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RESEARCH ARTICLE

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Planetary geoarchaeology as a new frontier in archaeological science: Evaluating site formation processes on Earth's Moon

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Abstract

On October 4, 1957, *Homo sapiens* crossed a new threshold of technological innovation after constructing an artifact capable of entering Low Earth Orbit and effectively paving the way for a future of space exploration. This artifact was Sputnik 1, launched by the Soviet space program which triggered the “space race” of the mid-20th century. Over the past 65 years, we have continued to explore and populate our solar system with rockets and spacecraft including satellites, probes, landers, and rovers. This expansion into our solar system has left traces of our presence on several planets including the Earth, Mars, Mercury, and Venus along with Earth's Moon, Titan, and several galaxy travelers in the form of asteroids and comets. Today, we have entered the realm of a new privatized and global space race, effectively a “new space race” or “new Space Age.” As we expand our material footprint into new extraterrestrial environments, there is a growing need to understand the types of unique site formation processes capable of altering, destroying, or preserving this rapidly increasing archaeological record known as space heritage. Such understandings are germane to the subdiscipline of geoarchaeology, that part of archaeology dedicated to studying the interaction between humans, cultural heritage, and environmental systems from a geoscience perspective. Closely aligned and partially overlapping with the subdisciplines of space archaeology, archaeological science, and planetary geology, we introduce a new subfield we call planetary geoarchaeology to open discussion about how geoarchaeologists can play a role in addressing current and future issues surrounding the preservation and management of space heritage. To demonstrate the potential of the subdiscipline, we focus on the current archaeological record of the Moon, describe lunar site formation processes, and discuss the implications for the current and future preservation of space heritage in the lunar setting. Planetary geoarchaeology can be applied to practically every type of extraterrestrial environment, provided humans have left behind a measurable record. We hope this paper will spur more research studying human–environment interaction in space.

KEYWORDS

geoarchaeology, heritage, Moon, planetary science, space archaeology

1 | INTRODUCTION

Our species, *Homo sapiens*, first evolved in Africa around ~300,000 years ago, with our initial forays out of Africa and into new regions beginning around ~180,000 years ago (Hublin et al., 2017; Stringer & Galway-Witham, 2018). Humans' eventual colonization of Earth was met with fits and starts, but by ~16,000 years ago, every continent (apart from Antarctica) had been successfully peopled, demonstrating our species' unique ability for adaptive radiation across long distances and through diverse environments (Bergström et al., 2021; Waters, 2019). A key aspect of this success was the role of cultural evolution, especially technological innovation, such as the use of fire, stone tools, watercraft, and eventually, spacecraft (Potts, 2013; Smith & Davies, 2012). Regarding the latter event, the crucial moment came on October 4, 1957, when the first satellite, *Sputnik 1*, successfully exited our atmosphere and entered Low Earth Orbit (LEO), marking the first human-made object (i.e., artifact) to enter the region we colloquially refer to as "space" and effectively triggering the "space race" of the mid-20th century.

The "space race" marked a new era of exploration and international conflict for *H. sapiens* and resulted in the creation of an impressive range of cultural heritage and associated material culture, or what space archaeologists refer to as space heritage (Capelotti, 2015; Darrin & O'Leary, 2009; Finney, 1992; O'Leary & Capelotti, 2015; Westwood et al., 2017). Space archaeology is the archaeological investigation of the material culture associated with exploration, both within and outside Earth's atmosphere resulting from human behavior (Gorman, 2014, p. 6943). Space heritage encompasses many intangible and tangible elements linked to individual and national identities (Harrison, 2009). It includes artifacts originating on Earth and entering the archaeological record somewhere else (i.e., other celestial bodies, orbit, interstellar space, etc.), but encompasses all material culture related to space activity (Westwood et al., 2017, p. 1).

Over the last two decades, our species has entered a second era of exploration which has resulted in the spread of humanity's material footprint across several planetary bodies, effectively increasing the range of space heritage capable of study; a "new space race" or "new Space Age" (Gomes et al., 2013; Peeters, 2018). Unlike the former space race of the mid-20th century, the renewed interest in space exploration is marked by private companies that act more independently of governmental space policies and funding, prioritize equity funding and affordable access to space, and seek to develop novel space applications (Peeters, 2018). Currently, space exploitation is characterized by several critical elements occurring simultaneously: the development of space tourism, government and private investments in lunar surface habitation and mining initiatives or in situ resource utilization (ISRU), research and development in assembly and manufacturing in space, new orbits in cislunar space, and the launch of satellite internet constellations into LEO, to name a few (Denis et al., 2020; Gomes et al., 2013; Klima, 2022; Peeters, 2018; Vickers, 2019). These developments have major implications for preserving the archaeological record created previously, and the continued creation of an archaeological record throughout our solar system and beyond.

Archaeologists are the professionals tasked with the rediscovery, preservation, and stewardship of human history as represented in its material culture. From a contemporary archaeology perspective, this task includes stewardship and preservation of material remains from our past, present, and near future (Buchli et al., 2001). As we venture into the new Space Age, we argue that there is a need to understand the various natural and cultural processes within these new environments that affect the preservation of our current and future space heritage. Geoarchaeology—the subfield that draws from methods and concepts from the geosciences to study human–environment interaction—is uniquely poised to make novel contributions to space heritage studies across our solar system. We seek to introduce planetary geoarchaeology as a new subfield within archaeological science dedicated to this task.

Here, we address several key questions, including: How can geoarchaeology provide novel solutions to space heritage issues? What should be the underlying aims of planetary geoarchaeology? Finally, how can planetary geoarchaeology contribute to current and future exploratory missions within our solar system? To address these questions, we provide an example of planetary geoarchaeology by focusing on the archaeological record of the Moon, reviewing site formation processes occurring on the lunar surface, and discussing how these processes may be affecting this record. In the context of the new Space Age, our goal is to draw attention to the ever-expanding material record of our species across our solar system, and to encourage social scientists, archaeologists, and geoarchaeologists to work in concert with planetary scientists, engineers, and mission planners to consider how we can begin contributing novel solutions to the documentation, study, and preservation of space heritage.

2 | INTRODUCTION TO SPACE ARCHAEOLOGY

Since the launch of *Sputnik*, humans have sent more than ~5000 large objects, such as spacecraft and satellites, out of Earth's atmosphere (UCS, 2023; UN, 2023). However, the deliberate destruction, fragmentation, or accidental collision of these objects has resulted in more than ~21,000 objects larger than 10 cm and ~500,000 objects smaller than 1 cm (cf. Gorman, 2014, p. 88). Those objects comprise the current material record of space heritage throughout our solar system. Of particular importance to archaeologists are research and development facilities, launch and crash sites on Earth, satellites, scientific equipment, and other objects in various stages of orbit, crashed or discarded on extraterrestrial surfaces. Since 1999, archaeologists and anthropologists have offered unique contributions to the documentation, study, and preservation of this space heritage, giving rise to a new subfield called space archaeology and heritage (Gorman, 2014; O'Leary & Capelotti, 2015; Darrin & O'Leary, 2009; Rathje, 1999).

Gorman (2014) defines space archaeology as "the study of the material culture associated with space exploration from the twentieth century onwards… [which]… includes terrestrial infrastructure related to the development, manufacturing, operation, and use of space systems, spacecraft and space debris located throughout the solar system and the landing sites of robotic and crewed missions on other planets and celestial bodies." While other terms have been submitted in the past, such as "exoarchaeology" (e.g., Capelotti, 2010), researchers agree that the shared focus is on the documentation, study, and preservation of space heritage.

Space archaeologists have approached the study of space heritage from a variety of angles (e.g., Campbell, 2004; Capelotti, 2004, 2015; Darrin & O'Leary, 2009; Gorman, 2005a, 2005b, 2009a, 2009b, 2009c, 2009d, 2014; Gorman & O'Leary, 2007; O'Leary & Capelotti, 2015; Rathje, 1999; Schiffer, 2013; Smith, 2019; Staski & Gerke, 2009; Steinberg, 2000; Walsh, 2012; Walsh & Gorman, 2021; Westwood et al., 2017). As previously mentioned, space archaeology is a form of contemporary archaeology. From a contemporary archaeological perspective, our task of preservation and stewardship is not relegated to the material record of the distant past but also should consider the near present (Hicks, 2010; Hicks & Mallet, 2019; Ingold, 2007). Agier (2013, p. 85) refers to contemporary archaeology as the study of the "trace of movement, change, [or] the first breath of the future." In line with this thought, and those by Schiffer (1972, 1983, 1987), Ingold (2007) calls for archaeologists to understand "things" in formation. Moreover, from this perspective, we can begin turning the "archaeological gaze" towards space heritage (Gorman, 2014). Several researchers have already begun discussing formation processes occurring in space, including the role of exoatmospheric conditions in altering satellites and debris in Earth's orbit (Clemens, 2009; Gorman, 2005b, 2009d), interplanetary space (Darrin, 2015; Sample, 2009) and briefly, the Moon (Capelotti, 2009, 2015; Gorman, 2016). Nevertheless, the role of environmental processes that are currently altering, destroying, or preserving space heritage on various extraterrestrial surfaces has yet to be explored in depth. Such a research objective falls under the purview of the archaeological subfield of geoarchaeology.

3 | TOWARDS A PLANETARY GEOARCHAEOLOGY

Geoarchaeology is a subfield of archaeology that draws from geoscience concepts (methods and theory) to solve archaeological problems (Gladfelter, 1977; Goldberg & Macphail, 2006; Hassan, 1979; Karkanas & Goldberg, 2018; Rapp, 1975; Rapp & Hill, 1998; Renfrew, 1976; SteWaters, 1992). Archaeologists have drawn from the geosciences to address issues that have arisen during archaeological investigation as early as the 1700s, but only since the 1960s has the field emerged as a subfield with its own theoretical concepts (Renfrew, 1976). During that time, geologists and archaeologists began working together to systematically and empirically study the dynamics between people and their environments (Hill, 2005). Recently, geoarchaeology has emerged as a nexus field, operating within and between geomorphology, geochemistry, quaternary geology, ecology, biology, pedology, and sedimentology, among others. Thus, geoarchaeology is a multi- and interdisciplinary subdiscipline that primarily studies the long-term patterns between humans, their material record (i.e., artifacts), and ecosystems (Hill, 2017).

