Science of the Moon (Section 8, Chapter 46)

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Abstract:
Science of the Moon discusses the present state of knowledge of the Moon, as well as the scientific questions remaining about the Moon's history and current attributes. This chapter covers events in lunar history, the geology of the Moon, properties and modification of the lunar regolith, the effects of radiation on the lunar surface, volatiles including those in the lunar Permanently Shadowed Regions, as well as the lunar seismic environment and what it indicates about the lunar interior. The chapter also lists instruments that, when deployed on the Moon or utilized in a lunar sample analysis facility in a lunar base, contribute to knowledge of the Moon. Presented within the chapter are unanswered questions regarding cratering on the lunar surface, the transition from bedrock to regolith, lunar tectonism, the crustal structure and composition of the Moon, reserve potential for in-situ resources, and the nature of the volatiles on the Moon.

1. Science of the Moon

Humanity has learned a great deal about the Moon, particularly over the last 60 years, with both remote sensing surveys and ground truth data. The ability to analyze Apollo and Luna samples provided scientists with the geochemical clues that the Moon formed approximately 4.5 billion years (Ga) ago. The leading theory involves a giant impact; a Mars-sized impactor struck Earth, sending pieces of both into orbit; the pieces in orbit coalesced into the Moon. Another theory involves co-formation of the Earth-Moon system. These particular theories of lunar formation were not conceived prior to the return of lunar samples, because scientists had no way of knowing the two planets had a nearly identical oxygen isotope signature. Other discoveries include the asymmetry between the lunar near side and far side, the lack of a current global magnetic field but evidence of a dynamo in the past, the presence of subsurface mass concentrations (mascons), moonquakes, and the properties of rocks and regolith. These discoveries have led to even more questions about the Moon; the following sections identify and describe some of these remaining questions. [Hartmann and Davis, 1975; Cameron and Ward, 1976; Canup, 2019; Canup, 2012; Lunar Exploration Roadmap Steering Committee, 2016; Lock et al., 2018]

1.1 The History of Lunar Surface Development

Our current knowledge of the geology, geophysics, and geochemistry of the Moon is provided by observations and analysis of samples from the very top of the lunar crust. These observations indicate the primordial lunar crust formed during solidification of a global, Lunar Magma Ocean (LMO). After its formation, the Moon was a molten mass. As the magma cooled slowly, the geochemistry of the LMO allowed specific minerals to form. Minerals that were denser than the surrounding LMO liquid sank to the bottom, toward the lunar core. The mineral plagioclase, which was less dense than the surrounding LMO liquid, rose to the top, forming the primordial lunar crust. The magma continued to crystallize. The last material to form is known as urKREEP (K for potassium, REE for rare earth elements, and P for phosphorous); these elements are incompatible with most rock-forming minerals. Isotopic dating of Apollo samples indicates the formation of urKREEP occurred by 4.3 Ga ago. The Moon was certainly not a simple, quiet place during or after this time. Magmas continued to be generated within the Moon that mixed the components of the LMO and resulted in different lithologies, including the magnesium suite (Mg-suite). Also occurring simultaneously, large impactors struck the newly formed lunar surface, forming large impact basins. These basins include the South Pole-Aitken basin, Procellarum, Imbrium, and other smaller basins. After basin formation, mare lavas flooded and filled them by approximately 3.1 Ga ago, although evidence from meteorites indicates mare volcanism occurred even as late as 1 Ga ago. Degassing via volcanism and impact events likely contributed to a transient atmosphere for the Moon at this time, which dissipated due to the lack of gravity needed to maintain the atmosphere and leading to a very thin concentration of volatile elements surrounding the Moon called an exosphere. Continued impacts and the resulting surface "gardening", and thermal cycling, led to the formation of the lunar regolith (see Chapter 8 for additional information). In addition, the lunar surface has been bombarded by micrometeorites, solar wind, and cosmic rays over the last three billion years; the evidence of which manifests itself in agglutinates, nanophase iron, and differences in certain elements' isotopic ratios due to neutron capture cross sections, among others. Lunar geologic history is divided into five periods; the Imbrium Epoch is further divided into upper and lower units (Table 1.1). [Wood et al., 1970; Smith et al., 1970; Gaffney and Borg, 2014; Joy and Arai, 2013; Needham and Kring, 2017; Hörz et al., 1991; McKay et al., 1991; Molero et al., 2015]

Table 1.1: Lunar history periods (Wilhelms et al., 1987)

Stratigraphic Age	Age of the Moon
Pre-Nectarian (early crustal materials, basin and crater materials, volcanic materials)	3.92Ga-4.55Ga
Nectarian (Janssen Formation – Nectaris basin, additional basin and crater materials, as well as volcanic materials)	3.85Ga – 3.92Ga
Lower (Early) Imbrian Epoch (Fra Mauro Formation – Imbrium basin, additional crater and volcanic materials, Hevelius Formation – Orientale basin)	3.8Ga-3.85Ga
Upper (Late) Imbrian Epoch (Krieger crater, extrusion of mare materials)	3.2Ga-3.8Ga
Eratosthenian Period (mare materials; craters Lambert, Eratosthenes, Timocharis, Euler, Delisle, and Diophantus)	1.1Ga-3.2Ga
Copernican Period (end of mare volcanism; craters Copernicus, Pytheas, Kepler, Aristarchus, and Tycho)	Present-1.1Ga

