrate in each trampled area (see the previous section). The Lunar Roving Vehicles of the Apollo 15, 16 and 17 missions had four wheels with riveted in a chevron pattern, and their impressed trails are different concerning those left by the eight-wheeled Lunokhod 1 and 2 (Russia) and four-wheeled Yutu 1 and 2 (China), which display longitudinal and transversal patterns. During landing and take-off, the engine of the Lunar Module made a crater ejecting tons of substrate and rocks and removing several centimetres of substrate over a broad area (Metzger et al., 2011). The lunar soft landers, like the Surveyor III, and the Lunar Module impressed the characteristic circular footpaths on the lunar surface as well (see Halajian, 1968; Benaroya, 2018). In addition, the installation of scientific equipment and sampling operations left their own traces that depend on the shape of the instruments used, as well as a heavily trampled area by the crew.

Bioerosion is understood as the process when a rigid substrate is mechanically or biochemically excavated by one or several organisms (Pemberton et al., 2001). On the Moon, the astronauts have broken the rocks with hammers to get fresh samples (Fig. 5a-b). Indeed, if during the landing/take off and the sampling, the rocks were affected, this could be considered as bioerosion as well. Examples of bioturbation plus bioerosion are spacecrafts or other special objects that were crashed, intentionally or not, on the lunar surface, and core drillings (see Baucon et al., 2017) (Fig. 5c-d).

Finally, throughout the manned and non-manned missions, tons of technical artefacts have been left on the Moon, such as remains of crashed spacecrafts, rovers, and sub-satellites (Spennemann, 2004, 2007) (Fig. 6). Numerous devices were also installed, such as retroreflectors and seismometers, to conduct long-term experiments. Within the artefacts, likely the USA flags and commemorative plaques are the most representative, although other artefacts such as a religious book, photographs (Fig. 6e) or golf balls were left by the crews. On the other hand, it is important to highlight that many rubbish bags were abandoned on the Moon surface throughout the Apollo missions (Spennemann, 2004, 2007) (Fig. 6f).

As commented before, until now, Moon ichnology is causally related to human technology. It is possible to find technofossils (technical artefacts: e.g., Lunar Module, flags, books), technotraces (bioturbation and bioerosion traces: e.g., bootprints, drill holes) but not traces in a traditional sense or simple artefacts. Interestingly, it is possible that the information provided by some of the technotraces (e.g. the bootprints), is the only data available on the technofossil (the boots/overshoes), in a particular place (the Moon). Usually, human technology is used as the basis for technostratigraphy and biohorizons that can signal the beginning of the "Anthropocene" (Barnosky, 2014; Dibley, 2018), and the Moon traces could be the extraterrestrial evidence of the "Anthropocene" out of the Earth (Gorman, 2014; Zalasiewicz et al., 2014). The evolution of human technology is currently accelerating, as seen for example in smartphones (Zalasiewicz et al., 2018). Precise information about the date of the market launch of a human-produced artefact make these technofossils chronostratigraphically useful markers for erecting first appearance interval zones. They can also be compared typologically in case of no access to our present-day databases in the future. At this point, the information provided by technotraces about non-preserved technofossils is important and conceptually similar to the ichnostratigraphy concept used in ichnology (see Seilacher, 2000; Mángano et al., 2012). There is a wealth of data online about the provenance and date of manufacture of all the technical artefacts used in the lunar missions. Thus, it could be possible to know the first appearance datum of each mission site based only on the technofossil record, which always is older than the mission itself. Moreover, part of the space technology (e.g. plastics, metallic alloys) used in several missions allows a potential chronological correlation inside (e.g. Moon, Mars, Venus, Jupiter) (Zalasiewicz et al. 2016), and even outside the Solar System (Voyager 1 space probe).

5. THE ICHNOLOGY OF THE MOON: UNIQUENESS VS CONVENTIONALITY, OR RECURRENT PATTERNS?

The uniqueness of the human traces on the Moon is one of the most interesting aspects to analyse. Despite the obvious differences between the properties of the surfaces of the Earth and the Moon (e.g. disparity in the forces of gravity, presence/absence of the atmosphere and life support conditions), is it possible to assess the ichnological record of the Moon understanding it, at least in some specific terms in comparison with our planet, for potential ichnological analogues? Thus, the arising and intriguing concept is that some environmental settings on Earth can be considered potentially analogous with Moon records, but also to other planetary and satellite records within our Solar System, and perhaps even beyond.

A good starting point is to contrast the general environmental and planetary conditions of the Moon against possible ichnological analogues of the Earth’s surface. We identify three types of analogue that will be discussed in the next sections: 1) according to the preservational window (see further explanations in the next section), places where traces can be exposed for a long time, as on an abyssal sea floor or in a cave that has very slow sedimentation rates just like the Moon; 2) according to the physical and mechanical properties of the substrate, in which volcanic ash falls resemble to lunar soil and regolith; and 3) according to the use of the traces as cultural keystones, comparing the arrival at the Moon with other relevant explorations of humanity, such as Antarctica and the North Pole expeditions, or even the first human traces in the New World.

Preservational window

We consider the preservational window as the time-lapse in which a substrate remains mechanically modifiable and able to be bioturbated (soft substrate) before lithification; this concept is based in previous background (see Cohen et al., 1991, 1993).