Goarchaeologists have three main research objectives (Butzer, 1982, p. 38; Renfrew, 1976, pp. 2–5; Waters, 1992, p. 5). The first objective is placing an archaeological site into its temporal context, thereby shedding light on how and when objects became a part of the archaeological record. The second objective is reconstructing the spatial context of archaeological material by studying the natural and cultural processes that serve to preserve, alter, or destroy the archaeological record (Stein, 2001). Finally, the third objective is reconstructing a site's original context when archaeological material was initially deposited. Each objective is crucial for understanding past human behavior, the environments humans inhabited, and the depositional and preservation history of discarded material culture. For example, understanding archaeological site formation processes (objective 2) is part of an important research agenda for archaeologists, because misinterpretations of these processes, and how those processes produce artifact patterning, can result in errors in reconstructing past human behavior (Mandel et al., 2017). Schiffer (1987, p. 7) defined site formation processes as "the factors that create the historic and archaeological records." These factors include both natural (geological) and cultural (human) depositional and postdepositional processes that work in concert to create the geologic contexts that we encounter today during archaeological survey and excavations. Given the dynamic nature of earth surface processes, geoarchaeologists study site formation processes based on the type of depositional setting in which an archaeological site may be preserved. These depositional settings include eolian, alluvial, rockshelter/cave, coastal, hillslope, glacial, spring, and lacustrine. Our argument here is that this should also include extraterrestrial settings, such as Lunar, Venusian, and Martian surfaces, to name a few (also see Staski & Gerke, 2009). Here, we provide an example of planetary geoarchaeology by focusing on lunar formation processes.

4 | CASE-STUDY: PLANETARY GEOARCHAEOLOGY OF EARTH'S MOON

Our research objective is understanding how space heritage in extraterrestrial environments may be preserved, altered, or destroyed. Thus, there is a need to understand the various types of site formation processes occurring throughout our solar system. Humans have left material on 10 different extraterrestrial surfaces: the Moon, Mars, Venus, Titan, Mercury, asteroids Ryugu, Eros, and Itokawa, and comets 9p/Tempe 1 and 67P Churyumov-Gerasimenko. What are the various depositional settings and surface processes that may affect the preservation of this space heritage in these settings? Understanding the depositional and postdepositional processes in each of these environments is crucial for understanding how our material footprint may be preserved throughout our solar system.

We suggest that each location or class of locations (e.g., planet, moons, asteroids, comets) should be addressed case-by-case. In this paper, we focus on Earth's Moon, briefly discuss the current archaeological record preserved on the lunar surface, review the various lunar surface processes potentially affecting the rich cultural record currently preserved on the lunar surface, and discuss how these processes may affect space heritage.

4.1 | Archaeological setting of Earth's Moon

On September 13, 1959, at 21:02 (UTC), the USSR probe Luna 2 (or Second Soviet Cosmic Rocket) became the first human-made object to crash into the Moon, effectively beginning the archaeological record on extraterrestrial surfaces within our solar system. Since that event, we estimate that humans have affected the lunar surface an estimated ~59 times, or around 0.97 times/year. Table 1 lists human interaction with the lunar surface, though providing an exhaustive list of occurrences is difficult. Capelotti (2009, 2010) was the first to catalog this record using images from the Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC-NAC), including landing sites and landers, footprints and rover tracks, scientific equipment, spacecraft debris, and surface disturbance areas. Similarly, Wagner et al. (2017) used LROC-NAC imagery to provide coordinates for several lunar missions, and NASA (2011) provided detailed descriptions of space heritage left on the lunar surface since 1969. A general map of international missions to the Moon is provided in Figure 1.

4.2 | Archaeological sites on Earth's moon

The archaeological record of the Moon can be divided into what Capelotti (2010) calls "main body" artifacts, which include Lunar Module ascent stages, Lunar Module descent stages, Saturn V third-stage rockets (S-IVB), subsatellite science probes, and lunar rovers. Associated with these "main body" artifacts includes various scientific equipment and features such as footprints and rover tracks. To this, we add impact (crash) areas, which include planned and accidental impact missions, such as those by early Luna (USSR), Ranger (USA), Surveyor (USA) missions and later Chandrayaan-2 (India), Beresheet-1 (Israel), Chang'e 5-T1 (China), and the Hakuto-R (Japan) missions.

Capelotti (2010, p. 21) outlined five areas of significance that could serve as archaeological preserves to protect space heritage from environmental deterioration or destruction from future human activity. These preserves include (1) the very first Apollo landing areas, which include the first human footprints on the Moon, as well as the last (to date), (2) the base camps and discarded ascent stages of Apollo 12 and 14, the wreckage of S-IVB third-stage rockets of Apollo 13, 14, 15, 16, and 17, and the record surrounding the Surveyor 3 and Apollo 12 missions, (3) the base camp and surrounding study areas of the Apollo 15, which includes the first rover tracks and the remains of the uncrewed Luna 2 mission, (4) the base camp and surrounding study area of the Apollo 17 mission and the remaining Luna 21 probe, and (5) Apollo 16 base camp and rover activity (Capelotti, 2010, pp. 21–22). While no legal solution was offered for how to achieve this preservation goal, as we detail below, it is clear that these sites (and others) *are* subject to the deleterious effects of many lunar surface processes, and such proposals should be earnestly considered as we continue to navigate the New Space Age.

4.3 | Geomorphic setting of the lunar surface

Historically, researchers in the past have often made the mistake of assuming that what archaeologists excavate include the remains of a once-living community "frozen" in time. This fallacy was coined by Ascher (1961) as the "Pompeii premise," referring, to the idea that the Roman city of Pompeii is perfectly preserved under ~5 m of volcanic ash. However, such a viewpoint ignores the role of the many natural and cultural processes that affect the state of material remains once they are discarded, or as Ascher put it, how the archaeological record is ravaged by "time's arrow" (Ascher, 1961; cf. Binford, 1981). Indeed, even at Pompeii postdepositional change alters the archaeological record (Schiffer, 1985). As we enter the new Space Age, we must not assume a "lunar premise" and suppose that the archaeological record on Earth's Moon is also perfectly preserved in a static environment. Instead, Earth's Moon is quite dynamic, having lunar surface processes that lead to deposition, erosion, and alteration of the lunar surface. Moreover, it is these processes that planetary geoarchaeologists can study to understand how they may affect space heritage on the lunar surface.

4.4 | Lunar formation processes

Like all celestial bodies within our solar system, the Moon is part of a dynamic gravitational system marked by an evolutionary history of orbits. The reorganization of these orbits due to close encounters with other celestial bodies creates inevitable collisions, which can result in either the annihilation or impact cratering of those bodies (cf. Hörz et al., 1991, p. 61). Until recently, impact cratering via meteoroid bombardment has served as the dominant geomorphic agent on the lunar surface. Figure 2 provides a concise overview of the history of geologic time on the Moon, which is marked by meteoroid impacts inducing lava flows and creating craters of various sizes. As we detail below, the Moon's population of various-sized lunar craters provide unique depositional settings capable of preserving space heritage. However, since 1959 humans have become the dominant geomorphic agent on the Moon's surface, effectively generating a lunar archaeological record.

The Moon's archaeological record is subject to various natural and cultural formation processes. Natural site formation processes on the Moon are categorized as those that belong to "airless bodies"—those surfaces that lack a complete atmosphere or magnetosphere (Grier & Rivkin, 2018). On Earth, geodynamic,

TABLE 1 List of lander and impactor disturbances on the lunar surface.

Anthropogenic disturbances on the lunar surface			
Mission	**Country**	**Launch date**	**Result**
Luna 2	USSR	9/12/1959	Impacted September 14, 1959.
Ranger 4	USA	4/23/1962	Impacted far side.
Ranger 6	USA	1/30/1963	Impacted February 2, 1964.
Ranger 7	USA	7/28/1964	Impacted July 30, 1964.
Ranger 8	USA	2/17/1965	Impacted February 20, 1965.
Ranger 9	USA	3/21/1965	Impacted March 24, 1965.
Luna 5	USSR	5/9/1965	Impacted May 12, 1965.
Luna 7	USSR	10/4/1965	Impacted October 7, 1965.
Luna 8	USSR	12/3/1965	Impacted December 6, 1965.
Luna 9	USSR	1/31/1966	Landed on Moon February 3, 1966.
Surveyor 1	USA	5/30/1966	Landed June 2, 1966.
Surveyor 2	USA	9/20/1966	Impacted September 23, 1966.
Luna 13	USSR	12/21/1966	Landed December 24, 1966.
Lunar Orbiter 3	USA	2/5/1966	Deorbited and impacted the Moon on October 9, 1967.
Surveyor 3	USA	4/17/1967	Landed April 20, 1967.
Lunar Orbiter 4	USA	5/4/1967	Decayed from orbit and impacted on October 6, 1967.
Surveyor 4	USA	7/14/1967	It may have impacted Moon. NASA lost contact 2.5 min before the scheduled landing.
Explorer 35	USA	7/19/1967	Presumed to have impacted Moon in the late 1970s.
Lunar Orbiter 5	USA	8/1/1967	Deorbited and impacted Moon on January 31, 1968.
Surveyor 5	USA	9/8/1967	Landed September 11, 1967.
Surveyor 6	USA	11/7/1967	Landed November 10, 1967.
Surveyor 7	USA	1/7/1968	Landed January 10, 1968.
Luna 15	USSR	7/13/1969	Presumed to have crashed on Moon July 21, 1969.
Apollo 11	USA	7/16/1969	Landed July 20, 1969.
Apollo 12	USA	11/14/1969	Landed November 24, 2969.
Luna 16	USSR	9/12/1970	The first mission to return lunar soil to Earth.
Luna 17	USSR	11/10/1970	The first robotic rover on Moon (Lunokhod 1).
Apollo 14	USA	1/31/1971	Landed February 9, 1971.
Apollo 15	USA	7/26/1971	Landed August 7, 1971.
Luna 18	USSR	9/2/1971	Failed and impacted lunar surface on descent.
Luna 20	USSR	2/14/1972	Landed February 21, 1972, and returned soil sample.
Apollo 16	USA	4/16/1972	Landed April 21, 1972.
Apollo 17	USA	12/7/1972	Landed December 19, 1972.
Luna 21	USSR	1/8/1973	Landed January 15, 1973, and deployed Lunohkod 2.
Luna 22	USSR	5/29/1974	Decayed from Moon orbit on September 2, 1975, and crashed.
Luna 24	USSR	8/9/1976	Landed August 18, 1976.
SMART-1	ESA	9/27/2003	Impacted Moon on September 3, 2006.
Kaguya (Selene)	JAXA	9/14/2007	Deployed Okina and Ouna, Kaguya and Okina impacted at the end of mission.

