Science Concept 7: The Moon is a Natural Laboratory for Regolith Processes and Weathering on Anhydrous Airless Bodies

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Science Goals:

a. Search for and characterize ancient regolith.

b. Determine the physical properties of the regolith at diverse locations of expected human activity.

c. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials.

d. Separate and study rare materials in the lunar regolith.

INTRODUCTION

The Moon is unmodified by processes that have changed other terrestrial planets, including Mars, and thus offers a pristine history of evolution of the terrestrial planets. Though Mars demonstrates the evolution of a warm, wet planet, water is an erosive substance that can erase a planet's geological history. The Moon, on the other hand, is anhydrous. It has never had liquid water on its surface. The Moon is also airless, as opposed to the Venus, the Earth, and Mars. An atmosphere, too, is a weathering component that can distort a planet's geologic history. Thus, the Moon offers a pristine history of the evolution of terrestrial planets that can increase our understanding of the formation of all rocky bodies, including the Earth.

Additionally, the Moon offers many resources that can be exploited, from metals like iron and titanium to implanted volatiles like hydrogen and helium. There is evidence for water at the poles in permanently shadowed regions (PSRs) (Nozette *et al.*, 1996). Such volatiles could not only support human exploration and habitation on the Moon, but they could also be the constituents for fuel or fuel cells to propel explorers to farther reaches of the Solar System (NRC, 2007). If fuel can be produced on the Moon, the weight of a launch vehicle from Earth could be greatly reduced, thus reducing the cost of launch. As a result, the Moon can be a springboard for future exploration missions outside the Earth-Moon system.

The resources on the Moon are most easily accessible from the regolith. The lunar regolith is the top unconsolidated layer of fragmented, fine-grained, cohesive, clastic material. Regolith is composed of crystalline rock fragments, mineral fragments, breccias, aggregates held together with impact glass called agglutinates, and glasses (Heiken *et al.*, 1991). Because of the lunar environment, namely that it is anhydrous and airless, lunar regolith is very unique from the terrestrial soils of the Earth, Venus, Mars, and perhaps Mercury. Also, because of the Moon's formation, size, and location in the Solar System, the Moon's regolith differs from that of asteroids, particularly in agglutinate abundance.

Figure 7.1 shows a schematic cross section of the upper lunar crust. The regolith composes roughly the top 10m, though it varies from 4–5 m in the maria and 10–15 m in the highlands. Regolith is formed from the constant bombardment of the lunar surface by space weathering processes, including most prominently meteoroid impacts. Such impacts (ranging from micrometer to kilometer size) pulverize and mix any exposed rock on the surface. This process occurs at a rate of about 1mm of regolith production per million years, though it is likely that regolith production was faster in the past due to an increased impactor flux.

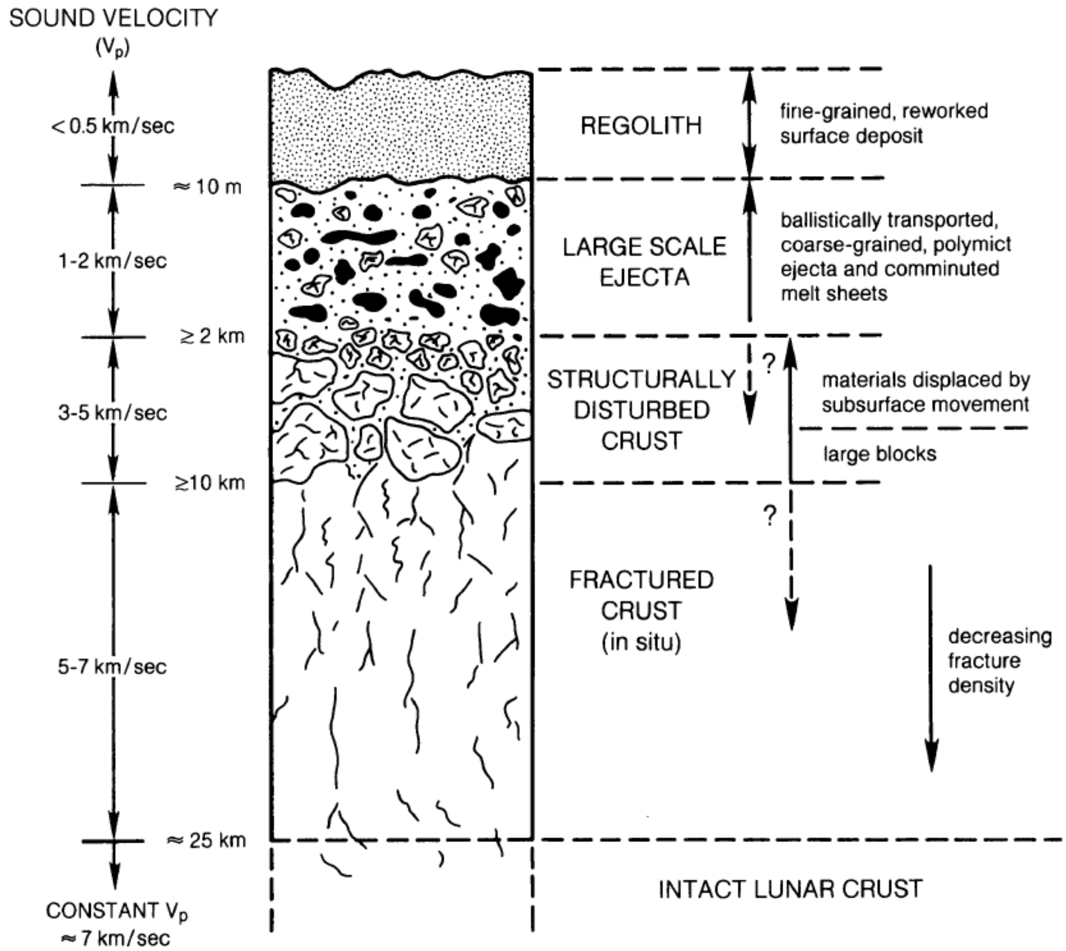

FIGURE 7.1 A schematic cross section of the top portion of the lunar crust (Heiken *et al.*, 1991) that shows the results of widespread impact cratering. Depths are inferred from seismic measurements and sound speed.

Impacts are also responsible for gardening of the regolith. Gardening is the process of churning the regolith by impact bombardment (Jolliff and Ryder, 2006). The top ~0.5 mm of the surface is turned over about 100 times in one million years, but it takes billions of years to turn over 10 cm to 1 m of the surface (Gault *et al.*, 1974).

The top few centimeters of the regolith are relatively loose, particularly due to the gardening process, but the regolith becomes quite dense in just the first 30 cm (with a relative density of 92%) (Heiken *et al.*, 1991). In the top few millimeters of the regolith, three processes dominate regolith production: comminution, agglutination, and vapor deposition. Figure 7.2 is a visual representation of these processes. Comminution is the process of breaking up rock into smaller pieces and eventually to the very fine-grained regolith. Agglutination is the process of forming aggregates of the lunar soil. When a micrometeorite hits the surface, it transfers kinetic energy to the surface, melting particles. The melted glass can then splash onto other grains, sticking to them and holding grains together. This process also releases a vapor of volatiles, called sputtering, and it can even vaporizes some regolith grains. Some of the vapor may escape into space, but some may also be redeposited on the surrounding grains or become trapped in the melted glass before it cools. The process of sputtering and vapor deposition also produces another unique feature in the lunar regolith: minute droplets of iron metal, herein referred to as nanophase-iron (np-Fe^0). Hydrogen reacts with FeO in the soil to reduce the FeO to metallic iron (Kramer *et al.*, 2011; Pieters *et al.*, 1993). This np-Fe^0 has important spectral properties, potentially causing misinterpretation of remotely obtained spectral data. Iron and glass are also potentially useful for building future infrastructure, perhaps through sintering (Hintze *et al.*, 2008).

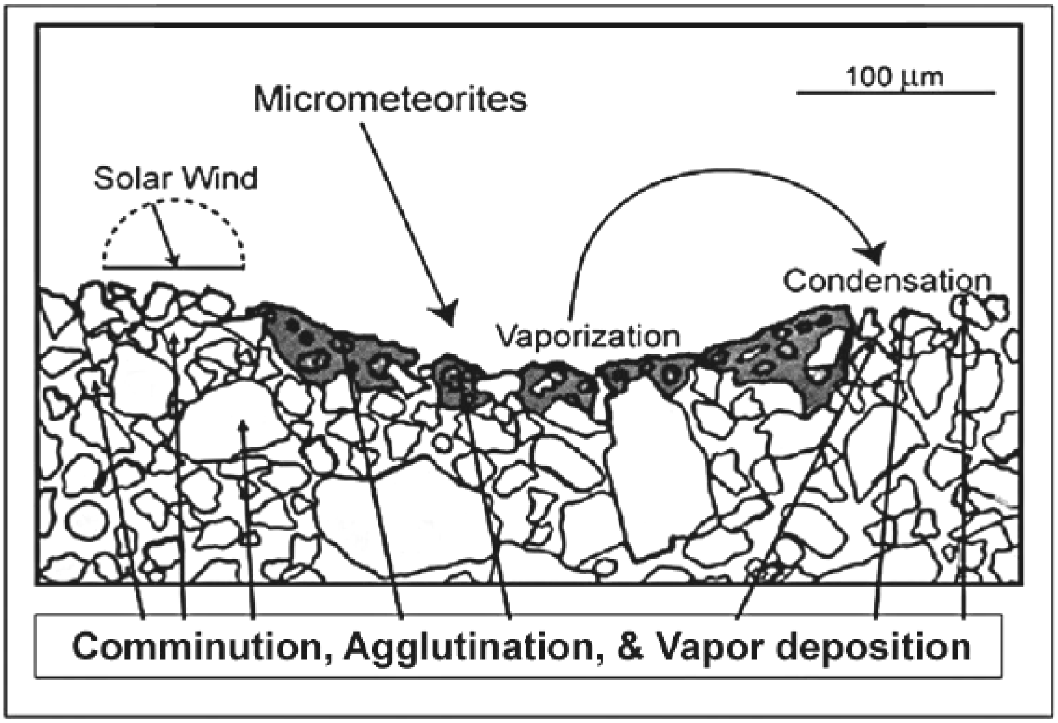

FIGURE 7.2 The processes that affect the top few millimeters of the lunar regolith: comminution, agglutination, and vapor deposition. Micrometeorites impact the soil, breaking particles and melting silicate material that splash to form agglutinates. Some melt vaporizes or releases volatiles which can condense on other particles. Figure 3.6 from NRC (2007).

Importance of Studying the Regolith

The Moon is covered in a layer of regolith, varying in thickness. Except on very steep slopes, for example on a crater wall or rille, no bedrock is exposed. Regolith is, therefore, the prime interface between explorers and the Moon. The regolith is also the boundary between the rest of the Solar System and the Moon, and is constantly affected by the solar wind, galactic cosmic rays, and impacts. It is the source of virtually all the information that is known about the Moon, and it is our most accessible resource (Jolliff and Ryder, 2006). Thus, understanding and learning more about this interface is of primary importance for future exploration of the Moon.

Regions of the Moon

For the purpose of this section, we have divided the Moon into a set of regions. These regions differ by location, as well as mineralogical/chemical makeup (Table 7.1).

TABLE 7.1 Regions of the Moon Defined

Region	Definition	Sampled?
Polar Regions	Regions of >±70° latitude	NO
Permanently Shadowed Region	Regions of constant shadow from the sun	NO
Illuminated Region	Regions that remain illuminated for >50% of the lunar day	NO

Highland Regions	Oldest regions on the Moon, light albedo regions	NO
Nearside	Highland regions concentrated from -90° to 90° longitude	YES
Far Side	Highland regions concentrated from 90° to -90° longitude	NO
Mare Regions	Dark albedo regions, composed of >10 wt% Fe	NO
Nearside	Mare regions concentrated from -90° to 90° longitude	YES
Far Side	Mare regions concentrated from 90° to -90° longitude	NO
Cryptomare	Regions where there is access to normally buried mare	NO
Highland-Mare Boundary Regions	Regions with access to both highland and mare regions	NO
Nearside	Highland-mare boundary regions concentrated from -90° to 90° longitude	YES
Far Side	Highland-mare boundary regions concentrated from 90° to -90° longitude	NO
Geochemical Terranes	Areas geochemically different from the surrounding regions, (Jolliff *et al.*, 2000)	NO
South Pole-Aitken Terrane	Region surrounding the South Pole-Aitken Basin, 6–10 wt% Fe	NO
Feldspathic Highlands Terrane	Region of >70km crustal thickness	NO
Procellarum KREEP Terrane	Region defined by Th >3.5 ppm	YES

Methodology

Remote sensing datasets are the primary source of information on which any assessment of lunar landing sites must be based. In recent years, a diverse array of spacecraft have completed flybys or orbited the Moon, creating a rich addition to data from samples, landers, and Earth-based observations. We used a number of these datasets in our assessment of landing regions and sites for Science Concept 7. The datasets we collected are shown in Table 7.2, along with information about the mission and instrument, the spatial resolution of the data, and the source from which we obtained the data. Most data processing and map projection were performed in Arc-GIS 10. Some pre-processing was done using ISIS and IDL 7.1.

TABLE 7.2 Table of Datasets Used

Data set	**Mission/ Instrument**	**Resolution**	**Source**
Topography	LRO LOLA	256 ppd ≈ 120 m/pix	USGS
Slope	LRO LOLA	16 ppd ≈ 1.895 km/pix	PDS, Rosenburg *et al.*, 2011
Roughness	LRO LOLA	16 ppd ≈ 1.895 km/pix	PDS, Rosenburg *et al.*, 2011
Polar Illumination	LRO LOLA	240 m/pix	PDS
Clementine 750 nm Albedo	Clementine UVVIS	100 m/pix	USGS
Clementine Mineral Mosaic	Clementine UVVIS	200 m/pix	USGS
Clementine OMAT	Clementine UVVIS	200 m/pix	USGS, Lucey *et al.*,

			2000b
FeO Abundance (Between +/-70 latitude)	Clementine UVVIS	100 m/pix	USGS, Lucey *et al.*, 2000a
TiO2 Abundance (Between +/-70 latitude)	Clementine UVVIS	100 m/pix	USGS, Lucey *et al.*, 2000a
FeO Abundance	LP GRS	0.5 deg=15 km/pix	USGS
TiO2 Abundance	LP GRS	2 deg = 60 km/pix	USGS
Th Abundance	LP GRS	0.5 deg=15 km/pix	USGS
Rock Abundance (Between +/-60 latitude)	LRO Diviner	32 pix/degree ≈ 947 m/pix	PDS, Bandfield *et al.*, 2010
Soil Temperature (Between +/-60 latitude)	LRO Diviner	32 pix/degree ≈ 947 m/pix	PDS, Bandfield *et al.*, 2010
WAC Mosaic	LRO WAC	100 m/pix	USGS
NAC Images	LRO NAC	0.5 m/pix	PDS
Lunar Orbiter Mosaic	Lunar Orbiter	~60 m/pix	USGS
USGS Geologic Maps			USGS
Lunar Impact Crater Database			LPI

The majority of maps shown in this section are projected using an orthographic projection, datum Moon 2000, and centered at 0 degrees latitude and either 0 or 180 degrees longitude. When appropriate, the center point of the projection will be rotated to better display the poles of the Moon or regions of interest near 90 or -90 degrees longitude. Maps will be labeled as necessary when they deviate from this standard layout. Figure 7.3 shows the typical map layout with latitude and longitude ticks labeled; in subsequent maps latitude and longitude will not be labeled unless the layout of the maps differs from that of Fig. 7.3.

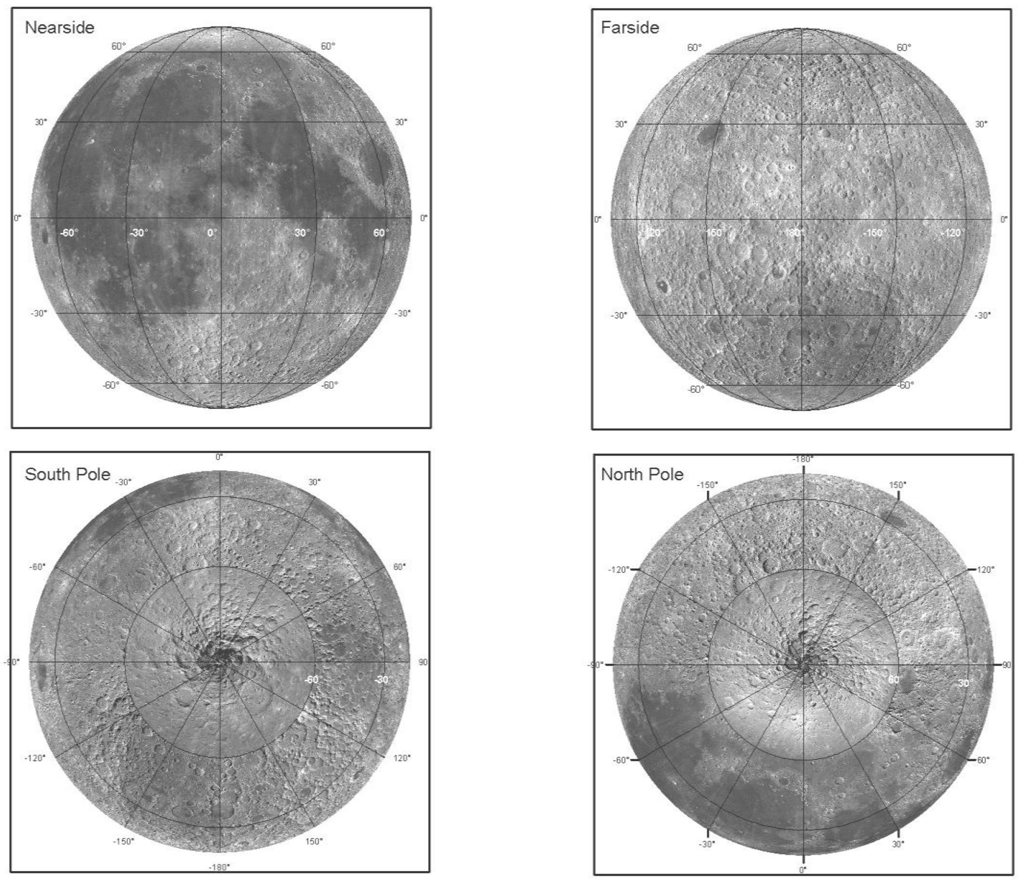

FIGURE 7.3 LROC WAC mosaic displayed in the typical projection for maps in this report. Maps are orthographically projected, datum Moon 2000.

Limitations of the Datasets

Any remote sensing method has unique limitations. Spatial resolution is an important limiting factor on how much information any remote sensing instrument can provide. For example, Lunar Prospector gamma ray spectrometer FeO measurements have 0.5 degree-per-pixel resolution. This corresponds to square pixels of 15×15 km. A feature smaller than the pixel size of any measurement cannot be studied using that measurement. The value returned for that pixel is the average of the actual surface values for every point inside the pixel.

Another important limitation of remote sensing datasets is the depth into the surface a technique is able to probe. Multispectral imaging techniques like the Clementine UVVIS or LRO WAC measurements collect information only from approximately the top micron of the lunar surface. Because measurements collect only information from such a small depth, surface effects dominate the information gathered from these techniques. Other techniques like gamma-ray spectroscopy collect information from approximately the top 30cm of the regolith. While this is still largely surficial, there is potential for these techniques to incorporate heterogeneity not sensed by multispectral imaging into their results. Table 7.3 summarizes measurement parameters for a variety of remote sensing techniques.

TABLE 7.3 Summary of observational measurement parameters for different remote sensing techniques (Jolliff and Ryder, 2006).

Technique	Spatial resolution	Depth of signal	Data set
Multispectral imaging	~100 m	~ 1um	Clementine UVVIS
Gamma-ray spectroscopy	50-200 km	30 cm	LP GRS
Thermal neutrons	50-200 km	100 cm	LP NS
Epithermal neutrons	50-200 km	50 cm	LP GRS
Fast neutrons	50-200 km	50 cm	LP GRS

SCIENCE GOAL 7A: SEARCH FOR AND CHARACTERIZE ANCIENT REGOLITH

Introduction

The ancient lunar surface recorded the initial geological evolution of the Moon and provides a record of dynamical processes in the inner Solar System. Specifically, analysis of the Apollo samples has established that lunar regolith has efficiently retained materials bombarding the Moon for most of the history of the Solar System (Wieler *et al.*, 1996). Regolith forms when the lunar surface, exposed for millions of years, is continuously struck by meteorites ranging in size from giant basin-forming impactors to micrometeorites, and charged atomic particles from the Sun and the stars (Heiken *et al.*, 1991; Lucey *et al.*, 2006). Subsequently, particles of asteroids, interplanetary dust, comets, terrestrial planet debris, solar wind particles, and galactic cosmic-rays are implanted in surface regolith (Lucey, *et al.* 2006). Surface regolith impacted by different particles may then be buried by various mechanisms (McKay *et al.*, 2009). The implantation and burial cycle repeats itself on the upper surface regolith. Thus, we expect to find buried regolith between different layers of lunar material (McKay *et al.*, 2009; Fagents *et al.*, 2010). Micrometeorite impact and gardening damages the present lunar surface record of more ancient particles implanted in the regolith (Crawford *et al.*, 2010). Conversely, regolith preserved in the deep layers has been undisturbed since its formation and therefore preserves a record of implanted material over billions of years (McKay *et al.*, 2009).

Particles Implanted in the Lunar Regolith

Solar wind and noble gases

The Sun releases streams of high-energy particles, and the Moon, lacking an appreciable atmosphere and global magnetic field, has been trapping these particles for the past 4 billion years (Wieler *et al.*, 1996). Initial samples from the Apollo missions established the fact that lunar regolith contains a large amount of trapped solar wind material. Consequently, preserved regolith could contain records of the composition and evolution of the solar atmosphere over time (Wieler *et al.*, 1996; Levine *et al.*, 2007). The solar wind consists of plasma composed of ionized atoms that originate in the Sun's atmosphere. This plasma represents a particle influx of 3×10^8 protons $cm^{-2}\ s^{-1}$, and is the main source of volatiles in the lunar regolith (Haskin and Warren, 1991; Vaniman *et al.*, 1996). The plasma of ionized atoms is composed of ~95% H, 4% He, and less than 0.5% C, N, O, Ne, Mg, Si, Fe, Ar, Kr, and Xe (Haskin and Warren, 1991; Vaniman *et al.*, 1996; McKay *et al.*, 1991). Solar wind particles penetrate to depths of microns to millimeters in the lunar regolith, and progressively arrange themselves in the outer layers of exposed grains (Dran *et al.*, 1970; McKay *et al.*, 1991).

Planetary scientists have a particular interest in the major noble gas components on the Moon because these elements can provide information about lunar and solar history (Wieler and Hever, 2003). The major noble gas components consist of five categories. First are gases in the weak lunar atmosphere, which could potentially limit the present degassing of the Moon, such as ^{4}He, $^{36,40}Ar$, and ^{222}Rn. Secondly, ^{40}Ar, ^{129}Xe, and $^{131\text{-}136}Xe$, which are parentless radiogenic and fissiogenic isotopes existing at grain surfaces. These elements are useful for constraining lunar degassing history, the time of lunar formation, and when a sample was exposed to the solar wind. Thirdly, all solar wind isotopes implanted into the regolith provide a precious archive of solar history. Fourthly, radiogenic isotopes like ^{40}Ar that are produced *in situ* can be used for age dating. Finally, cosmic-ray-produced isotopes like ^{21}Ne and ^{38}Ar can be used to study the exposure history of the lunar regolith.

"Comparing the quantity of solar wind noble gases in the regolith column with those anticipated during the last four billion years of regolith existence could help planetary scientists understand the average solar wind long-term flux" (Wieler and Hever, 2003). Geiss and Bochsler (1991) and Kerridge *et al.* (1991) reported a possible intensity and composition variation of solar wind during the history of the Solar System. Explicitly, solar wind Xe is believed to have been two to three times greater in the past (Geiss, 1973). Moreover, the $^{15}N/^{14}N$ ratio could have increased by 15% per Gyr, which implies an increase in solar activity (Kerridge, 1975). Wieler *et al.* (1996) also proposed temporal alterations in the solar wind Kr/Ar and Xe/Ar ratio.

Understanding the variations in the intensity of solar wind is especially important because this information could yield information about early evolution of the Sun and how it affected the development of life on Earth (Fagents *et al.*, 2010). The accepted solar model predicts that the Sun's luminosity was about 70% of its current value 4 Ga. This notion cannot explain the geomorphological evidence for liquid water on the early Earth and Mars. The apparent higher temperatures on the early Earth and Mars could be explained by a young Sun a few percent more massive, and consequently more luminous, than estimates based on models that assume its present mass (Whitmire *et al.*, 1995; Sackmann and Boothroyd, 2003). A number of astronomical studies (*e.g.*, Wood *et al.*, 2002) support this hypothesis by predicting a very intense solar wind early in the Sun's evolution. If this hypothesis is correct, evidence for this strong solar wind should be preserved in the Moon's regolith. However, a lack of such evidence could disprove the hypothesis of a more massive young Sun. Finding evidence to either support or challenge models of the Sun's evolution would advance our understanding of the evolution of all Sun-like stars (Wood *et al.*, 2002).

Terrestrial atmospheric gases

Various volatile elements are implanted into the regolith, including N, H, C, and the noble gases. Some have likely been implanted directly by solar wind ions. However, the great abundance of nitrogen and a variation of 30% in the $^{15}N/^{14}N$ isotopic ratio suggest that some other volatiles could have come from the Earth's atmosphere at a time when our planet had no geomagnetic field (Ozima *et al.*, 2005). Evidence recorded in samples of ancient lunar regolith could help us estimate the time when the Earth's geomagnetic field first appeared and could help us understand the origin and historical record of Earth's geomagnetic field. We may use ancient regolith as a tracer of magnetic field evolution if we know the time when terrestrial atmospheric components were implanted in regolith.

Meteorite fragments

Lunar and Martian meteorites found on the Earth confirm that transport of planetary material within the Solar System is possible. The active geology of the Earth, however, restricts the preservation of these materials (Armstrong *et al.*, 2002). On the Moon, lack of atmospheric or hydrologic processes, as well as lack of crustal recycling, could preserve meteorites from the terrestrial planets.

Recovering terrestrial fragments could provide information about the early planetary environment, including information about early life on Earth, and a record of the rate at which material has been transferred between the terrestrial planets during the history of the Solar System. Since meteorites from terrestrial planets would have hit the Moon at very high speed, we expect fragments that survived initial impact with the lunar surface to be very small, but it is possible that microfossils could have survived and might be embedded in ancient regolith (Armstrong *et al.*, 2002; Crawford *et al.*, 2008). A more complete meteorite record could help constrain models of lithopanspermia (Mileikowsky *et al.*, 2000; Burchell, 2004). Armstrong *et al.* (2010) suggest that some regions on the Moon may have as much as 11–18 ppm, or 300–510 kg km^{-2} of terrestrial material.