One of the most important investigations completed during Apollo was core sampling of the lunar regolith, which provided information about the evolution of the regolith and about its textural and structural complexities. Study of the core samples also indicated the lunar regolith is layered. The lunar regolith also preserves information about the Universe. For example, regolith traps atoms from the Sun, as well as cosmic ray particles generated outside the Solar System. Data obtained from regolith regarding the history of the Moon also contain information about the composition and early history of the Sun, and the nature and history of cosmic rays. The regolith has preserved information about the rate of impacts and cosmic dust deposition on the Moon, and by inference, the Earth. Learning about each from studies conducted on lunar samples is certainly a reward of lunar science. [Smith, 1991; Benaroya, 1995; NRC, 2007]

1.2 Geology

1.2.1 Volcanism

With each new sample analyzed, and with each new data set obtained by remote sensing, the history of the Moon is further detailed. Of particular interest is the petrogenesis of lunar materials; this helps refine the models of lunar formation, differentiation, and magma evolution. The crystallization process locks in an isotopic signature, which defines the absolute age of the rock. Unfortunately, for some isotopic systems, this signature can be disturbed by the heat and pressure associated with impact, although this property has also been used to determine the ages of lunar impacts. Particularly, the impact disruption of samples older than 3.9 Ga may make it difficult for the oldest episodes of lunar volcanism to be explained precisely. [Pepin et al., 1972; Culler et al., 2000]

Lunar volcanism can be divided into three epochs: pre-mare volcanism (i.e., Mg-suite), mare-filling volcanism, and late-mare volcanism (i.e., high-Ti and low-Ti mare basalts). The episodes of later volcanism are of interest because they can yield information about the thermal history of the lunar interior. Because lavas originate from the partial melting of rocks, the geochemistry is indicative of the original material and the heat source. Thus, lavas serve as probes of the mineralogy and chemical composition of otherwise inaccessible planetary interiors. Although the mare rocks cover only 17% of the Moon's surface and only 1% of the crustal volume, they provide a broad picture of the Moon's geochemical processes. [Duke and Mendell, 1988; Vondrak, 1992; NRC, 2007]

According to a detailed analysis of spectral properties, Apollo and Luna missions have sampled at most one third of the volcanic basalt types exposed on the near side of the Moon. More intelligent sampling can now be made through the detailed photographic and geochemical analysis of the Moon provided by remote sensing orbiters such as Chandrayaan and the Lunar Reconnaissance Orbiter. Good sampling also requires thorough field work, in which samples are taking from identifiable rock units such as those exposed in the walls of rilles, wrinkle ridges, lobate scarps, craters, and volcanic domes. Volcanic stratigraphy and the changes in basalt composition with time may be studied at these locations by automated or teleoperated lunar landers. Where such features are not exposed, samples can be obtained by drilling or trenching in the lunar surface. Lava tubes with skylights, volcanic vents, and pyroclastic flows also provide enticing locations for both science and resource utilization. A series of landings and traverses within the rings of determined basins would provide an opportunity to visit shield volcanoes and fissure vents that may have erupted only enough lava to fill the bottoms of ring depressions. A geologic investigation of mare basalts could be completed by visiting mare locations with different ages and different spectral signatures; visiting progressively older mare basins for field studies will eventually provide the observations and samples necessary for reconstruction of the history of lunar mare volcanism with a greater degree of confidence. [ESA, 1992; Taylor et al., 1985; NRC, 2007]

1.2.2 Meteorite Impacts

The Moon provides a unique look at the inner Solar System impact record because the surface has preserved evidence of impacts for an estimated 4 Ga. In addition to impact ages determined for Apollo samples at very specific locations on the Moon, the relative age of lunar surfaces has been established by crater counting (determining the number of craters per surface unit and the size/density ratio), as well as impact ejecta stratigraphy and crater morphology. Studying these impacts would create a unique record of the historical abundances of comets and Earth-crossing asteroids. Unfortunately, extrapolations of lunar impact history suggest craters older than about 4.2 or 4.3 Ga have not been preserved due to the continuous bombardment of the surface. Further defining the rate of changing bombardment with time may reveal answers about the origin theories, as well as a proposed "lunar cataclysm". This particular cataclysmic event would explain a prevalence of 3.9 Ga impact ages in lunar samples and has been proposed as a contributor to life on Earth; however, it has yet to be proven. By studying the features of the craters, the composition of the glass formed by the impact, and the distribution of fragments of the impacting object, it should be possible to distinguish primary from secondary craters, the compositional characteristics of the impacting object, and the age of each crater. Meteorite impacts, and in particular micrometeorite impacts, dominate surface weathering processes. Erosion rates have been calculated for the Moon. The internal stratigraphy of craters is also of major interest and could be mapped and sampled using tele-operated equipment. Most of the excavation could be done by remote control, with an astronaut visiting the site only periodically to map trench walls and collect samples. The information gained, in conjunction with that from samples taken from the rim and radially outward, would yield first-order insight into the petrologic character of the materials and into the mechanics of impact cratering including accompanying thermal processes and regolith mixing [Duke and Mendell, 1988; ESA, 1992; Gehrke, 1992; Marov, 1997 (personal communication); Taylor and Spudis, 1988; Culler et al., 2000; NRC, 2007; Neal, 2009; Fassett and Thompson, 2014]