The abyssal plain zone, one of most extreme environments on the Earth's surface, represents the deeper ocean floor and extends in depth below 2000 m, reaching an average maximum of 5000 m (Nichols, 2009). Except at hydrothermal vents, it is characterized by having low temperature, absence of light, mainly soft muddy bottoms, and extremely limited food resources (Vinogradova, 1997). The abyssal seafloor is mostly covered by fine sediments (medium sands to clays), and with no *in situ* primary production (except at spatially rare hydrothermal vents and cold seeps) (Smith et al., 2008). Among disparities with the lunar environment, one of the most notorious, apart from being sub-aqueous, is the presence of plenty of life forms on the abyssal substrate. The habitat structure of abyssal sediments is mainly biogenic consisting of the tests of giant protozoans and the burrows, mounds, and tracks of megabenthos (Smith et al., 2008, and references therein).

Beyond these disparities, probably the most remarkable similarity is the substrate stability after burrowing, which generates within this system relative long-term preservation windows. Although abyssal plains have inherent characteristics depending on the geographic position (e.g. Pilkey, 1987), sedimentary processes are dominated by turbidity currents and contour currents (Nichols, 2009), beyond that most abyssal plains are free of these sedimentary processes. For instance, Carvalho et al. (2011) determined extremely low rates of sedimentation on both Northeast Atlantic abyssal plains, Porcupine and Iberian basins, being the thickness of sediment layers sampled down to 100–300 mm below the water – sediment interface that encompass the entire Holocene epoch (10 ky). Therefore, a biological disturbance of the abyss seafloor can be considered as a long term "incipient trace fossil", following the concept of Bromley (1996) to design unfossilized animal traces. Thus, should Moon traces be understood as modern traces or fossilized? Perhaps the non-gravity conditions and the lack of atmosphere on the Moon, besides inherent regolith substrate composition and consistency, create conditions of long-term preservation as well.

Regarding the preservational windows there is another interesting approach to explore. Some caves in the Earth's surface can work as a "closed system", after the modification of substrate due to animal or human activity. These caves can remain practically closed for long periods of time, keeping almost undisturbed the original conditions of trace formation. And, after a different lapse of time, these caves could be opened again, offering the possibility of being disturbed. This can result in long term hiatuses between these moments of activity. An interesting study case was reported by Romano et al. (2019), where the atmospheric conditions and/or microorganism activity have not modified considerably the substrate properties after trace formation, so the window of preservation represents around 14,000 years with no disturbance of substrate in cases of non-consolidation.

Although far from being a near analogous model to Moon ichnology, the elucidation of preservation history in this kind of closed caves and on abyssal sea floors can provide a key feature to solve extraterrestrial ichnological issues. For instance, are the Moon traces preserved in the same way that they were produced? Satellite images of Moon surface demonstrated that rover tracks of Moon landings in the 60's and 70's endured against cosmic rays and other destructive factors, such as outstanding temperature variations and micro-collision of small meteorites (Fig. 7). Vehicle tracks and bootprints will probably remain visible for hundreds of thousands of years, and the equipment left behind will remain for millions of years under the slow battering of micrometeoroids (Vaniman et al., 1991). For a quantitative comparison, it is advisable to generate 3D models (e.g. photogrammetry with new or historical photographs - i.e., involuntary photogrammetry; laser scanner; Fig. 8) in successive moments and evaluate the areal/volumetric differences among them. On the other hand, as happens in abyssal bottoms and caves, the lunar substrate is still soft and new alterations, such as missions and meteroids, would disturb the previous bioturbation traces (e.g. bootprints, rover trails). In this regard, the Apollo 11 landing site has been proposed as a protected area, due to an exoheritage and exoconservationism reason, by NASA’s request that future crewed and robotic missions keep a distance of at least 75 m from the site –although this seems a small distance in our opinion–, to not disturb the traces of the first successful manned mission to the lunar surface (Matthews and McMahon, 2018). Similarly, a protection proposal within the Underwater Cultural Heritage the site of the Titanic wreck in the deep sea has been entreated (Aznar and Varmer, 2012).

In this sense, there are new questions to answer in the future concerning tectonic activity and preservation of traces. New research suggests that along the wrinkle ridges of the nearside *maria* (i.e. basaltic plains) of the Moon, there are signs of ongoing ridge modification, related to active nearside tectonic activity (Valantinas and Schultz, 2020). A possible approach will be to assess if this activity can play a role in substrate modification, thus altering human traces, at least those related with soft substrate deformation (e.g. bootprints, rover trails).

Physical and mechanical properties

From a petrologic point of view, it is interesting to assess analogues on Earth's surface. As commented before (see section 3), Moon basement and eroded substrate on it are composed of a variety of rock and volcanic products. Despite the whole context of rheological differences between the volcanic substrates of the Moon and the Earth surface due to the product of atmosphere and different gravity forces, a brief discussion of some comparative points can be useful. For example, the Laetoli Beds, from Laetoli Basin rocks in northern Tanzania, are composed of about 123 m of aeolian tuffs and fall-out tuffs divided into two units averaging 64 m and 44-59 m in thickness, respectively from base to top (Ditchfield and Harrison, 2011). The Upper Laetolil Beds are well recognized because of several outstanding findings, such as early hominin records belonging to *Australopithecus afarensis* and remarkable tracks and trackways of hominin footprints and other mammals (Harrison and Kweka, 2011). Tracks from the Laetolil Beds exhibit an average depth of 13 mm with well-developed displacement rims and preserve some anatomical features (Leakey and Hay, 1979). These beds are probably derived from tephra that was erupted from Sadiman, an extinct volcano located 20 km to the east of the Laetoli locality (Ditchfield and Harrison, 2011).