Galactic particles

Since the formation of the Solar System our Sun has made about 20 circuits around the Milky Way, exposing the lunar surface to different galactic environments. Three different environments have implanted a variety of particles on the lunar surface (Talbot and Newman 1977; Gies and Helsel 2005; Crawford *et al.*, 2010). First, during spiral arm passages, the Sun encountered denser interstellar environments, implying the deposition of about 1 kg/m^2 of interstellar dust on exposed planetary surfaces. Secondly, the flux of galactic ionizing radiation could also have left records on the Moon. A variety of galactic processes influence the galactic cosmic ray flux in the inner Solar system over different timescales, from greater than 1 Gyr to of order of 100 Myr, including an enhanced supernova rate associated with passage through galactic spiral arms and variations due to the oscillation of the solar orbit about the plane of the galaxy. Finally, the vertical oscillations above and below the galactic plane and passages through spiral arms cause variations in the gravitational potential that may perturb the orbits of comets in the Oort cloud. Such perturbations could periodically increase the impactor flux in the inner Solar System, and thereby increase the cratering rate there (Torbett, 1986; Clube and Napier, 1986; Matese *et al.*, 1995; Stothers, 1998; Leitch and Vasisht, 1998; Crawford *et al.*, 2010).

Ancient Regolith Deposits

The current lunar surface regolith has been subject to overturning by meteorite impacts for the last 4 Gyr. The record of past Solar System processes at the surface is thus averaged over most of Solar System history, frustrating attempts to understand ancient planetary, solar, and galaxy processes and events. To study these we must obtain well-preserved samples of regolith dating back to, or even prior to, the lunar cataclysm. Ancient regolith or preserved regolith may be encapsulated between basalt flows, beneath impact ejecta, or beneath pyroclastic deposits (McKay *et al.*, 2009) and can be accessed through drilling or by examining the walls of craters that expose such layers (Weider *et al.*, 2010) (Fig. 7.4).

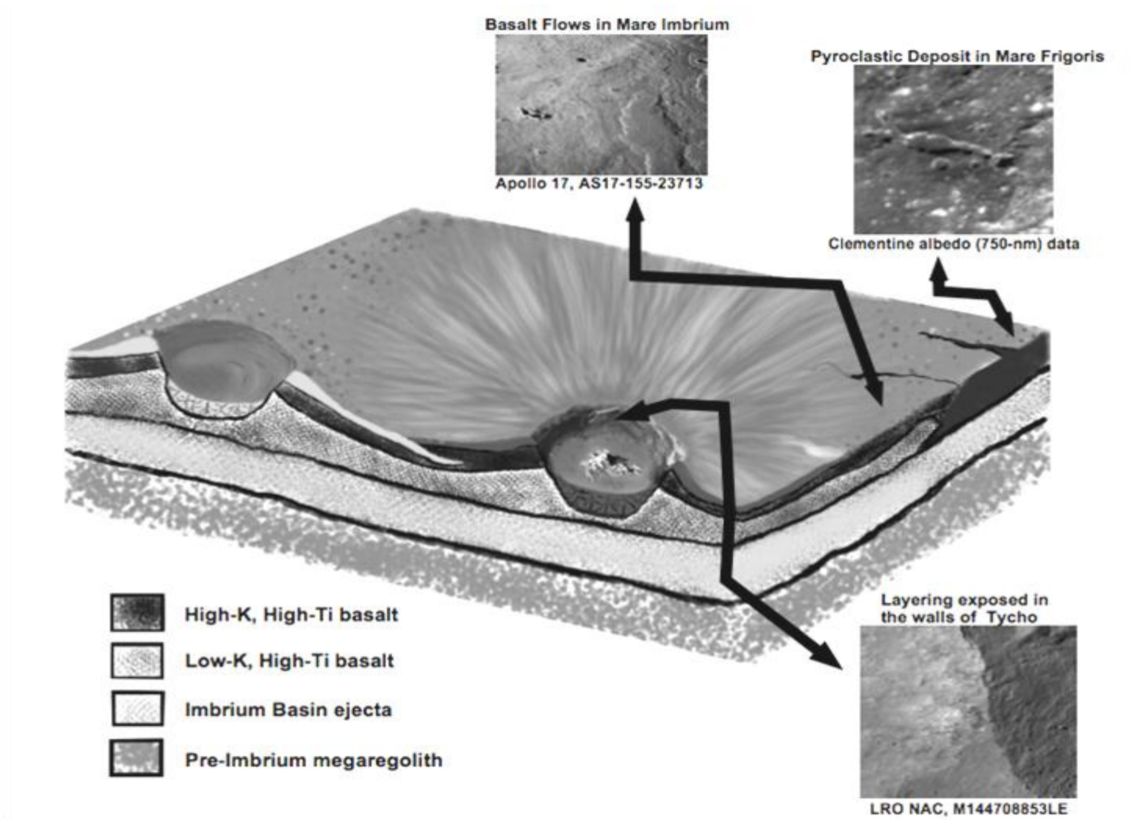

FIGURE 7.4 Locations of encapsulated ancient regolith.

Ancient Regolith Trapping Mechanisms

Basalt flows

Most exposed mare surfaces date from about 3.8 and 3.1 Gyr, and geographically constrained volcanism may have continued as recently as 1 Gyr ago (Hiesinger *et al.*, 2003). Ancient volcanism likely also occurred prior to 3.8 Gyr. Ancient regolith layers became trapped when young lava flows covered older flows, preserving layers of regolith between them. The preserved regolith layer may be dated using the ages of the underlying and overlying basalts as upper and lower limits. Only regolith particles that survive the thermal effects of the molten overlying lava flow can provide significant information about the ancient cosmic environment. Fagents *et al.* (2010) estimated that implanted solar wind particles should be preserved in ancient regolith at depths between 3.7–38 cm beneath overlying lava flows with thickness between 1–10 m, respectively. The rate of regolith accumulation changes as a function of exposed surface age, as well as with absolute age. Early regolith formation rates ranged from 3 to 5 mm/Myr, while the present regolith formation rate is <1 mm/Myr (Hörz *et al.*, 1991). A single lava flow would have to remain exposed for ~20–200 Ma in order to accumulate enough regolith to shield implanted particles.

Pyroclastic deposits

In addition to lava flows, fire fountains driven by gas exsolution from erupting lava also took place on the Moon (Hiesinger and Head, 2006) scattering melt as fine droplets. These pyroclastic deposits can be distinguished from lava flows using multispectral remote sensing techniques that can detect glass beads or large quantities of titanium-rich black spheres. Lunar pyroclastic deposits extend over more than ~2500 km^2 and can be found widely dispersed on the highlands adjacent to young maria. A variety of pyroclastic glass beads and fragments were found at different Apollo landing sites (orange and black vitrophyric beads that formed during lava fountains of gas rich, low-viscosity, Fe-Ti-rich basaltic magmas at the Apollo 17 site, and green glasses of volcanic origin at the Apollo 15 site; Delano, [1986]). Like basalt flow layers covering ancient regolith, layers of pyroclastic deposits could have encapsulated ancient regolith.

Continuous crater ejecta blankets

Impact craters are surrounded by debris ejected from the crater interior. Ejecta deposits are thickest at the crater rim and thin with increasing distance from the crater. The continuous ejecta blanket near the crater expands approximately one crater radius of the crater rim, regardless of the crater size. Pre-existing regolith within the ejecta blanket is mixed and buried (through the process of ballistic sedimentation), but some buried regolith may escape additional modification and scattering.

Accessing Ancient Regolith

Ancient regolith encapsulated between basalt flows, under pyroclastic deposits, or under ejecta blankets may be accessed by drilling. Examination of the lunar cores and drive tubes from Apollo did not show any stratigraphic horizon that could provide information about the stratigraphy of the lunar regolith, however, and a single core may neglect some layers, or show local stratigraphic layers only. Alternatively, a trench could provide a two-dimensional view of regolith, and access fragments of continuous layers. Soil mechanics suggest that the sidewall of a trench could remain standing and intact up to 3 meters, and deeper trenches can be produced by offsetting the wall in steps (McKay, 2009). Impact craters excavating through basalt flows of different ages could expose sub-surface boundaries (Weider *et al.*, 2010). Young lunar surfaces have been less exposed to space weathering effects; fresh craters characterized by bright rays and rough material (Copernican aged craters) may better preserve the stratigraphy of ancient regolith in their walls than older craters.

Methods and Requirements

We suggest the following target site requirements to maximize the potential for finding preserved ancient regolith:

- Near mare basalt flows of varying ages
- Near pyroclastic deposits
- Near continuous ejecta blankets of craters
- Near or in Copernican-age craters that penetrate older terrains

In order to pinpoint locations that fulfill the target site requirements above, we developed the following procedure:

1. Compile surface maps of the modeled ages of mare basalts
2. Map and determine the locations and ages of cryptomare deposits
3. Map the locations of pyroclastic deposits
4. Map of the locations of Copernican-age craters and the geologic units in which they reside

5. Calculate the theoretical depths of crater continuous ejecta blankets to determine how deep ancient regolith is buried
6. Correlate the compiled maps to determine landing sites that best meet Science Goal 7a

Discussion and Site Selection

Sites near mare basalt flows of varying ages

Ancient regolith layers may be preserved beneath or between mare basalt flows if sufficient time for regolith formation was available between the flow events. Modification of these regolith layers by micrometeorites, solar wind, and other space weathering processes would have been halted at the time of the overlying lava flow, preserving the state of the regolith and its implanted volatiles at that time.

Absolute ages for basalt flows cannot be determined remotely; however, ages have been modeled for most of the surface mare basalt flows on the Moon and are presented in Fig. 7.5. These mare basalt flows represent regions on the Moon where regolith of a certain age may be preserved. For example, a regolith of age 3.1 Gyr (that is, a regolith no longer modified after 3.1 Ga) could potentially be found beneath any mare basalt flow of that age.

Buried mare basalts, termed cryptomare, are often considered the most ancient mare basalts (Terada *et al.*, 2007). These buried basalt flows are located when craters excavate dark, mafic material that is observed against light highlands material. These dark haloed impact craters provide indicators for where ancient mare flows may be buried, and thus are indicators for where even more ancient regolith may be preserved. No definitive cryptomare material exists in the existing sample suite, so absolute ages have not been determined for these deposits. The meteorite Kalahari 009 from NE Africa, however, contains basaltic clasts radiometrically dated to ~4.35 Ga that may be samples of cryptomare material (Terada *et al.*, 2007). Cryptomare deposits provide the opportunity to sample regolith that may be definitively dated at ages older than any exposed surface mare flow. Their locations are shown in Fig. 7.6.

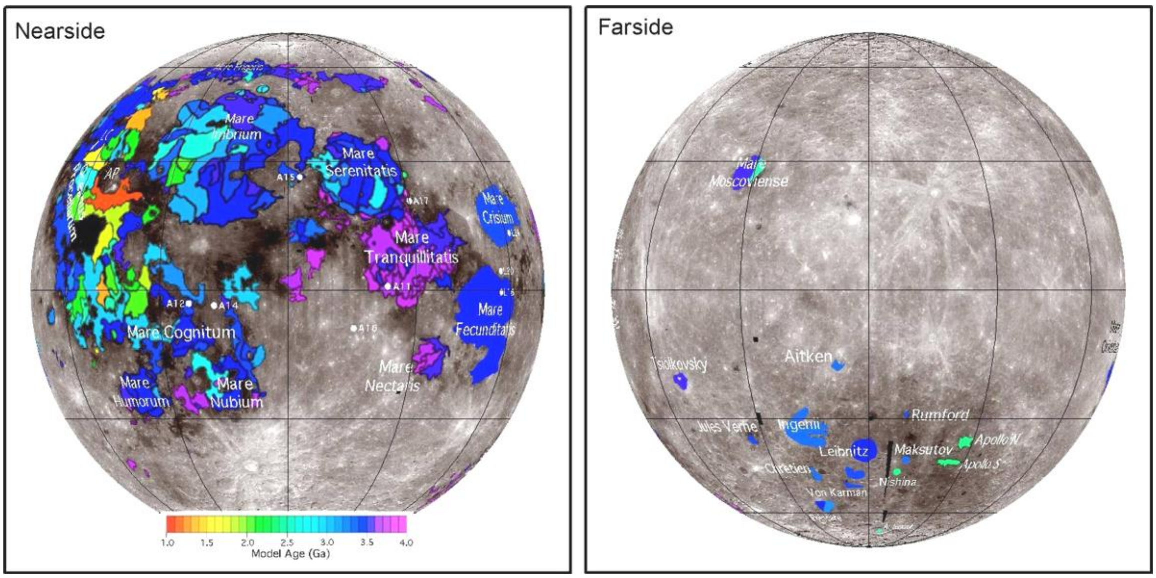

FIGURE 7.5 Estimated surface ages of mare basalts based on crater counting.

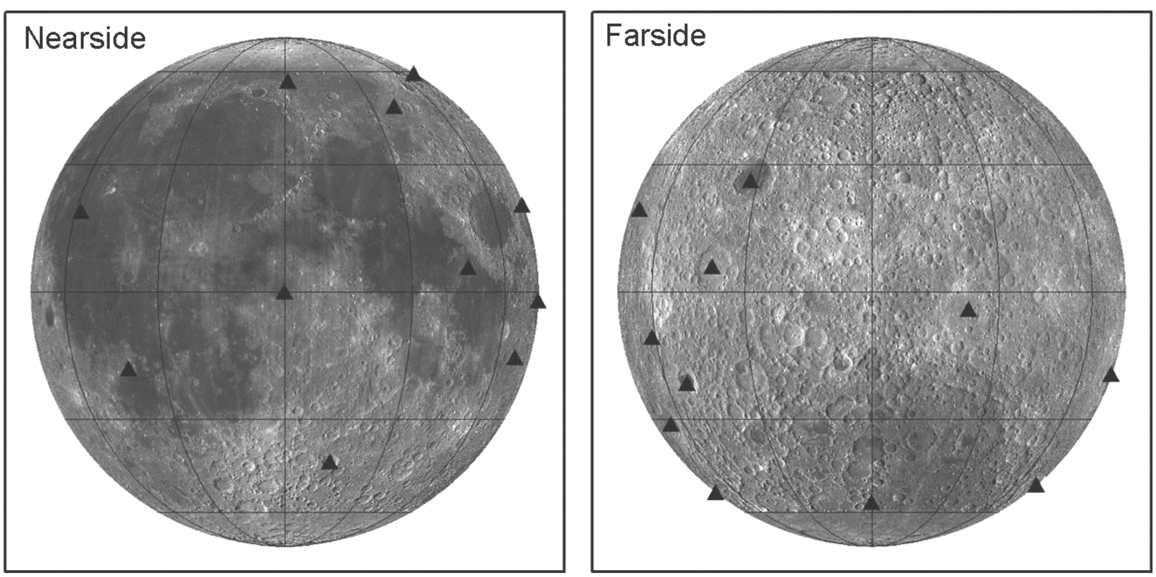

FIGURE 7.6 Locations of cryptomare deposits. Base map: LROC WAC mosaic.

Mare basalt flow layers are a particularly appealing method for preserving regolith because if both the underlaying and overlaying lava flows can be sampled along with the regolith in between, the age of the regolith and all products within it will be bracketed between the absolute ages for the lava flows.

Sites near pyroclastic deposits

Pyroclastic deposits may also cover and preserve ancient regolith. The locations of pyroclastic deposits identified on the Moon are shown in Fig. 7.7.

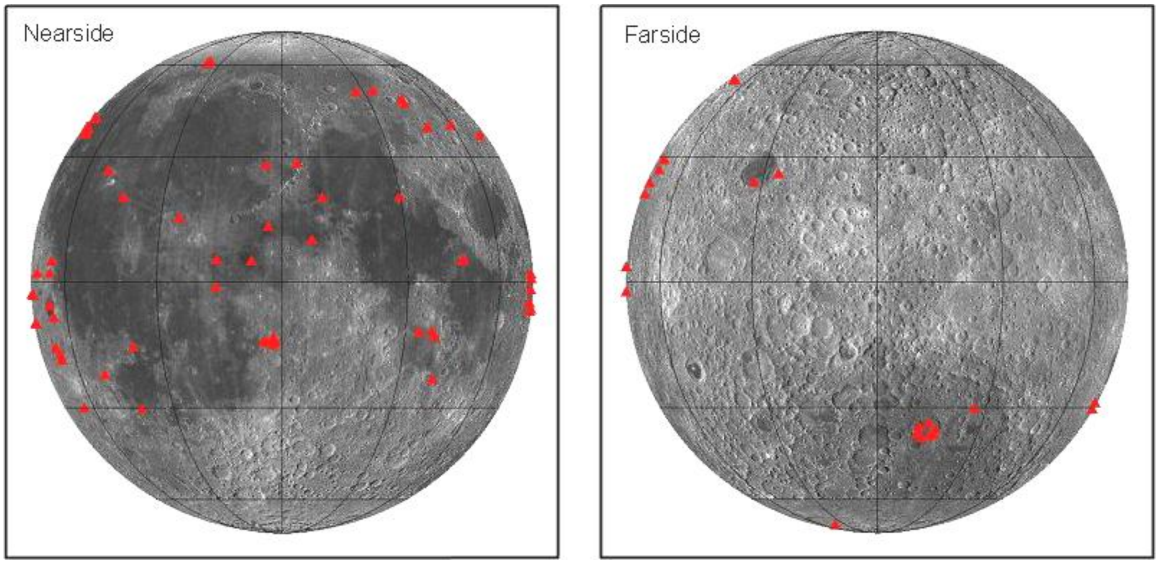

FIGURE 7.7 Locations of pyroclastic deposits identified by the Lunar Pyroclastic Volcanism Project (http://astrogeology.usgs.gov/Projects/LunarPyroclasticVolcanism). Base map: LROC WAC mosaic.

Sites near continuous ejecta blankets of craters

Every crater will deposit a continuous ejecta blanket of a size proportional to the size of the crater itself. In general, the continuous ejecta blanket of a crater extends to 1 or 2 crater radii beyond the rim (Kring 1995; McGetchin *et al.*, 1973). The regolith preserved beneath the ejecta blanket of a crater ceases to be modified by space weathering processes at the time of crater formation, so the preserved regolith can be dated to the age of the crater. However, mixing of the crater ejecta with the underlying regolith upon deposition may make the boundary of the ancient regolith layer difficult to discern. Because of the heavily cratered nature of the Moon, any landing site will most likely be near or on a continuous ejecta blanket. Smaller craters on top of continuous ejecta blankets will provide the opportunity to sample regolith beneath the ejecta blanket. The depth of excavation necessary to access the underlying regolith can be estimated based on the thickness of the continuous crater ejecta blanket. The ejecta blanket is thickest at the crater rim and decreases with distance according to Equation 7.1:

$$\delta = 0.14R_c^{0.74} \cdot (r/R_c)^{-3.0\pm0.5}, \quad (7.1)$$

where δ is the thickness of the ejecta blanket, R_c is the radius of the complex crater, and r is the distance in meters from the point of impact.

Sites near or in Copernican-age craters that penetrate older terrains

In addition to the types of locations discussed above in which regolith is buried by volcanic or cratering processes, ancient regolith can be found simply by excavating into the lunar surface. As new regolith accumulates it buries older regolith. Although mixing processes continue, in general deep regolith is older than surface regolith. Craters act as natural drills into ancient terrain and provide an opportunity to sample deep regolith layers. Without a continuous boundary such as a mare basalt flow on top of ancient regolith layers, it is more difficult to constrain the absolute age of buried regolith; however, ages of different types of geologic terrains have been estimated in geologic mapping of the lunar surface. These estimates can be used to locate craters that have penetrated into ancient terrain. The locations of Copernican age craters (younger than ~1.1 Gyr) are shown in Fig. 7.8.

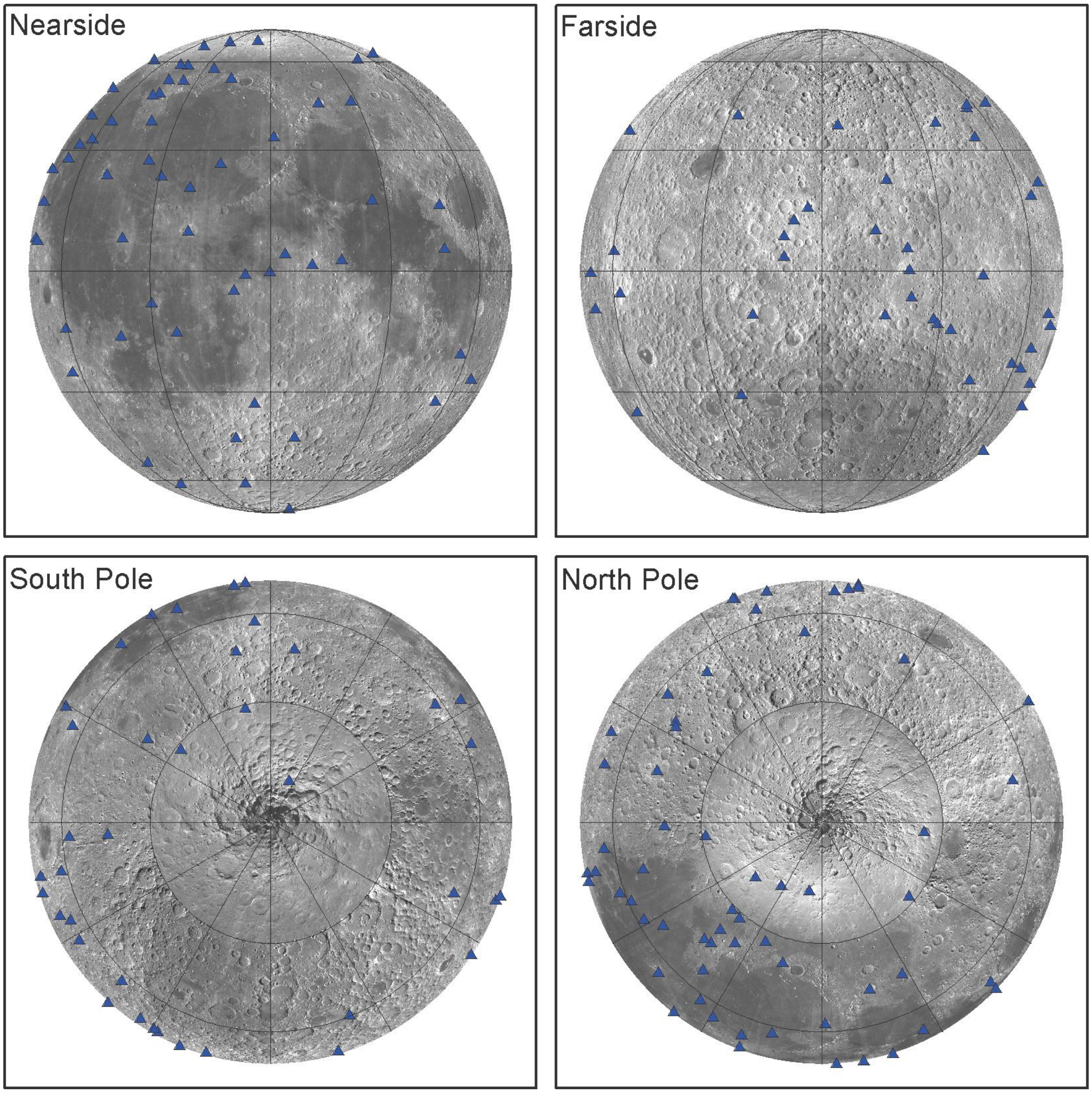

FIGURE 7.8 Locations of Copernican age craters on the Moon. Base map: LROC WAC mosaic.

Science Goal 7a Landing Site Recommendations

Figure 7.9 is a composite map showing the modeled ages of mare basalts, the locations of cryptomaria, and locations of pyroclastic deposits. Landing sites in any of these locations or at Copernican age craters penetrating more ancient terrain, as shown in Fig. 7.10, have the potential to sample ancient preserved regolith and satisfy Science Goal 7a.

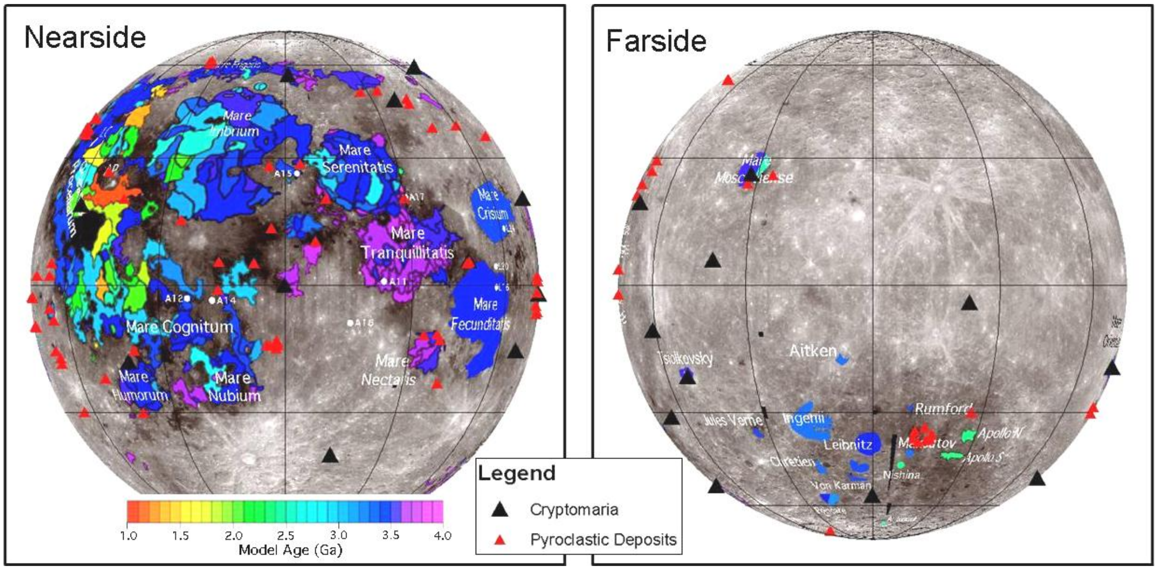

FIGURE 7.9 Locations where ancient regolith may be found preserved beneath basalt flows, cryptomaria, and pyroclastic deposits.