1.2.3 Impact of Solar Wind, Solar Flares, and Galactic Cosmic Rays

As described in Chapter 9, the Moon is almost completely devoid of an atmosphere and an intrinsic magnetic field, which means its surface, like those of other airless bodies in the Solar System, is in direct contact with the interplanetary medium and is subject to space weathering. Because lunar geological evolution has almost completely ceased for more than three billion years, the evolution of the lunar surface has been dominated by these external processes. That is, changes to the lunar surface are caused by meteorite impact, thermal cycling, and radiation. Particle radiation sources for the lunar surface are solar wind, solar flares (solar particle events), and galactic cosmic rays. For example, high-energy particles from solar and galactic cosmic rays induce nuclear reactions with regolith atoms, as well as the formation of nuclear particle tracks. The resulting changes in stable and radioactive isotopes, apparent when compared to chondritic abundances, have been used for determining lunar surface exposure ages. Conversely, the observed irradiation effects can help unravel the history of external radiation over several billion years. Using this approach, the variations of the composition of the solar wind over the last few billion years have been determined. Studies of the amorphous layers on lunar grain surfaces produced by solar wind irradiation seem to indicate a systematic increase in solar wind speed during the last two billion years. The total number of solar particles collected on the Moon and the distribution of solar noble gas isotopes reveal that either the solar wind flux or the flux of suprathermal particles, or both, were higher in the past than they are today. Unfortunately, radiation studies of Apollo samples have been limited to the last 1 to 2 billion years, due to the maximum coring depths. Thus, the radiation database would greatly benefit from a dedicated sampling program, which could be combined with a deep drilling program. [Adams and Shapiro, 1985; ESA, 1992; Grindlay, 1992; Pieters and Noble, 2016]

One significant impact from solar wind and flares is the charging of the lunar surface. Photoemission of electrons causes the sunlit portion of the lunar surface to be positively charged, whereas plasma electrons cause the lunar nighttime surface to be negatively charged. Plasma ions, and secondary electrons generated from the ionization of the surface by plasma electrons, are also factors in the charging of the lunar surface. Moreover, the local plasma environment on the surface varies with the lunar month including solar wind dayside, nightside wake cavity, magnetosphere, magnetotail lobes, and plasma sheet. Local topology has also been shown to contribute to surface charging effects. Within shadowed regions such as those within polar craters, called Permanently Shadowed Regions (PSRs), local plasma wake systems form with electrical potential differences that can reach 1 keV. These regions in particular pose a hazard to astronauts and rovers whose movement within this low plasma environment produces triboelectric charging and is proportional to its speed. This surface charging is thought to drive the levitation and transport of lunar dust less than 20μm in diameter, with heavier grains estimated to remain closer to the surface and lighter grains soaring even to 10km above the lunar surface. Both Surveyor and Apollo missions observed dust levitation and transport. However, measurements from the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission indicate a contribution from interplanetary dust particles and meteorite showers to the lunar dust cloud, and the LADEE mission did not detect lunar dust at its orbit altitude, leading to the conclusion that dust grains do not have sufficient energy to make it into orbit. Scientific investigations of lunar dust would include testing the levitation and transport mechanisms proposed, as well as monitoring the influx of interplanetary dust particles and meteorites. Knowledge of the electromagnetic plasma environment at the lunar surface will also provide valuable observations to assist in understanding surface charging and the potential hazards to humans and electronics. [Stubbs et al., 2007; Zimmerman et al., 2012; Horányi et al, 2015; Jackson et al., 2015]

1.2.4 Volatiles

The Moon has such a small tilt in its axis of rotation relative to the Sun that craters at the poles never see sunlight. These are referred to as PSRs. Because they do not experience solar heating, the temperature in the craters is maintained at or below 40K. It was in these PSRs that signals indicative of water-ice observed by the Arecibo telescope, as well as Clementine and Lunar Prospector orbiters, which were confirmed by later missions such as Chandrayaan-1, the Lunar Reconnaissance Orbiter (LRO), and the Lunar CRater Observation and Sensing Satellite (LCROSS). The LCROSS mission, as well as complementary monitoring missions such as LRO, detected additional compounds and mercury. The nature of the regolith containing these volatiles, as well as the origin of the water and other volatiles, including in locations outside of the PSRs, continues to be debated. Some suggest solar wind implantation of hydrogen into the regolith coupled with a water molecule migration process; other suggest releases of water by volcanic offgassing early in the Moon's history; and still others propose cometary impact as the source of water in the PSRs. Processes for how the ice formed help determine the extent of future prospecting of these resources on the Moon. Science experiments studying these volatiles and the volatile cycle must focus on quantifying the volatiles present, their variability in concentration, depth or extent, and origin.
[Nozette et al., 2001; Anand, 2010; Colaprete et al., 2010; Gladstone et al., 2010; Siegler et al., 2016; Needham and Kring, 2017; Lunar Exploration Analysis Group, 2017; Cannon and Britt, 2020]