The key feature that allows comparing these deposits as a possible ichnologic analogue to the Moon record, beyond the volcanic composition of strata, is that the sediments are quite homogenized, hiding sedimentary structures (see Ditchfield and Harrison, 2011). Among particular points allowing this comparison, can be mentioned the substrate composition in both contexts. In the Laetolil Beds, footprints are preserved in ash falls composed of natrocarbonatite and melilitite lava globules (Leakey and Hay, 1979). Regarding the footprint preservation process, it is inferred that ashes must have been cemented rapidly (thus differently from that occurring on the Moon) to have prevented erosion of sand-size globules by wind (Leakey and Hay, 1979). Natrocarbonatite ash seems to have been dissolved due to the rainfall, releasing carbonates into solution and crystalizing carbonates in a few hours due to the Sun’s heat (Leakey and Hay, 1979). The evidence suggests that the episode has taken place in a brief period, probably the onset of a single rainy season during the eruption of the nearby Sadiman volcano (Leakey and Hay, 1979).

The response of the Laetoli strata to mechanic stress can be compared with some lunar regolith characteristics. Of course, the weathering processes involved in the origin and development of Laetoli strata are far from those produced at the Moon surface as an atmosphere is present. This similarity in mechanical dynamics is probably because of the relative density property, which depends on how the particles are assembled geometrically (see Carrier et al., 1991). Thus, when the arrangement of individual regolith grains is more closely packed, the values of relative density increase. Relative density, based on astronaut footprints, displayed an average bootprint depth in the intercrater areas at all of the Apollo landing sites of 70 mm, which corresponds to an average relative density of 66% for the top 150 mm (Carrier et al., 1991). Our main hypothesis is that some observed features (e.g. average depth, displacements rims) in volcanic settings on Earth, which had been previously described in Laetoli deposits, are mostly due to relative density and not necessarily to petrographic composition. However, certain features, such as grain size, are envisaged as key factors to be considered in footprint formation. A high relative density on Moon soils appears to “simulate” the water content and other characteristics of Earth soils. Therefore, the seeking of possible analogues on Earth to assess footprint formation on the Moon, it is a potential topic to develop in further contributions.

The use of the traces as cultural keystones

Technofossils and technotraces are the main evidence of human influence on the Earth and are the unique type of trace present on the Moon. Moreover, the traces left on the lunar surface are the consequence of exploration campaigns in a hostile place, where it is impossible to survive without external help. In this sense, the main concern after arriving at the site is being able to return, even leaving the material to get it, and eventually returning with new samples (see Lockley et al., 2016). An interesting remark was made by Lockley (1998), who compared the lunar ichnology with the trace fossils where an organism travels to and from a central dwelling point, being the Lunar Module this central point (Domichnia) and the astronauts and rover locomotion traces (Repichnia) with a radial pattern reflecting the comings and goings. Studying the traces in the long term preservational windows of the Moon will allow precise dating of the human activity. Each recognized technical artefact, tracks and trails, and bioerosion traces will offer the opportunity to correlate with a particular time-lapse based on the technology involved, and thus relate them to a specific historical and cultural moment. Potentially analogous are explorers who have travelled to isolated places, such as Antarctica, the North Pole or the Himalayans, and left in there a number of artefacts able to be dated (e.g. Cullen, 1986; Zarankin and Senatore, 2005; Rowe, 2017). After the exploits of numerous polar expeditions in the early 19th century, perhaps overshadowed by Amundsen, Scott and Shackleton’s travels to reach the South Pole in the early 20th century (Roberts, 2011), groups of seal hunters settled in small seasonal settlements (Zarankin and Senatore, 2005). The remains left by these hunters are different from those of the expeditionaries, being that they had fixed camps and exploited the resources they found.

So far, there are only exploration-related traces on the Moon. Between the years 1969 and 1972, the Apollo missions left behind on the Moon twenty-three large scale technical artefacts, made up of six categories: Lunar Module ascent stages, Lunar Module descent stages, Saturn V third stage rockets (S-IVB), sub satellite science probes, lunar rovers, and an enormous amount of minor sized material (*sensu* Capelotti, 2010). In the near future, several expeditions are expected to set foot on the Moon again, and prosperous colonies will be established as the basis for further exploration and for exploiting mineral resources. This hypothetical situation will generate new types of traces not seen before on the Moon (e.g.

feeding and resting traces). This situation could resemble the Precambrian-Cambrian transition, in which from having a substrate with none or few usually simple traces, the substrate was colonized by tracemakers who left a very diverse and abundant trace fossil record (Seilacher and Pfüger, 1994).

The concept of understanding Moon artefacts as archaeological contexts follows the main goal of creating a cultural database of humankind as a migratory species, as proposed by Capelotti (2010).

Ichnology as a science can be opened to a set of new approaches. Studying human tracks and trackways, rover trails, patterns of rocks drilling (and the mechanical response of these rocks), and aging of materials under radiation exposure will be used to plan future explorations and Moon settlements.