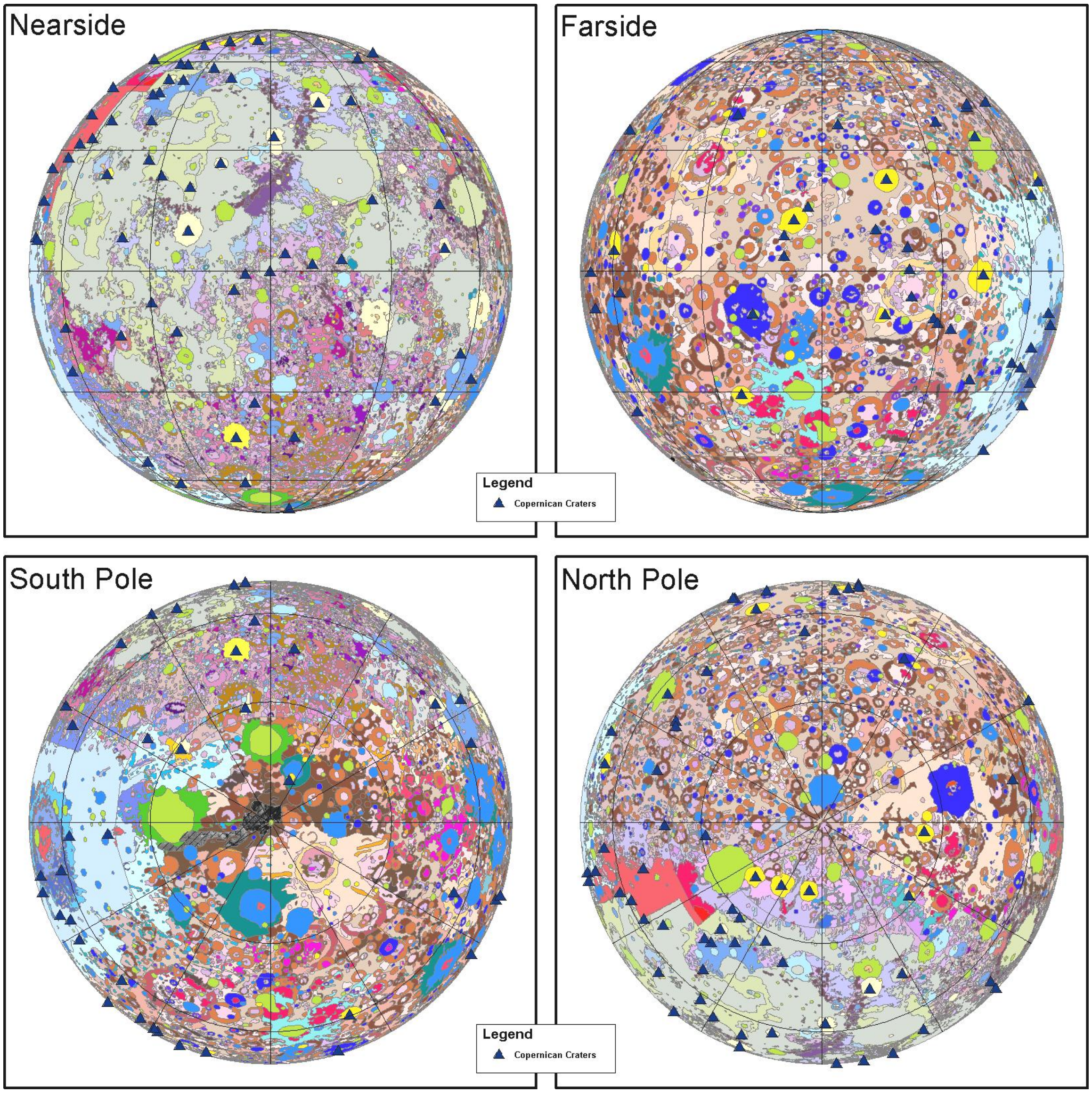

FIGURE 7.10 Locations of Copernican age craters on the Moon superposed on USGS geologic maps of the lunar surface.

SCIENCE GOAL 7B: DETERMINE THE PHYSICAL PROPERTIES OF THE REGOLITH AT DIVERSE LOCATIONS OF EXPECTED HUMAN ACTIVITY

Introduction

The lunar regolith poses many unique challenges to human explorers, but it can also be a great asset (Taylor *et al.*, 2005). Understanding the properties of regolith in different regions of the Moon will be essential to exploiting regolith-based resources.

We developed a list of important regolith characteristics to study based primarily on the properties outlined in *The Lunar Sourcebook* (Heiken *et al.*, 1991). To aid in site selection, we also defined a set of specific regions, or terrains, on the lunar surface at which various physical properties of the regolith might change. Keeping the NRC 2007 report in mind, our objective was to determine how the physical properties of the regolith might change between and within our defined regions. The NRC 2007 report emphasizes heat flow, volatile concentrations, properties at the poles, and other properties at depths within the regolith greater than the Apollo drill cores' three meter depths, so we gave special consideration to these topics as well. Finally, for each region we analyzed some of the possible effects that the chosen landing sites will have on human explorers.

Background

The physical properties of the lunar regolith can and should be studied at any location on the Moon. Unfortunately, the Apollo and Luna mission only sampled a limited area of the Moon, at nine different nearside sites of varied terrain. It is plausible, then, that the missions have not fully characterized the regolith. Our objective here is not necessarily to choose specific landing sites but to suggest regions of interest for reconnaissance missions that will allow explorers to gain information about the regolith. This initial information can then be used to determine the best location(s) for a lunar habitat or other extended stay.

We utilized the list of regions on the Moon described in Table 7.1. These regions vary by composition, both chemical and mineralogical, as well as location on the Moon. Since we may not be able to sample (or may not need to sample) all of these regions, we must prioritize them and suggest a minimum number of sites to visit that will allow a more comprehensive understanding of the lunar regolith. To prioritize the regions, we used two sets of constraints: scientific constraints and human factor constraints.

First, we used a set of scientific constraints. We developed a catalog of lunar regolith properties that should be studied at any landing site based on properties outlined in *The Lunar Sourcebook*. This list can be broken into geotechnical properties, optical properties, chemical properties, and electrical properties. Although each property can be studied at each region, some regions are more scientifically interesting than others. To organize this comparison, we developed a decision matrix (Table 7.4) of physical properties versus region, rating each region on a scale of -2 to 2 (extremely undesirable/ineffective to highly desirable/effective). Since studying the physical properties of the regolith can and should be done anywhere on the Moon and studying all properties possible is desirable, there were no negative values given in this matrix. The limiting factors to studying each of these properties at any chosen landing site are the scope of the science instrument package and time to study properties *in situ*. Generally, locations that have already been studied gained a 'no priority' or 'low priority' rating, whereas places that have not been visited are given a higher priority rating. The geotechnical properties are thought to be similar nearly everywhere in the equatorial regions of the Moon (Carrier 2005), so these have generally been given a 'no priority' or 'low priority' rating as well. Water ice in the lunar PSRs could potentially cause the physical properties of the regolith to behave differently than at equatorial regions so many chemical properties in the polar regions were rated as a higher priority to study.

TABLE 7.4 Regolith Property vs. Region Decision Matrix. Ranking: -2 = Extremely Undesirable; -1 = Undesirable; 0 = No Priority/No Effect/Unknown; 1 = Priority/Effective/Desirable; 2 = High Priority/Highly Desirable. PSR = Permanently Shaded Region; Polar Illum = Polar Illuminated Region; N.H = Nearside Highlands; F.H = Farside Highlands; FHT = Feldspathic Highland Terrane; PKT.M = Procellarum KREEP Terrane Mare; Non-PKT.M = Non-Procellarum KREEP Terrane Mare; F.M = Farside Mare; Crypto = Cryptomare; SPAT = South Pole-Aitken Terrane; HMB (Any Type) = Highland-Mare Boundary of any region.

Property / Region	PSR	Polar Illumin	NH	FH	FHT	PKT.M	Non-PKT.M	F.M	Crypto	SPAT	HMB (Any Type)	Total
Particle Size Distribution	1	1	0	0	0	0	0	0	1	0	0	3
Particle Shape	1	1	0	0	0	0	0	0	1	0	0	3
Specific Gravity	1	1	0	0	0	0	0	0	1	0	0	3

Bulk Density and Porosity	2	1	0	0	0	0	0	0	1	0	1	5
Relative Density	2	1	0	0	0	0	0	0	1	0	1	5
Compressibility	2	1	0	0	0	0	0	0	1	0	1	5
Shear Strength	2	1	0	0	0	0	0	0	1	0	0	4
Permeability	2	1	0	0	0	0	0	0	1	0	0	4
Diffusivity	2	1	0	0	0	0	0	0	0	0	0	3
Bearing Capacity	2	1	0	0	0	0	0	0	1	0	0	4
Cohesion	2	1	0	0	0	0	0	0	1	0	0	4
Slope Stability (Angle of Repose)	1	1	0	0	0	0	0	0	0	0	0	2
Trafficability	1	1	0	0	0	0	0	0	0	0	0	2
Mineralogical Composition	2	1	1	1	2	1	1	1	2	2	1	15
Chemical Composition	2	1	1	1	2	1	1	1	2	2	1	15
Age	1	1	1	1	1	1	1	1	2	2	1	13
Variation of Soil with Depth	2	1	0	1	1	1	1	1	2	2	1	13
Record of Solar History	2	1	0	0	0	0	0	0	2	1	1	7
Electrical Properties	1	1	0	0	0	0	0	0	0	0	0	2
Reflectivity and Emission of Radiation	1	0	0	0	0	0	0	0	0	0	0	1
Heat Flow	2	2	0	1	1	2	1	1	1	1	1	13
Abrasiveness	1	0	0	0	0	0	0	0	0	0	0	1
Albedo	0	0	0	0	0	0	0	0	1	0	0	1
TOTAL	35	21	3	5	7	6	5	5	22	10	9	128

Second, we used a set of human factor constraints. We developed a list of human factor issues and operational considerations that we must consider when studying the properties of the regolith. Although many of the human factor issues are more relevant for future missions (*e.g.*, building a lunar outpost), we still believe it is pertinent to include them to help prioritize the regions of interest. How the lunar regolith affects humans, after all, is the overarching purpose of this Science Goal. Again, to help prioritize regions, we developed a decision matrix for this constraint, shown in Table 7.5. The rating scale we used for this decision matrix was the same as for the physical properties matrix (from -2 corresponding to extremely "undesirable/ineffective" to 2 corresponding to "highly desirable/effective"). Regions that would be extremely difficult or potentially dangerous for long duration stay were rated with negative values, while regions that have a positive relation to human activity were given positive values. In this decision matrix, 0 often corresponds to the region having an unknown effect on human habitation and related activities although it can also mean that the region simply has neither a positive nor negative effect on humans. Polar regions demonstrate an intriguing dichotomy. PSRs, though ranked high in science value may prove to be difficult to accommodate long-duration stay because of the lack of access to solar illumination for power and a lack of direct communication with Earth. However, illuminated regions may have access to PSRs, allowing the science goals to be fulfilled while reducing the risk to human explorers.

TABLE 7.5 Human Factor Issues vs. Region Decision Matrix. Ranking and acronyms same as Table 7.4.

Human Issue / Region	**PSR**	**Polar Illumin**	**N H**	**F H**	**FHT**	**PKT. M**	**Non-PKT. M**	**F. M**	**Crypto**	**SPAT**	**HMB (Any Type)**	**Total**
Landing Facilitation	-2	2	0	0	0	0	0	0	0	0	0	0
Habitat Location	-2	2	0	0	0	0	0	0	0	0	0	0
Human Health	-1	2	0	0	0	0	0	0	0	0	0	1
Rover Mobility	-1	0	0	0	0	0	0	0	0	0	0	-1
Digging Facilitation, Construction, Waste Placement	0	0	0	0	0	0	0	0	0	0	0	0
Structure / Infrastructure Placement	-1	1	0	0	0	0	0	0	0	0	0	0
Human Issue / Region	PSR	Polar Illumin	N H	F. H	FHT	PKT. M	Non-PKT. M	F. M	Crypto	SPAT	HMB (Any Type)	Total
Earth Communicati on	-2	2	1	1	1	1	1	1	1	1	1	9
Exploitation	2	2	1	1	1	1	1	1	1	1	1	13
TOTAL	-7	11	2	2	2	2	2	2	2	2	2	22

All of the Apollo missions included science experiments to be made on the lunar surface, providing basic information about the regolith and surface environment. Most of them were included in the Apollo astronaut's EVAs. Experiment results are summarized in *The Lunar Sourcebook*. In the same time period the Soviet Luna missions also landed on the lunar surface and studied its properties, imaging areas around the spacecraft, making density, temperature, and radiation measurements, and sampling regolith. Through sample analysis, the lunar highlands and mare regolith were shown to be mineralogically different, especially in the amounts of Al_2O_3 and FeO. For the finest fractions of the regolith (from less than 10 µm to 45 µm), the highlands have a significantly larger amount of Al_2O_3 than the mare, but a lower amount of FeO (Taylor *et al.* 1996; Taylor *et al.* 2001a, Taylor *et al.* 2001b; Taylor *et al.* 2001c; Pieters *et al.* 2001;

Taylor *et al.* 2002; Taylor *et al.* 2003). Figure 7.11 shows the average over these sizes of mare, highlands, and boundary Apollo sites. The mineralogical makeup of the regolith is specifically important for extraction of resources (Heiken *et al.*, 1991) and building infrastructure. Iron, titanium, and oxygen are examples of resources that can be removed from the regolith through mineral extraction. The mineralogical content of the regolith can also aid in sintering launch and landing pads or roads (Hintze *et al.*, 2008; Taylor 2005).

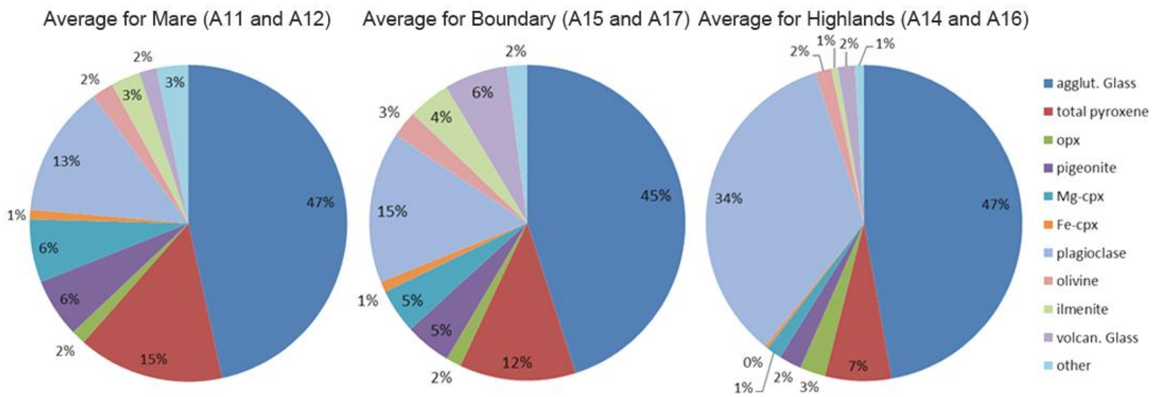

FIGURE 7.11 Pie charts comparing the mineralogical composition of the average values for Apollo mare, highland and boundary regions. These charts use averages of the finest fraction (from less than 10 µm to 45 µm) of Apollo samples.

Geotechnical properties of the regolith, including density, thermal conductivity, and particle size/shape, are expected to be the same or similar most everywhere, with the possible exception of the poles (Carrier 2005). A suite of instruments that can sample the geotechnical properties of the regolith can and should be included in any mission (robotic or human). These properties are the most likely to affect human explorers' endeavors in building a lunar base. Figure 7.12 is an iconic image, but it also demonstrates some important regolith properties.

FIGURE 7.12 Apollo 11 astronaut Edwin "Buzz" Aldrin photographed this footprint in the lunar regolith. The photograph was part of an experiment to study the geotechnical properties of the Moon (specifically the effects of pressure applied to the surface). Image AS11-40-5878.

Regolith density affects several other physical properties, such as thermal conductivity, seismic speed, shear strength, compressibility, and the dielectric constant. Density was a significant source of curiosity and trouble to Apollo astronauts. Within the top few centimeters of the regolith, the properties of the soil change greatly from light and fluffy to very hard and compact; Apollo 15 astronauts had extreme difficulty drilling to the assigned depth of 3 m, reaching only 1.4 m and 1 m because of difficult drilling conditions. Figure 7.13 shows the lunar regolith's characteristic of increasing density with depth.

Thermal conductivity is the ability of the regolith to transfer heat beneath the surface. Thermal conductivity may be important for any human-related products buried beneath the surface (outpost, storage facilities, equipment, etc.). Because of the importance of thermal conductivity to mission operational issues, one of the specifically defined purposes of Science Goal 7b is to study the heat flow, in particular to a depth of 10 m (NRC 2007). One of the main purposes of this requirement is that the Apollo heat flow probes were not as effective as hoped due to difficult drilling conditions (the deepest probe reached 292 cm. Measuring the thermal conductivity of the regolith in more detail will also help confirm results from Apollo showing that diurnal temperature cycles can no longer be detected below 80 cm. Decreased thermal conductivity of deep regolith poses the problem of waste heat removal for future missions.

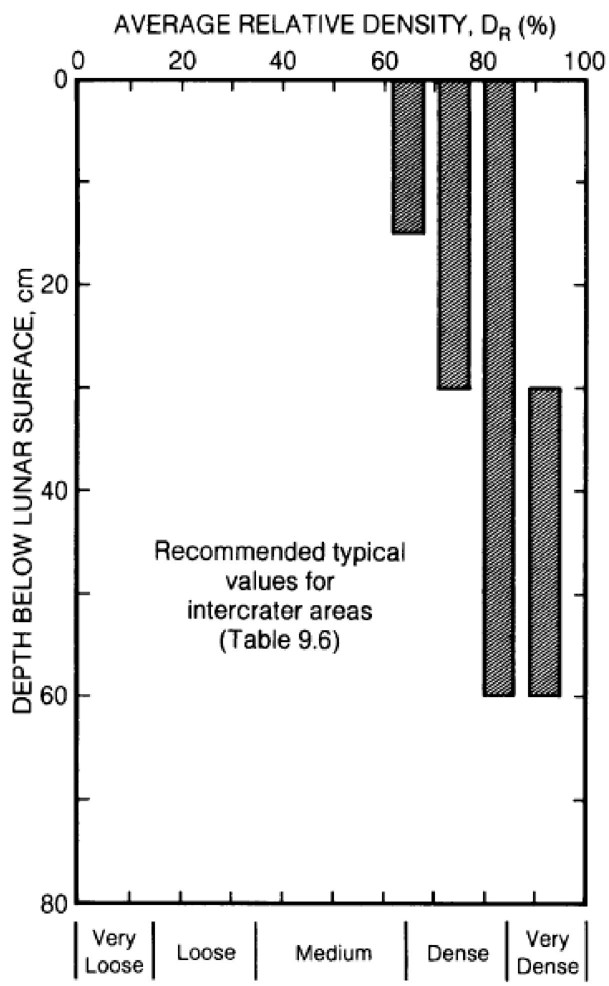

FIGURE 7.13 Plot of recommended values for relative density of the lunar regolith. With increasing depth, the regolith becomes dense to very dense quickly (Heiken *et al.*, 1991).

Particle size and shape are important properties of the regolith. Particle size is a variable that controls, to various degrees, the strength and compressibility of the material as well as its optical, thermal, and seismic properties. Particle shape and size together affect cohesion, abrasiveness, and space weathering effects. For example, the smallest size fraction of the regolith is the most likely to show space weathering effects, like reduction of iron to nanophase-iron (np-Fe0) (Pieters *et al.*, 1993). The fine fractions are also held together by micrometeorite impact melts to form agglutinates (Fig. 7.14). Agglutinates, np-Fe0, and the very nature of the finest fractions of the regolith itself are particularly interesting because of their uniqueness to the Moon. Unique particle size and shape affects the way the soil fails in shear, causing the regolith to behave differently than expected: regolith thrown up as the Apollo lunar roving vehicle (LRV) drove followed rooster-tail trajectories (Mullis, 1971) instead of ballistic ones, as shown in Fig. 7.15. Size and shape of regolith particles are also factors of the regolith's exceptionally abrasive nature. Understanding how the size and shape of the regolith vary with depth and between sites and how they can affect human physiology and hardware is a top priority.

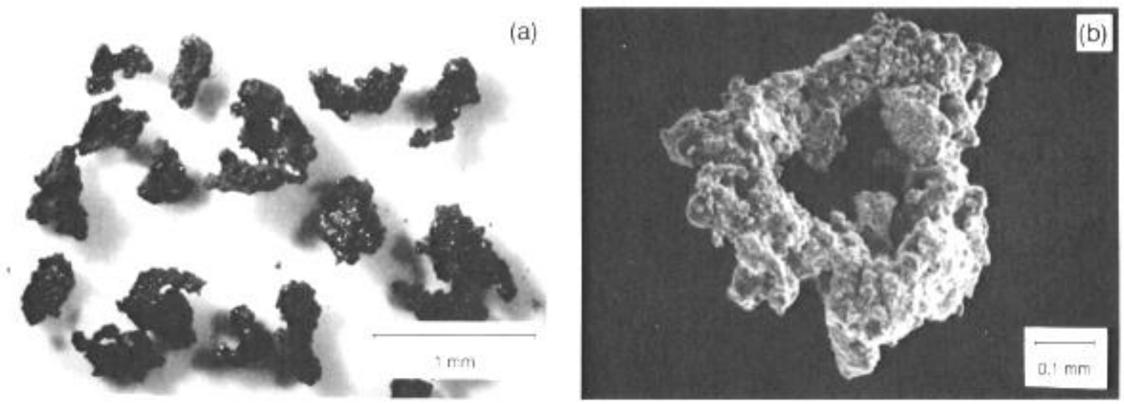

FIGURE 7.14 Agglutinates from Apollo 11 sample 10084, NASA Photo S69-54827. This figure shows typical agglutinates found in the lunar regolith. Agglutinates were a surprising feature because they are not found in Earth soils. (a) Photo taken with an optical microscope. (b) Scanning electron photomicrograph (Heiken *et al.*, 1991).

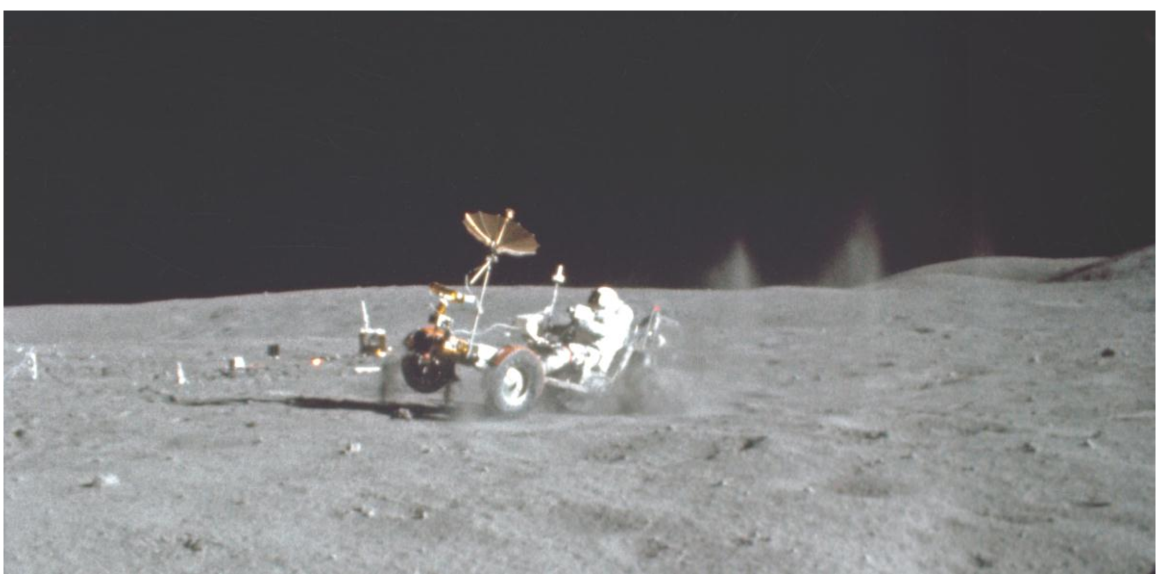

FIGURE 7.15 The rooster-tail trajectory of regolith thrown out from the LRV wheels is a curiosity of the regolith's shear failure (Mullis, 1971).

The lunar regolith also has distinct electrical properties, including electrical conductivity and photoconductivity. The electrical conductivity is relatively low and large changes in photoconductivity occur across the terminator. Charging of particles across the terminator could be enough to levitate the upper, thin layer of soil particles above the surface. Electrostatic levitation could extend up to several meters above the lunar surface and the ensuing 'dust storm' would follow the terminator around the Moon (Colwell *et al.*, 2009). Horizon glow may also be related to electrical properties of the regolith and dust migration. Dust levitation removes the smallest grains from the topmost soil layers on illuminated slopes and exposes them to the higher energy solar wind ions and solar cosmic rays. The result is the forward scattering of sunlight on the darker surrounding areas (Criswell, 1972).

Methods and Requirements

Experiments studying the physical properties of the regolith can and should be performed at any landing site location; however, in order to fully characterize regolith properties that may be markedly different from those at the Apollo and Luna landing sites, we have prioritized certain areas on the lunar surface for study. We compiled a list of the physical properties of the regolith that should be studied, determined what variation these properties might have with location, and then categorized the lunar surface into regions using a variety of parameters that may contribute to changes in the physical properties of the regolith in these regions.

Science Concept 7b landing site requirements:

- Sites in each of the three main geochemical terranes (SPAT, FHT, PKT)
- Mare and highland sites (and boundary regions) within each of the three terranes
- Sites in permanently shadowed and illuminated regions at the poles
- Sites of differing surface temperature
- Stations in varied locations at each site (*e.g.*, crater rims, intercrater regions, areas on ridges)

In order to locate sites of highest priority for studying regolith physical properties we followed the procedure below:

1. Compile maps showing the limits of the three main geochemical terranes
2. Create maps delimiting the boundaries of the maria and the highlands
3. Obtain maps of the permanently shadowed regions of the lunar poles
4. Categorize the previously visited landing sites based on the region types above
5. Denote regions where physical properties have previously been determined as the lowest priority
6. Use a decision matrix in conjunction with the maps above to develop a prioritized list of landing locations

Discussion and Site Selection

Sites in each of the three main geochemical terranes (SPAT, FHT, PKT)

Apollo sampled the area within and just outside of the PKT, but we have yet to obtain definitive samples the FHT and the SPAT. Of highest priority is the SPAT, which may provide samples of the lunar mantle, given the size and age of the SPA basin. The basin is also on the lunar farside at low latitudes. These characteristics are important because the farside of the Moon (mare or highland) has not been sampled. Additionally, the South Pole-Aitken basin may contain FHT material (Jolliff and Ryder, 2006), allowing a mission to potentially sample two geochemical terranes in one area. A heat flow experiment within the SPA basin could be used to study the temperature profile at lower latitudes than have been studied before. The next priority is to study the FHT in depth, not only because of the proposed thick crust in this region, but also because of its ancient age, relative lack of mare deposits, and its feldspathic composition (Jolliff and Ryder, 2006). Thus, we suggest sampling, in priority order, areas within the SPAT, the FHT, and if possible, more extensive sampling of the PKT.