1.3 Geophysics

Due to the absence of global resurfacing and weathering, the Moon exceptionally preserves valuable evidence of planetary formation and early solar system processes. This history is studied through several disciplines including geology, geochemistry, and geophysics. Geophysical inquiries constrain the current temperature, state, structure, and composition of the lunar interior. These investigations include seismic, magnetic, gravity, heat probe, and laser ranging experiments. A precise understanding of the current state of the lunar interior is the first step towards unlocking its past. The following paragraphs provide a summary of the current state of knowledge of the lunar interior and highlight outstanding geophysical investigations.

1.3.1 The Lunar Interior

The interior of a planet is probed through a variety of geophysical methods and datasets. Among the most precise constraints are seismic analyses that observe mechanical waves reflecting off discontinuities within the subsurface including the thickness of the crust, mantle layers, as well as the inner and outer cores. Fig. 1 shows a cross-section of the Moon summarizing the current state of knowledge of the interior structure. Modern computation tools and analysis methods have enabled a re-analysis of the Apollo seismic data that suggests the Moon has a differentiated metallic, iron-rich core up to ~330 km, as well as a seismically attenuating partially molten layer 150 km thick above the core absorbing energy from farside moonquakes. Some questions remain regarding the nature and existence of this layer. The lunar core, similar to the Earth, contains a differentiated solid inner and fluid outer layer where the iron is mixed with up to 6% light elements such as sulfur or carbon, although some have suggested nickel. Electromagnetic sounding analyses have obtained an upper limit on a conducting metallic core of 430 km, however, these are also consistent with no core as the small size of the lunar core make it very difficult to detect in magnetic field data. Precise measurements of the global gravity field variations along with topography have enabled the thickness of the crust to be mapped with an average crustal thickness of 34 - 43 km, nearly 30% thinner than previous estimates.

The top priorities for improving the state of knowledge of the lunar internal structure include:

- A global geophysical network of at least four surface stations, each with a broad-band and short period seismometer, a heat-flow probe, electric probes, and a fluxgate magnetometer with continuous operations for ~10 years and with a wide geographical distribution (including the farside)
- Sample returns providing a more representative set of the whole Moon to determine the variability in compositional reservoirs and better understand the paleomagnetic field.
- Global mapping of magnetic, electric properties and surface composition (including the distribution of volatiles) from low lunar orbit with special attention at the poles to better understand the PSRs.

Measurements of electromagnetic fields at the lunar surface provide an understanding of the electrical conductivity, which is used to also understand the composition as a function of depth. Surface heat flow measurements constrain the thermal conductivity, which is used to better understand the temperature profile of the interior. Both of these are expected to vary laterally as well as vertically, so global stations or multiple locations are needed. A detailed discussion of lunar seismology and magnetism follow. [Elardo and Shahar, 2017; Jaumann et al., 2012; Jawin et al., 2019; Steenstra et al., 2017; Weber et al., 2011; Wieczorek et al., 2013]

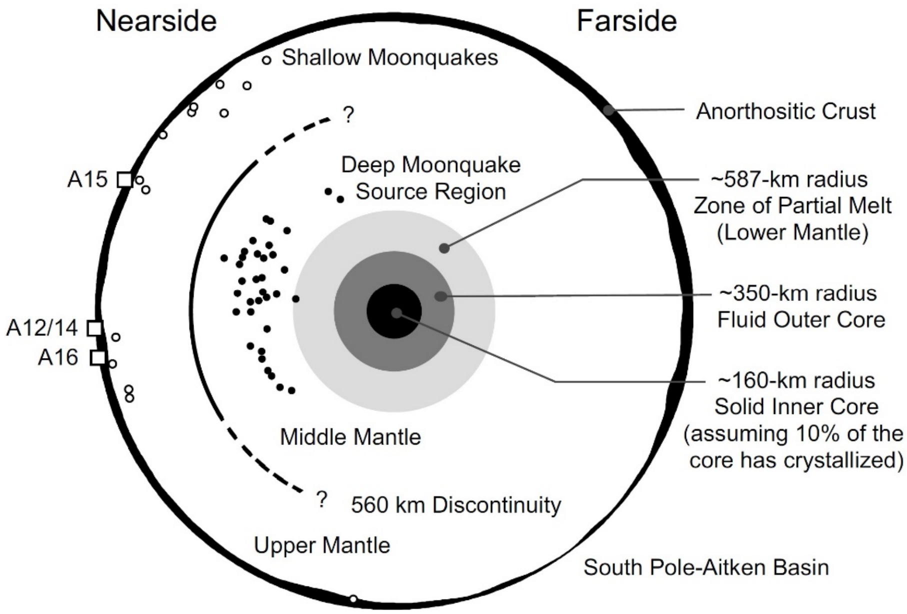

Fig. 1: Interior Structure of the Moon, Based primarily on Apollo data (modified from Wieczorek et al., 2006).

