THE LUNAR REGOLITH AS UNDERSTOOD FROM NEAR AND FAR.

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Introduction: Before astronauts left their first bootprints, a basic understanding of the unsorted fragmental debris covering the Moon's surface, the regolith, was gleaned from images collected by the Ranger, Lunar Orbiter, and Surveyor spacecraft. Though not universally agreed upon, it was thought that the regolith was produced by impact events, was fine grained at the surface, and was generally at least several meters deep [e.g., 1–4]. Understanding such properties of the regolith was one of the science highlights of these Apollo precursor missions, though their main goal was to gain knowledge required to design for future lunar surface operations.

But for the science of the lunar regolith, the samples returned by Apollo were both an immediate revelation of processes wholly unique from those on Earth, and a slow reveal of intricate agents of change occurring on the lunar surface. Our understanding of these processes continue to evolve even now, fifty years later, as technology advances and orbital measurements provide new context and meaning. Here we review what we have learned about the key processes that give the Moon its distinctive appearance and form the basis of our understanding of how a planetary body evolves when its surface is laid bare to the space environment.

Regolith Generation: Hypervelocity impacts of all sizes work to break surface rocks into smaller fragments. This can happen in catastrophic events, such as those that produced the Moon's megaregolith, the kilometers-thick fractured and brecciated debris from basin-forming impacts that makes up the upper crust of the lunar highlands and results in its high porosity [e.g., 5,6]. However, the dominant process by which surface rocks are transformed into finer grained regolith is by the "sandblasting" effects of smaller but frequent micrometeoroid impacts [e.g., 7]. Thermal fatigue due to extreme temperature cycling has also been recently identified as a contributor to regolith generation [e.g., 8].

Meter-scale blocks on the Moon survive on the order of several hundred million years [9], and rock abundance rapidly declines at fresh impact craters at a rate that can be used to determine the age of craters that are younger than ~1 Gy [10]. Thermal measurements suggest that regolith generation is so efficient that the average areal fraction of surface rocks is just 0.4% [11]. Whether or not a relatively fresh impact crater has rocks in its ejecta can be used to determine whether it excavated to a depth greater than that of the local regolith; rocky craters suggest mare regolith depths are frequently less than 5 m, whereas the highlands regolith is thought to be substantially thicker [e.g., 12,13]. Other methods to estimate local regolith depth include determination of crater equilibrium diameter, crater morphology, and seismic investigation [e.g., 3,4,14,15].

Physical Properties: The average grain size (by mass) of Apollo regolith samples is typically 60–80 µm and over 90% of the regolith is <1 mm in in size [e.g., 16]. While never observed in situ, photometric and thermal measurements show that the uppermost regolith (upper few mm) is an extremely porous (>80% porosity) "fairy castle structure" where grains are precariously supported by adhesive and electrostatic forces [e.g., 17–19]. This upper structure has profound effects on remote reflectance and emissivity observations.

Below the surface, density rapidly increases, and thermal infrared measurements show that the characteristics of the upper ~10 cm of the regolith display remarkably little variation across the Moon, apart from at the most recently formed impact craters [19]. While it was known that fresh impact craters have higher nighttime temperatures due to the exposure of rocks and impact melt [e.g., 20], these observations revealed a new class of crater: those whose extreme distal ejecta (~10–100 crater radii) exhibits cooler than average nighttime regolith temperatures [21]. Within these "cold spots", it appears that some aspect of the impact process lowers the density of the upper ~10 cm of regolith. Regolith gardening (see below) then rapidly restores typical thermophysical properties within ~100–200 ky [22].