(Continues)

TABLE 1 (Continued)

Anthropogenic disturbances on the lunar surface			
Mission	**Country**	**Launch date**	**Result**
Chang'e 1	China	10/24/2007	Impacted on March 1, 2009, at the end of the mission.
Chandrayaan-1	India	10/22/2008	Moon impact probe impacted November 14, 2008.
LCROSS	USA	6/18/2009	Intentionally deorbited and impacted Moon on October 9, 2009.
GRAIL-A (Ebb)	USA	9/10/2011	Intentionally deorbited and impacted Moon on December 17, 2012.
GRAIL-B (Flow)	USA	9/11/2011	Intentionally deorbited and impacted Moon on December 17, 2013.
LADEE	USA	9/7/2013	Intentionally deorbited and impacted Moon on April 18, 2014.
Chang'e 3	China	12/1/2013	Lander and rover landed and deployed on December 14, 2013.
Manfred Memorial Moon Mission	China	10/23/2014	Impacted on March 4, 2022.
Chang'e 4	China	12/7/2018	Rover landed on January 3, 2019.
Beresheet	Israel (private)	2/22/2019	Crashed during descent April 11, 2019.
Chandrayaan-2	India	7/22/2019	Lander/rover crashed September 6, 2019.
Chang'e 5	China	11/23/2020	Landed December 16, 2020. Lunar sample return from lander which is still operational.
Hakuto-R	Japan	12/11/2022	Launched on December 11, 2022 and communication lost on April 26, 2023 during descent. Presumed crashed.

Note: This list is not exhaustive (i.e., it does not include undocumented missions or crashes by hovering flights, space junk, satellites, or other space heritage that would be considered archaeological) and is therefore limited to missions resulting in surface landing, impact, or crash sites where general location is known or has the potential to be located.

tectonic, geomorphic (fluvial, mass-wasting, eolian, glacial, etc.), atmospheric–hydrospheric, and biologic processes pace the creation and destruction of topography through physical and chemical breakdown of rock (soil formation), erosion, transport, and deposition of sediments. Conversely, the Moon's lack of an atmosphere means that it is subject to a variety of its own unique natural depositional and postdepositional processes or what planetary scientists call "space weathering" (Figure 3; Denevi et al., 2014; Hapke, 1973, 2001; Poppe et al., 2018; Xiao et al., 2013).

Natural formation processes on the Moon include extreme variability in surface temperature (Emhoff, 2009; Williams et al., 2019), solar radiation or wind (Bhardwaj et al., 2015; Denevi et al., 2014; Giacalone & Hood, 2015; Martinez et al., 2022; Naito et al., 2020; Zhang et al., 2020), meteoroid and micrometeoroid (microparticle) impact and subsequent alteration of lunar regolith (Hapke, 1973, 2001; Hörz et al., 1991; Pieters & Noble, 2016; Pieters et al., 2000), mass movement events (i.e., debris slides, flows, rockfalls, creep) (Bart, 2007; Kokelaar et al., 2017; Pike, 1970; Scaioni et al., 2018; Senthil Kumar et al., 2013, 2016; Xiao et al., 2013), thermal contraction, and shallow and deep Moonquakes causing faulting (Latham et al., 1969; Senthil Kumar et al., 2016).

Cultural formation processes occurring on the lunar surface include the impact of rockets and probes (impactors), landing events, crashes, tracks (human and rover), surface disturbances, and the deposition of a variety of cultural heritage (photographs, scientific equipment, golf balls, etc.). This activity disturbs the lunar surface, can cause erosion and deposition of lunar dust and regolith, and can generate impact craters (both purposeful and accidental). Understanding how each of these formation processes operate to form the archaeological record is crucial for understanding current and future space heritage on the lunar surface, and therefore a brief overview of each of these processes is provided.

4.4.1 | Lunar regolith: Formation and deposition

Geoarchaeologists consider sediments (solid inorganic and organic particles that move around a landscape) and soils (weathering of in-place sediments due to physical and chemical processes during landscape stability) to understand how archaeological materials may be affected by natural formation processes. The lunar surface consists of three materials: (1) anorthosite flows (highlands or *terra*), (2) basalt flows (referred to as Mare), and (3) sediments (regolith) and "soils" (weathered regolith) occurring as a debris blanket 4–10 m thick across the lunar surface comprised of vesicular glasses welded together, basalts (agglutinates), impact glass, brecciated meteoroid fragments, and fragments of igneous intrusive and extrusive rocks (Lucey et al., 2006).

For archaeological purposes, lunar regolith is the critical geologic unit. Lunar regolith is poorly sorted with grain sizes ranging from micrometer to boulder and sorting values ranging from 1.99 to 3.73 ϕ (Hörz et al., 1971). Research has demonstrated an inverse relationship between mean grain size and sorting, with the coarsest samples being the most poorly sorted (McKay et al., 1991, fig. 7.15). Regolith is primarily produced by impact cratering which results in pulverized

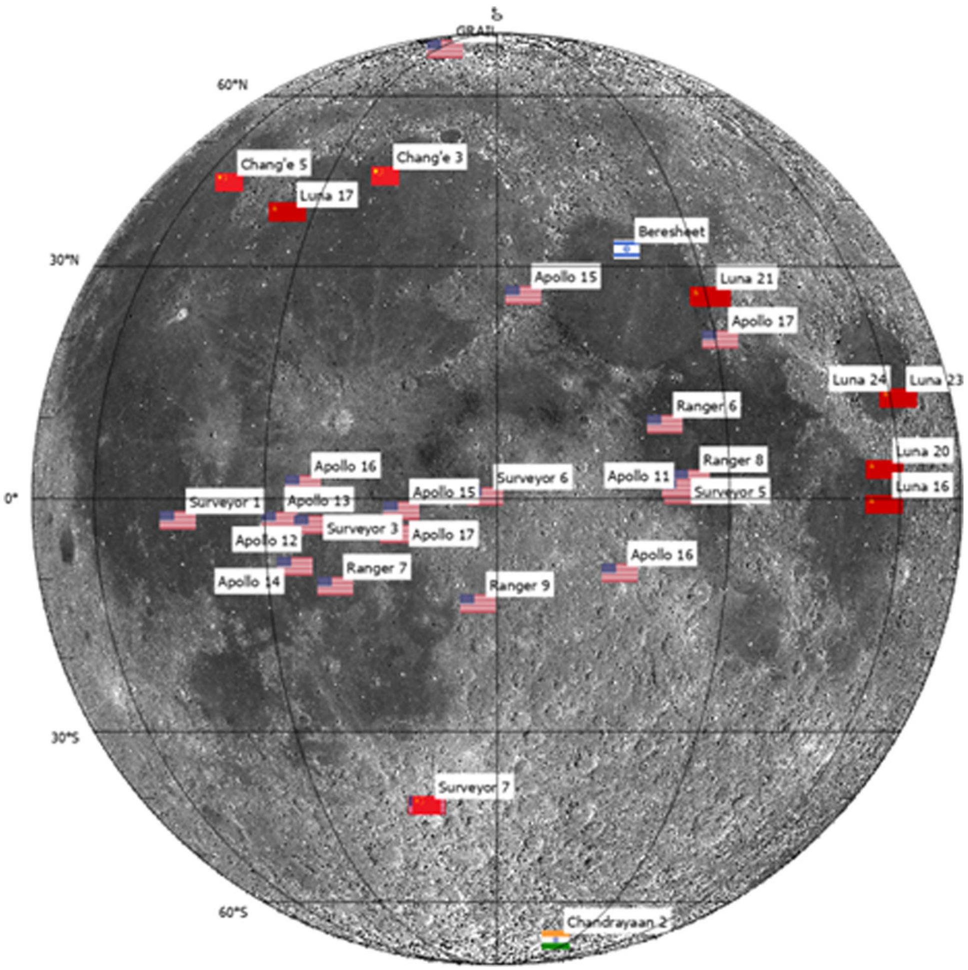

FIGURE 1 A general and nonexhaustive overview of some key missions to the Moon through 2022.

material including impact melts and porous breccias (McKay et al., 1991, p. 285). Lunar mineral composition is fewer than a 100 (compared to the Earth's thousands) with composition including olivine, high-Ca clinopyroxene (augite), high-Ca plagioclase feldspar (anorthite), and Fe–Ti oxide (ilmenite) combined with agglutinates (glass) formed by impact vitrification (Housley et al., 1974; McKay et al., 1991).

Historically, the primary natural process for moving sediment around the Moon's surface is impact cratering from meteroids. Over the past few billion years of the Moon's geologic history, meteoroid impacts formed craters up to hundreds of kilometers in diameter and leading to the basins seen today. However, today's impacts (fortunately) are much smaller, including meteoroids ranging from 0.1 mm to 20 m (Hörz et al., 1971). Upon landing, the first observations of regolith material were described by the Apollo 11 team in *Mare Tranquillitatis*, which had an apron of fine regolith with scattered blocks as large as 5 m (Vaniman et al., 1991). The Apollo 12 crew described some crater rims on *Oceanus Procellarum* as "rubbly" (Shoemaker et al., 1970), highlighting their potential role as small depositional settings (see Section 4.4.4).

Understanding lunar regolith production and deposition is important for understanding the preservation of space heritage. First, lunar sediments are angular due to a lack of moving fluids (atmosphere/water) on the Moon (Zelenyi et al., 2021). Given that the Moon has 1/6th Earth's gravity and air pressure of around 10^{-12} Torr or 133.322 Pa (Liu et al., 2010), highly angular and electromagnetically charged dust moves at much faster rates and farther than on Earth. Lunar dust is particularly harmful to humans (i.e., breathing in material brought into living quarters) and can degrade the performance of bearings, compromise seals, contaminate life support systems, and affect the moving parts of various equipment (Taylor et al., 2005; Zelenyi et al., 2021). Second, mass-wasting of regolith typically occurs near unstable and rubbly crater rims, and therefore in the future, space heritage is more likely to be buried within those settings. Understanding the physics of anthropogenic surface disturbance, especially its impact on space heritage, should be a major research area in future missions.