1.3.2 Lunar Magnetism

The Moon does not currently have a global magnetic field originating from a dynamo, but does have areas of enhanced magnetization concentrated within areas of the crust. This magnetization has been measured at the surface during the Apollo missions, and from orbit by Lunar Prospector, Kaguya, and others. These areas of enhanced magnetic field can scale up to 100km in altitude and >40nT in strength. Moreover, a recent analysis of crustal fields observed a distinct low in magnetization beneath the Procellarum KREEP Terrain region, likely due to the enhanced heat production concentrated there. In addition, paleomagnetic analyses of Apollo samples show lunar rocks contain thermoremanent magnetization measuring the magnetic field magnitude, orientation, and age of the sample when it formed. Both data sets imply a long-lived global dynamo (from 4.25 Ga until as recent as ~1 Ga) with surface field strengths between ~5-100 µT, similar strength to the Earth's field today. However, thermal evolution models of magnetic field dynamo processes are not able to fully explain both the high initial intensity and the lower-level, long-lived paleomagnetic observations. This may require two or more different dynamo mechanisms. The exact timing, strength, and structure of these fields are not precisely known. One theory uses the observations of enhanced crustal fields antipodal to impact basis to suggest that impacts may generate transient magnetic fields within the surface plasma environment that created the crustal magnetization. Observations of lunar surface swirl features, finely structured bright and dark albedo anomalies of 1-5 km scale size sometimes associated with these crustal magnetic fields, further suggest that space weathering process at the lunar surface have important implications. Moreover, the existence of a paleomagnetosphere has implications for the origin of the volatile content observed at the lunar surface, and may have increased solar wind bombardment at the poles.

Another method used to probe the interior structure of the lunar mantle and possibly down to the core is Electromagnetic Sounding. While Electromagnetic Sounding uses only magnetic fields, Magnetotellurics relies on simultaneous horizontal components of both the electric and magnetic fields at the surface. Both methods determine the strength and orientation of induced fields; this is used to derive an electrical conductivity profile. These methods are complementary to seismic velocities and are used to understand the composition and structure of the interior. Additionally, full characterization of the near surface lunar plasma environment is helping understand how induced magnetic fields interact with current systems formed at the surface. This technique will better constrain the composition, temperature, structure, the existence of a partially molten layer at the core mantle boundary, and size and state of the core. Future analysis of returned samples will provide additional data points for a better understanding of the paleomagnetic field, as well as future sounding analyses will better constrain lateral and vertical differences in electrical conductivity. Moreover, additional dynamo mechanisms, including modeling and theory development based on improved temperature and compositional inputs, will provide additional insights into these outstanding questions. [Lin et al., 1998; Hood et al., 1999; Mitchell et al, 2008; Grimm and Delory, 2012; Shimizu et al., 2013; Tsunakawa et al., 2015; Tikoo et al., 2017; Hemingway and Tikoo, 2018; Evans et al., 2018; Wieczorek, 2018; Fuqua Haviland et al., 2019; Garrick-Bethell et al., 2019]

1.3.3 Lunar Seismology

Seismic stresses release energy within the Moon in the form of moonquakes. These events are caused by tidal, thermal, and tectonic stresses, as well as by meteoroid impacts. Seismology offers the most precise measurement of interior structure when compared to other geophysical techniques. The velocity of the waves differs based on the composition of the interior layers, the path taken between the source of the event, and the surface seismometer. Seismometers can be linked into a network of simultaneous observations that increases the fidelity of the data returned in terms of the depth and location of the event. Four Apollo stations (A12, A14, A15, A16) contained three component long period, and vertical only short period seismometers as a part of the Apollo Lunar Science Experiment Package (ALSEP), which operated as continuous network from 1972-1977. These stations contained both passive and active seismic experiments. The Apollo seismic network formed roughly an equilateral triangle of ~1,000 km per side on the lunar nearside. This short extent of the seismic array limited the global observation and in particular, only one farside event was found. Thermal stresses occur over the lunar day due to the large temperature extremes experienced at the surface and contribute to boulder breakdown and regolith production. As discussed above, the reanalysis of deep moonquakes, caused from tidal stresses, found reflections off a differentiated core with a seismically attenuating melt layer above the core. This layer likely formed beneath the crust, enriched in incompatible elements similar in composition (high-Titanium rich) to the KREEP signature measured on the lunar nearside which sank to the core-mantle boundary during a mantle overturn event. Other analyses use an elevated temperature profile and rheological model to demonstrate that no melt is required in this region. Moreover, brittle-ductile failure, the mechanism proposed to explain the deep moonquakes also located in this region, is not consistent with melt. More work and observations are needed to better understand the deep lunar interior. Other questions include lateral variations in composition and temperature, and nature of shallow moonquakes. Shallow moonquakes are thought to be associated with recent tectonic activity along young thrust faults; these are believed to be caused by global cooling and recorded in the form of lobate scarps observed at the surface. Future seismic observations should include a global network to include the farside and will illuminate the lunar interior in great detail. [Taylor, 1985; Wilhelms, 1985; ESA, 1992; Johnson and Wetzel, 1992; Spudis, 1996; Weber et al., 2011; Garcia et al., 2011 and 2012; Nimmo et al., 2012; Khan et al., 2014; Watters et al., 2019]