Mare and highland sites (and boundary regions) within each of the three terranes

Within the three geochemical terranes are regions of mare, highlands, and boundaries between the two. Sampling both the mare and highlands regions in each of these terranes will help to more fully characterize the regolith. For example, how the mare, highlands, or boundary regions differ between each of the terranes is unknown for FHT and the SPAT regions. Even in the PKT region, there are limited data for regions inside and outside the PKT. Apollo 16 is the only Apollo highland site outside the PKT, while the only Apollo highland site within the PKT is Apollo 14. Apollo 12 is the only mare site within the PKT. No Apollo representations of mare-only sites outside the PKT exist, though Apollo 17 does represent a highland-mare boundary and Apollo 11 is located on the PKT boundary. Luna 16 and 20 did land in mare sites outside the PKT, but they did not have the same sampling instruments as Apollo.

The primary targets for this requirement are the highland-mare boundaries within each geochemical terrane because these sites allow sampling of both regions at once. Of the three geochemical terranes, the SPAT region should be sampled first. The next priority is the FHT. Of lowest priority are the regions inside and outside the PKT, as they have already been sampled, though not necessarily comprehensively. If possible, more samples from mare and highland sites outside the PKT, especially at greater distances from the PKT boundary, are needed to better understand the area.

Cryptomare, or ancient buried mare, may also prove to have unique physical properties, particularly in their chemistry and mineralogy. We have not yet sampled this specific type of mare, and they rate high as areas of interest in our decision matrices. Cryptomare deposits are best found in the ejecta of craters that have excavated into the ancient layer.

Sites in permanently shadowed and illuminated regions at the poles

Table 7.1 defines two types of areas within the polar regions: the PSRs and illuminated regions. Both PSRs and illuminated regions rank exceptionally high in terms of science goals, but from a human factors and operational perspective, PSRs rate dangerously low in all aspects, except exploitation of resources, while illuminated regions rate extremely well.

Sites of differing surface temperature

Heat flow measurements into the lunar regolith were only performed on Apollo 15 and 17. Figure 7.16 shows the thermal profile determined from the Apollo 15 and 17 heat flow probes. The Apollo 15 drill cores required for the heat flow sensor deployment did not reach their full 3 m intended depth because of complications, leading to an incomplete and not well-constrained temperature profile for the site. Also, since the Apollo landings were primarily equatorial, the thermal profile at depth within the regolith is unknown at lower latitudes. Heat flow is of particular concern to the human issues because it relates to habitat deployment.

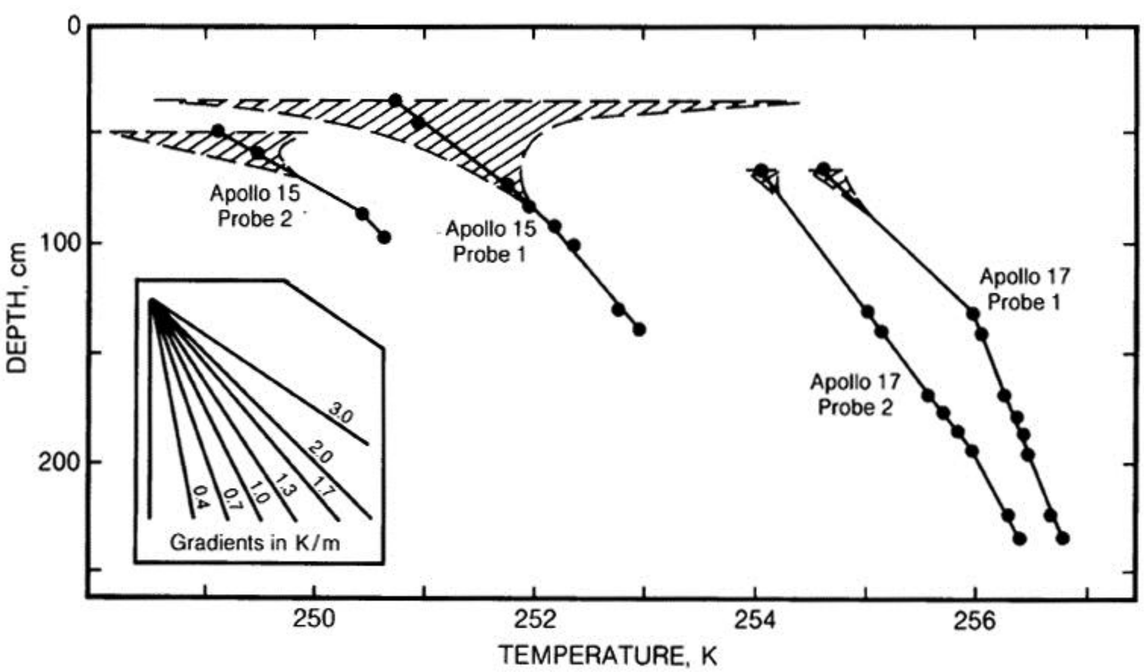

FIGURE 7.16 Apollo 15 and 17 heat flow profiles as a function of depth into the regolith (Heiken *et al.*, 1991).

Stations in varied locations at each site

Some physical properties of the regolith are dependent upon location within a single region, or even within a single landing site. This potential difference could be caused by different mineralogical composition within the site, such as from two different lava flows or a highland-mare boundary. Differences could also be caused by maturity of the regolith. For example, the regolith in the ejecta of a fresh crater is sharp, angular, and generally more unconsolidated than an older, more weathered regolith, and these two regolith types will also appear spectrally distinct because of space weathering effects.

Landing Site Recommendations

Science Goal 7b aims to characterize the lunar regolith as completely as possible. As such, this goal can be fulfilled at any location on the Moon. Specific consideration should be taken for locations of expected future human activity, as these are the sites that should be best characterized for the health and safety of the human explorers. We have also divided the Moon into distinct regions based on compositional and location differences, and we have prioritized these regions based upon science goals and human issues.

Figure 7.17 shows a compiled map of Jolliff *et al.*'s (2000a) three geochemical regions with the mare highlighted and cryptomare locations accentuated. The map's legend also shows these regions ranked in order of interest, defined from Table 7.6, which is based on the science goals and human factors decision matrices. The regions are prioritized in the following way: Top priority is given to the polar regions (especially an illuminated region with access to a PSR), followed by a cryptomare deposit, the SPAT, and the FHT. Although Table 7.6 shows that highland-mare boundaries rank higher than the FHT, highland-mare boundaries can be studied in any of the geochemical terranes (anywhere where mare meets highland), so we suggest choosing landing sites at highland-mare boundaries within their prioritized geochemical terranes.

TABLE 7.6 Results of Science Goal 7b Decision Matrix. Acronyms same as Table 7.4.

Issue	PSR	Polar Illum.	N.H	F.H	FHT	PKT.M	Non-PKT.M	F.M	Crypto	SPAT	HMB (Any Type)
Human	-7	11	2	2	2	2	2	2	2	2	2
Science	35	21	3	5	7	6	5	5	22	10	9
TOTAL	28	32	5	7	9	8	7	7	24	12	11

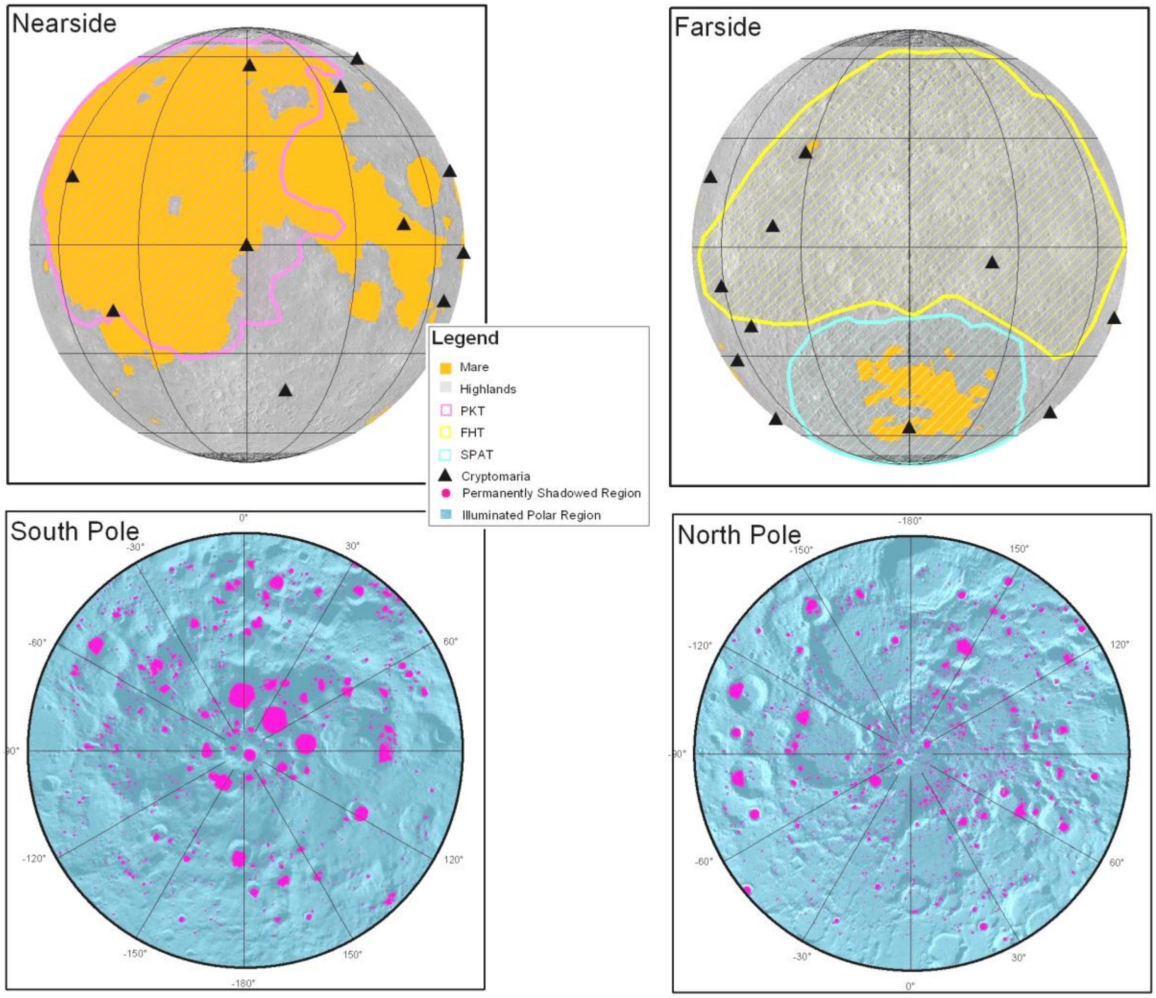

FIGURE 7.17 Science Goal 7b regions of interest. Highest priority goes to regions that have not been sampled before, because the purpose of this goal is to more fully characterize the regolith, especially considering regions of expected human activity. Of top priority are the polar regions. Illuminated regions with access to PSRs (the PSRs are highlighted in the figure) are the location of choice for polar regions. After polar regions, cryptomare deposits are the next priority, as they may also prove to have unique physical properties. SPAT and finally FHT regions should also be studied, and in particular, highland-mare boundaries should be the target site for these regions, allowing sampling of both mare and highland materials.

SCIENCE GOAL 7C: UNDERSTAND REGOLITH MODIFICATION PROCESSES (INCLUDING SPACE WEATHERING), PARTICULARLY DEPOSITION OF VOLATILE MATERIALS

Introduction

Regolith modification can take several forms, from very large scale impacts to much smaller-scale processes that together are called space weathering. Space weathering is a modification process that alters the regolith in various ways – it is not a single process, but rather a suite of processes that alter the regolith and transfer volatiles to the regolith. Understanding space weathering and regolith modification processes is crucial for understanding spectral data obtained from remote sensing of the lunar surface.

The diverse effects of space weathering are dependent on both the maturity of the regolith at the surface, as well as the composition of that regolith. Sciences Goal 7c compels identification of locations that can allow sampling of regolith of different age and composition within the scope of a single landing site. Additionally, this goal could benefit from choosing a site near a previous lander, rover, or other spacecraft, allowing the sampling of an artificial surface that has been exposed to the lunar environment for a known time period.

Background

Though space weathering is often described as if it were a single process, it actually consists of several individual processes:

- Micrometeorite bombardment
- Solar wind
- Solar cosmic rays
- Galactic cosmic rays

Increasing exposure to space weathering processes is expressed as maturity, which can be defined in several ways that are discussed below. Figure 7.18 illustrates the variety of space weathering processes that affect the Moon.

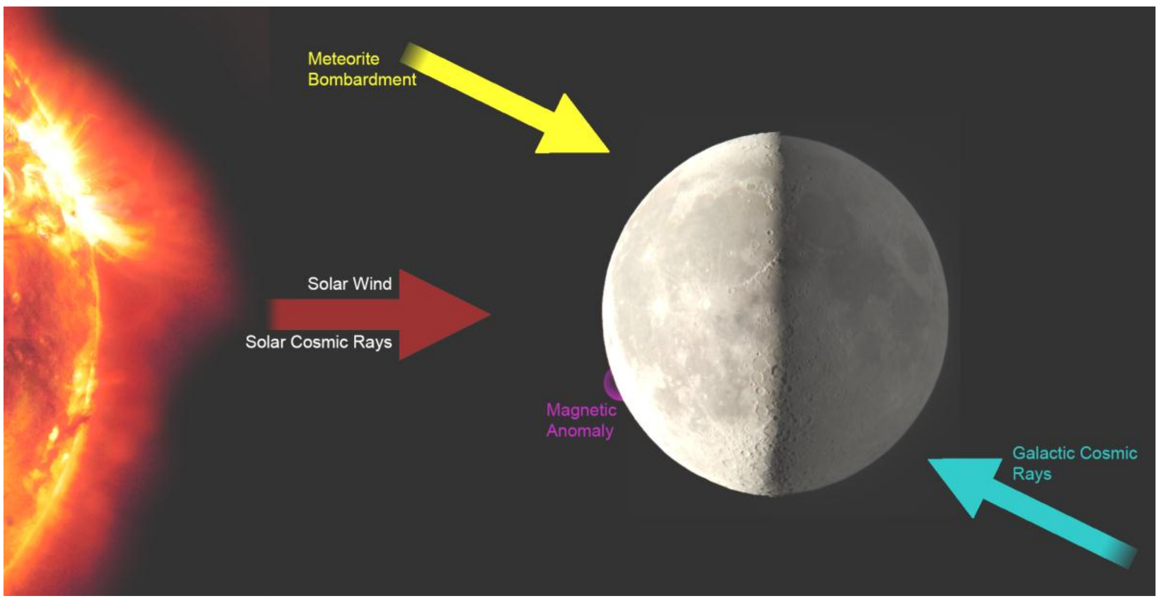

FIGURE 7.18 Schematic illustration of the space weathering effects on the Moon. The Moon is constantly bombarded by solar wind and solar cosmic rays expelled from the Sun and galactic cosmic rays from other parts of the solar system. The normal path of solar wind particles can be disturbed by magnetic anomalies on the Moon. Electrostatic charging of the lunar surface between the nearside and farside can cause dust to be elevated along the terminator.

Micrometeorite bombardment is the impact of dust-sized particles onto the lunar surface. Micrometeorites are primarily responsible for the formation of agglutinates, aggregates bonded by impact melt glass form only on airless bodies like the Moon. Agglutinates comprise a large percentage of the regolith (about 25–30%) and agglutinate abundance increases with time until a steady state is reached (Heiken *et al.*, 1991). Agglutinate particles are usually smaller than 1mm and are the primary carriers of the single domain, iron metal called nanophase iron (np-Fe^0). This np-Fe^0 can cause changes in infrared and ultraviolet fluorescence, making spectroscopy difficult and potentially leading to misinterpretation of remote sensing data. Consequently, np-Fe^0 is a very good indicator of a soil's maturity. Perhaps even more important than the nano-sized metallic droplets in agglutinates from a human exploration viewpoint is the fact that agglutinates retain gases from the solar wind, including hydrogen and helium, in relatively high abundances. Such volatiles can potentially support human habitats and may be used as propellant for future missions to farther reaches of the Solar System.

Solar wind consists of a stream of charged particles that is ejected from the sun, but penetrates less than a micrometer into the regolith. The solar wind is responsible for some volatile implantation into the regolith, including hydrogen, carbon and nitrogen. Most volatiles, though, are lost to space through solar wind sputtering, which is the displacement of nuclei in a target material by energetic particles. Solar wind particles are deflected by magnetic fields, so in locations on the Moon where enhanced magnetic fields exist, the effects of space weathering on the regolith are expected to be modified. Presence of solar wind deposited hydrogen in the regolith is an important factor in reducing FeO in the regolith to native iron in the production of np-Fe^0 particles. In the presence of a magnetic field, the charged hydrogen particles of the solar wind would be deflected from the center of the magnetic anomaly and deposited at the edges of the field. The enhanced hydrogen abundance around magnetic fields is thought to lead to formation of larger np-Fe^0 particles, while inside the magnetic anomaly regolith remains unweathered by the solar wind (Kramer *et al.*, 2011). Figure 7.19 shows Reiner Gamma, an example of an anomalously weathered lunar swirl. By studying magnetic anomalies on the Moon, we may be able to deconvolve the effects of the solar wind from the other space weathering processes active on the Moon, a valuable result for understanding space weathering on other airless bodies.

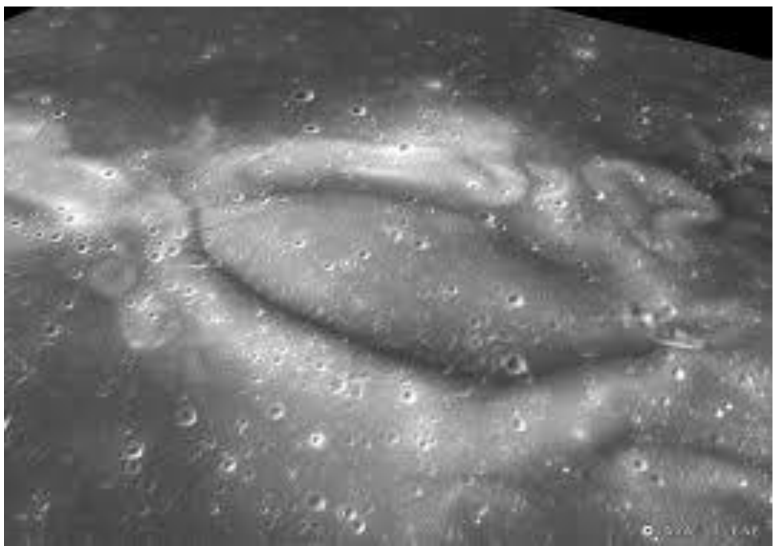

FIGURE 7.19 Reiner Gamma is an example of a lunar swirl—a surface feature related to some magnetic anomalies on the Moon. Magnetic anomalies have the potential to deflect solar wind charged particles away from the regolith, retarding space weathering at the location of the anomaly and enhancing space weathering at the edges.

Solar cosmic rays (SCRs) are energetic charged particles that originate from the Sun. SCRs can penetrate the regolith to depths up to a few centimeters, though they only implant heavy nuclei into the top millimeter of the soil. They can also cause a high density of radiation damage. Similarly, galactic cosmic rays (GCRs) are also energetic charged particles, but they originate from outside the Solar System. Normally, GCRs are stopped within the top 10cm of regolith, but the lighter particles, mainly protons and alpha particles, can cause a cascade of particles that affect meters of regolith. Figure 7.20 shows a visual representation of how far into the regolith the different processes of space weathering can penetrate.

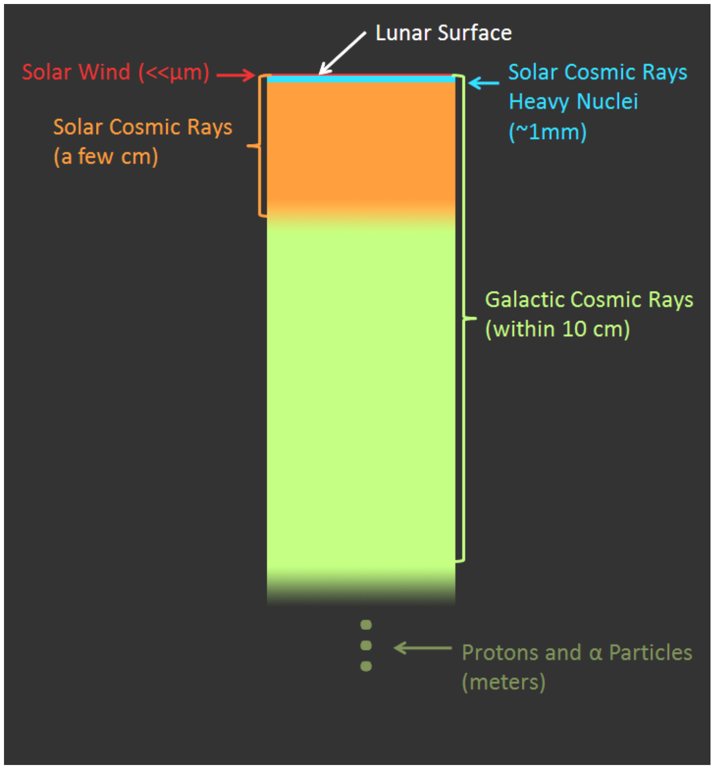

FIGURE 7.20 Schematic illustration of the penetration depth of various space weathering processes.

The original composition of the regolith experiencing space weathering affects the weathering process. In particular, FeO content of the original material affects the np-Fe^0 abundance, so mare soils, which have on average three or more times the total FeO content of highlands soils, accumulate more np-Fe^0 particles. Thus, spectral effects of space weathering differ between highlands and mare soils (Noble *et al.*, 2001). Opaque mineral content also may have effects on the maturity of soils as detected from orbit that are not well understood. Remote sensing studies of maturity on the Moon reveal anomalously mature values in Mare Tranquillitatis, which is a high-Ti area of the Moon (Lucey *et al.*, 2000b). Sampling locations of diverse composition to fill out the existing sample suite will enhance understanding of the compositional controls on space weathering processes, which can then be applied to other airless bodies.

As with the physical properties of the regolith, the effects of space weathering can and should be studied at any landing site. The motivation for studying the modification processes of the regolith is threefold. First, a primary objective of understanding the effects of space weathering is needed to better understand spectral data obtained from the Moon and other airless bodies. Potentially, if we measure these spectral effects at a small number of sites, we may be able to better calibrate our global spectral dataset. Understanding space weathering also allows us to obtain better age dating of lunar craters. The accumulating effects of space weathering make freshly excavated, bright regolith optically darker, so as a crater ages its ejecta darkens (Fig. 7.21). However, not all bright rays are young—some are bright simply due to their composition. A more complete understanding of the process of space weathering as it proceeds with time and varies with composition will lead to the development of a more reliable chronometer for the Moon and other space weathered bodies. Finally, space weathering has been active on the Moon since its formation. Understanding space weathering processes can help understand volatile emplacement and solar history.

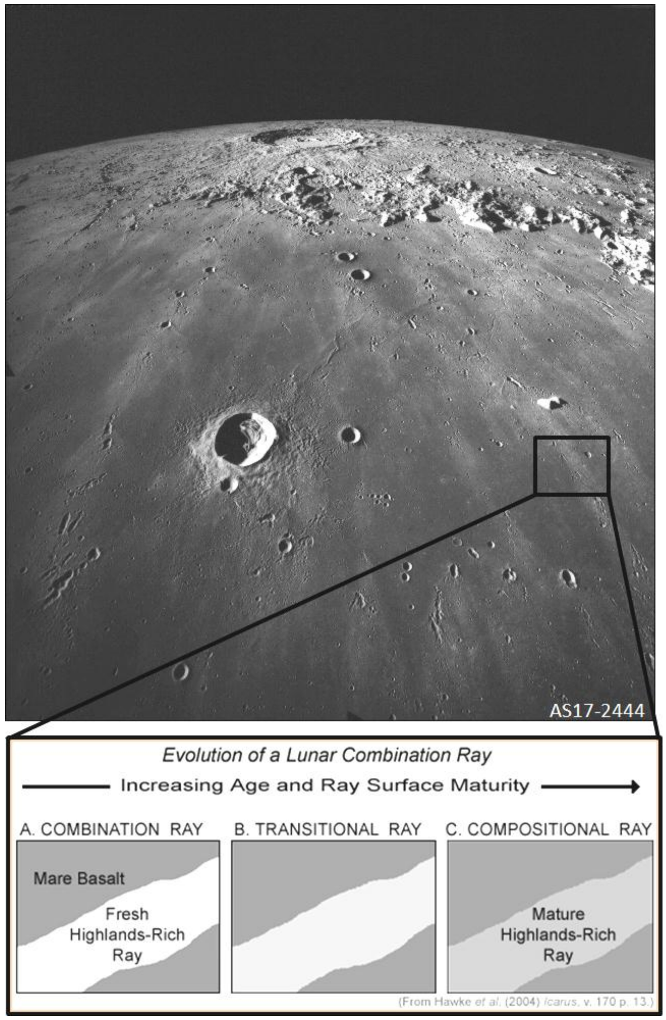

FIGURE 7.21 Evolution of a lunar combination ray (Copernicus, the large crater near the limb). As time progresses, the bright ray matures and darkens. However, some rays are bright due to composition rather than age. Lower portion of figure from Hawke *et al.*, (2004).

It is important to note that, athough the Moon is a laboratory for studying space weathering processes on all airless bodies, processes that fall under the term 'space weathering' are varied and affected by numerous factors. Thus, space weathering is expected to proceed differently on different airless bodies. Composition has been shown to exert strong control on the effects of space weathering in lunar regolith; since asteroids differ compositionally from the Moon and from each other, the effects of space weathering should not be expected to be the same. Indeed, asteroids composed of dark, opaque materials (*e.g.*, C types) show very little evidence for optical maturation of the type seen on the Moon, while asteroids composed of bright, relatively transparent components (*e.g.*, S types) display strong effects of optical alteration (Clark *et al.*, 2002). Regions of the Moon enriched in opaque minerals also show optical maturity anomalies, and may provide insight into space weathering on opaque oxide-rich asteroids. As on the Moon, availability of iron in any form on the body affects the production of np-Fe^0 in vapor-deposited rims surrounding regolith particles.