6. FINAL THOUGHTS AND CONCLUDING REMARKS

In this paper, the aim and scopes of the ichnology have been discussed based on much evidence left by humans on the Moon, such as bootprints, rover trails and vehicles, through at least fifty manned and unmanned missions. Traces are the result of substrate modifications made by one or several individuals due to a behaviour. This definition includes the traces in a traditional sense, in which organisms make tracks, galleries, and other traces, with their own bodies and/or the help of simple artefacts (an object used with a purpose). Manufactured technical artefacts are the product of one or several orders of substrate modification created with a purpose and further use. They are also considered traces and named technofossils. Accordingly, the multimedia technology, buildings, art, among others, are conceptually considered objects of study of ichnology, and this opens a future debate on epistemology, limits, and scope with other scientific disciplines, such as archeology and anthropology. On the other hand, the technofossils are generally related with the evolutionary and cultural history of hominids, but are not a prerogative of them only, because other organisms use or create an artefact for an ulterior purpose. Technofossils may be used by organisms to modify the substrate as well, producing traces of technofossils, that are here named technotraces.

All the ichnological record preserved on the Moon comprises technofossils and technotraces and are the reflection of human technology at the time of mission development. The human-produced technical artefacts are currently undergoing rapid evolution and can be useful in chronostratigraphy, once organised in range or interval zones. Moreover, they are the base of the technostratigraphy to be considered in the framework of the “Anthropocene”. The technofossils and technotraces left on the Moon, as well as others left on other planetary bodies (e.g. Mars, Venus) and the spaceships that still fly through space, could be considered the evidence of the “Anthropocene” out of Earth. Nevertheless, Mars and Venus have an atmosphere, and this implies that the technofossils and technotraces left on its surfaces may be made under physical and chemical agents other than the Moon. Also, humans have not physically reached their surface, so both their technofossils and the technotraces have been left by unmanned vehicles (Lockley et al., 2016).

The Moon and the Earth present hugely different environmental and geological conditions, but it is possible to propose several analogies between them from an ichnological point of view. The slow sedimentation rates of the Moon are comparable with those of abyssal sea floors and caves. In all the cases, the traces are exposed for a long time and could be disturbed by subsequent activities. In this sense, conservation measures have been proposed to protect landing sites from lunar missions as cultural heritage of humanity. Bioturbation trace formation allows comparing the physical and mechanical properties of the substrate between in volcano fall deposits and lunar soil and regolith. Beyond the composition of both deposits, the sediments are fairly homogeneous, and the traces preserve well-developed displacement rims and some morphological features. Understanding the behaviour of the lunar soil will be of key importance in the near future for the development of communities on the Moon. Moreover, the technofossils and technotraces on the Moon are typical of exploration missions in a hostile place similar to those left by humans in the earliest campaigns to Antarctica and the North Pole. In these places, where it is difficult to survive without external help, traces related to how they got there, where they lived at the time, and the activities they carried out, have been found. Furthermore, they have also left some evidence to prove that they had been there, besides discarding some objects that they would no longer need.

The technological signal of these travels can be correlated with a particular time-lapse, and thus relate them to a specific historical and cultural moment. It is fascinating to think that ichnology, on the shoulders of a technofossil, the Voyager 1 space probe, and as a representative of the extended phenotype of *Homo sapiens*, is now traveling even beyond the solar system.

An intriguing line of research is opening. The Moon's ichnology is challenging our conception of traditional points of view about nature, not only of the meaning of trace fossils, but very nature of fossils. The records of the human activity at Moon will survive without modification for hundreds of thousands of years, or even more and they will allow a detailed chronostratigraphical assignment of each Moon mission. An additional thought to be explored in the future is related to human bauplan expansion, because of the incorporation of technology. This resulted in the creation of a wide set of traces that, although reflecting human nature, are modifying our conception of tracemaker-substrate relationship. Some examples are deep drillings, seismic exploration, landing, and take-off of traces. The Moon's ichnology -and planetary ichnology- are allowing us to witness our own change as species in real-time. Probably, soon, these traces will allow us to recognize what we were, and what we can be.

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References

Andrady, A.L., 2003. Plastics and the Environment. John Wiley and Sons, West Sussex.

Astibia, H., 2012. Tunelboka y Gorrondatxe (Getxo, Bizkaia), fósiles humanos para el Antropoceno. Euskonews. 640, 1–11.

Avanzini, M., Ceoloni, P., Conti, M.A., Leonardi, G., Manni, R., Mariotti, N., Mietto, P., Muraro, C., Nicosia, U., Sacchi, E., Santi, G., Spezzamonte, M., 2001. Permian and Triassic tetrapod ichnofaunal units of Northern Italy: their potential contribution to continental biochronology. Natura Bresciana. 25, 89–107.

Aznar, M.J., Varmer, O. 2013. The Titanic as underwater cultural heritage: challenges to its legal international protection. Ocean Dev. & Intl. L. 44, 96–112.

Barbree, J., 2014. Neil Armstrong: A Life of Flight. St. Martin´s Press: New York.

Barnosky, A.D., 2014. Palaeontological evidence for defining the Anthropocene. Geol. Soc. Spec. Publ. 395, 149–165. https://doi.org/10.1144/SP395.6

Baucon, A., de Carvalho, C.N., Barbieri, R., Bernardini, F., Cavalazzi, B., Celani, A., Felleti, F., Felleti, A., Schonlaüb, H.P., Todaro, A., Tuniz, C., 2017. Organism-substrate interactions and astrobiology: Potential, models and methods. Earth-Sci. Rev. 171, 141–180. https://doi.org/10.1016/j.earscirev.2017.05.009

Benaroya, H., 2018. Building habitats on the moon: engineering approaches to lunar settlements. Springer, Chichester.