1.3.4 Thermal Properties of Lunar Soil

The thermal properties of lunar soil were measured during the Apollo missions, as well as globally and remotely during the Lunar Reconnaissance Orbiter mission. The experiments installed on the Moon during Apollo provided extensive information on the temperature and thermal properties of the lunar surface layer, at specific locations, to a depth of 3 meters. These measurements included surface temperature variations, near-surface thermal properties, subsurface temperature variations, and thermal conductivity. All of this information is essential to understand the total heat budget near the lunar surface and the contribution from the lunar interior.

Thermal inertia, which is the ability of a material to resist heating or cooling at the same rate as its surroundings, is indicative of mineralogy and materials and can provide information about the makeup of the lunar surface. Thermal inertia studies of the Moon indicate the conductivity and density of the lunar soil must vary with depth. Additionally, many "hot spots" that cool more slowly during the lunar night correlate with the interiors of fresh craters where large blocks are exposed. In the regolith, which is dominated by particles under 1mm in size and having a large ratio of surface area to mass, heat is absorbed more rapidly than it is in large blocks or outcrops with a small ratio of surface area to mass. It has been shown that rocks smaller than 30cm tend to have thermal losses like regolith, but rocks larger than 10 meters retain heat as if they were a solid outcrop. Rocks tend to be excellent thermal insulators; this property must be anticipated when designing an experiment involving, or exploiting, the thermal properties of lunar materials. [Heiken et al., 1991]

1.4 Geochemistry

Given that only a fraction of the lunar surface has been sampled, many more analyses still need to be completed to provide sufficient information regarding the composition of the crust to fully determine the history of the Moon. Any new chemical data on lunar materials will be helpful in answering questions about the crust's origin and constitution.

1.4.1 Surface and Soil Chemistry

The chemical composition of lunar regolith reflects its mixed origins. That is, all regolith samples brought back from the Moon contain some components exotic to the collection site. This was by design; sites were selected to provide the greatest amount of scientific knowledge about the Moon, through the greatest variety in samples, achievable within a small distance of the landing site. This same strategy is used for study site selection on Mars. Most, if not all, of the materials sampled at a lunar base will be regolith materials; bedrock may only be exposed in the walls of very steep craters, and it has not been sampled to date. Most sampling strategies will contribute to regolith characterization regardless of the overall purpose of the study. [McKay et al., 1991]

As described in chapter 8, the lunar surface can be divided into the darker lowlands (maria) and the brighter highlands (terrae). Their difference in albedo reflects the difference in chemical composition. Greater distinctions in the chemical makeup of the lunar surface have been provided by orbiting instruments such as gamma ray spectrometers and other spectral imagers; these provided information about locations rich in KREEP and titanium that are not distinguishable by albedo. Further investigations of samples from different sites are essential to obtain better estimates of lunar soil composition. Additional data would also significantly improve knowledge of the composition of the lunar crust. As more sophisticated sensors and techniques are developed for more detailed and precise measurements collected in-situ or at a lunar base, real-time assessments and adjustments of exploratory activities can be made. [Heiken et al., 1991; Spudis, 1996]

1.4.2 Internal Chemistry

Variations in trace element abundances in minerals record inputs from parent rocks and mixing processes over time. For example, most lunar rocks have a significant europium anomaly because plagioclase crystallization causes a loss of europium from the melt as the europium is incorporated into the plagioclase structure. Any future minerals that form from that melt will show that withdrawal of europium in their trace element abundances. Another example is the source of mare basalts. These lavas come from depths greater than 200km and thus provide direct information on the composition of the lunar interior. So far, the samples with the most primitive compositions are from glassy materials that came to the lunar surface via pyroclastic eruptions. These glasses have the lowest Fe/Mg ratios and the most unfractionated patterns of refractory elements among all lunar samples. It also appears that they reflect a more volatile lunar interior than previously thought. Consequently, one major goal of future lunar sample recovery must be to gather additional samples of these glasses. [Heiken et al., 1991; ESA, 1992]

1.5 Sample Missions and Experiments

In this section, candidate lunar science experiments are presented. These experiments are aimed at investigating the most important unanswered questions about the Moon. A selection of these questions is given in table 1.2. A more detailed summary of research issues regarding Science of the Moon can be found in Heiken et al. (1991), Hiesinger and Head (2006), NRC (2007), Neal (2009), the Planetary Science Decadal Survey (Space Studies Board, 2011), and the Global Exploration Roadmap (ISECG, 2018) and references therein. Sample return at the South Pole-Aitken Basin has been cited as a significant priority to planetary scientists, particularly since that area is unsampled and unique according to remote sensing studies.