4.4.2 | Thermal gradient

The Moon has no atmosphere to insulate heat; hence drastic variations in the Moon's thermal surface gradient occur (Williams

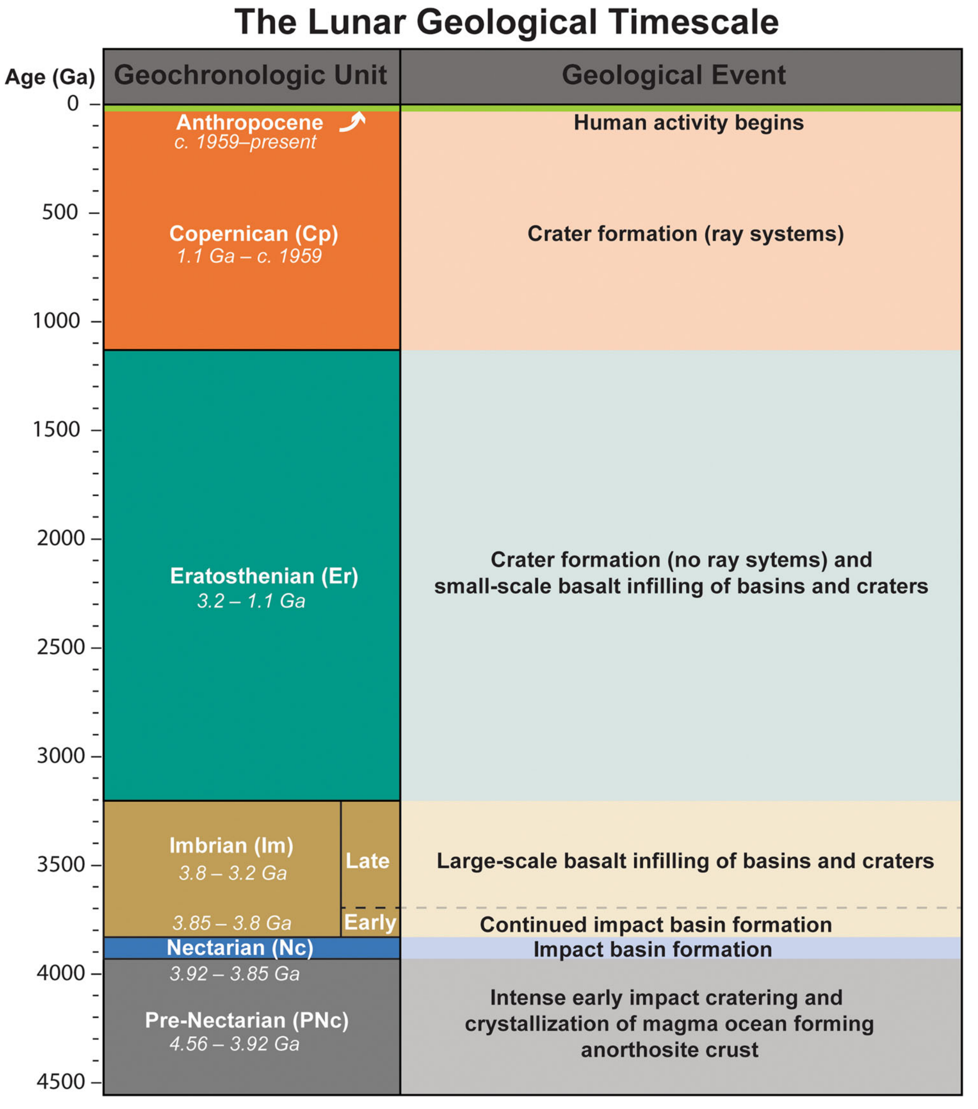

FIGURE 2 Geologic timescale of the Moon including the beginning of human–moon interaction we refer to as a Lunar Anthropocene (data from Wilhelms et al. [1987] and Liu and Guo [2018]).

et al., 2019). The Diviner instrument on the Lunar Reconnaissance Orbiter (LRO) provided surface temperature measurements, allowing researchers to calculate and compare winter and summer seasonal temperature variability (Williams et al., 2019). Lunar daytime is about 27.3 days (2 weeks) with a mean surface temperature of 107°C (224°F) day and −153°C (−243°F) night. At its equater, the Moon's surface temperature can reach a boiling point of 120°C (250°F). During lunar nighttime at the equator, however, temperatures can drop to −130°C (−208°F).

Understanding exactly where on the Moon certain temperature variations may be most extreme could provide unique insight into the preservation of space heritage. Space shuttle thermal protection systems are typically geared to withstand up to 1650°C (3000°F) during atmospheric exit and reentry. The internal components of planetary spacecraft are designed to withstand between −35°C and 65°C (−95°F and 149°F) (Darrin & Mehoke, 2009). Recent research has demonstrated that in topographic lows with permanently shadowed regions (PSRs), especially the lunar polar regions, temperatures can drop to −253°C (−424°F) serving as cold traps with the capability of preserving water ice (Li et al., 2018; Spudis et al., 2013). As observed by the Clementine probe, PSRs could serve as a reservoir for hydrogen (Arnold, 1979; Nozette et al., 2001). Moreover, water ice preserved in areas on the lunar South Pole, such as Shackleton Crater for example, may preserve rich million-year-old environmental archives of lunar surface processes. As a result, the ARTEMIS Program has selected Shackleton Crater as a potential landing area (NASA, 2019). Space heritage that is left or has already been left near the equator—especially in areas that lack a permanent shadow—is susceptible to extreme variations in temperature. Conversely, space heritage objects on the lunar South Poles may witness favorable preservation conditions.

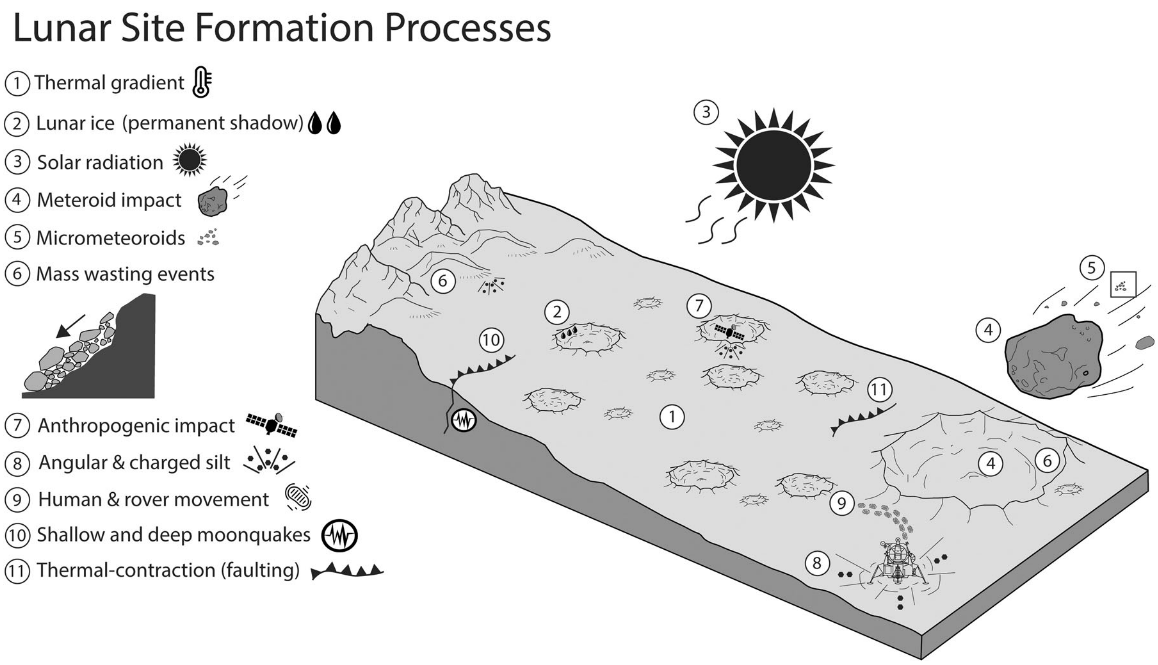

FIGURE 3 Natural and anthropogenic site formation processes capable of altering, destroying, or preserving space heritage on the lunar surface today and in the future.

4.4.3 | Cosmic rays and radiation

The Moon's lack of an atmosphere or magnetic field also means that there is no protection from charged particles including galactic cosmic rays and solar wind, or solar energetic particles (SEPs) (Bhardwaj et al., 2015; Denevi et al., 2014; Giacalone & Hood, 2015; Martinez et al., 2022; Naito et al., 2020; Zhang et al., 2020). SEPs are also characterized by intense and unpredictable events, such as those that may derive from solar flares or corona mass ejections with high energy. They are therefore strongly penetrating and capable of producing secondary radiations, such as neutrons and gamma rays (cf. Zhang et al., 2020). Radiation on the Moon has recently been measured as total absorbed dose rate in silicon of 13.2 ± 1 µGy/h and a neutral particle dose rate of 3.1 ± 0.5 µGy/h by China's China's Chang'E 4 lander (Zhang et al., 2020). These rates translate to an average dose equivalent of 1369 µSv/day on the lunar surface, or about 2.6 times higher than the International Space Station (ISS) and 200 times higher than Earth's surface (Berger et al., 2017).

The effects of solar radiation on lunar regolith have been well-studied (e.g., Grier & Rivkin, 2018; Hapke, 1973, 2001; Housley et al., 1974). The main effects of ionization of the lunar regolith include structural changes induced by amorphization (Brucato et al., 2004; Poppe et al., 2018) and sputtering (Martinez et al., 2022; Wurz et al., 2007). Amorphization from cosmic rays occurs at the microscopic level and, over time, results in a nanometer-thick glass coating on exposed grains (Poppe et al., 2018). Cosmic ray sputtering causes the reddening and darkening of Fe-rich regolith (Hapke, 1973, 2001) which lowers the albedo, reddens the spectral scope, contributes sodium and potassium into the Moon's exosphere, obscures absorption bands, and generates characteristic magnetic electron spin resonance features of lunar regolith (Martinez et al., 2022).

The effects of solar radiation on the surface weathering of space heritage may be ameliorated in several ways. First, Chandrayaan-1 detected a ~360 km the presence of lunar mini magnetospheres (LMMs) on the Moon over the Crisium antipode magnetic anomaly region (cf. Bhardwaj et al., 2015; Wieser et al., 2009). Lunar Prospector observations suggest that LMMs may shield the lunar surface from solar wind by a factor of four (Giacalone & Hood, 2015). In the future, should our understanding of the presence of LMM increase to higher resolution mapping (e.g., Vorburger et al., 2013), such areas may minimize the risk of human hazards, however, such a hypothesis has yet to be tested. Second, Naito et al. (2020) demonstrated that the effects of cosmic radiation are severely diminished when beneath the surface of the Moon. Finally, archaeologist Capelotti (2010, p. 22) suggests the construction of archaeodomes, which could both shield space heritage in situ and protect key areas from solar radiation and micrometeroid bombardment, and potentially provide more restricted tourism access. Based on these considerations, when possible, astronauts could consider leaving space heritage within holes in the lunar surface, such as lava tubes, burying materials to retrieve later (caching), or even constructing domes over key sites to ensure the preservation of key areas (e.g., Tranquility Base). However, it should be noted that a substantial (>100 years) amount of time may be needed for these precautions to be deemed necessary when considering natural processes such as micrometeroid bombardment.