Location in the solar system is another factor affecting space weathering on the different airless bodies. The effectiveness of the agglutinate formation process is dependent on the energy and frequency with which micrometeorites bombard the surface of the regolith. Micrometeorite flux may be higher closer to the Sun at Mercury's orbit than at the Moon, and lower at the more distant orbits of the asteroid belt (Cintala, 1992). In addition, impact speeds are higher closer to the Sun than at the orbit of the asteroid belt, as shown in Fig. 7.22 (Cintala, 1992; Matson *et al.*, 1977). These factors may contribute to different populations of agglutinate particles on Mercury, the Moon, asteroids, and outer Solar System bodies, leading to differing optical properties.

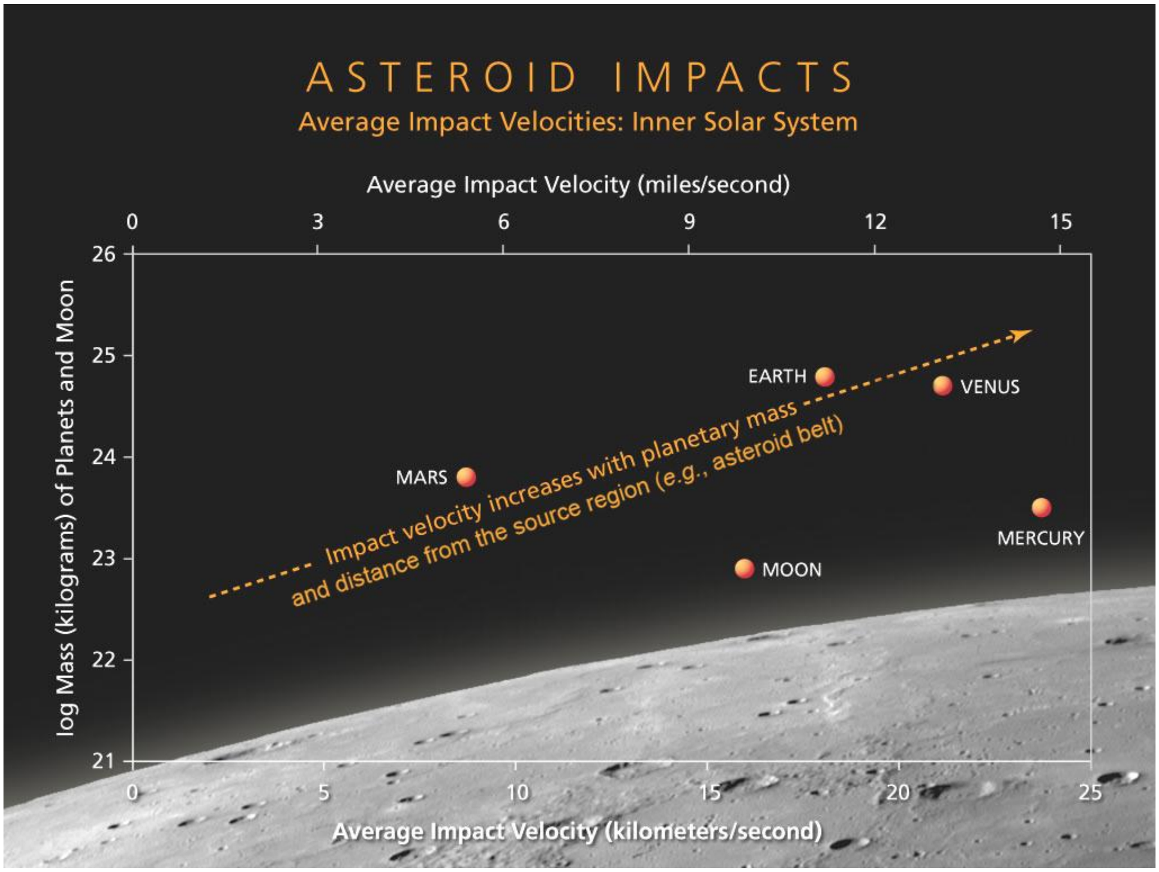

FIGURE 7.22 Plot of the log mass of the inner Solar System planets and the Moon against the average impact speeds of asteroids for each body. Impact speeds are related to the size of the body being impacted, but can be affected by proximity to a larger body or distance from the source region of the impactor. Illustration Credit: LPI (Andrew Shaner and David A. Kring). Background image of Mercury's surface courtesy of NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington, PIA12421.

The solar wind is an important space weathering agent whose key effects include implantation of volatiles into regolith and delivery of H^+ for the reduction of FeO to native iron. In conjunction with micrometeorite bombardment, solar wind particles vaporize regolith material which can then be redeposited as fine-grained rims surrounding regolith particles. The presence of a magnetic field is known to deflect charged solar wind particles. This process has consequences for material and optical properties of regolith shielded or partially shielded by magnetic fields. Mercury's magnetic field may prevent the solar wind from interacting directly with the regolith, reducing effects of sputtering, vaporization and redeposition of native materials, and solar wind volatile deposition (Pieters *et al.*, 2000). Magnetic anomalies on the Moon may provide an accessible analog for study of this process.

Although composition, location in the solar system, and magnetic properties of a body can create variation in the process and results of space weathering on that body outside the scope of what can be directly observed on the Moon, the Moon remains a valuable and accessible site for study of these processes. Examination of lunar samples has provided insight contributing to the identification of S-type asteroids as possible parent bodies for ordinary chondrites (Pieters *et al.*, 2000), and further study of the lunar example of space weathering will continue to enhance understanding of the process throughout the Solar System.

Methods and Requirements

As with many of the Science Concept 7 Science Goals, regolith modification can be studied to first order at any location on the Moon. Exposed regolith everywhere on the Moon is subject to reworking and mixing as a result of micrometeorite bombardment and energetic particle interactions, so every regolith sample collected provides the opportunity to study these processes. However, Science Goal 7c delimits specific priorities for study, including returning samples of different initial composition and exposure history, as well as examining of volatile deposition in the regolith. The science goal definition also points out the usefulness of using artificial materials exposed on the lunar surface for a known length of time as a controlled experiment in space weathering. In order to address these specific goals, we defined four target site requirements:

- Sites that allow sampling of immature, mature, and intermediate regolith.
- Sites that allow examination of the effects of FeO content and opaque mineral content on space weathering.
- At magnetic anomalies, where solar wind volatile deposition may be modified.
- At locations where man-made materials have been exposed on the lunar surface for a known length of time.

In order to locate sites that address the four target site requirements for Science Goal 7c, we developed the following procedure:

1. Obtain global optical maturity maps.
2. Obtain global FeO maps; use these to define high-iron and low-iron regions.
3. Obtain global TiO_2 maps as a proxy for opaque minerals; define regions well represented in the sample suite and regions that have not been sampled.
4. Compile a map of magnetic anomalies identified in the literature.
5. Compile maps of all landed and crashed spacecraft and man-made material on the Moon; suggest the use of LROC NAC imagery where available to determine the extent of intact debris present at locations of crashed spacecraft.
6. Overlay the areas of interest determined on the previous maps and identify locations fulfilling requirements for Science Goal 7c target sites.

Discussion and Site Selection

Sites that allow sampling of immature, mature, and intermediate regolith

Regolith freshly created in an impact event matures with time exposed to the process of space weathering on the lunar surface. Very fresh regolith is considered immature; regolith that has reached steady state with respect to the modification processes of space weathering is considered mature. A remote sensing metric for discussing maturity is the optical maturity parameter, which largely removes compositional effects (Lucey *et al.*, 2000b). Figure 7.23 shows variations in the optical maturity parameter across the lunar surface, particularly in the rays of very young craters. However, on a small scale, material of varying maturity may be found at nearly any landing site. In Apollo core samples, maturity decreased by a factor of two after excavating into the regolith by a half meter (Lucey *et al.*, 2006). We therefore do not consider finding material of different maturities a landing site constraint.

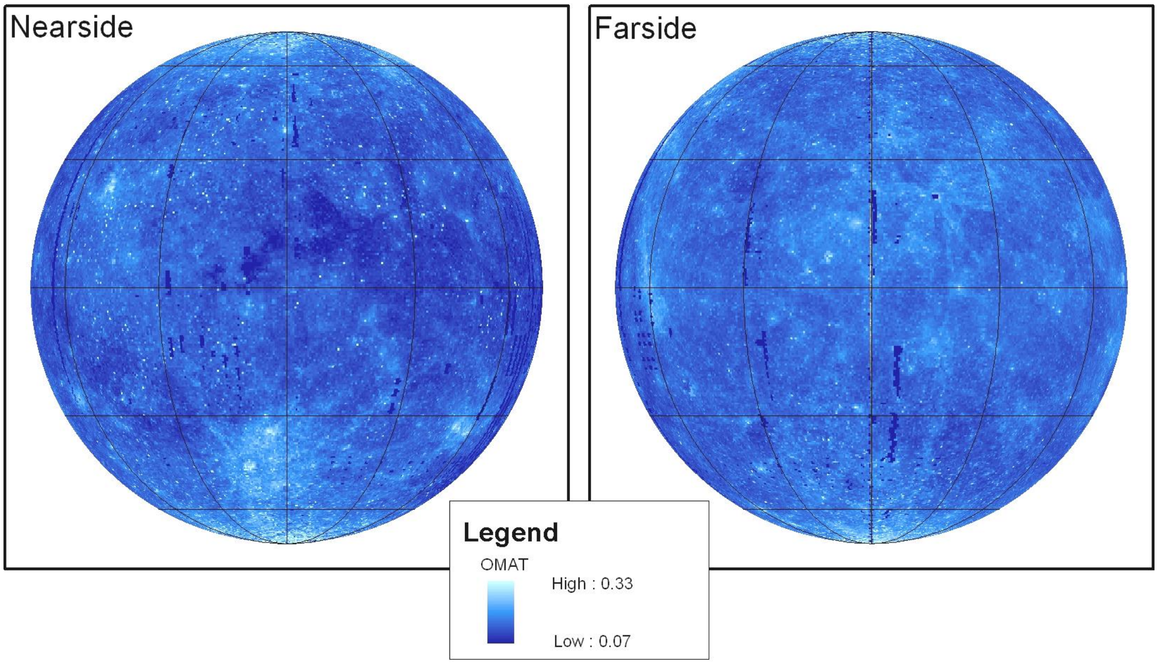

FIGURE 7.23 Lucey *et al.*'s (2000b) optical maturity (OMAT) map. Lighter regions indicate more immature regolith, darker regions more mature regolith.

Sites that allow examination of the effects of FeO content and opaque mineral content on space weathering

The original iron content of a material affects production of nanophase iron particles during the space weathering process. Mare regions of the Moon have iron content as high as 20 wt% FeO, while the highlands regions have much lower FeO, averaging around 4 wt% (Lucey *et al.*, 2006). We divide the Moon into 'low-FeO' and 'high-FeO' regions, with the dividing line at 10 wt%. Figure 7.24 shows the lunar nearside and farside with high-FeO regions highlighted in shades of yellow. These high-FeO regions correspond well with mare regions.

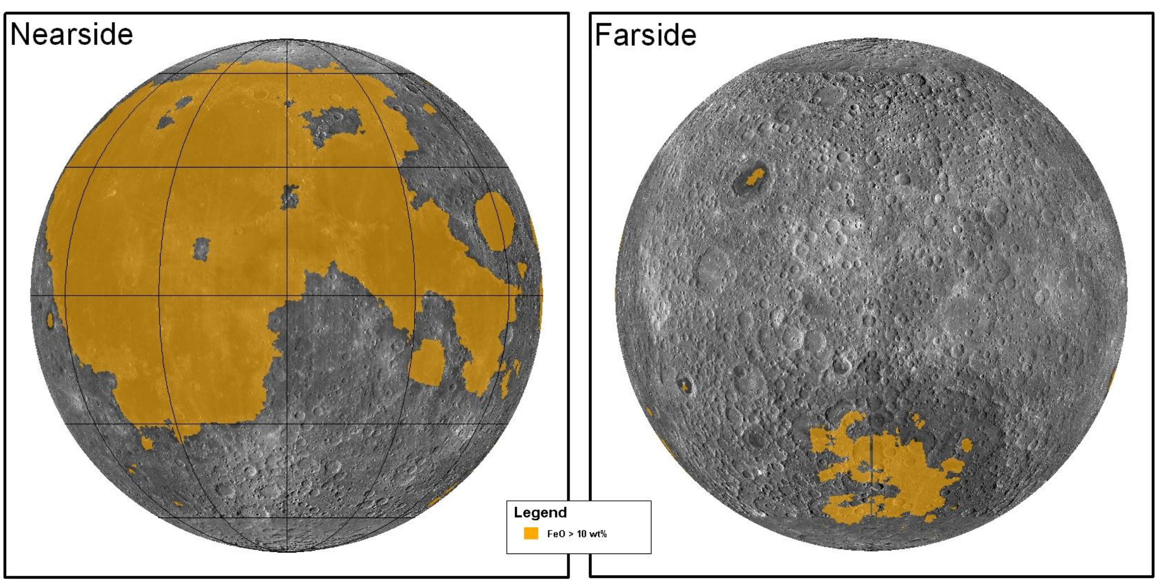

FIGURE 7.24 Areas of greater than 10 wt% FeO are considered areas of high iron. These regions correspond well with mare regions.

Opaque minerals have space weathering properties different from other materials. Ilmenite ($FeTiO_3$) is the most abundant opaque mineral on the Moon, and most of the titanium in the Moon's crust is in this form. Because of this, TiO_2 abundance, as measured by Clementine spectral algorithms or the Lunar Prospector gamma ray spectrometer, can be used as a proxy for abundance of opaque lunar minerals. Using TiO_2 as a proxy allows location of regions with opaque mineral contents not already studied. Figure 7.25 shows a histogram of the titanium content of Apollo and Luna soils and rock samples, demonstrating that low- and high-titanium samples have been obtained and well characterized. However, the lunar samples create the false impression of a bimodal distribution of titanium on the lunar surface that is not seen in remote sensing data. Materials with moderate titanium content have not been well sampled and are high priority for improving our understanding of the effects of opaque minerals on space weathering. Figure 7.26 shows the lunar farside and nearside with regions of moderate titanium content highlighted.

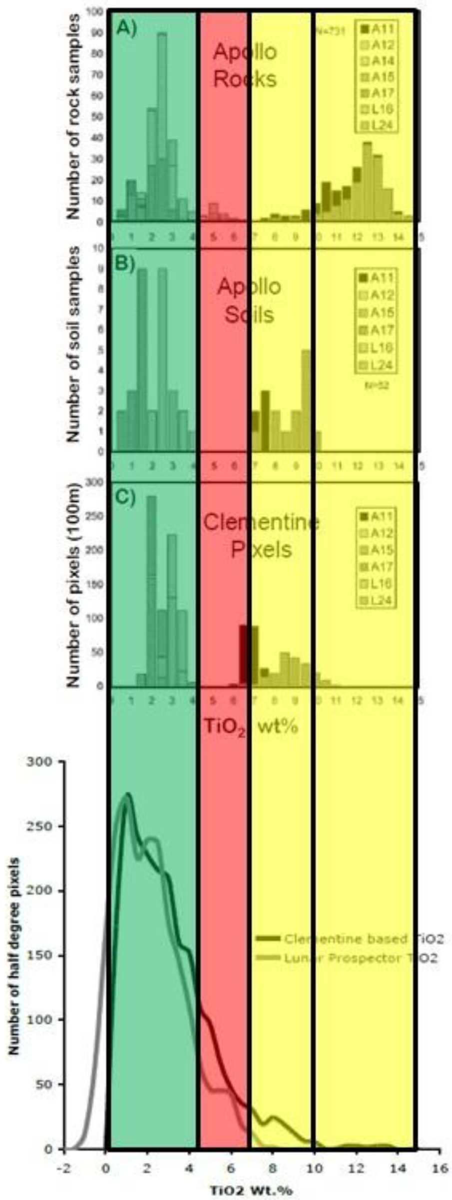

FIGURE 7.25 The apparent bimodal distribution of TiO_2 in Apollo and Luna samples. The colors correspond to the colors used in the TiO_2 maps shown in Fig. 7.26.

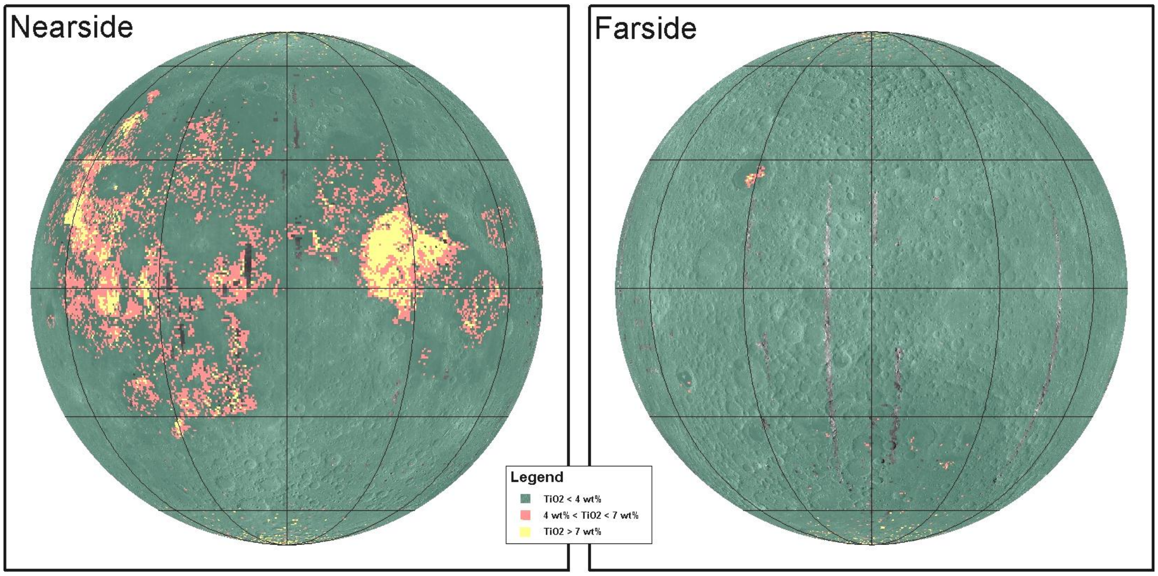

FIGURE 7.26 Clementine of TiO_2 distribution maps (Gillis *et al.*, 2003). The highest priority landing sites sample moderate titanium areas (red), followed by high titanium areas (yellow), and finally low titanium areas (green).

At magnetic anomalies

The Moon does not have a planetary magnetic field, but certain locations of the lunar surface have relatively high magnetic field strength. Many of these locations are associated with lunar swirls, a type of surface feature that shows anomalous space weathering. Calculations have shown that lunar magnetic anomalies have the potential to deflect solar wind charged particles away from the regolith at those locations, retarding space weathering at the location of the anomaly and enhancing it at the edges (Kramer *et al.*, 2011). Studying the regolith at these locations, where all processes of space weathering except for those related to the solar wind occur, provides a possible analog for space weathering on airless, magnetized bodies like Mercury. Understanding lunar magnetic anomalies can help deconvolve the effects of the different space weathering processes for a better understanding of space weathering throughout the solar system. Figure 7.27 shows a map of the locations of magnetic anomalies summarized by Blewett *et al.* (2011).

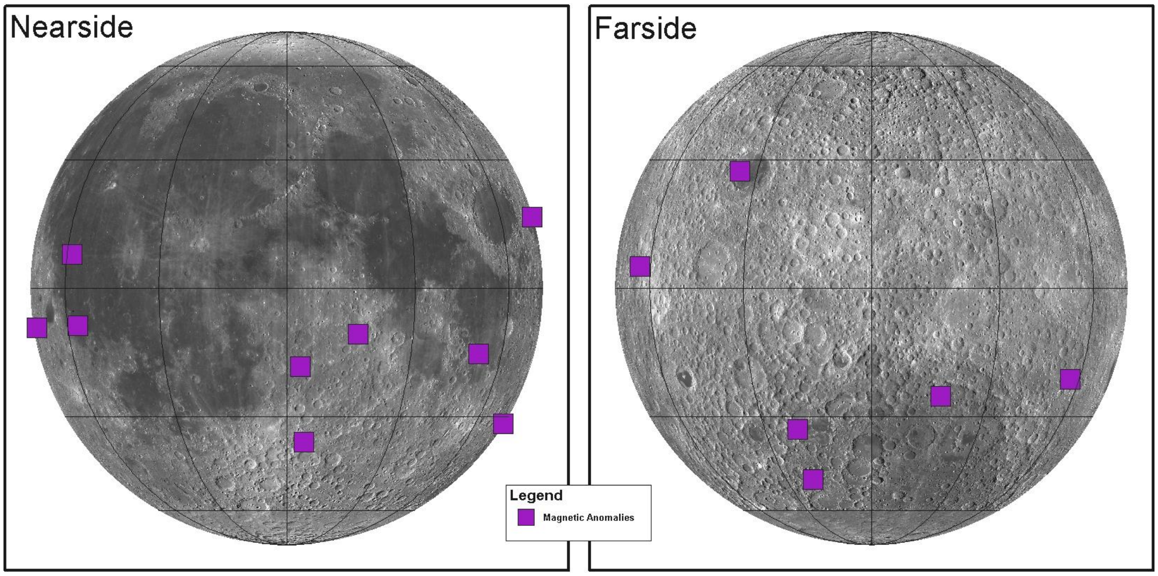

FIGURE 7.27 Locations of known magnetic anomalies on the Moon.

At locations where man-made materials have been exposed on the lunar surface for a known length of time

Studying space weathering effects on a known material for a known length of time may enhance our understanding of space weathering as it progresses with time. Knowing how space weathering affects a known material will help us calibrate a space weathering chronometer. Artificial materials could be brought to the Moon for the purpose of setting up experiments of this type, but man-made materials already exist on the Moon in a number of locations from previous missions. Old spacecraft can be recovered and studied to the same end. Apollo 12 returned man-made material (Surveyor 3) from the Moon; however, the descent module's engines stirred up regolith, sandblasting the target. Consequently, space weathering effects were difficult to study on returned Surveyor 3 samples. Figure 7.28 shows the locations of all landed and crashed spacecraft and rovers on the Moon. Locations of all crashed spacecraft could be examined with high-resolution imagery to determine whether any material survived the impacts.

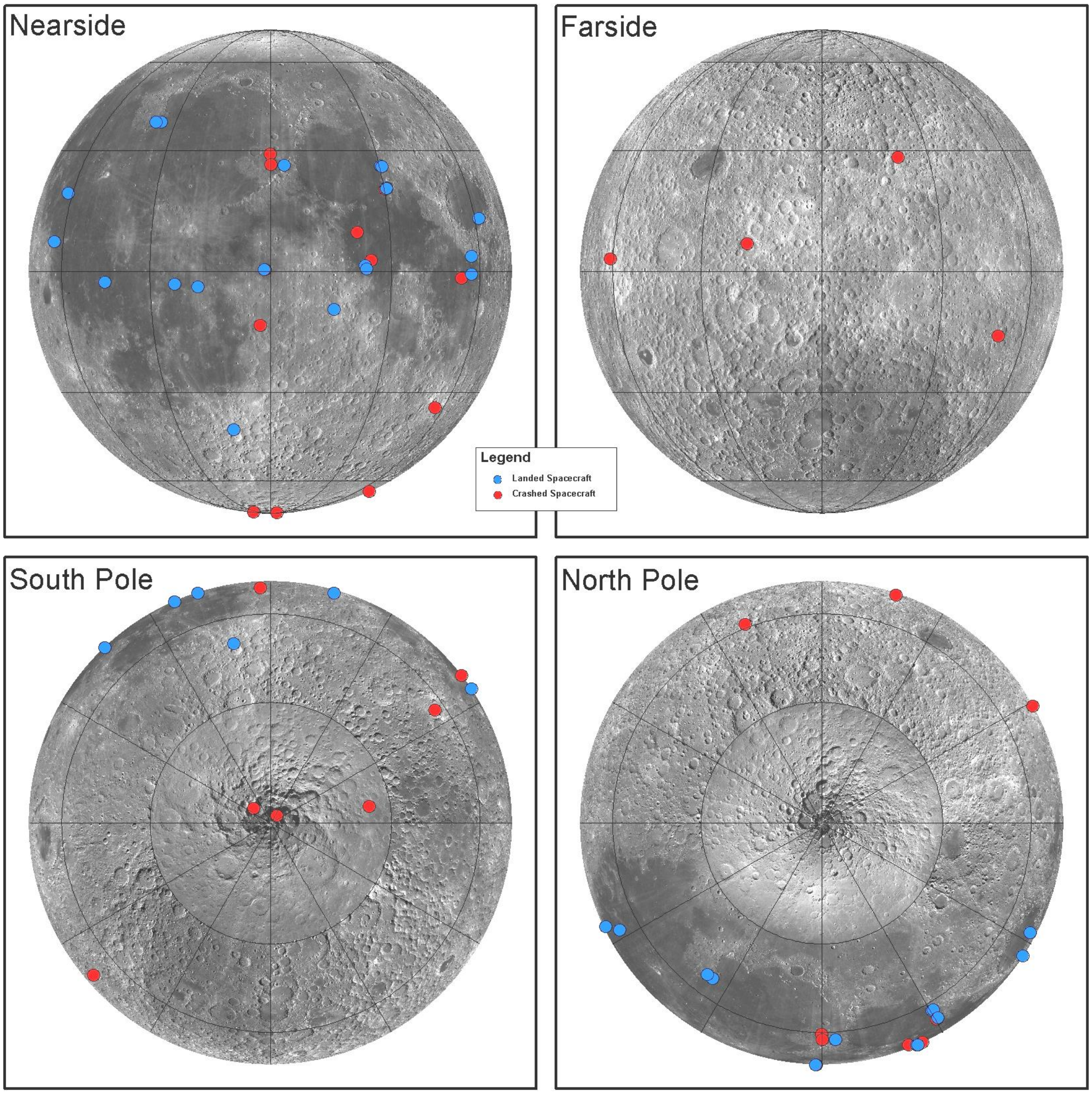

FIGURE 7.28 Locations of crashed and landed spacecraft on the lunar surface. Blue demarks landed spacecraft, while red demarks crashed spacecraft.

Science Goal 7c Landing Site Recommendations

The overarching objective of Science Goal 7c is to understand regolith modification processes, including the deposition of volatile material. Space weathering occurs at every location on the lunar surface, so to first order these processes can be studied at any landing site. However, we have prioritized locations and regions that offer the best opportunity to fully characterize the processes of space weathering. FeO content of the regolith has an important effect on the final space weathering product, so regions of both high and low FeO content should be sampled. Regions with intermediate TiO_2 content should be sampled to expand the sample suite to fully reflect the variation of the lunar surface. Magnetic anomalies on the Moon offer important and unique science returns, and locations of man-made materials on the lunar surface provide the opportunity to gain a better understanding of the weathering process with time in a ready-made experiment. These locations and regions are summarized in Fig. 7.29.