Bertling, M., Braddy, S.J., Bromley, R.G., Demathieu, G.R., Genise, J., Mikuláš, R., Nielsen, J.K., Nielsen, K.S.S., Rindsberg, A.K., Schlirf, M., Uchman, A., 2006. Names for trace fossils: a uniform approach. Lethaia. 39, 265–286. https://doi.org/10.1080/00241160600787890

Behrensmeyer, A.K., Kidwell, S.M., Gastaldo, R.A., 2000. Taphonomy and paleobiology Paleobiology. 26, 103–147. https://doi.org/10.1016/j.ancene.2019.100233

Bromley, R.G., 1996. Trace fossils: biology, taphonomy and applications. Chapman & Hall, London.

Borgo, S., Franssen, M., Garbacz, P., Kitamura, Y., Mizoguchi, R., Vermaas, P.E. (2014). Technical artifacts: An integrated perspective. Appl.Ont. 9(3-4), 217–235.

Buatois, L.A., Mángano, M.G., Aceñolaza, F.G., 2002. Trazas fósiles: Señales de comportamiento en el registro estratigráfico. Museo Paleontológico Egidio Feruglio. Trelew.

Capelotti, P.J., 2010. The Human Archaeology of Space: Lunar, Planetary and Interstellar Relics of Exploration. McFarland, Jefferson.

Brey, P., 2005. Artifacts as Social Agents, in: H. Harbers (Ed.), Inside the Politics of Technology: Agency and Normativity in the CoProduction of Technology and Society, Amsterdam University Press, 61-84.

Carrier, D., 2005. The four things you need to know about the geotechnical properties of lunar soil. Lunar Geotechnical Institute, Lakeland.

Carrier, W., Olhoeft, G., Mendell, W., 1991. Physical properties of the lunar surface, in: G. Heiken, D. Vaniman, B. French (Eds), Lunar Sourcebook, Cambridge Univ. Press, New York, pp. 475–594.

Carvalho, F.P., Oliveira, J.M. Soares, A.M., 2011. Sediment accumulation and bioturbation rates in the deep Northeast Atlantic determined by radiometric techniques. ICES J. Mar. Sci. 68, 427–435. https://doi.org/10.1093/icesjms/fsr005

Cohen, A.S., Lockley, M., Halfpenny, J., Michel, A.E., 1991. Modern vertebrate track taphonomy at Lake Manyara, Tanzania. Palaios. 6, 371–389. https://doi.org/10.2307/3514964

Cohen, A.S., Halfpenny, J., Lockley, M.G., Michel, E., 1993. Modern vertebrate tracks from Lake Manyara, Tanzania and their paleobiological implications. Paleobiology. 19, 433–458. https://doi.org/10.1017/S0094837300001407X

Cullen, R., 1986. Himalayan mountaineering expedition garbage. Environ. Conserv. 13, 293–297.

Dawkins, R., 1982. The extended phenotype. Oxford University Press, Oxford.

Dibley, B., 2018. The technofossil: a memento mori. J. Contemp. Archaeol. 5, 44–52. https://doi.org/10.1558/jca.33380

Ditchfield, P., Harrison, T., 2011. Sedimentology, lithostratigraphy and depositional history of the Laetoli area, in: Harrison, T. (Ed.), Paleontology and Geology of Laetoli: Human Evolution in Context, Geology, Geochronology, Paleoecology and Paleoenvironment. Springer, Dordrecht, pp. 47–76.

Ekdale, A.A., 2010. Making Tracks. Ichnos. 17, 228–231. https://doi.org/10.1080/10420940.2010.510023

Falkingham, P.L., 2014. Interpreting ecology and behaviour from the vertebrate fossil track record. J. Zool. 292, 222–228. https://doi.org/10.1111/jzo.12110

Gorman, A.C., 2014. The Anthropocene in the solar system. J. Contemp. Archaeol. 1(1), 87–91. https://doi.org/10.1558/jca.v1i1.87

Gorman, A.C., 2016. Culture on the Moon: Bodies in time and space. Archaeol. 12(1), 110–128. https://doi.org/10.1007/s11759-015-9286-7

Gorman, A.C, O'Leary, B., 2007. An ideological vacuum: The Cold War in outer space, in: Schofield, J., Cocroft, W. (Eds), A Fearsome Heritage: Diverse Legacies of the Cold War. Left Coast Press, Walnut Creek, pp. 73-92.

Haff, P.K. 2014. Technology as a geological phenomenon: implications for human well-being. In: Waters, C.N., Zalasiewicz, J.A., Williams, M., Ellis, M.A., Snelling, A.M. (Eds.), A Stratigraphical Basis for the Anthropocene. Geological Society, London, Special Publications, 395, 301-309.

Halajian, J.D., 1968. Albedo and photometry of Surveyor footprints. Planet. Space. Sci. 16, 1465–1474.

Harrison, T., Kweka, A., 2011. Paleontological localities on the Eyasi Plateau, including Laetoli, in: Harrison, T. (Ed.,), Paleontology and geology of Laetoli: Human evolution in context Springer, Dordrecht, pp. 17–45.