4.4.4 | Meteroid impact

As previously discussed, the geologic history of the Moon is one marked by meteoroid impacts, including those that cause large (tens of kilometers in diameter) basin-forming impacts, those with sizes that occur somewhere in the middle range (meters), and micrometeroids (<2 mm; see Section 4.4.5) (Poppe et al., 2018). The geologic and geomorphic importance of macroscopic meteoroid impacts cannot be understated, as they serve as a major geomorphic agent on the lunar surface, creating topographic and structural features of the Moon, such as mountain peaks (mons) and ranges, of course, impact craters (Hörz et al., 1991, p. 62).

Impact craters are the dominant landform on the surface of the Moon (Melosh, 2011, pp. 10–14). Fresh impact craters can be grossly characterized as "circular rimmed depressions" that vary in size from 0.1 μm to ~2500 km diameters, such as those seen in the South pole Aitken basin. In more detail, lunar craters have been separated into three broad categories (Figure 4): (1) simple craters that are bowl-shaped with smooth floors without central peaks that are less than 20 km in diameter, (2) complex craters that are typically larger than about 20 km and often have terraced walls, central peaks, and at larger sizes may have flat interior floors or internal rings instead of central peaks, and (3) at the very largest sizes, multiring basins that are characterized by multiple concentric circular scarps, including both peak ring and multiring types (Smith & Sanchez, 1973). The complexity of lunar craters is a product of size (diameter) and time, as those craters larger than 15–20 km typically evolve from simple to complex craters due to space weathering and mass-movement events (Hörz et al., 1991, p. 62; Melosh, 2011, pp. 224–230).

The formation of impact craters is conventionally broken down into three key processes: (1) initial contact/impact and compression of lunar regolith and underlying bedrock, (2) excavation and displacement of lunar regolith (ejecta), and (3) collapse of rubbly rims (Cintala & Grieve, 1998; Collins et al., 2012; Grieve & Head III, 1981; Hörz et al., 1991; Shoemaker, 1962). These processes are directly relevant to the geoarchaeology of space heritage because of their capability to destroy or bury archaeological sites. Burial of space heritage is especially possible during oblique impacts, which create elongated craters with steep crater walls that are susceptible to collapse (Collins et al., 2012; Hörz et al., 1991, p. 71). Ejection debris caused by lunar cratering (ejecta) originate close to the point of impact and forms continuous deposits that increase in radial distance from the crater's center as a curtain and could also bury space heritage (Figure 5; Hörz et al., 1991, p. 70). Particle-size distributions of ejecta reveal a fining upward sequence, with coarser fragments and boulders depositing at the base of an ejecta curtain and finer near-surface derived dust higher in the curtain (Hörz et al., 1991, p. 70; Oberbeck, 1975). In addition, the particle size distribution of ejecta mean that softer and deeper sediments may be preserved on the insides of crater walls, which can prove problematic for exploration. Such conclusions were made by the Russian rover Lunokod 2, which sank up to 20 cm during its travels around Le Monnier crater (Florensky et al., 1978). In sum, lunar craters represent depositional settings and cratering processes represent

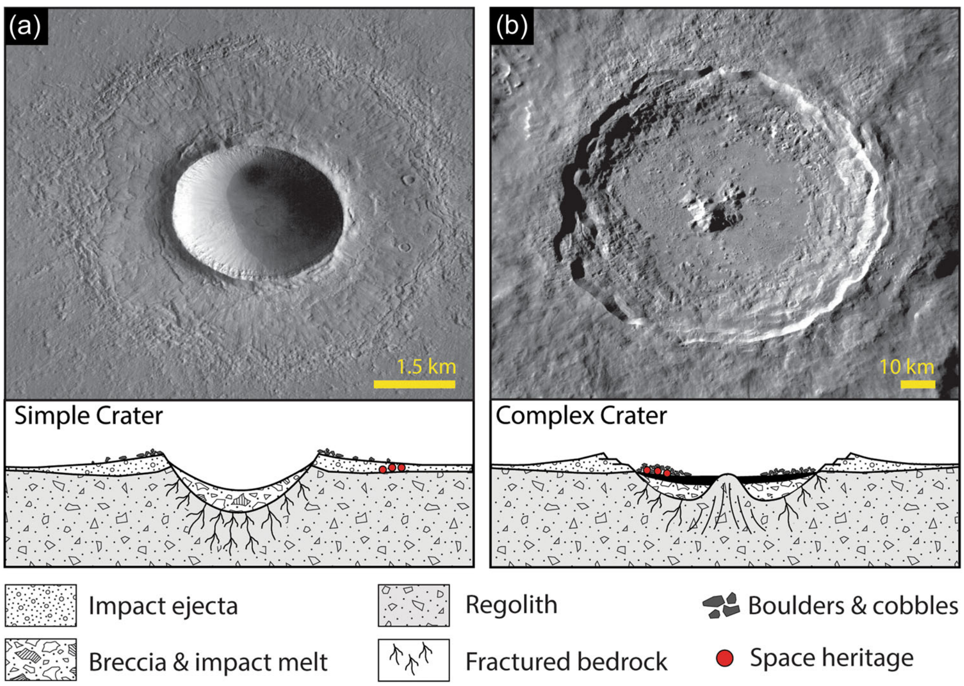

FIGURE 4 (a) Simple and (b) complex impact craters on the lunar surface representing two types of depositional settings for space heritage (modified from Scaioni et al. [2018, p. 50]); Space heritage is susceptible to burial either through (a) proximity to ejecta during impact or (b) burial under mass movement events near crater rims. Although not illustrated here, a third type of crater includes multiring basins that are characterized by multiple concentric circular scarps. Figures courtesy of NASA-JPL LROC-NAC.

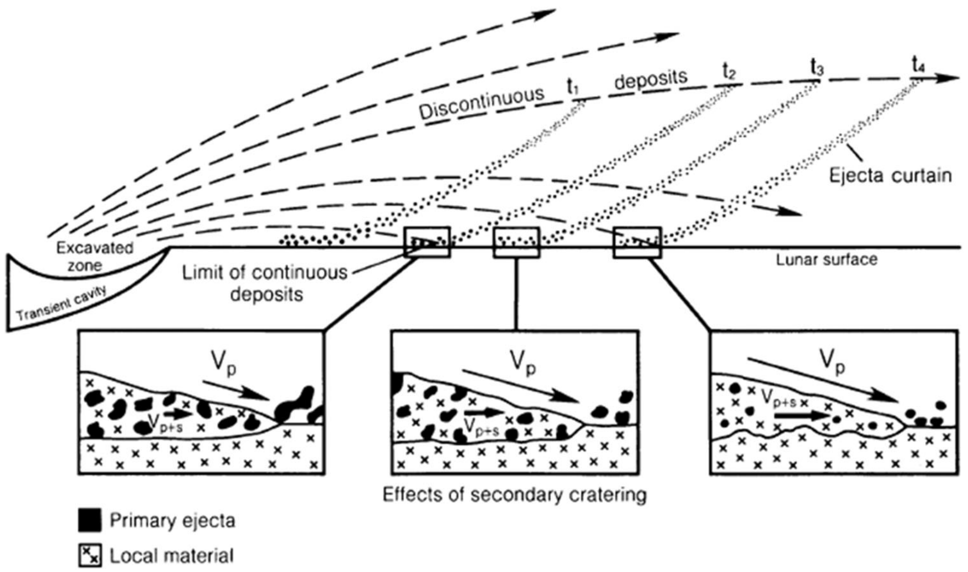

FIGURE 5 Ejection processes following direct impact on the lunar surface (from Hörz et al. [1991], p. 71). Impacts and corresponding blankets can serve as both erosional and depositional processes, respectively, and therefore are capable of burying and/or adversely impacting space heritage.

key depositional events on the lunar surface capable of altering, destroying, or burying space heritage.

4.4.5 | Micrometeoroid impact

Another primary depositional process on the moon that is directly relevant to the preservation of space heritage is micrometeroid bombardment. Following the deposition of lunar regolith (sediments), lunar "soil" formation occurs due to bombardment of micrometeoroids and charged particles that alter the composition, chemistry, and color of regolith; a process referred to as "space weathering" (Figures 6 and 7; Hapke, 1973, 2001; Pieters & Noble, 2016; Pieters et al., 2000; Poppe et al., 2018). This process creates an in situ reworking zone of lunar regolith composed of light and dark gray, very fine-grained, loose clastic material of basaltic and anorthositic rocks and agglutinatic glass, called a "high maturity zone" or "mixing zone" (Hapke, 2001; McKay et al., 2001; Morris, 1976; Wiesli et al., 2003). The "gardening" or mixing process increases the lunar regolith's maturity (darkening and thickness). Such observations have been made in drill cores returned from Apollo 15, 16, and 17 (see Morris, 1976). Maturity zones range from 50 cm to 1 mm based on the calculation of the ferromagnetic resonance (FMR) maturity index, which is intensity (I_s) divided by total iron content (FeO) (Morris, 1976). The FMR index provides an estimation of lunar soil maturity, as well as an estimation of the relative surface exposure age. In short, it takes around 14 ± 4 Myr to form around 5 cm of lunar soil and around 450 ± 100 Myr to form 50 cm (Arnold, 1975; Morris, 1976).

Space weathering of lunar regolith includes (1) direct impact involving submillimeter-sized micrometeoroids that can form repetitive and frequent impacts to agitate the lunar surface (e.g., shattering, burying, exhuming, tumbling, and transporting individual sediment grains), (2) darkening and reddening of silica-rich lunar regolith by creating both amorphous and iron-rich depositional rims on individual grains (Keller & McKay, 1993, 1997; Poppe et al., 2018), and (3) vaporization of minerals and glass welding (vitrification) of lunar regolith caused by heat from impact, which reduces iron (Fe) from silicates (Si) to metal (nanophase iron—npFe°) during melting (Hapke, 2001; Housley et al., 1974; Pieters & Noble, 2016; Pieters et al., 2000; Poppe et al., 2018). Regarding the later, research focused on the formation of nanophase iron (npFe°) is ongoing, but recent experimental research by Sorokin et al. (2020) and observations made by the Chang'e-5 project (Li et al., 2022), suggests that npFe° is the product of impact vaporization and vapor deposition.