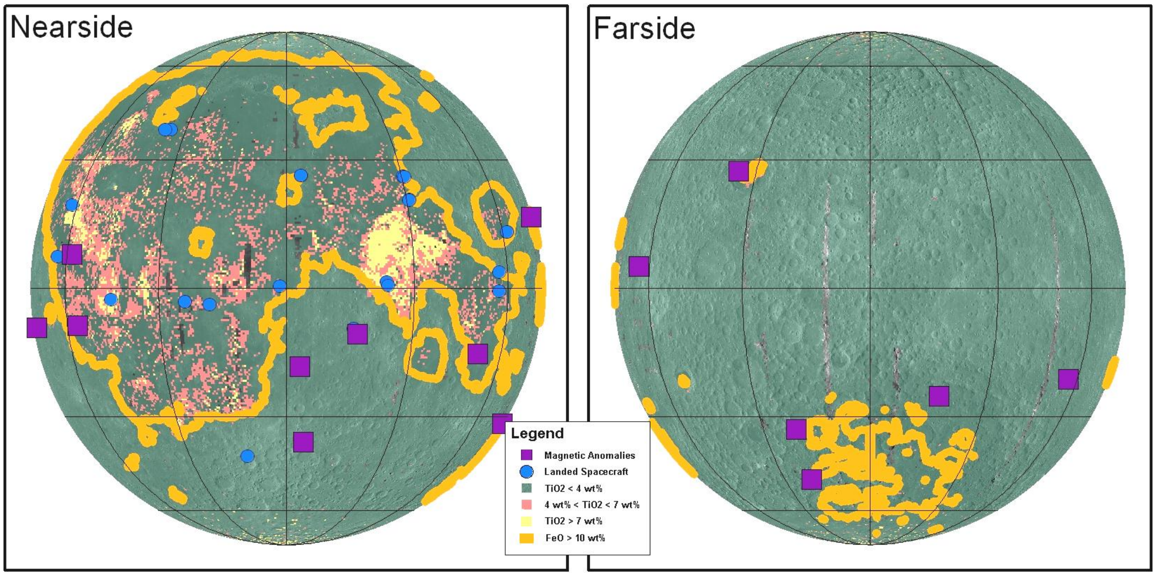

FIGURE 7.29 Map of suggested landing regions for Science Goal 7c. We have prioritized these regions in the following manner: Sampling of regions of varying FeO and TiO_2 are of top priority. Intermediate TiO_2 samples are of higher priority than low or high TiO_2 because of the bimodal appearance of Apollo and Luna samples compared to spectral observations. Next are regions of landed spacecraft because they could potentially be used as a space weathering controlled experiment. Finally, regions modified by the presence of a magnetic anomaly should be studied. Though these regions may show 'anomalous' space weathering, they are useful in understanding space weathering on other bodies with magnetic fields, like Mercury.

SCIENCE GOAL 7D: SEPARATE AND STUDY RARE MATERIALS IN THE LUNAR REGOLITH

Introduction

The presence on Earth of meteorites from the Moon, Mars, and asteroids suggests that material from Earth, as well as these other bodies, could also be found on the Moon. The exchange of impact-liberated material between planetary bodies in the inner Solar System has been modeled; new sampling and searches for meteoritic material on the Moon could help to improve the models. Moreover, if ancient meteorites ejected from the Earth could be found on the Moon, we could learn more about Earth's own early history (NRC, 2007).

Samples of rare material need not be only meteorites from other Solar System bodies. Material consisting of lunar impact ejecta itself is also a target for study. Ejecta may provide a way to sample distant locations on the Moon at another site of interest, providing a way to study two or more distinct lunar regions without the need for multiple missions.

Background

The definition of 'rare materials' for Science Goal 7d is not explicitly defined in the NRC (2007) report. For the purposes of this report we have defined rare in two ways. First, rare can refer to meteoritic material, or more specifically, meteoritic fragments of a few millimeters in diameter.

The second definition of rare can mean lunar material unique to the region of the Moon in which it is found. In this case, we can also consider material that may not be rare in absolute terms, but is rare in a particular site. For example, allochthonous lunar material found in secondary craters may be considered 'rare'.

'Extralunar' material – meteoritic material

We will first consider meteoritic material on the Moon. Meteoritic material is important for several reasons. It may contain volatiles, such as water, or even biomarkers, such as simple hydrocarbons (ten Kate *et al.*, 2010). The chance of finding meteorites containing volatiles or biomarkers (likely in carbonaceous chondrites) on the Moon is greater than on Earth, primarily because the Moon lacks an atmosphere. Meteorites that reach Earth are biased – only the strongest meteorites survive Earth's atmosphere. Weaker ones are destroyed, but often these weaker meteoroids are the ones that may contain volatiles or biomarkers. The Moon lacks an atmosphere and therefore may record a more precise and unbiased meteorite record. Meteoritic traces that appear to be of a variety not found on Earth have been found in lunar samples, supporting the idea that studying meteoritic material on the Moon may allow us to study types of meteorites not present on Earth (Puchtel *et al.*, 2008). Carbonaceous chondrites may help explain the origin and history of the Solar System, volatiles in it, and perhaps even the presence of important organic compounds like those needed for life (ten Kate *et al.*, 2010).

Theoretically, to first order, we can find meteoritic material anywhere on the Moon, but for the purpose of this study we should identify sites that have a greater potential to find, especially, larger fragments.

On Earth, one way to find meteoritic material and fragments is to look inside and around very recent impact craters. More explicitly, the impact melt may contain chemical traces of the impactor. Impact melt is composed primarily of the target rock, but also includes traces of the impactor that were melted during impact (Puchtel *et al.*, 2008). In fresh lunar impact craters the probability of finding traces of the impactor (whether fragments or in impact melt) is greater because post-impact alteration of the impactor is much reduced compared to the terrestrial environment. Figure 7.30 shows an example of a new crater that has formed in the time between the Apollo missions and the LRO mission.

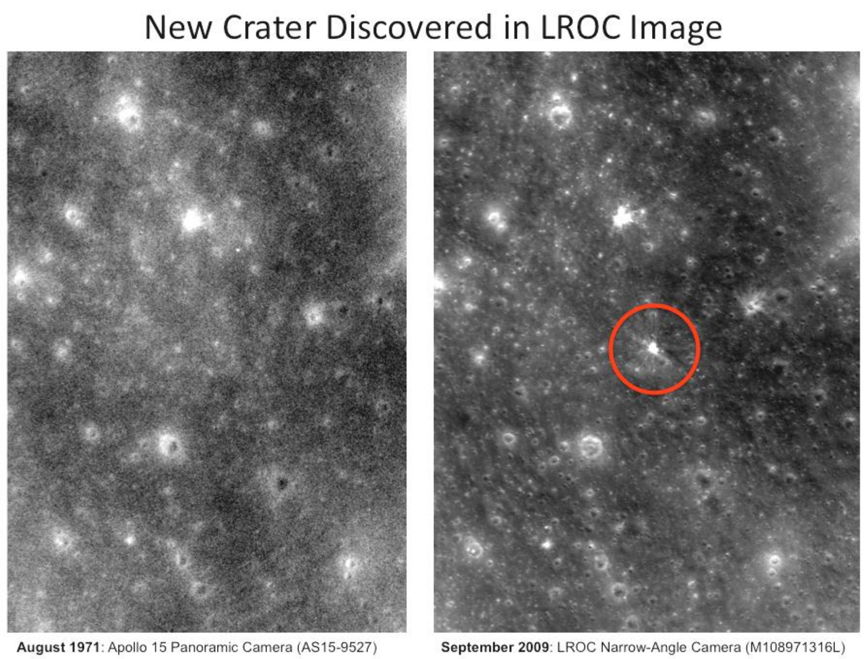

FIGURE 7.30 New impact crater on the Moon, determined to have formed within the last 39 years by comparing images from the Apollo Panoramic Camera and the LROC NAC. This particular crater is only about 10m in diameter. Image credit: NASA/GSFC/Arizona State University; LROC NAC Image M108971316L.

Meteoritic fragments may also be found in crater ejecta blankets. Some of the impactor may be pulverized or melted by the impact and mixed with ejected material. As with any search for meteoritic material, a way to screen large quantities of regolith and pick out rare materials like meteorites is needed. Additionally, on the Earth, meteorites are sometimes found by searching for siderophile elements such as iron and nickel, but orbiting satellites are not capable of detecting such small traces of elements. Perhaps, alongside a screening technique, a siderophile-detection system could be developed for human (or robotic) use on the ground.

It may be possible to find ancient meteorite fragments from a time when the impactor flux was greater. In the early Solar System there was more material in the inner regions of the system to impact the planets (Tera *et al.*, 1974). Because of the greater impactor flux, there may be a greater chance of finding meteoritic material (including material from the early Earth) trapped in the ancient regolith on the Moon. For example, it is obvious that large impacts have not occurred on the Earth in recent times, but there is significant evidence for large impacts in Earth's past. Finding a fragment of the early Earth on the Moon "could provide a new window into early Earth history" (NRC, 2007). Science Goal 7a discusses ancient regolith in detail, including where it may be found. For example, ancient regolith may be trapped between lava flows of different ages, or under distinct layers of lunar material. Craters that penetrate different aged material are excellent targets to search for ancient regolith because they serve as natural drills into the regolith layers. Craters excavate much deeper than is currently possible by manmade instruments. In this case, even old craters may be useful in identifying old terrains and ancient regolith where there is potential to find meteoritic material from a time of greater impactor flux, some of which may have originated on the early Earth.

'Intralunar' material – lunar material from distant locations

In addition to rare, 'extralunar' meteoritic material on the Moon, locally rare material of lunar origin that has been transported from another region of the Moon to its current location via impact ejecta is of interest for study. The most prominent features in this category of rare material are secondary craters and ejecta rays located far from their primary source. Secondary craters can be found both close to and far from the original primary crater. Material from secondaries close to the primary is not particularly useful because the ejecta itself can likely be sampled, so we are predominantly interested in secondaries at locations far from the original crater. Figure 7.31 illustrates the extent of distal ejecta material across the lunar surface from the crater Tycho.

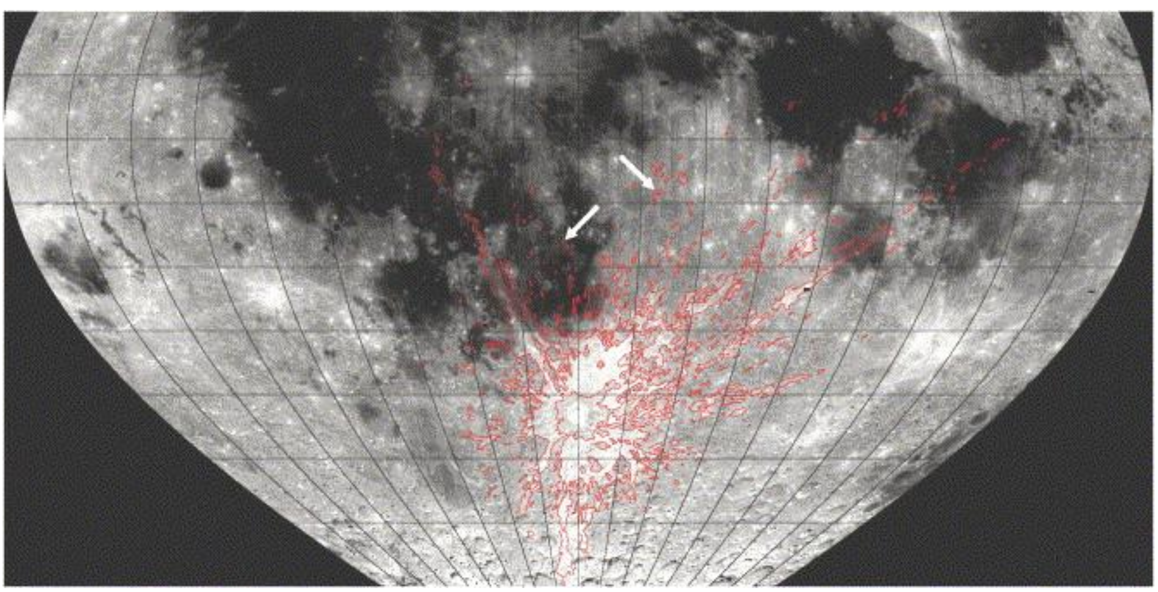

FIGURE 7.31 The extent of Tycho's ray system, including secondary craters and secondary crater clusters, indicated in red outline. Tycho is a relatively large crater, so its secondaries reach vast distances. Tycho is also a prime example for crater ray sampling. Apollo 17 landed about 2000km away from Tycho, yet astronauts were still able to sample one of Tycho's rays, thus collecting rare material from a distant location. Credit: (Dundas and McEwen, 2007).

Secondaries close to and far from the primary crater are morphologically different. Close secondaries often have irregular shapes, fall in crater chains, or form 'herringbone' patterns (Shoemaker, 1962; Oberbeck and

Morrison, 1973). Depending on the magnitude of the impact, some 'close' secondaries may be suitable for study if the primary crater cannot be sampled during a mission. Distant secondaries, on the other hand, may appear more like small primary craters because of the high reimpact speeds. Unfortunately, as impact speed increases, the survivability of the secondary impactor material decreases.

A mission should not depend on the location of secondaries near the landing site. Rather, when deciding between various landing sites of equal potential for science return, a landing site with access to secondary may be more appealing because of the chance to study material from another location of the Moon.

Methods and Requirements

Because the regolith is highly mixed and material from impacts becomes widely distributed over the Moon's surface, there is potential to find rare materials in the regolith anywhere on the Moon if the means to detect the material is present. However, some locations on the Moon may provide a better chance of finding the rare materials defined in Science Goal 7d. Meteoritic material may be more easily discerned in relatively fresh craters of Copernican age, material from the early Earth or other terrestrial planets may be more easily isolated in ancient regoliths, and material from faraway locations on the Moon is more likely to be found in secondary craters or crater rays. These preferred target site requirements for finding rare material on the Moon are listed below.

Science Goal 7d landing site requirements:

- Near or in craters of Copernican age
- Locations where ancient regolith may be found (see Science Goal 7a)
- Near secondary craters of faraway impacts

In order to locate sites fulfilling the requirements listed, we followed the procedure below.

1. Compile a map of the locations of Copernican-age craters
2. Compile a map showing locations of recent impact candidates on the Moon sighted from Earth
3. Compile maps of secondary craters identified for key impact basins and maps of craters identified as secondary whose primary craters are uncertain
4. Refer to Science Goal 7a for locations where ancient regolith may be found
5. Overlay the maps listed above to determine sites that can satisfy the requirements for Science Goal 7d

Discussion and Site Selection

This section discusses landing sites that will fulfill the criteria presented in the methods section above.

Near or in craters of Copernican age

Copernican age craters are those thought to have formed in the last 1.1 Ga, since the formation of Copernicus crater (Hawke *et al.*, 2004). These are the youngest and least degraded craters on the lunar surface, and meteoritic material from the impactors that created these craters may be more easily identified in these craters than in older, more heavily modified ones. Figure 7.8 in Science Goal 7a above shows the locations of craters identified as Copernican age.

Crater-forming events continue to occur even in the present day. Some of these very recent craters may be very good sampling locations for meteoritic traces because of their freshness, but generally are not identified in the literature. We attempted to identify new, very young craters by comparing Lunar Orbiter images from the 1960s with Lunar Reconnaissance Orbiter images from 2009 to present. Craters from impacts between the two missions can be detected if the image resolution is sufficient. We identified about twenty 'young' crater candidates in LROC imagery, looking for very sharp, very well defined rims with bright rays, bright ejecta, and well-delineated round shapes. For the majority of these candidates, however, a comparison with LO imagery was not possible for a lack of data in the chosen areas.

NASA's Marshall Space Flight Center (MSFC) conducts automated observations of possible lunar impacts. Locations of possible lunar impacts observed by the MSFC Automated Lunar and Meteor

Observatory (ALaMO) between November 2005 and June 2011 are shown in Fig. 7.32 below. These locations should be checked using high-resolution imagery to confirm impacts; once confirmed they provide very young locations to search for meteoritic material.

The Optical Maturity Parameter (OMAT) (Lucey *et al.*, 2000b), may be a possible tool for assisting in the determination of the relative ages of bright rayed craters, but a method for using it in this way has not been well developed (Grier *et al.*, 1998). We tried to use the optical maturity technique to identify recent lunar craters with immature by mapping thirty-three craters around Tycho. Because we could not rule out the possibility that the optical maturity parameter would belong to the ejecta of Tycho crater that covers the area, and because the craters did not show the usual morphological features that are typical for new craters, we did not include these craters for further consideration here.

Figure 7.32 shows the relatively young craters identified in this study as possible locations for isolating meteoritic material from the impactors creating the craters.

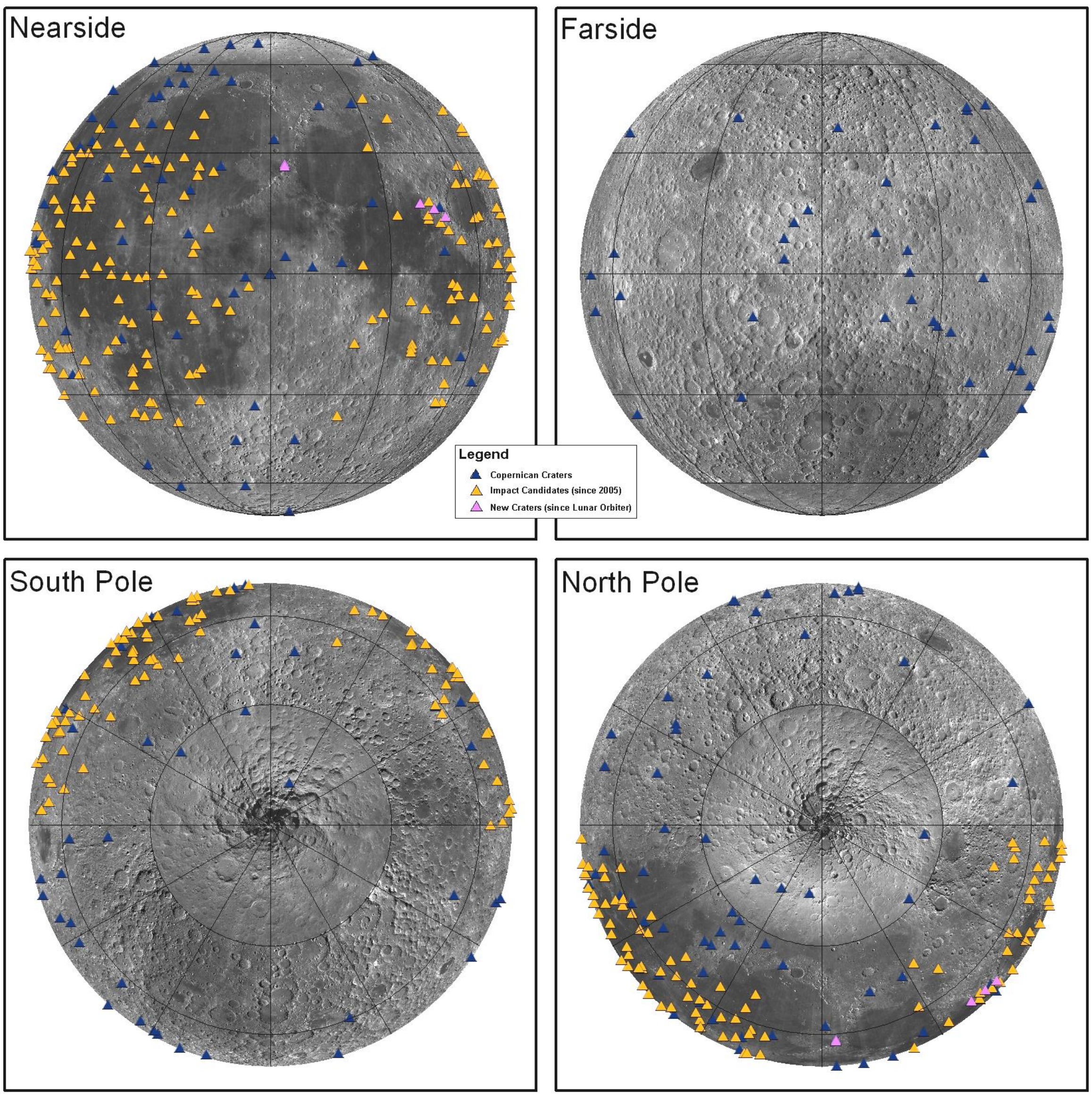

FIGURE 7.32 Locations of all Copernican, post-Lunar Orbiter impacts, and post-2005 candidate lunar impacts. Base map: LROC WAC mosaic.

Locations where ancient regolith may be found

Preserved ancient regolith deposits will contain traces of meteoritic material that impacted the Moon during the time period when that regolith was exposed to the space environment. In addition, because the impactor flux in the past was higher than at present, ancient regolith deposits may contain higher quantities of meteoritic material and have a higher probability of containing material ejected from Earth or the other terrestrial planets in giant impact events. For possible locations of preserved ancient regolith deposits the reader is referred to the discussion in Science Goal 7a.

Near secondary craters of faraway impacts

When impact events occur on the Moon, ejecta from the original impact can travel great distances because of the absence of an atmosphere to create drag. In this way, material from very distant areas of the Moon can be transported to another location on the Moon. Though secondary craters are not a site selection criterion, a mission should take advantage of studying secondary craters if they are within an acceptable distance from the landing site. Thus, by cataloging secondary craters from various primary impact locations on the Moon, we can provide guidance for locations where distant lunar materials can be sampled. At this point, maps for secondary craters are grossly incomplete. Ideally, a map of the global distribution of secondary craters could aid in the evaluation of landing sites. Figure 7.33 shows locations of all secondary craters identified in this study.

Science Goal 7d Landing Site Recommendations

Figure 7.34 shows compiled maps of all young craters and secondary craters identified on the Moon. These maps are not comprehensive, but serve as a guide for some locations where meteoritic material may be found in young craters, and in particular how determining the source craters of secondary craters may allow missions to sample two regions of the Moon while only visiting one.

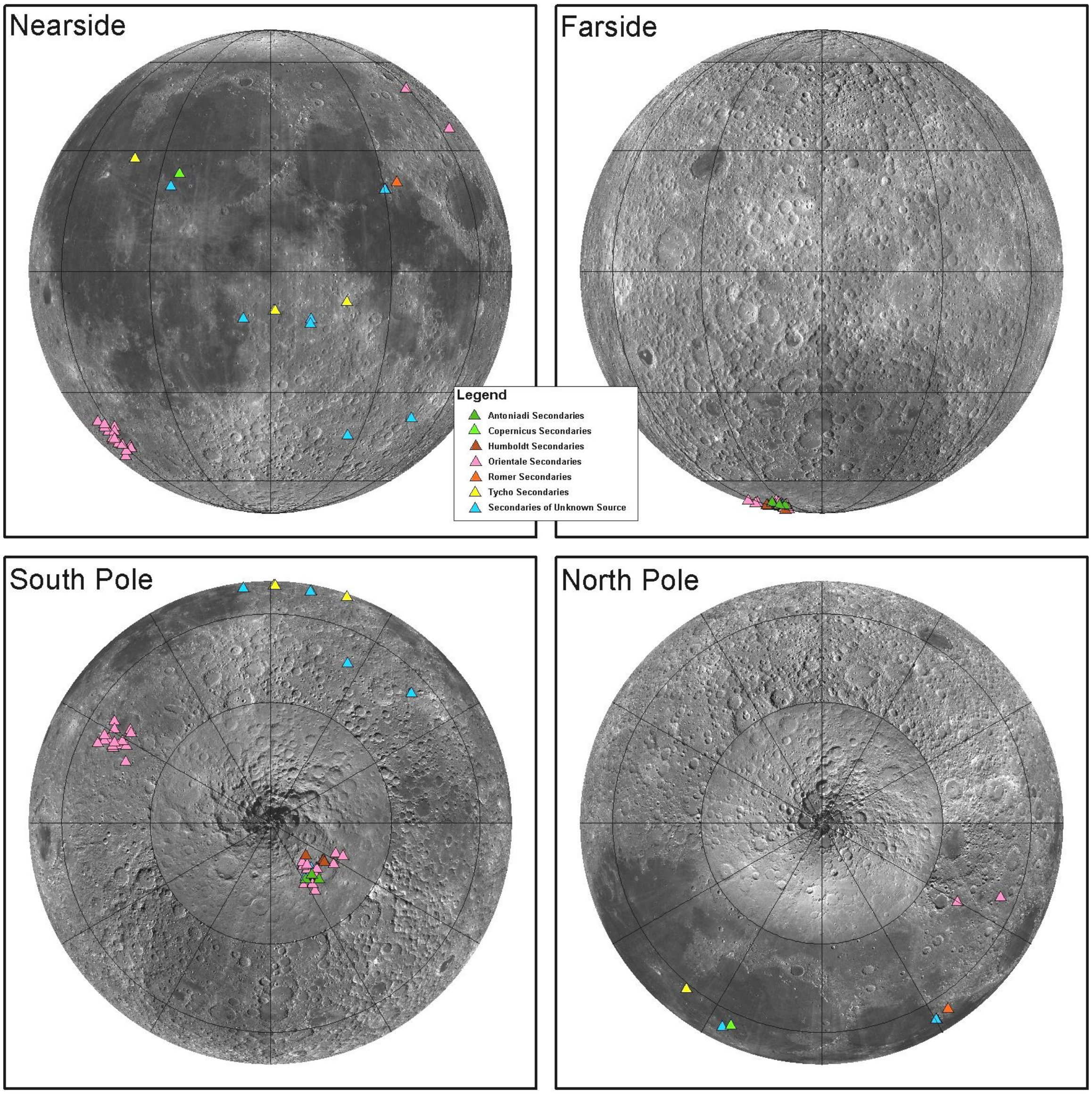

FIGURE 7.33 Locations of all secondary craters compiled in this study. Base map: LROC WAC mosaic.