Hasiotis, S.T., Platt, B.F., Hembree, D.I., Everhart, M.J., 2007. The trace-fossil record of vertebrates, in: Miller, W. (Ed.), Trace Fossils. Elsevier, Amsterdam, pp. 196–218. https://doi.org/10.1016/B978-044452949-7/50138-8

Horz, F., 1991. Lunar Surface, Processes, in: G. Heiken, D. Vaniman, B. French (Eds), Lunar Sourcebook, Cambridge Univ. Press, New York, pp. 61–120.

Houck, K. J. 1982a. Modal petrology of six soils from Apollo 16 double drive tube core 64002. J. Geophys. Res. 87, 210–220.

Houck, K. J. 1982b. Petrologic variations in Apollo 16 surface soils. J. Geophys. Res. 87, 197–209.

Kim, J.Y., Kim, K.S., Lockley, M.G., 2008. Hominid ichnology: tracking our own origins. Ichnos 15, 103–105. https://doi.org/10.1080/10420940802467785

Kitamura, Y., Mizoguchi, R., 2010. Characterizing functions based onontological models from an engineering point of view, in: Galton, A., Mizoguchi, R. (Eds.). Proc. Formal Ontology in Information Systems (FOIS). IOS Press, Amsterdam. pp. 301–314.

Leakey, M.D., Hay, R.L., 1979. Pliocene footprints in the Laetolil Beds at Laetoli, northern Tanzania. Nature 278, 317–323.

Lee, L.H., 1995. Adhesion and cohesion mechanisms of lunar dust on the Moon's surface. J. Adhes. Sci. Technol. 9, 1103–1124. https://doi.org/10.1163/156856195X00932

Lockley, M.G., 1998. The vertebrate track record. Nature. 396, 429–432. https://doi.org/10.1038/24783

Lockley, M.G., 1999. The Eternal Trail: A Tracker Looks at Evolution Perseus, New York.

Lockley, M.G., Meyer, C., 2000. Dinosaur tracks and other fossil footprints of Europe. Columbia University Press, Columbia.

Lockley, M.G., Meldrum, J., Kim, J.Y. 2016. Major events in hominin evolution, in: Mángano, M.G., Buatois, L.A. (Eds.) The Trace-Fossil Record of Major Evolutionary Events Volume 2: Mesozoic and Cenozoic. Springer, Dordrecht, pp. 411–448.

Mángano, M.G., Buatois, L.A., MacNaughton, R.B., 2012. Ichnostratigraphy, in: Knaust, D., Bromley, R.G. (Eds.) Developments in Sedimentology. Elsevier, Amsterdam. pp. 195–212.

Mather, D.H., 2014. Moon boot: the story of the Apollo lunar overshoe and the race to walk on the Moon. Space Effects Limited, Durley.

Matthews, J.J., McMahon, S., 2018. Exogeoconservation: Protecting geological heritage on celestial bodies. Acta Astronaut. 149, 55–60. https://doi.org/10.1016/j.actaastro.2018.05.034

McKay, D.S., Heiken, G. Basu, A. Blanford, G. Simon, S. Reedy, R. French, B.M. Papike, J., 1991. The lunar regolith, in: Heiken, G., Vaniman, D., French, B. (Eds), Lunar Sourcebook, Cambridge Univ. Press, New York, pp. 285–356.

Mendillo, M., 2001. The Atmosphere of the Moon, in: Barbieri, C., Rampazzi, F. (Eds), Earth-Moon Relationships. Springer, Dordrecht, pp. 271–277.

Metzger, P.T., Smith, J., Lane, J.E., 2011. Phenomenology of soil erosion due to rocket exhaust on the Moon and the Mauna Kea lunar test site. J. Geophy. Res. Planets 116, 1–22. https://doi.org/10.1029/2010JE003745

Minter, N.J., Braddy, S.J., Davis, R.B., 2007. Between a rock and a hard place: arthropod trackways and ichnotaxonomy. Lethaia 40, 365– 375. https://doi.org/10.1111/j.1502-3931.2007.00035.x

Nichols, G., 2009. Sedimentology and stratigraphy. John Wiley & Sons, West Sussex.

O'Brien, B.J., Hollick, M., 2015. Sunrise-driven movements of dust on the Moon: Apollo 12 Ground-truth measurements. Planet. Space Sci. 119, 194–199. https://doi.org/10.1016/j.pss.2015.09.018

Padian, K., Olsen, P.E., 1984. The fossil trackway *Pteraichnus*: not pterosaurian, but crocodilian. J. Paleont. 58, 178–184.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001. Ichnology & sedimentology of shallow to marginal marine systems, in: Geological Association of Canada, Short Course Notes Volume 15. St. John's, AGMV Marquis.

Pilkey, O.H., 1987. Sedimentology of basin plains. in: Weaver, P.P.E., Thompson, J. (Eds), Geology and Geochemistry of Abyssal Plains. Geological Society, London, Special Publication 31, 1–12.

Ritter, S., Petersen, M., 2015. Interpreting Earth History: A Manual in Historical Geology (8th ed.). Long Grove, Il: Waveland Press.