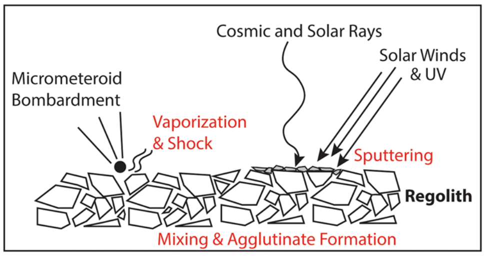

FIGURE 6 Formation of "lunar soil" on the lunar surface via space weathering as bombardment of micrometeoroids and various charged particles occurring at the microscale (adapted from Pieters and Noble [2016]).

Some studies have sought to determine the rate of micrometeroid impact on the Moon. For example, Luna 10 was the first experiment to obtain direct measurements of micrometeoroid impacts on the lunar surface. The probe utilized piezoelectric

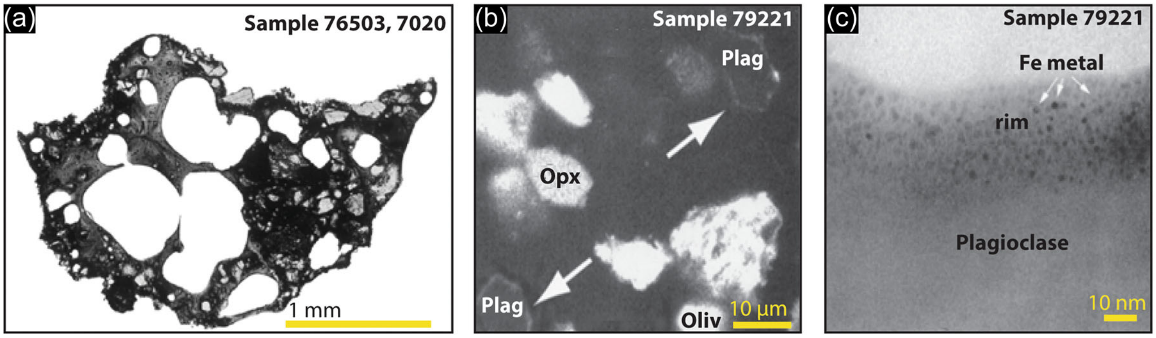

FIGURE 7 The product of space weathering on lunar agglutinates. (a) Example of lunar regolith agglutinate (modified from Lucey et al. [2006]). (b) Digital X-ray Fe Kα of iron-bearing (brighter) minerals in NASA bulk sediment sample 79,221, white arrows point to locations of (c) nanophase iron (npFe°) rims formed on anorthosite plagioclase due to a combination of micrometeoroid and charged particle bombardment revealed by transmission electron microscope from soil sample 79,221 (modified from Pieters et al. [2000]).

TABLE 2 Types of mass wasting processes that have been identified on the lunar surface.

Mass wasting processes	Definition	Source
Debris (rock) falls	Abrupt downslope movements via detachment of cobble and boulder-sized regolith or bedrock on steep slopes.	Fielder (1963), Bruneth et al., (2013), Bickel et al. (2020), Kokelaar et al. (2017), and Senthil Kumar et al. (2016)
Debris creep	Slow down-slope movement of regolith and rock.	Pike (1970) and Xiao et al. (2013)
Granular flows	Avalanches of fine granular material without liquid water.	Bart (2007) and Senthil Kumar et al. (2013)
Debris flows	Mass movement of a combination of loose regolith; smaller particles than debris slides.	Bart (2007), Pike (1970), Senthil Kumar et al. (2013), and Xiao et al. (2013)
Debris slides	Downslope movements of regolith along ruptures or thin zones of intense shear strain. Particles move en masse.	Scaioni et al. (2018) and Xiao et al. (2013)
Rockslides	Sheets of rock sliding along discrete failure planes, often along geologic discontinuities.	Brunetti et al. (2015) and Xiao et al. (2013)
Debris slumps	Sudden mass movements of rocks and fine material over short distances; typically, more volume than slides.	Scaioni et al. (2018) and Xiao et al. (2013)

detectors, which measured 198 particle impacts for 11 h and 50 min, constituting a rate of 4×10^{-3} impacts per $m^2\,s^{-1}$ (1.47×10^5 impacts $m^{-2}\,a^{-1}$) (Nazarova et al., 1966). Later, experiments conducted by Lunar Orbiters 1–5 used highly sensitive pressure switches for 17 months and measured a higher rate of 0.16 per $1\,m^2$/day (5.84×10^1 impacts $m^{-2}\,a^{-1}$) (Gurtler & Grew, 1968). As a result, micrometeoroids could cause severe harm to humans and serve as a destructive postdepositional process to space heritage over longer periods of time (>100 years). Future landings and disposal of important space heritage should seek ways to mitigate problems associated with long-term micrometeroid bombardment.

4.4.6 | Mass wasting events

Largely identified via LROC-NAC imagery, mass wasting events appear to be a key process by which regolith moves on the lunar surface other than by direct impact events (Table 2). Mass wasting occurs when rock, soil, or both move downslope in coherent or semicoherent mass due to surface rupture (Highland & Bobrowsky, 2008). On Earth, mass movements on slopes are common and include falls, topples, slides, flows, creeps, and slumps and are largely initiated by the influence of gravity, water, humans, and earthquake ground motions. Pike (1970) was one of the first to point out that mass wasting events appear to be common on the Moon when he used Apollo 10 imagery to recognize creeps, slumps, debris flows, and rock falls on the lunar surface (cf. Scaioni et al., 2018). Since those observations, LROC-NAC imagery has allowed several types of mass movement events to be observed and described in detail based on their morphology, emplacement modes, and material size (Xiao et al., 2013). These include debris and rock falls, granular flows, granular avalanches, debris flows, creep, slides, and slumps (Table 2; Bart, 2007; Kokelaar et al., 2017; Scaioni et al., 2018; Senthil Kumar et al., 2013, 2016; Xiao et al., 2013). While water is absent on the Moon, mass wasting events generally occur due to some triggering mechanism that causes regolith to move in association with the angle of repose (Kokelaar et al., 2018). Triggering mechanisms for mass wasting events include gravity (e.g., creep and slides), meteoroid impact (Scaioni et al., 2018), shallow moonquakes via thermal contraction (Senthil Kumar et al., 2016), and anthropogenic surface disturbances (Xiao et al., 2013).

Because various mass movement events can bury space heritage, it is important to understand these processes. Key depositional environments where mass movements may bury space heritage include near lunar crater rims (both outside and inside), near areas of structural weakness, and on slopes. Triggering mechanisms for mass movement is primarily gravity or impact-based, and therefore future missions to the lunar surface should consider the role of human activity for triggering mass movement events, especially near space heritage objects.

4.4.7 | Anthropogenic surface disturbance

Human activity on the lunar surface will continue to be the dominant geomorphic agent eroding and translocating regolith with the potential to affect space heritage (Capelotti, 2010). Understanding the dynamics between human–Moon interaction and their role in affecting space heritage objects and features is particularly important as we enter the new Space Age. In 2011, with the help of a multidisciplinary board of contributors that included an archaeologist (O'Leary), NASA officially recognized this issue and began to consider the impact of human activity on space heritage on the lunar surface (NASA, 2011). Key cultural site formation processes on the Moon that lead to the erosion and deposition of lunar regolith include accidental and purposeful impacts (i.e., crashes), lander descent and ascent, hovering flights, rover movement, and human activities (e.g., walking, building, and in the future, mining and construction).

Currently, crewed missions to the Moon, including the dispersal of landers and rovers, cause the most disturbance on the lunar surface. As several space archaeologists have already discussed (e.g., Capelotti, 2010, 2015; Staski & Gerke, 2009), the impact of anthropogenic sedimentation produced by landing apparatus was perhaps first realized during the successful landing of Apollo 12's lunar lander. As discussed by Metzger and Mantovani (2021), the exhaust plume from the lander's descent engines created a high-velocity spray that removed dust from the nearby Surveyor 3 probe which had coated itself with dust during its own landing (also see Immer et al., 2011; Lane et al., 2012). During the Apollo landing, sandblasting crushed the surface of the paint, mixed dust into the crushed paint pigment, and punctured the paint with individual sand grains (P. Metzger, personal communication, April 11, 2023). Apollo 12's crew noted the pitting on the probe before returning it back to Earth for study (Capelotti, 2015, p. 51; NASA, 2011, p. 11; Staski & Gerke, 2009, pp. 513–517). As demonstrated by the Surveyor 3 probe, ejecta paths from landers pose a significant threat to space heritage objects and features on the lunar surface. Figure 8 illustrates multiple lander ejecta paths for spacecraft with bi-, tri-, and quad-directional engine configurations. Interestingly, Prem et al. (2020), noted that lander exhaust gases during descent can reach PSRs (cold traps) and contaminate ice, especially near polar regions. Any space heritage objects preserved in cold traps would therefore be subject to contamination via exhaust propagation.

Rovers also can serve as agents of sedimentation. For example, linear exterior wheel speeds have been calculated to redeposit lunar regolith at distances ranging from 3 to 200 m depending on rover wheel speed (Table 3; NASA, 2011). As a result, researchers suggest avoiding approaching heritage areas directly, and recommend entering and exiting the same location to minimize disturbance and contamination of heritage areas (NASA, 2011).

Low altitude hovering flights can also redistribute lunar regolith, especially when the flights are less than 40 m above the surface. While the erosion rate and flux of lunar regolith due to rover hovering is subject to debate (Metzger et al., 2011), several researchers have attempted to calculate lunar particle flux. For example, Morris et al. (2016) found that lunar particle flux directly under a lander hovering 3–5 m above the surface is approximately 2.0 kg/m^2, which results in a scouring rate of 1.3 mm/s for loosely packed lunar regolith, but this rate varies depending on lander altitude, size, speed, and regolith particle size. A review by Metzger

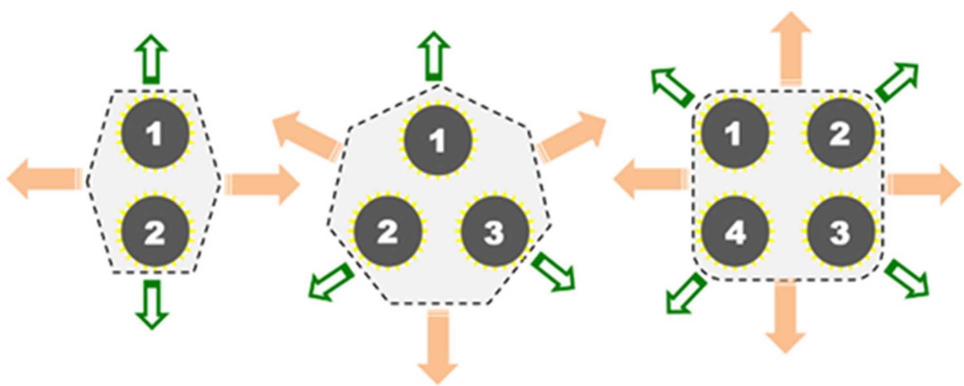

FIGURE 8 Diagram of ejecta paths for bi (left), tri (center), and quad (right) engine configurations. Orange arrows denote direction of maximum ejecta flux (plume reflection planes) while green arrows identify areas of minimum ejecta flux (from NASA [2011]). Anthropogenic surface modifications represent a major lunar surface process capable of erosion, deposition, and postdepositional alteration of space heritage as revealed by experiments on the Surveyor 3 materials and observed by Buzz Aldrin during Apollo 11.

et al. (2011) provided differing results, however, and argued that calculated ejecta velocities for dust ranged from 1000 to 3000 m/s, sand-sized particles ranged from 100 to 1000 m/s, and rocks went about 10 m/s. While research on human-induced erosion rates is ongoing, it is clear that anthropogenic activity is a major erosion process on the lunar surface and will be an issue for space heritage preservation in the future (Metzger et al., 2011).