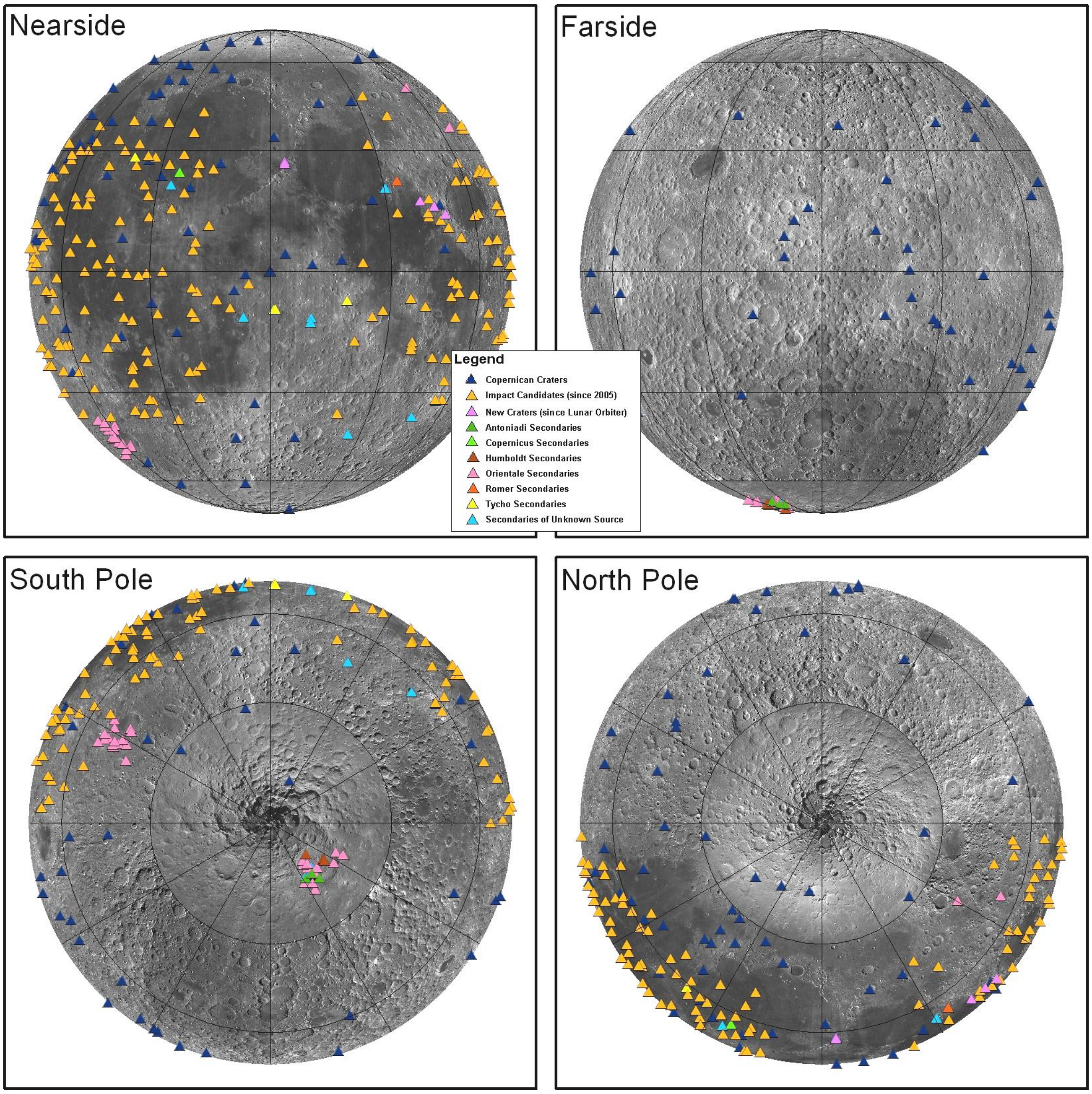

FIGURE 7.34 Locations of young craters and secondary craters compiled in this study. Meteoritic material may be more easily located in these young craters. Material from distant regions of the Moon may be found in these secondary craters. Base map: LROC WAC mosaic.

SUGGESTED LANDING SITES AND CASE STUDIES

As examples of potential missions that could fulfill the requirements of Science Concept 7, we defined two case studies – one at Mare Moscoviense and one on the rim of Tycho Crater. These case studies explore how sites might be selected to meet various aspects of the Science Concept 7 Science Goals. Some sites may be more applicable for a certain goal than others, but we have tried to demonstrate how valuable science return can be gained from any site. An important note is that the region of top priority for Science Concept 7 is actually the lunar poles. However, our case studies focused on two non-polar sites. For polar studies, we direct the reader to Science Concept 4 and the case studies considered therein.

Mare Moscoviense

The Moscoviense Basin, and in particular the boundary between Mare Moscoviense, the basin's inner ring, and the rest of the basin floor, is an appealing location to study. Moscoviense Basin is located about 4 km above the average lunar radius (Gillis-Davis *et al.*, 2006) in the northern portion of the Moon's farside, well within the FHT terrane. Figure 7.35 shows the Mare Moscoviense landing site on a global Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) map of the Moon.

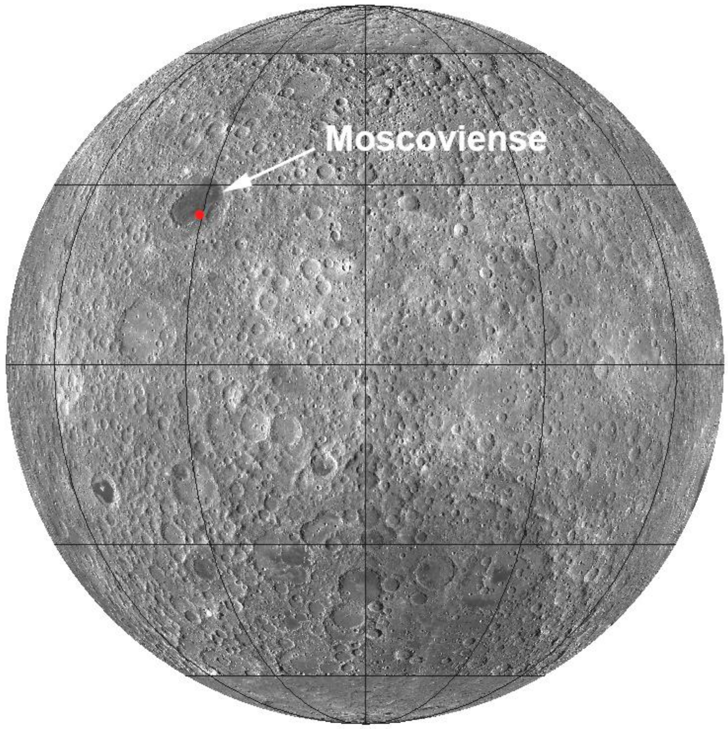

FIGURE 7.35 An LROC WAC mosaic of the Moon showing Mare Moscoviense and our suggested landing site with a red dot.

Our hypothetical landing site, situated at approximately 149.4° E and 24.8° N, can satisfy multiple aspects of each Science Goal of Science Concept 7. An LROC WAC mosaic and geologic map of the region are shown in Fig. 7.36. Within the inner ring of the Moscoviense basin lie Mare Moscoviense and our proposed landing site. Mare Moscoviense is one of the few mare regions on the farside of the Moon and it is also composed of several different mare units of unique compositions. The proposed landing site is located at a boundary between two mare units and a highlands unit. The mare units are anomalous for the farside, but there is also a highlands unit within accessible distance from the landing site. Spectral data show that this highlands unit is, in fact, similar in composition to the rest of the FHT region. Iron maps, however, show that the region is enriched in iron. Some locations within the areas of exploration, however, do not have high iron content. We believe that, although the region has a higher iron content, it will still be relatively representative of the FHT, based on the Clementine data (Fig. 7.37), and is therefore a reasonable location to study and characterize the regolith.

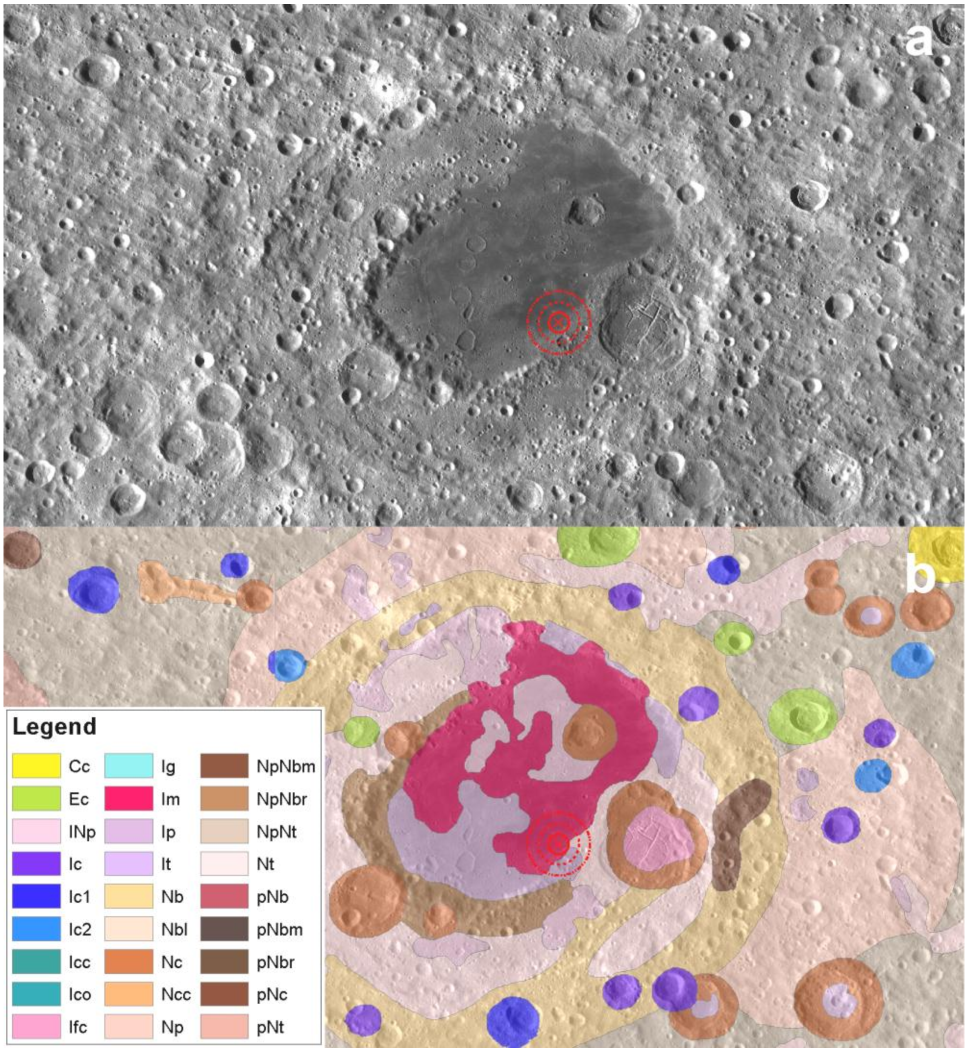

FIGURE 7.36 Image of Moscoviense Basin region in a LROC WAC mosaic (a), and a geologic map of the same area (b). The landing region is denoted with a red "X," surrounded by circles of areas for study.

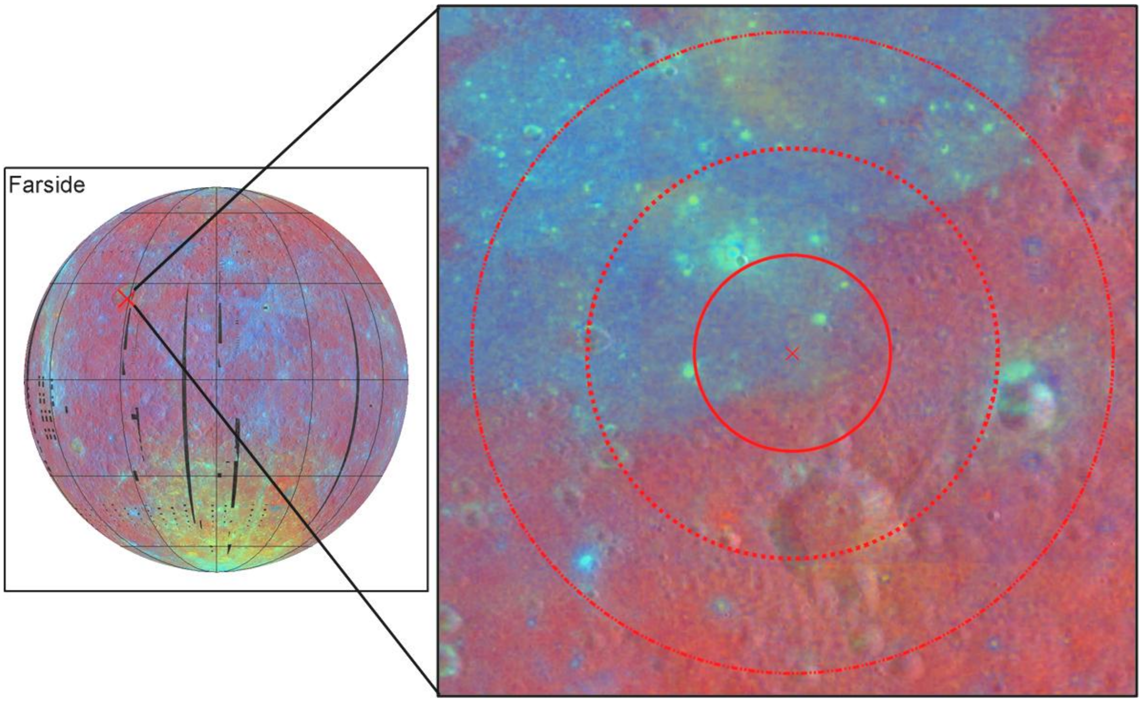

FIGURE 7.37 Clementine mosaic of the farside hemisphere zoomed into the Mare Moscoviense region, demonstrating that the highlands in the region are representative of the FHT in general.

The Mare Moscoviense landing site, shown in Fig. 7.38, is located on the youngest mare unit. As such, this landing site has an exceptionally flat surface, with a slope of 2.3° (Rosenburg *et al.*, 2011). Regions of interest within these exploration areas will be discussed further in context of each individual Science Goal.

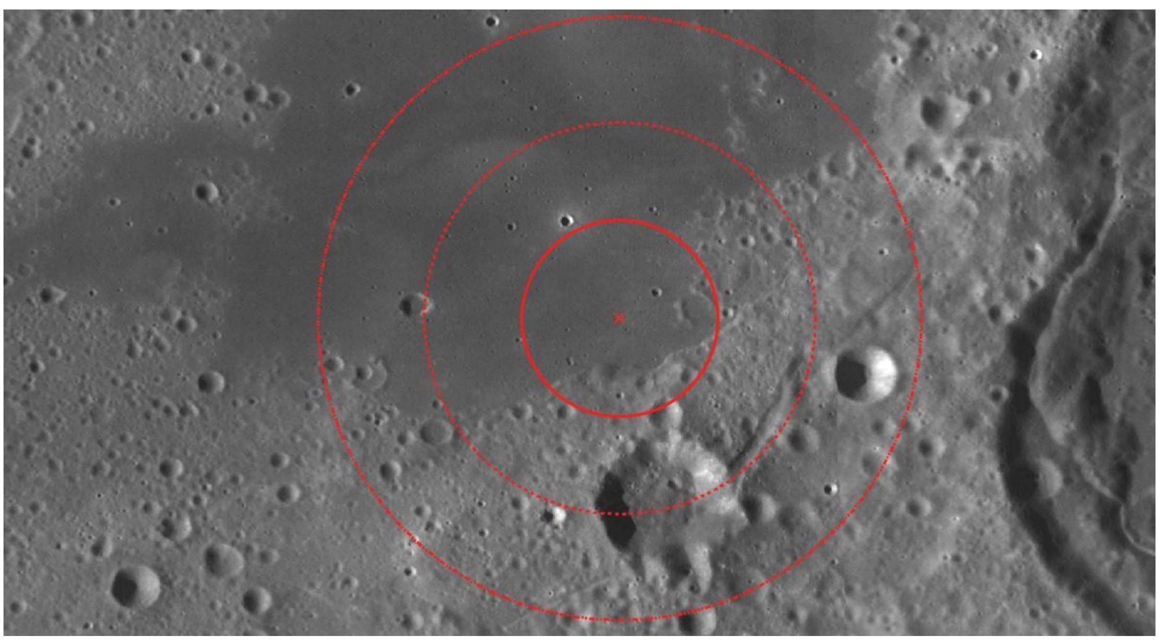

FIGURE 7.38 View of the Mare Moscoviense landing site, denoted by a red "X" and surrounded by circles denoting areas of exploration. The circles have radii of 10 km, 20 km, and 30 km, respectively.

Science Goal 7a

WAC and NAC imagery of the lunar surface reveals a fresh crater located approximately 11 km from our landing site (the bright, fresh crater at the 11 o'clock position just outside the 10-km exploration area in Fig. 7.38). This 1.1-km-diamter crater lies within an Eratosthenian (2.6 Gyr) high-titanium mare basalt and approximately 10 km from an Imbrium (3.4 Gyr) low-titanium mare basalt, which could be impact melt (Thaisen *et al.*, 2011). The crater is shown in detail in Fig. 7.39. Ancient regolith might be found in the crater walls of fresh craters and encapsulated between layers of basalt flows of different ages. The fresh Mare Moscoviense crater appears to have distinctive rim strata that suggests layers of regolith sandwiched by two layers of basalt (Kring *et al.*, 2011). Consequently, we propose that within the rim of this fresh crater we might find an ancient regolith layer of Eratosthenian age between Eratosthenian and Imbrium age basalts.

An additional feature of interest for the Moscoviense landing site is the proximity of two pyroclastic deposits in the area. The locations of the vents are thought to be roughly 62 km and 136 km away from the landing site, but it is possible, due to the nature of pyroclastic volcanism on the Moon, that material from those vents could be found at the landing site. Thus, we can complete another aspect of Science Goal 7a.

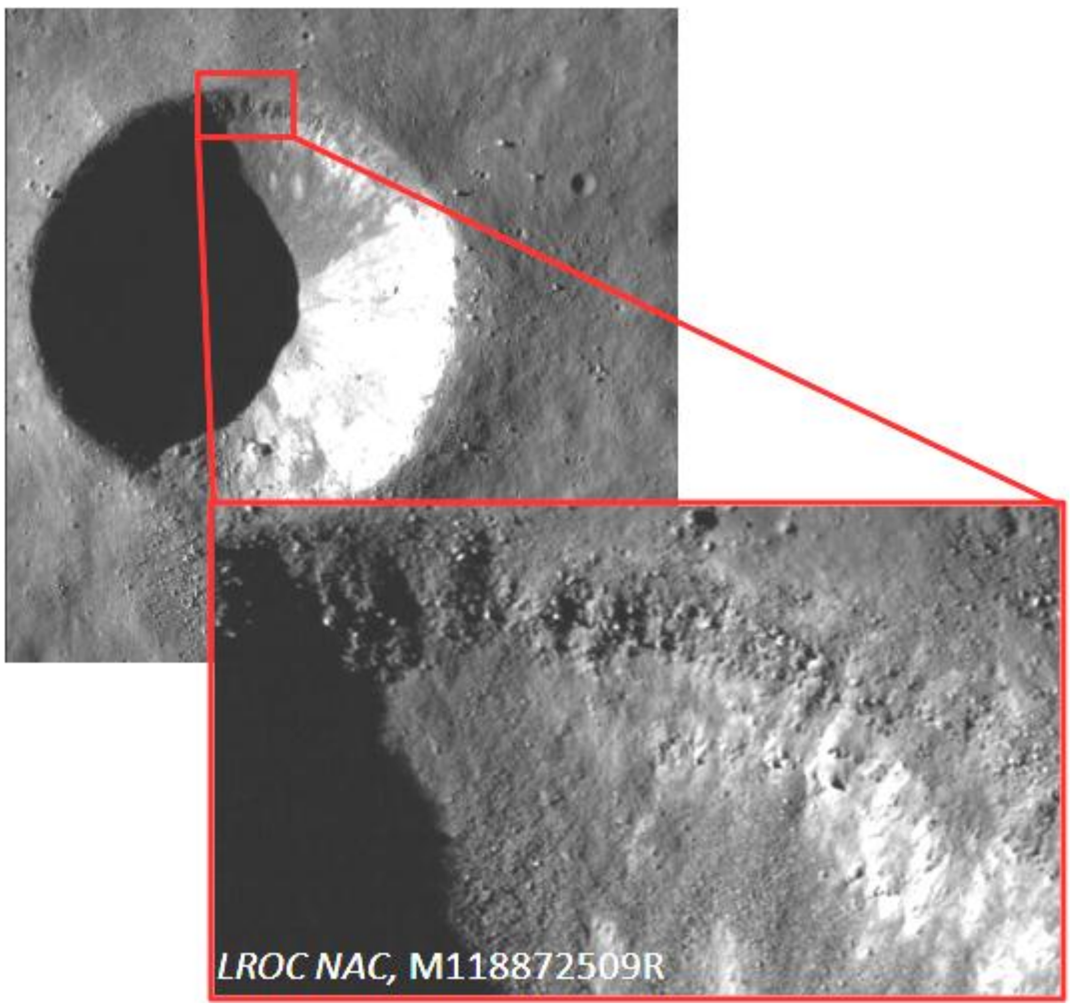

FIGURE 7.39 The fresh Mare Moscoviense crater, with a zoomed in view of the layering present in its walls. This crater is about 1.1 km in diameter. Layering in the walls may contain ancient regolith of Eratosthenian age between Eratosthenian and Imbrium age basalts. LROC NAC Image #M118872509R.

Science Goal 7b

The choice of Moscovience in relation to Science Goal 7b, which refers to determining the physical properties of the regolith at diverse locations of expected human activity, is justified for several reasons. There are a variety of terrains of different ages and compositions in the chosen landing area, including diverse mare basalt units (Thaisen *et al.*, 2011). It is one of the few farside basins that has abundant mare deposits (Gillis-Davis *et al.*, 2006). Further, the mare units that are present in the basin are of different ages and compositions. Mare Moscoviense is located in a region of some of the thickest crust (Gillis-Davis *et al.*, 2006), and has an abnormally large gravity anomaly. The basin lies within the FHT (Jolliff, *et al.* 2000a) and presents a cross section into the original highlands crust (Thaisen *et al.*, 2011). To date, no mission has sampled a farside highland-mare boundary. There is also the possibility of finding cryptomare deposits in the oldest mare unit. Finding cryptomare deposits will aid in the characterization of ancient lunar regolith. The cryptomare may have physical or chemical properties that may be useful to future human explorers. Finally, the presence of rills in the area indicates the possibility of finding exposed bedrock, which may be helpful in determining the depth of the regolith in the Moscoviense region. Figure 7.40 shows a geological map of the suggested landing site, with areas of potential exploration circled around the site at 10 km, 20 km, and 30 km radii.

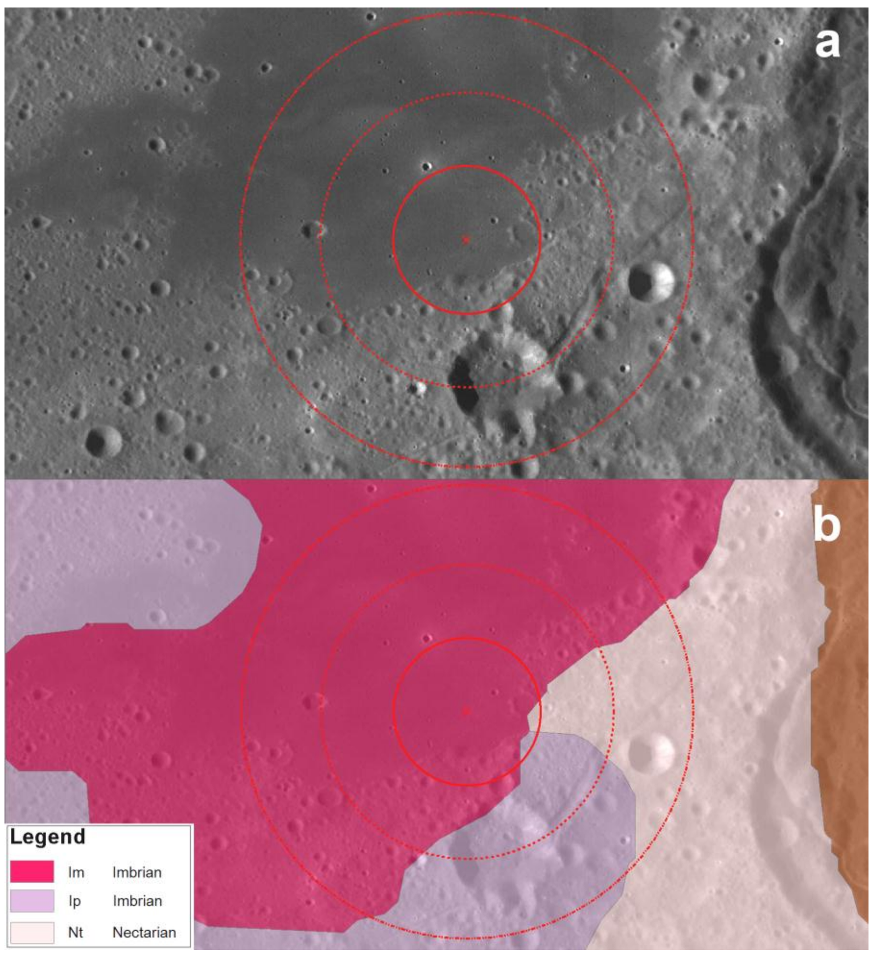

FIGURE 7.40 Image of Moscoviense basin landing site in a LROC WAC mosaic (a), and a geologic map of the same area (b). The landing site is marked by an “X” with circles of potential exploration areas with 10 km, 20 km, and 30 km radii around the site. There are three geologic units of a variety of ages and compositions within 10 km of the site. Im (Mare Materials of Dark Plains, the bright pink region) is of Imbrian age, Ip (Smooth Light Plains, light purple region) is of Imbrian age, Np (Rolling Terra, light pink region) is of Nectarian age. Cryptomare deposits may be in Nectarian aged region.

Science Goal 7c

The Mare Moscoviense site is a unique location that provides the opportunity to fulfill multiple aspects of Science Goal 7c. Mare Moscoviense is the site of a magnetic field anomaly and a group of high-albedo lunar swirls (Figs. 7.41 and 7.42). The landing site chosen is within 10 km of a lunar swirl and is well within the Moscoviense elevated magnetic field anomaly. Samples of regolith both on and off the swirls would provide insight into the effects of a magnetic field on space weathering. A solar wind experiment at the location of the landing site could confirm orbital data studying the effects of lunar magnetic anomalies on solar wind flux (Lue *et al.*, 2011). The Moscoviense Basin is filled with a number of mare basalt flows of varying composition, including low-titanium and high-titanium flows of varying ages (Gillis, 1998; Thaisen *et al.*, 2011; Kramer *et al.*, 2008). The landing site selected is in a region of low titanium, but is within 3 km of a region of moderate titanium content and within 15 km of a region of high titanium content (Fig. 7.43). Samples from Mare Moscoviense could be compared to mare samples in the Apollo and Luna sample suites to investigate first-order differences in weathering of mare regolith under the influence of a magnetic field (Moscoviense) as compared to mare regolith not protected by a magnetic field (Apollo and Luna).