Roberts, P., 2011. Heroes for the past and present: a century of remembering Amundsen and Scott. Endeavour 35(4), 142–150. https://doi.org/10.1016/j.endeavour.2011.08.002

Romano M., Citton P., Salvador I., Arobba D., Rellini I., Firpo M., Negrino F., Zunino M., Starnini E., Avanzini M., 2019. A multidisciplinary approach to a unique Palaeolithic human ichnological record from Italy (Bàsura Cave). eLife 8, e45204. https://doi:10.7554/eLife.45204.

Rowe, S., 2017. On the provenance of a historic sledge shoe fragment, said to have been collected by Edward Wilson at the South Pole in 1912. Polar Rec. 53, 413–426. https://doi.org/10.1017/S0032247417000365

Schuerger, A.C., Moores, J.E., Smith, D.J., Reitz, G., 2019. A lunar microbial survival model for predicting the forward contamination of the Moon. Astrobiology. 19, 730–756.

Scott, R.F., Carrier III, W.D., Costes, N.C., Mitchell, J.K., 1970. Mechanical properties of the lunar regolith, Apollo 12 Preliminary Science Report. NASA Spec. Publ. 235, 161–182.

Scott, R.F., Carrier, W.D., Costes, N.C., Mitchell, J.K., 1971. Apollo 12 Soil Mechanics Investigation. Geotechnique. 21, 1–14.

Seilacher, A., 2000. Ordovician and Silurian arthrophycid ichnostratigraphy, in: Sola, M.A., Worsley, D. (Eds.), Geological Exploration in Murzuq Basin. Elsevier, Amsterdam, pp. 237–258.

Seilacher, A., Pflüger, F., 1994. From biomats to benthic agriculture: A biohistoric revolution, in: Krumbein, W.E., Peterson, D.M., Stal, L.J. (Eds.), Biostabilization of sediments.

Bibliotheks und Informationssystem der Carl von Ossietzky Universität Odenburg, pp. 97–105.

Slyuta, E.N., 2014. Physical and mechanical properties of the lunar soil (a review). Solar Sys. Res. 48, 330–353. https://doi.org/10.1134/S0038094614050050

Smith, C.R., De Leo, F.C., Bernardino, A.F., Sweetman, A.K., Arbizu, P.M., 2008. Abyssal food limitation, ecosystem structure and climate change. Trends Ecol. Evol. 23 518–528. https://doi.org/10.1016/j.tree.2008.05.002

Spennemann, D.H., 2004. The ethics of treading on Neil Armstrong's footprints. Space Policy, 20, 279–290. https://doi.org/10.1016/j.spacepol.2004.08.005

Spennemann, D. H., 2007. Extreme cultural tourism from Antarctica to the Moon. Ann. Tour. Res. 34, 898–918. https://doi.org/10.1016/j.annals.2007.04.003

Taylor, G.J., Warren, P., Ryder, G., Delano, J., Pieters, C., Lofgren, G., 1991. Lunar rocks, in: Heiken, G., Vaniman, D., French, B. (Eds), Lunar Sourcebook, Cambridge Univ. Press, New York, pp. 183–284

Valantinas, A., Schultz, P.H., 2020. The origin of neotectonics on the lunar nearside. Geology 48, 649–653. https://doi.org/10.1130/G47202.1

Van Lawick-Goodall, J., 1970. Tool-using in primates and other vertebrates. Ad. Stud. Behav. 3, 195–249.

Vaniman, D., Reedy, R., Heiken, G., Olhoeft, G., Mendell, W., 1991. The lunar environment. in: Heiken, G., Vaniman, D., French, B. (Eds), Lunar Sourcebook, Cambridge Univ. Press, New York, pp. 27–60.

Vinogradova, N.G. 1997. Zoogeography of the abyssal and hadal zones. Advances in Marine Biology Academic Press. 32, 325–387. https://doi.org/10.1016/S0065-2881(08)60019-X

Zalasiewicz, J., Williams, M., Waters, C.N., Barnosky, A.D., Haff, P., 2014. The technofossil record of humans. Anthropocene Rev. 1, 34–43. https://doi.org/10.1177/2053019613514953

Zalasiewicz, J., Williams, M., Waters, C.N., Barnosky, A.D., Palmesino, J., Rönnskog, A.-S., Edgeworth, M., Neal, C., Cearreta, A., Ellis, E.C., Grinevald, J., Haff, P., do Sul, J.A.I., Jeandel, C., Leinfelder, R., McNeill, J.R., Odada, E., Oreskes, N., Price, S.J., Revkin, A., Steffen, W., Summerhayes, C., Vidas, D., Wing, S., Wolfe A.P. 2017. Scale and diversity of the physical technosphere: a geological perspective. Anthr. Rev. 4(1), 9-22.

Zalasiewicz, J., Waters, C. N., do Sul, J. A. I., Corcoran, P. L., Barnosky, A. D., Cearreta, A., Edgeworth, M., Gałuszka, A., Jeandel, C., Leinfelder, R., Steffen, W., Summerhayes, C., Wagreich, M., Williams, M., Wolfe, A.P., Yonan, Y., (2016). The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. Anthropocene 13, 4–17. https://doi.org/10.1016/j.ancene.2016.01.002

Zalasiewicz, J, Waters, C.N., Williams, M., Summerhayes, C.P., 2018. The Anthropocene as a Geological Time Unit: A Guide to the Scientific. Cambridge Univ. Press, Cambridge.