Table 1.2: Unanswered Scientific Questions about the Moon [Heiken, 1991; Hiesinger and Head, 2006; NRC, 2007; Neal, 2009; Space Studies Board, 2011; Jaumann et al., 2012; Khan et al., 2014; Lunar Exploration Roadmap Steering Group, 2016; Lunar Exploration Analysis Group, 2017; ISECG, 2018]

Area	Main Questions
Surface history and cratering rate	• Was there a terminal cataclysm circa 3.9 Ga ago? • Has cratering flux varied during the last 3 Ga? • How has space weather changed the lunar surface? • How do impacts continue to evolve the surface?
Cratering mechanisms	• What are the variations in cratering flow with impactor velocity, composition, and target conditions? • How do crater central peaks and rings form? • How are large impact basins formed? • Are impact melt sheets differentiated?
Crater and basin ejecta	• What fraction of primary vs. local ejecta is present in continuous crater/basin deposits? • What are the shock level distributions within, outside, and beneath craters?
Lunar regolith and the Sun's history	• What is the nature of the regolith-bedrock interface? • What is the ratio of exotic to local material in the regolith and how did it get there?

	• What changes have occurred in lateral mixing of ejecta with time and crater size? • What has been the flux of micrometeoroids with time? • How, and to what extent, is lunar dust transported?
Mare basalt thickness	• What is the relationship between mare fill and mass concentrations (mascons)? • What are the thicknesses of individual lava flows?
Duration of mare volcanism	• How widespread are ancient highland basalts? What are their compositions? • What are the ages of the youngest mare basalts? • Is there molten rock inside the Moon today?
Highland volcanism	• When did highland volcanism cease?
Tectonism	• What is the global lunar stress history? • What are the origins of lunar wrinkle ridges? • What are the ages of young highland scarps?
Lunar crust and magma ocean	• How did the lunar crust form and evolve? • Was there a single Moon-wide magma ocean, a series of magma seas, or other early magma forms? • How deep was the magma ocean; i.e., what fraction of the Moon was involved? • What is the bulk composition of the crust?
Primary highland rock types	• How many magmas contributed to the development of the lunar crust? • Which rock types were formed in the original magma ocean?
KREEP	• What is the origin of KREEP? • How does the concentration of KREEP vary spatially within the lunar crust? • Is KREEP added to the surface by impact or volcanic processes?
Crustal structure and composition	• What are the global variations in crustal thickness and structure at fine scale? • Is the crust layered? • What is the cause of the varied crust thickness and offset between the Moon's center of mass and center of figure?
Lunar mantle	• What is the composition of the lunar mantle and how does it vary laterally? • What is the origin of mantle cumulate rocks? • What mantle discontinuities exist, and what is their relationship to the LMO? • Does a partially molten layer exist at the core-mantle boundary, and what is its origin and composition?
Lunar core	• What is the size and composition of the lunar core? • What is the nature of the core-mantle boundary?

	• What are the implications of a lunar core for models of lunar origin?
Global properties	• What is the global average lunar heat flow? How and why does it vary laterally? • What is the origin of the paleomagnetic field? • Was there once a core magnetic dynamo? If so, when did it start and stop? Were there two dynamo mechanisms at work?
Lunar exosphere	• What are the daytime and nighttime concentrations and compositions? • What are the dynamics of the ionosphere? • How will human activities affect the lunar exosphere?
Volatiles	• What is the nature of volatiles on the Moon? • How does the presence of these volatiles affect the regolith structure and individual grains? • What is the flux of volatiles over time? Has the flux changed over the history of the Moon? • Are there gas releases from the lunar interior?
Bulk composition of the Moon	• What is the lunar bulk composition? • What are the implications of the bulk composition for determining the original source of lunar material and its relation to the Earth? • How did the Moon differentiate and evolve?
Lunar resources	• What is the volume of specific available lunar resources, and where are they located?
Origin of the Moon	• What is the origin of the Moon? • If the collision-ejection hypothesis is valid, are there geochemical signatures in lunar rocks for both projectile and target? • What has been the evolution of the Moon's orbit through time?

Apollo and the Russian lunar exploration programs were dedicated to both lunar science and the preparation and implementation of a human lunar landing. Therefore, due to engineering constraints, landing site selection was one of the main objectives of remote sensing from lunar orbit, and only 14% of the lunar surface was observed from close range; only limited observations were made at medium to high latitudes. Since the Apollo and Luna programs, a wealth of compositional, topographic, and gravitational information has been obtained from numerous lunar missions. New instruments continue to be developed with increasing resolution and precision. Science will continue to be obtained from orbiters, landers, rovers, sample return missions, and eventually crewed lunar bases. Table 1.3 provides an overview of some instruments that would achieve further information on the physics, chemistry, geography, and available resources of the Moon.