Surface disturbances and human-induced impact cratering due to crashing and accidental crashes is another surface process on the Moon and will likely become even more frequent. Figure 9a–d illustrates key examples of anthropogenic surface disturbances events (crashes and subsequent impact cratering) on the lunar surface as revealed by LROC-NAC imagery, including impacts caused by Ranger 6, Ranger 9, Apollo 13, and Beresheet-1. Other surface disturbance includes various scientific experiments, rover movements, discard of artifacts, and human walkways, which can be seen in Figure 9e–h.

TABLE 3 Calculated dust travel distances (m) depending on lunar rover velocity (m/s) (from NASA, 2011).

Dust travel distance (m)	Velocity (m/s)
3	2
5	2.8
10	4
15	5
30	7
75	11
80	11.4
200	18

Finally, it should be noted that anthropogenic disturbances can serve as triggering mechanisms for mass movement events. Landings, crashes, and launches can potentially create major depositional episodes not limited to dust plumes, especially near crater rims. Such activity will likely increase as various private and government entities turn to ISRU activities over the next few decades (Vickers, 2019).

4.4.8 | Seismic activity: Shallow and deep moonquakes

Over the last few decades, internal tectonic activity in the form of "moonquakes" have been detected from Apollo-era seismometers placed on the lunar surface, LRO imagery, and thermal state modeling (Hörz et al., 1991; Kumar et al., 2019; Nakamura, 1980). Shallow (near-surface) and deep moonquakes have been observed since the late 1960s. The first direct measurements occurred between 1969 and 1977 when the Apollo missions measured 28 shallow moonquakes

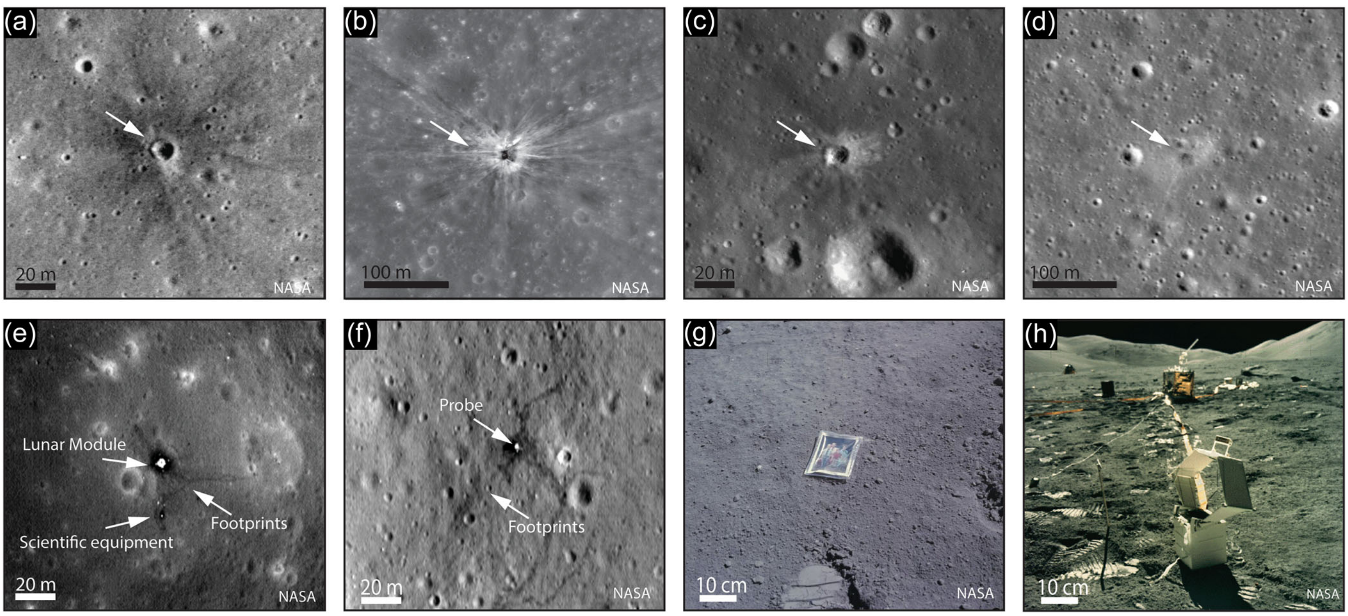

FIGURE 9 Examples of anthropogenic surface modification events on the lunar surface. (a) USA's Ranger 6 lunar probe impact on the eastern margin of *Mare Tranquillitatis* on February 2, 1964. (b) USA's Apollo 13 Saturn IVB upper stage impact north of *Mare Cognitum* on April 14th 1970 (30 m in diameter). (c) USA's Ranger 9 spacecraft impact in Alphonsus crater on March 24, 1965 (7 m in diameter). (d) Israel's Beresheet Moon lander impact on *Mare Serenitatis* on April 11, 2019 (10 m in diameter). (e) USA's Apollo 11 Lunar Module in *Mare Tranquillitatis* and associated lunar surface disturbance and artifacts, including landing, footprints, and scientific equipment. (f) USA's NASA Surveyor 3 probe in *Oceanus Procellarum* on April 20, 1967 and footprints from Apollo 13 which occurred over 37 months after probe landing and resulted in the recovery of some probe components back to Earth. (g) Photograph left by astronaut Charles Duke from USA's Apollo 16 mission to the Descartes highlands on April 21, 1972. (h) USA's Apollo 17 landing site on *Mare Serenitatis* on December 11, 1972 (image credits: figures courtesy of NASA-JPL Lunar Reconnaissance Orbiter Camera/GSFC/Arizona State University; modified from Wagner et al. [2017]).

(Latham et al., 1969). Shallow moonquakes are rare, with the Apollo seismic network measuring around five per year (Nakamura, 1980). Later, NASA's LROC-NAC provided images of sufficient resolution to identify features created by these processes, including fault scarps and cliffs formed during thermal cooling (Watters et al., 2012). These data demonstrate that the Moon has a history of thermal expansion during the initial billion years of existence, which over the last 3.5 Gyr has begun to cool and compress, thereby triggering moonquakes and effectively demonstrating that the Moon is still seismically active (Solomon & Chaiken, 1976).

Shallow moonquake events could trigger mass wasting events, especially rock falls (Senthil Kumar et al., 2013), and therefore have the potential to cause depositional events capable of burying space heritage. For example, Senthil Kumar et al. (2016) identified lobate scarps and boulder avalanches triggered by the largest shallow moonquake measured by the Apollo missions at Lorentz Basin on January 3, 1975. In addition, lunar craters are particularly susceptible to slope failure and subsequent mass movement events (see below) (Kokelaar et al., 2017). Future research should consider the role of shallow moonquakes and their potential to affect the preservation of space heritage.

5 | DISCUSSION

As we enter the era of privatized space exploration, or a "new Space Age," archaeologists need to start considering how they can contribute novel solutions to the spread of our material record across the solar system. It is also important to consider how space heritage is preserved, altered, or destroyed on the Moon and beyond (Capelotti, 2010; Darrin & O'Leary, 2009; Gorman, 2009a; O'Leary & Capelotti, 2015). In our opinion, the material remains of space exploration on the Moon represent a contemporary archaeology, a material record inextricably linked to current sociopolitical identities of the past, today, and future (also see Hicks, 2010; Hicks & Mallet, 2019; Ingold, 2007). From this perspective, we propose a new subdiscipline—planetary geoarchaeology—as a way for archaeologists to address the study of space heritage, especially as human–environment interaction on the Moon becomes a reality once again.

Archaeologists are equipped with tools capable of studying the past, and the contemporary present (Buchli et al., 2001). We argue that geoarchaeologists are uniquely poised to achieve this goal by applying site formation theory. By reviewing archaeological site formation processes on the lunar surface, we sought to contradict the idea that the space heritage on the Moon exists in a static depositional setting, preserved in perpetuity—or what we could, by analogy, call the "Lunar Premise." The lunar surface is dynamic, and includes impact events from meteoroids, bombardment by charged particles and micrometeoroids, mass movement events, shallow and deep moonquakes, and extreme variations in surface temperature. The lunar surface is also vulnerable to future anthropogenic disturbance and impact. Indeed, human activities on the lunar surface have left and will continue to leave a measurable geomorphic signature. Humans have emerged as a new major geomorphic agent on the Moon. Nevertheless, the new Space Age is only in its infancy, and before *H. sapiens*' inevitable expanded presence on the Moon, we should discuss ways to preserve current and future space heritage.

The Moon preserves the very first beyond-Earth effect of humanity in the form of a probe crash (Luna 2), the first footprint on an extraterrestrial surface (Apollo 11), and the introduction of the first microscopic organisms (tardigrades on Beresheet which crashed on April 11, 2019) (Figure 9). Over the next 3 years, at least eight spacecraft are scheduled to touch down on the lunar surface, originating from seven countries (the United States, China, Russia, India, South Korea, United Arab Emirates, and Japan) and several private companies (e.g., Beresheet) (Pickrell, 2022).

After our discussion here, we hope that the archaeological implications of those missions are obvious, especially considering that eventual goals for missions, such as NASA's Lunar Surface Innovation Initiative, which includes plans for major alterations of the lunar surface, such as reconnaissance prospecting and sampling, ISRU and processing (i.e., mining and construction of operating facilities), surface excavation and construction, and deep subsurface disturbance (Klima, 2022; Metzger et al., 2011; Morris et al., 2016; Vickers, 2019). As a result of the perceived impact that these activities may have on space heritage, on October 13, 2020, the Administrator of NASA and representatives of eight other national space agencies signed the Artemis Accords. Although nonbinding, a central aspect of these accords is an acknowledgment of the need to preserve space heritage, and a commitment to multilateral efforts to develop best practices and rules for such preservation (NASA, 2020). We believe that archaeology has begun making novel contributions towards this effort and should make it a central priority going forward.