Space weathering: Fresh impact craters are some of the most striking features on the Moon: their high-reflectance rays extend far from the crater, contrasting sharply against a darker background. Apollo samples revealed why these bright features fade with time: a process known as space weathering. The understanding of this process and precisely how it decreases the reflectance of regolith exposed on the surface of the Moon has unfolded slowly. Initial examination of returned samples revealed that in addition to the mineral, rock, and breccia fragments that comprise the lunar regolith, in typical soils over half of the particles are agglutinates [e.g., 23]. These agglutinates are formed via small impacts that simultaneously produce glass, which subsequently welds soil grains together, and convert ferrous iron to small iron particles that are strong absorbers of light [e.g., 24–26]. Thus, soils gradually darken as micrometeoroid bombardment creates agglutinates.

Charged particles from the solar wind also affect the regolith by amorphizing grain surfaces and ejecting elements like iron that are redeposited on nearby regolith grains [e.g., 27–29]. Both this process and micrometeoroid impacts [e.g., 30,31] are thought to result in thin rims containing small (average <5 nm [32]) iron particles that coat nearly all grains in a mature regolith and redden reflectance spectra. These iron particles, on grain rims and in agglutinates, are the principal cause for the changes in reflectance of soils as they mature. It was not until over 20 years after the end of the Apollo program that transmission electron microscopy was able to resolve these iron particles in lunar samples [30,33], though they were suggested to exist long before [34].

Regolith Gardening: Once regolith has been generated, the ongoing rain of impactors ensures that it is a dynamic environment, continually mixed and reworked to varying degrees at different depths. This process homogenizes the thermal properties and exposes, buries, and re-exposes soil to space weathering so that it is mature to greater depths. Initial models suggested that it takes ~10 My to garden the regolith to a depth of 2 cm [35]. However, images collected of the same location at different times have enabled views of the surface both before and after a new impact crater has formed [36,37]. These images reveal the extent to which the ejecta from an impact event affects the regolith beyond just the primary crater and its proximal ejecta deposits (e.g., surface changes are observed tens of km away from 10-m impact craters). When these secondary effects are considered, it is clear that regolith gardening is over 100 times more rapid than initial models suggested [37,38].

Below the surface, layers derived from discrete ejecta emplacement events can be observed within Apollo core samples [39–41], so that each core, even if separated by just a few meters, records the unique impact history of that location. This regolith layering is observed as differences in grain size and maturity, with some compositional variation (e.g., basaltic fragments found within the Apollo 16 highlands core [42]). Though ejecta can be emplaced at great distances, the largest effect of distal ejecta is to churn the local regolith through a process known as ballistic sedimentation [43]. This mixing implies that the regolith collected at or near the surface (all Apollo samples) is largely representative of the bedrock below, with a small but significant component of material that originated at greater distances.

Mysteries of the Lunar Regolith: Important and compelling problems remain to be solved in the coming years and decades of study of the lunar regolith. While the nearside regolith has been sampled, the deepest core extended to just 3 m, and no regolith has been examined alongside the context of its underlying bedrock. Farside regolith/megaregolith and the distinct history of the Feldspathic Highlands Terrane it contains is as yet unexplored. Similarly, regolith that formed early in the Moon's history and was later buried and preserved, such as below a basalt flow, holds key information about the early lunar environment and solar history, but has not been sampled. Additionally, though well known for most of the Moon, much remains to be learned about the geotechnical properties of polar regolith, with large implications for resources that that may be present.

Another important open issue is determining the origin, emplacement, and transport of volatiles stored in the lunar regolith. Solar wind implanted H has been proposed as a mechanism for the formation of OH and H_2O on surface grains, although its temporal and/or latitudinal variations across the surface are still being studied [44–46]. If and how volatiles migrate through the regolith to be stored in the subsurface of permanently shadowed regions at the poles is not yet known.

Although many details of how space weathering affects the lunar regolith are well known, fundamental issues remain. Chief among these are the relative roles of the solar wind and micrometeoroid bombardment in creating mature soil. Here studies of Apollo samples and recently collected remote observations are in sharp conflict [e.g., 47,48], with interpretations of samples suggesting micrometeoroid bombardment is the dominant space weathering agent, and remote sensing pointing to the solar wind. Additionally, the origin of the bizarre and beautiful lunar swirls and their implications for space weathering remains an important open question.

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