Table 1.3: Lunar Science Objectives and Lunar Science Program Elements

Objective	**Orbiter**	**Lander**	**Rover**	**Sample Return**

Selenophysics				
Crust/Core Dimension and Properties	Communication	Seismometer Electromagnetic Sounder		
Crust Properties	Multispectral, Stereo Cameras	Heat Flow Conductor	Sample Collection	Surface Sample and Drill Core Return
Magnetism	Magnetometer	Magnetometer, Electric Probe	Magnetometer	
Paleomagnetism		Drill Core Analysis	Sample Collection	Drill Core Return
Gravity Field	Gravimeter Altimeter			
Selenochemistry				
Crust Composition and Age	Multispectral Camera, Gamma Ray Spectrometer	Drill Core Analysis, Alpha and Gamma Ray Spectrometer, Mass Spectrometer, Multispectral Camera	Sample Collection, Alpha and Gamma Ray Spectrometer, Mass Spectrometer, Multispectral Camera	Surface Sample and Drill Core Return
Water Contents	Neutron Detector	Neutron Detector Electromagnetic Sounder	Neutron Detector, Sample Collection	Surface Sample and Drill Core Return
Interaction with Solar Wind, Galactic Cosmic Rays	Measurement of the Radiation Environment from Orbit	Surface Environment Measurements, Surface Sample, and Drill Core Analysis	Surface Environment Measurements, Surface Sample, and Drill Core Analysis	Surface Sample and Drill Core Return
Selenography and Resource Assessment				
Topology	High-resolution Stereo Cameras Altimeter	Stereo Camera	Stereo Camera	
Prospecting	Multispectral Camera, Gamma Ray Spectrometer	Sample Analysis	Sample Collection, Sample Analysis	Surface Sample and Drill Core Return

Essentially all experiments that can be conducted by landers, rovers, and on sample return missions may also take place at a lunar base, in more depth. Moreover, regolith excavations at a lunar base could address several important problems in lunar geoscience, as regolith stratigraphy could be studied in-situ. A cross-section from the surface to bedrock (3-8m in mare areas) would contain a record of the Sun's evolution during the past 3-4Ga. It would also contain detailed information on how the powdery regolith materials formed from solid rock, the efficacy of horizontal and vertical mixing, and the variation of volatile gases with depth. Also, the interface of the regolith with the bedrock is of great interest. It is not known to which extent the contact is gradational or sharp, or how much bedrock is preserved intact (which might be important for planning expansion of the base). Another major advantage of lunar base investigations over those conducted by Apollo or future robotic missions will be the ability to spend large amounts of time at selected areas. An overview of basic science equipment and capabilities required to support detailed investigations inside and outside a lunar base is given in Table 1.4. It is anticipated that studies will proceed from reconnaissance, in which instruments are emplaced and samples collected at various locations, to more detailed study, as samples are analyzed and questions are refined. A summary of proposed lunar science experiments, as well as their estimated typical mass and power requirements, is given in table 1.5. [Duke and Mendell, 1988; Taylor and Spudis, 1988]

Table 1.4: A Lunar Base Supporting Basic Geoscience Investigations [e.g., Duke and Mendell, 1988]

Elements	Science Equipment/Activities
Laboratory Facilities	Sample preparation Sample analysis (scanning electron microscope, microscope, X-ray, fluorescence) Sample storage (soils, rocks, cores, volatiles) Sample documentation/data facility Map preparation facility (computer system)
Geophysical Instrumentation	Seismometer Neutral ion mass spectrometer (remote station) Seismic stations (remote emplacement) Traverse gravimeter Active seismometer Magnetometer Electric probe

Table 1.5: Mass and Power Requirements of Proposed Lunar Science Experiments

Field of Research	Instrument	Mass (kg)	Power Requirement (W)
Seismology	Passive Seismometer Active Seismometer	25 175	10 10
Lunar Surface Properties	Heat Flow Probe Electrical Properties Experiments 10m Drill 1km Drill	7 15 250 20,000	5 10 6,000 (peak) 500,000 (peak)
Magnetic Field	Magnetometer and ~1m boom	7	2
Lunar Surface Dust	Ejecta and Meteorite Experiment	5	1
Volatiles Detection/ Subsurface Structure	Electromagnetic Sounder	3	6
Volatiles Detection	Neutron Detector (composite scintillator, thermal and epithermal energy ranges)	5	5
Gravimetry	Traverse Gravimeter	15	10
Orbit Determination	Laser Ranging Retroreflector	10	0

Lunar Resource Evaluation	Laser-Induced Breakdown Spectrometer Combined Mössbauer Spectrometer/X-ray Fluorescence Analyzer Geophysical Diffraction Tomography Lunar Regolith Analyzer	30 1 15 20	5 <100 25
Science Packages			
Geologic Field Equipment Package	Regolith Drill, Cameras, Multispectral Imager, etc.	350	500
Geophysical Monitoring Package	Magnetometer, Seismometer, Heat Flow Probe, etc.	200	100
Geoscience Lab	Microscope, Magnetometer, Mössbauer Spectrometer, etc.	50	200
Geophysics Network	Seismometers, Heat Flow Probes, Spectrometers, etc.	50	50

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