Zarankin, A., Senatore, M.X., 2005. Archaeology in Antarctica: nineteenth-century capitalism expansion strategies. Int. J. Hist. Archaeol. 9, 43–56. https://doi.org/10.1007/s10761-005-5672-y

Zellner, N.E.2017. Cataclysm no more: new views on the timing and delivery of lunar impactors. Origins Life Evol. B. 47, 261–280. https://doi.org/10.1007/s11084-017-9536-3

Figure captions

Figure 1. Location of the most representative exploration missions on the lunar surface. Capital letters are the initial/s of the space program. Numbers represent each mission. A – Apollo (USA); C – Chang'e (China); L - Luna (Russia); S – Surveyor (USA); SM – Smart (European Union). Source: NASA/Goddard Space Flight Center/Arizona State University.

Figure 2. Examples of different types of traces.

Figure 3. Different types of technotrace on the moon. Bioturbation. a) Instant in which Aldrin produces a bootprint during the Apollo 11 mission. b) Close up view of a bootprint on the lunar surface (Apollo 12 mission). c) Lunar Rover trail and astronaut trackway of the Apollo 15 mission. d) Lunar Rover trail close to Mountain Hadley (Apollo 15 mission). Source: NASA Image and Video Library.

Figure 4. Different types of technotrace on the moon. Bioturbation. a) Aldrin works with a core tube. b) Trench for taking a sample at Head Crater (Apollo 12 mission). c) Young sampling fillet rock during the Apollo 16 mission. d) Moon surface after sample works (Apollo 17 mission). Source: NASA Image and Video Library.

Figure 5. Different types of technotrace on the moon. Bioerosion. a) and b) An astronaut takes a sample of rock with a hammer (Apollo 16 and Apollo 17 missions respectively). c) Drilling the lunar surface in the Apollo 15 mission. d) Image of the Ranger 7 impact crater (about 14 m of diameter) in *Mare Cognitum*. Source: a), b) and c) NASA Image and Video Library; d) NASA/GSFC/Arizona State University.

Figure 6. Different types of technofossil on the moon. a) chevron shaped wheel of the Lunar Rover vehicle (Apollo 17 mission). b) Conrad near the Surveyor III with the Lunar Module in the second plane (Apollo 12 mission). c) Aldrin unpacks experiments from the Lunar Module during the Apollo 11 mission. d) Apollo 16 Lunar Surface Experiments Package. e) Duke family photograph on the lunar surface (Apollo 16 mission). f) Discarded Primary Life Support System backpack (Apollo 17 mission). Source: NASA Image and Video Library.

Figure 7. NASA's Lunar Reconnaissance Orbiter (LRO) image of Apollo 17 landing site. ep - experiments package; at – astronaut’s trackway; cds – Challenger descent stage; lvt – lunar vehicle trail. Source: NASA's Goddard Space Flight Center/ASU.

Figure 8. Photogrammetric 3D model of the Aldrin bootprint, Apollo 11 mission. a) Lunar surface before trampling. b) and c) Different views of Aldrin´s bootprint. d) 3D texturized model of the Aldrin´s bootprint. e) Digital elevation model in which dark blue is deeper than light blue. f) Rendered image mixing wireframe and texturized models. Source: a), b) and c) NASA Image and Video Library. The 3D model is housed in https://skfb.ly/6SwSA.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Abstract

Humankind began with extra-planetary expeditions in the 1960s. To date, more than fifty manned and unmanned lunar missions have taken place. Maybe, the most iconic image of these campaigns is the bootprint left and photographed by the astronaut Edwin Aldrin. Nevertheless, there is also other evidence of human activities on the Moon, such as rover trails, drill holes, vehicles, and rubbish. For some researchers, ichnology only studies the traces made by one or several individuals with their own bodies, but other authors advocate that artefacts as well as traces made by these artefacts are also traces. In this context, the ichnology of the Moon allows both analysis of the traces left on the lunar surface themselves and discussion of the aim and scopes of ichnology. The Moon ichnology, which arises from the development of hominid ichnology, includes technical artefacts (called technofossils, e.g. Lunar Module, flag, religious text) and traces of technical artefacts (comprised in the new category technotraces, e.g. bootprints, drill holes) but not traces made by individuals with parts of their bodies. Although the lunar environment is very different from that of the Earth due to the absence of atmosphere, magnetic field, water, organic material and life, it is possible to propose three ichnological analogies between the Earth and its satellite. First of all, traces on the Moon surface are subjected to very slow sedimentation rates, similar to what occurs in abyssal bottoms or caves, among other environments. Moreover, physical and mechanical properties allow comparison with processes leading to the formation of traces in volcanic ash deposits with those acting on the soil and regolith of the Moon. Finally, cultural similarities have been identified between the traces left by humans on the Moon and comparable expeditions of humankind, such as Antarctica and the North Pole. The evolution of human technical artefacts has been used to help characterize the onset of the "Anthropocene". These artefacts can be included within the technosphere and can also be thought to be phenotypic expressions of human genes. Therefore, the traces left on the Moon

as well as others which are in other celestial bodies or even in the space, can be considered evidence of extended phenotype of *Homo sapiens* and the “Anthropocene” beyond the Earth.

Highlights

The traces on the moon surface allow to rethink the scope of ichnology.

The ichnological record of the Moon consists of technofossils and technotraces.

Technofossils are technological artefacts produced with a purpose or further use.

A technotrace is the trace produced by a technofossil.

There are some ichnological analogues between the Moon and the Earth.