Over the last two decades, space archaeologists have drawn attention to the need to consider the preservation of space heritage in various Earth-orbital positions (Clemens, 2009; Gorman, 2005b, 2009d), interplanetary space (Darrin, 2015; Sample, 2009), the ISS (Ali et al., 2022; Walsh & Gorman, 2021), and on Earth (Westwood et al., 2017). Planetary geoarchaeology is dedicated to studying space heritage on extraterrestrial surfaces and extends the applications of space archaeology by increasing our understanding of the past and future under two key principles.

The first principle of planetary geoarchaeology we propose aims to understand the geoarchaeology of space and celestial bodies through the preservation and stewardship of space heritage. Archaeologists and anthropologists have long been dedicated "stewards of the past." As noted in the *Society of American Archaeology's Principles of Ethics*, stewardship is the overall guiding concept of archaeological research (Lynott, 1997). As noted by Lynott (1997), the key principle of Stewardship (Principle No. 1), states that:

> The archaeological record, that is, *in situ* archeological materials and sites, archaeological collections, records, and reports is irreplaceable. It is the responsibility of all archaeologists to work for the long-term

> conservation and protection of the archaeological record by practicing and promoting stewardship of the archaeological record. Stewards are both caretakers of and advocates for the archaeological record. In the interests of stewardship, archaeologists should use and advocate use of the archaeological record for the benefit of all people; as they investigate and interpret the record, they should use the specialized knowledge they gain to promote public understanding of support for its long-term preservation. (p. 592)

We argue here that this stewardship should extend onto other parts of our solar system, and therefore the guiding principle of preservation and stewardship of space heritage should represent the fundamental principle of planetary geoarchaeology. One example of how NASA scientists and archaeologists are currently collaborating to ensure this goal is the International Space Station Archaeological Project (ISSAP) (Walsh, 2012; Walsh & Gorman, 2021). ISSAP represents the first large-scale contemporary archaeology project in space, and has begun a experiments studying the relationship between patterns of material culture and human behavior on the ISS. These researchers have incorporated archaeological methods to evaluate sociocultural aspects of everyday life on the ISS. Archaeological projects, such as the ISSAP, are working to shift narratives away from those that view material culture in space as simply "space trash" (e.g., Kilic, 2022) towards discussions that highlight this material as important space heritage linked to individual and national identity. We hope the relationship between archaeologists and NASA continues in the future.

Archaeologists can also contribute key information about space heritage preservation by contributing data to aid in end-of-mission planning. For example, considering where to end certain missions (e.g., landers or rovers) and evaluating various formation processes to help ensure the protection of cultural materials and heritage. For example, from our review, it is clear that while lunar craters offer opportunities to sample for ice in permanently shadowed areas, craters (especially near rims) operate as depositional settings. Various triggering mechanisms, including natural and cultural surface disturbances, can trigger several mass movement events (e.g., rockfalls, avalanches, and debris flows) in such settings. This also has implications for the safety of future missions, as well as any scientific investigations of sites within or around crater margins.

A second key principle of planetary geoarchaeology is to provide data that can aid in future missions by following the three key research objectives germane to geoarchaeology (see Section 3). Geoarchaeologists empirically study the dynamics between humans and their environment, wherever that takes place. Space heritage currently on the Moon, and especially on other surfaces with more active depositional environments (e.g., eolian dunes on Mars), can be buried, hidden, destroyed, or potentially lost. Postdepositional processes occurring on the surface of extraterrestrial bodies have implications for preserving our species' history of exploration. Planetary geoarchaeology is necessary to address our history in space. Moving forward, we see the subdiscipline involved in four initial types of research: predictive, experimental, active/primary, and policy. The most immediate way planetary geoarchaeologists can study space heritage is through predictive research to understand all the types and effects of natural and cultural formation processes concerning space heritage. Historically and currently, the primary goal of a mission has been and will continue to be to ensure a success. Little attention has been paid to what occurs to objects once they are left behind. Planetary geoarchaeologists can address this issue, first by providing reviews of site formation processes on various planetary surfaces, and then by qualitatively and/or quantitatively making estimations about how those processes may affect different varieties of space heritage in the future. We provided a qualitative overview focused on the geoarchaeology of the Moon. However, we envision future research attempting to quantify when and how a certain site may be affected or buried. While some research focused on the effects of lunar surface processes on the life history of objects has already occurred with Apollo 12 and Surveyor 3 (Capelotti, 2009, 2010; Immer et al., 2011; Lane et al., 2012), other planets could provide further opportunities for planetary geoarchaeology. For example, on Mars, research aimed at calculating the rates for the inevitable burial of various rovers and associated tracks should be a primary area of research for future planetary geoarchaeologists, for example, dune systems encroachment toward the "homeplate" study area for the Spirit rover on Mars or the role of Mars' cryosphere in affecting space heritage. These studies could be applied case-by-case for the planets of Mercury, Venus, Saturn's Moon Titan, and five different comets and asteroids.

By targeting our review on lunar surface processes, we made several suggestions that can aid in preserving space heritage on the lunar surface. First, the safest area on the Moon is somewhere beneath the lunar surface, away from the deleterious and damaging effects of space weathering (charged particle and micrometeroid bombardment) and anthropogenic surface disturbance (future landings, hovering flights, or crashes). Second, permanently shadowed areas may be best for the preservation of manmade materials. However, these areas commonly occur under crater rims with higher mass wasting potential resulting gin the potential burial or destruction of space heritage. Finally, Capelotti (2010, p. 22) suggests that shielding Apollo base camps with domes could provide one way to protect key areas from natural processes such as solar radiation and extreme temperatures, as well as allow for space tourism.

A second way that planetary geoarchaeologists can contribute to the planetary sciences is by engaging in experimental research. Those experiments could evaluate the interaction between burial conditions and preservation of space heritage. For example, currently, several certified reference materials for Mars (MGS-1) and Moon (JSC-1A) sediment exist, and archaeologists could consider scientific experiments to measure preservation effects on various materials (e.g., osseous, organic, and metals etc.). Other experiments could include understanding the types of effects that space travel and human activity have on potential geological samples associated with archaeological sites (e.g., sedimentary structures formed within soil micromorphology samples when entering or exiting orbit).

A critical goal of planetary geoarchaeologists is the direct archaeological study of materials in situ on extraplanetary surfaces (e.g., archaeologists involved in missions to study space heritage in real time). While archaeologists have not yet been involved in space missions, perhaps the first example of unintended planetary geoarchaeological investigation occurred on November 20, 1969, when Apollo 12 landed about 180 m away from the Surveyor 3 prove 37 months after its landing on April 20, 1967 (Capelotti, 2009, 2015). Astronauts Conrad and Bean visited Surveyor 3, and removed parts of the probe, including a camera consisting of complex electromechanical components, optics, and solid-state electronics. These materials were returned to Earth and studied by 40 teams of NASA engineers and material scientists, providing the first study of lunar formation processes from human-made objects left on an extraplanetary surface (NASA, 1972). Although not slated as an archaeological investigation, P. J. Capelotti has called this "the first example of extraterrestrial archaeology—and perhaps more significant for the history of the discipline—formational archaeology, the study of environmental and cultural forces upon the life history of a human artifacts in space" (cf. O'Leary, 2009b, p. 30). As our explorations of the Moon and Mars continue to expand, opportunities to study the space heritage returned from extraterrestrial contexts in similar ways increases, and we envision planetary geoarchaeologists leading the way forward in this regard. Ultimately, we argue for archaeologists being involved.

Finally, planetary geoarchaeologists can help guide government litigation concerning preserving and protecting space heritage. As of 2023, the International Council on Monuments and Sites (ICOMOS) has created the Scientific Committee on Aerospace Heritage where planetary geoarchaeologists in the future can directly contribute to those discussions O'Leary (2015) writes:

> The Outer Space Treaty, ratified in 1967, specifies that those nations that place artifacts on the Moon retain ownership of them, while prohibiting title to the surface of the Moon. The Outer Space Treaty also emphasizes the importance of access to space and international peaceful cooperation (Hertzfeld & Pace, 2013). The Outer Space Treaty does not address preservation issues at lunar sites that will be relevant when new players such as China land their astronauts on the Moon, nor does it address the Google Lunar XPrize competition for the first commercial venture to place robotics on the lunar surface. (p. 9)

Although the Google Lunar XPrize competition is no longer relevant, several current missions (e.g., Beresheet-1 and Hakuto-1) grew out of that competition. The use of space continues to grow both nationally and commercially. From this perspective, future international agreements, criteria for the evaluation of significance, and protocols could be put forth via the World Archaeological Congress that could outline how we can collectively manage space heritage, although the Convention does not specifically address outer space or other celestial bodies besides Earth. Geologists, archaeologists, and anthropologists ought to consider how these future efforts can happen. Hopefully, if planetary scientists consider including space archaeology and heritage, new funding opportunities for planetary geoarchaeology and historic preservation will emerge. It is clear that NASA could provide funding to support planetary geoarchaeology research and encourage collaboration, especially given the success of NASA's (2011) recommendations to space-faring entities.

6 | CONCLUSION

As we enter the new Space Age and continue to expand our material culture across the solar system, we urge the larger international archaeological community to continue to turn their attention towards the preservation of space heritage. Social scientists, anthropologists, and archaeologists are ideally situated to contribute novel solutions to issues in space heritage preservation. We propose the inclusion of planetary geoarchaeology as one critical avenue of inquiry, providing an example of how the field can make valuable contributions to the larger field of planetary science. Despite common misconception, the lunar surface is not a static setting, but in fact is quite dynamic and characterized by many formation processes capable of altering, destroying, and/or preserving space heritage. Those processes, described and investigated by lunar scientists, include charged particle and meteoroid bombardment, a highly variable thermal gradient, shallow and deep moonquakes, mass movement events including debris flows, slumps, and creeps, rock avalanches and slides, and grain avalanches, and most recently, surface disturbance via hovering flights, landings, crashes, and human activity. Planetary geoarchaeologists can provide knowledge about how these forces and events can affect material culture significant to our species recent history of space exploration. By introducing the subfield of planetary geoarchaeology, we hope to spark discussions about how geoarchaeologists can contribute to space archaeology and the larger field of archaeology and the ongoing scientific exploration of space. We urge all our scientific colleagues to continue to think about and contribute their ideas how humans can document, study, and ultimately, preserve our forays into the solar system.

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