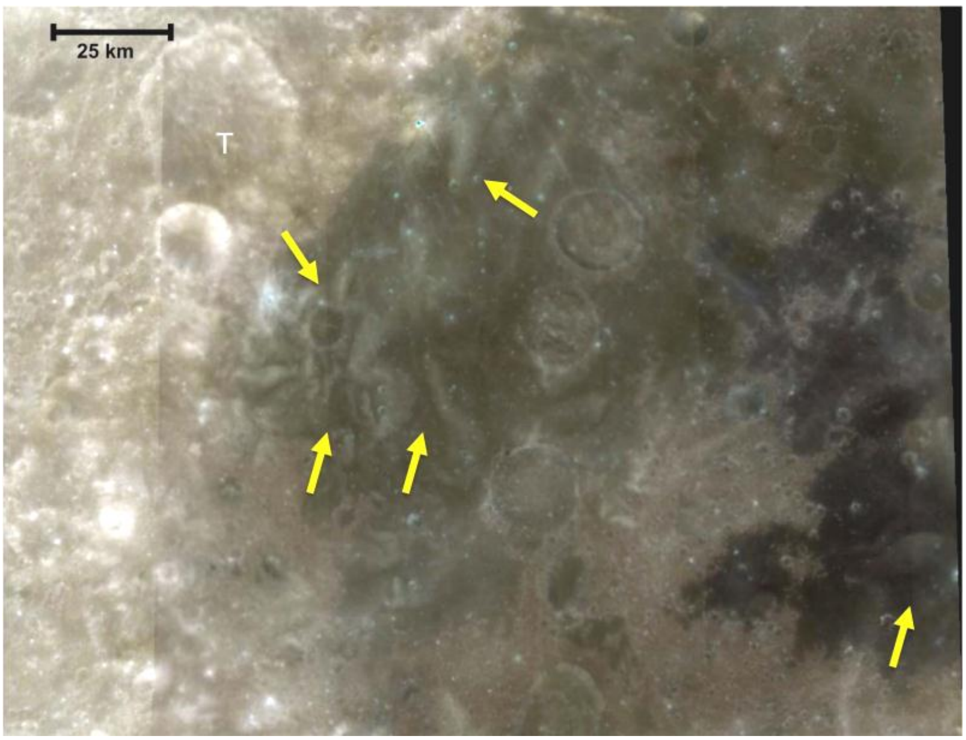

FIGURE 7.41 Yellow arrows point to bright lunar swirls on Mare Moscoviense. Clementine color composite image covers ~24.2°N-29°N, 142°E-149°E in sinusoidal projection. R=950nm, G=750nm, B=415nm. (Blewett *et al.*, 2011).

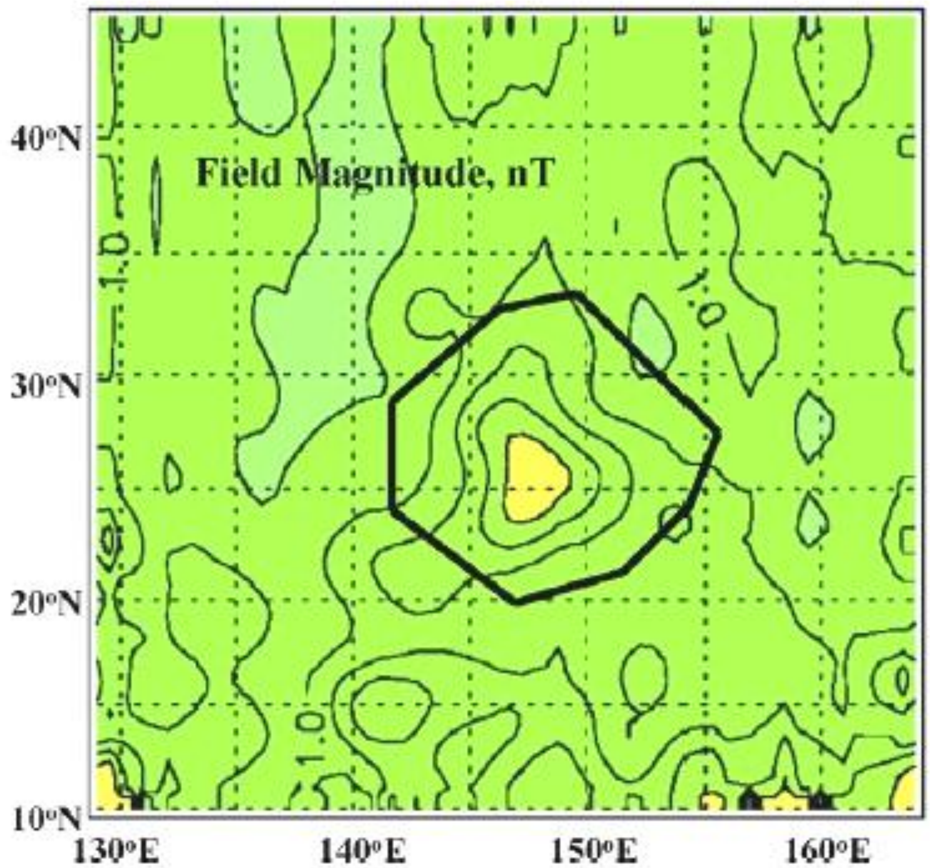

FIGURE 7.42 Magnetic field magnitude in nT at the Mare Moscoviense landing site, at altitudes ranging from ~25 to 32km. Bold black lines outline the general topographic structure of the Moscoviense basin rim. Our landing site falls in the main anomaly (yellow region) of field strength 2.7 nT. (Hood, 2011).

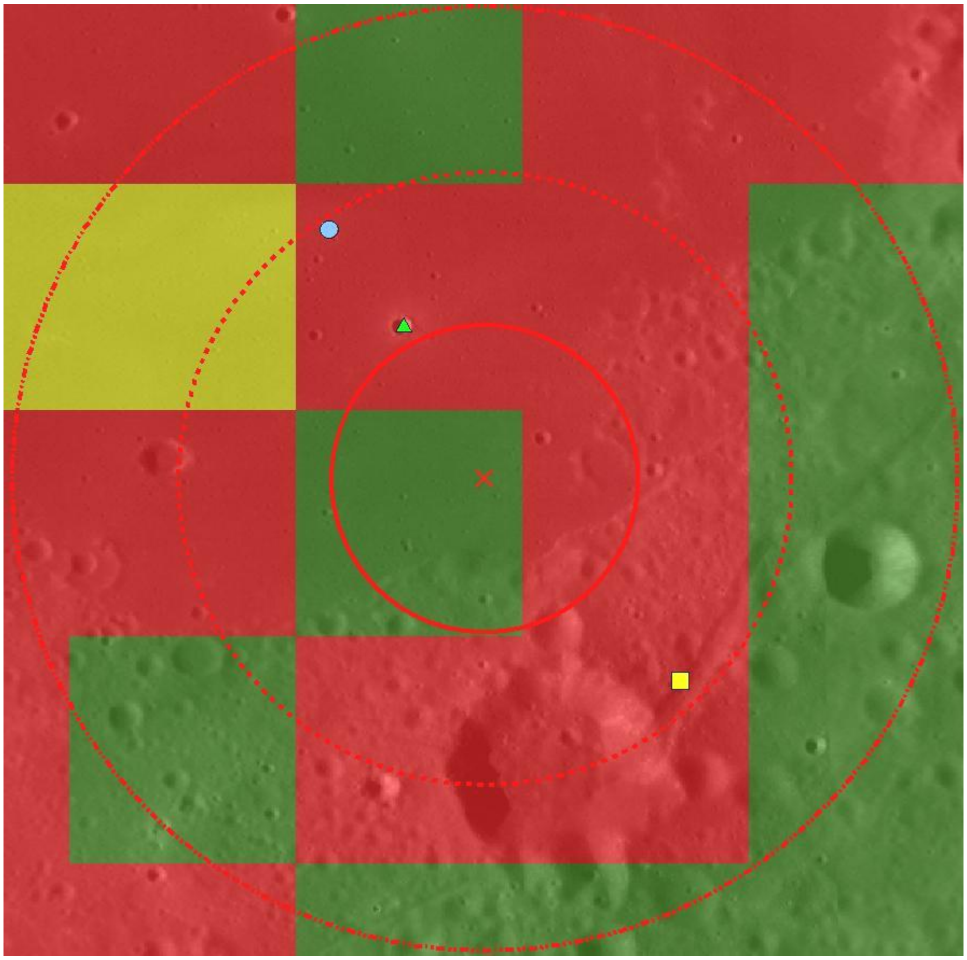

FIGURE 7.43 Landing site shown with Clementine-derived TiO2 abundances overlaid (Gillis *et al.*,2003). Samples of low, medium, and high-titanium regions would best satisfy the goals of 7C.

The process and formation of lunar swirls is not fully understood. Some researchers suggest that lunar swirls form as an interaction between lofted lunar dust and magnetic anomalies (Kramer *et al.*, 2011; Garrick-Bethell *et al.*, 2011). The finest fraction of the regolith may become charged and lofted from centimeters to kilometers above the surface when the terminator crosses, and they may interact with weak magnetic anomalies. The time the dust is lofted is not well known, but it is likely on the order of seconds to minutes, twice a lunar day (during the terminator crossing). The terminator crossing is something the Apollo sites experienced (though not with astronauts there), and dust has been observed 60 hours after sunrise or before sunset at the equator (Garrick-Bethell *et al.*, 2011). It is not clearly known how the dust grains may be deposited to create the lunar swirls, but dust transport timescales are believed to be on the order of 10^5 years. Thus, we believe that the lunar swirl near the Mare Moscoviense site will not pose a risk to explorers, especially if the mission does not occur during a time of terminator passage.

Science Goal 7d

Moscoviense basin has gone through extensive modification, including the introduction of rare foreign material by meteorites coming from different locations within the Solar System and ejected rare material from large impacts at distant locations on lunar surface. As discussed in Science Goal 7d, we expect to find well-preserved ancient material transported by meteorites during a period of heavy bombardment in the walls of fresh lunar craters. Moreover, rare material transported from distant regions on the lunar surface may reside in secondary craters or ancient ejecta. We believe that within the Eratosthenian age regolith layer found in the rim of the fresh crater shown in Fig. 7.39 rare materials implanted by ancient impact events could be identified. The fresh crater's ejecta also offers the opportunity to look for samples of the impactor that created the crater.

A summary of the details of the case study for the Mare Moscoviense landing site is shown in Fig. 7.44.

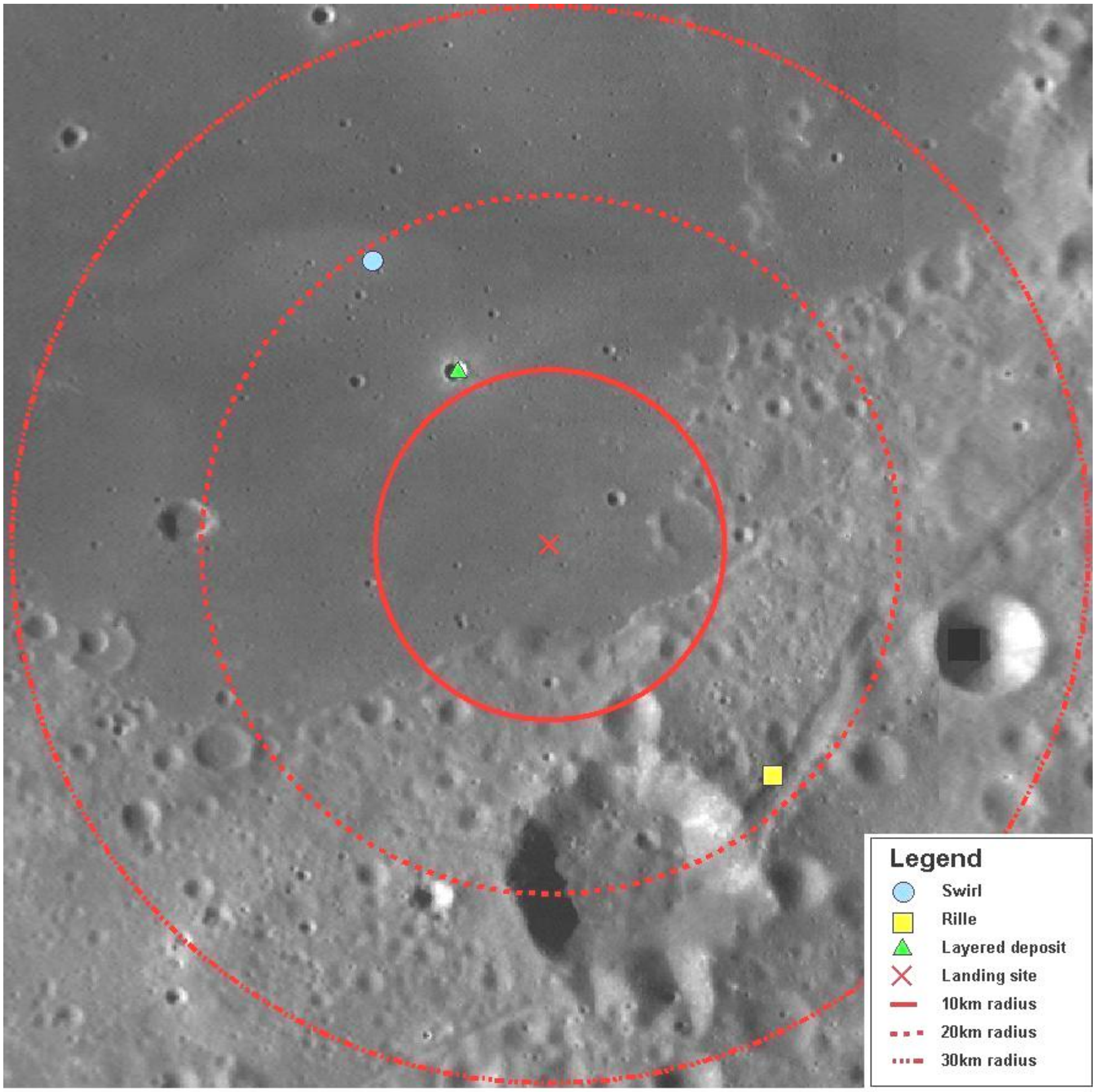

FIGURE 7.44 Detail of the Mare Moscoviense landing site, situated at approximately 149.4° E and 24.8° N, and its immediate surroundings in an LROC WAC mosaic. The landing region is denoted with an "X," surrounded by exploration area circles with 10 km, 20 km, and 30 km radii from the suggested landing site. We have marked stations to study, which are described in the legend. The Mare Moscoviense site provides an opportunity to study a layered deposit in the fresh Mare Moscoviense crater, a rille, and a lunar swirl within a 20 km radius of the landing site. In addition, there are three different geological units, as described in the Science Goal 7b section above, within only a 10 km radius. Two pyroclastic vents in the area may also be sampled if their deposits reach the site (which is possible due to the nature of pyroclastic volcanism on the Moon). Finally, there is a potential to sample cryptomare at the farthest reaches of our proposed circles of exploration. In summary, the Mare Moscoviense site provides an excellent opportunity to study every aspect of Science Concept 7 at a single landing site.

Tycho Crater

This case study is focused on the potential landing site located at approximately 41.4° S and 11.8° W, which is about 20 km to the north-west from the Tycho crater. Tycho is a popular and appealing location because it is a well-studied crater. A mission to Tycho has a great opportunity for gaining public interest, which is important for future missions to the Moon. Figure 7.45 shows an LROC WAC mosaic map of the lunar nearside, and the Tycho landing site is demarked with a red dot. Tycho (Fig. 7.46) is a complex crater located at 43.37° S, 348.68° E. Tycho is 82km in diameter and its central peak is 2km above the crater floor, which is 4.7km below the rim. In 1968, the Surveyor 7 landed on the ejecta blanket surrounding its outer rim.

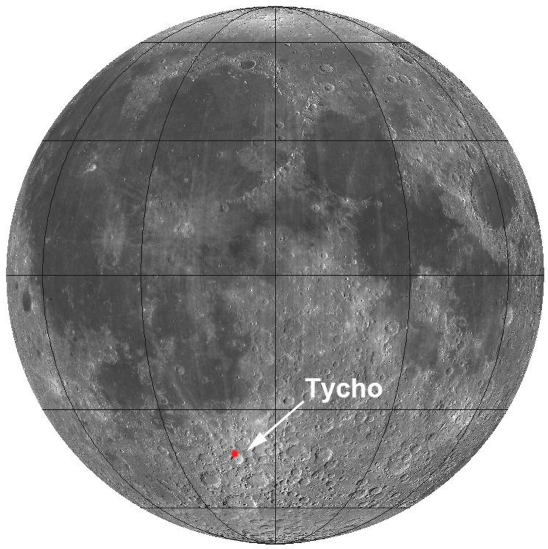

FIGURE 7.45 An LROC WAC mosaic of the Moon showing the Tycho landing site with a red dot.

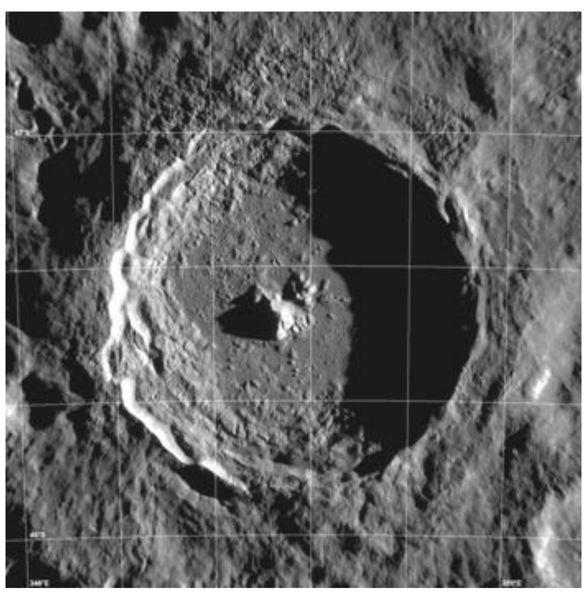

FIGURE 7.46 LROC WAC mosaic of Tycho crater. Mosaic is 130km wide, north is up (NASA/GSFC/Arizona State University).

Figure 7.47 shows a closer view of the proposed Tycho landing site. The slope in the region of the landing site is between about 4.5-8°, but slope data are from remote sensing (Rosenburg *et al.*, 2011); there may very well be flatter surfaces in the region. For example, we chose the landing site at approximately 11.5° W, 40.9° S because it is within a melt pond, likely formed by the Tycho impact, that appears flat and has low slope. This melt pond is shown in Fig. 7.48. The floor of the Tycho is covered irregularly by impact melt features (Fig. 7.49).

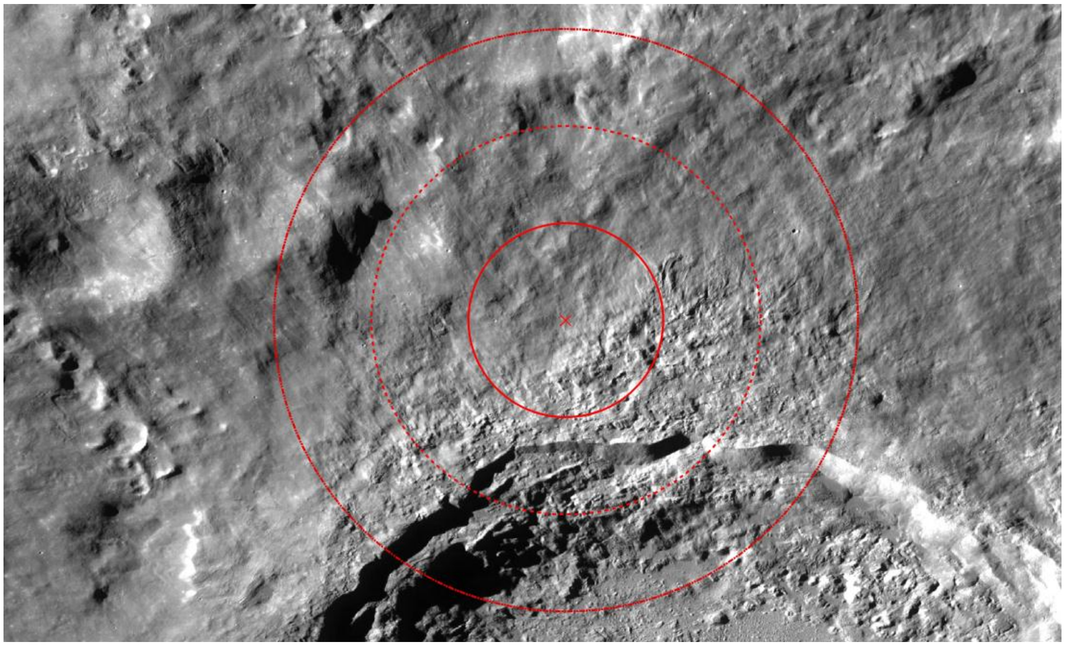

FIGURE 7.47 The Tycho landing site marked with a red "x", with circles denoting 10-km, 20-km, and 30-km radius exploration areas centered on the landing site.

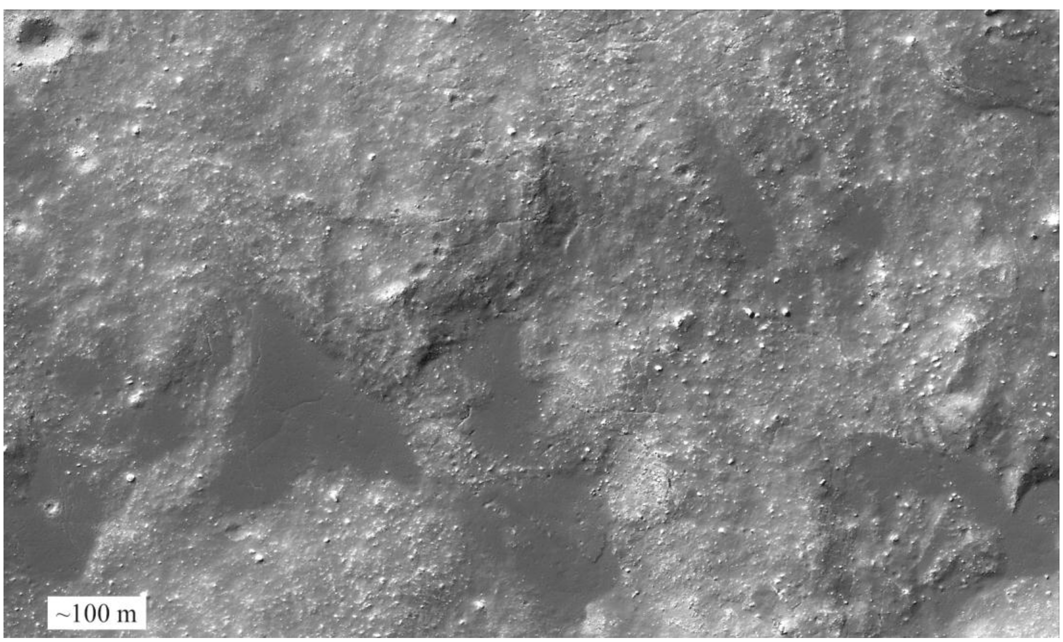

FIGURE 7.48 A close-up of the suggested landing site for Tycho. This site is within a melt pond on the ejecta blanket of the site. This provides a relatively smooth area, even though the surrounding area is rough. LROC NAC Image #M106950070L.

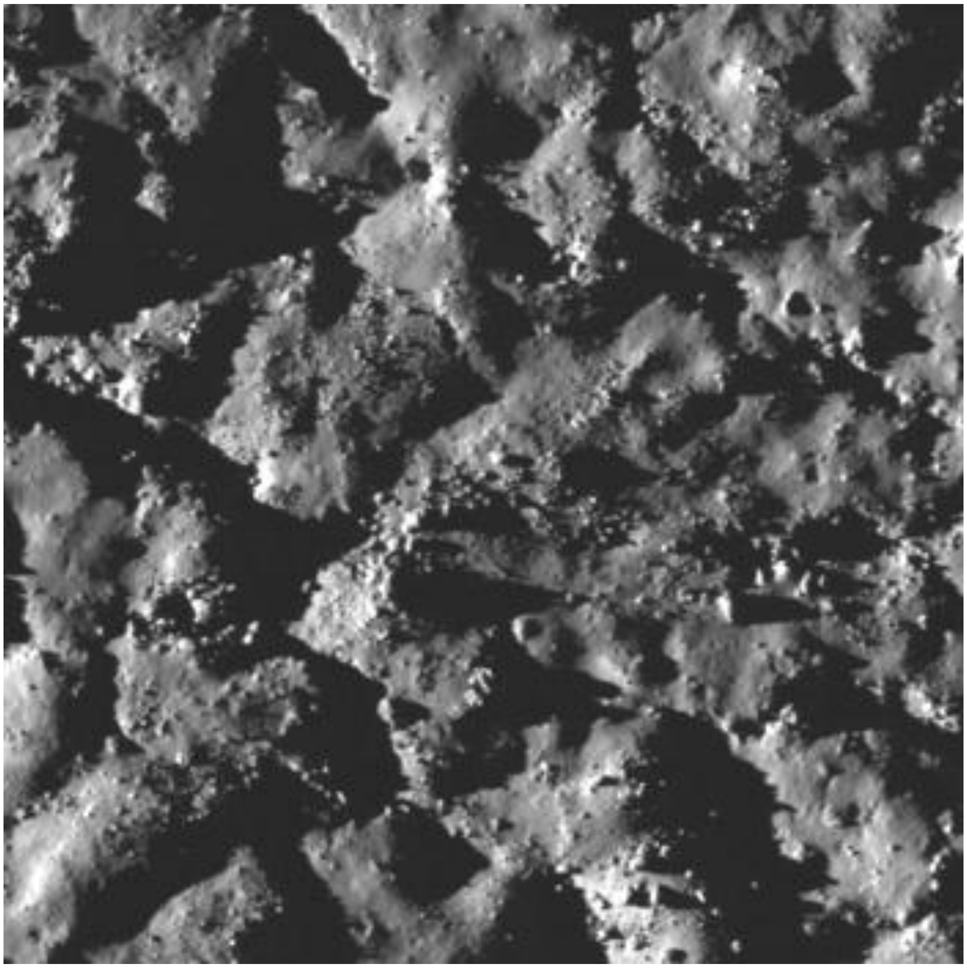

FIGURE 7.49 The chaotic floor of Tycho crater. The chaotic structure is formed by impact melt features. Image scale is 0.5m/pixel, image width is 500m. LROC NAC Image #M117568330R (NASA/GSFC/Arizona State University).

Tycho crater was created ~110 million years ago and is relatively young. The sharp rim of the crater and sharp slopes of its peak are features that are characteristic of young craters. The crater has a very high albedo and may be easily seen from Earth without any special instruments. The area surrounding Tycho is covered by many craters of various sizes; some of the smaller ones are Tycho secondary craters. Tycho has well-known and very distinctive ejecta rays, which range up to 1,500km long.

Figure 7.50 shows a Clementine UVVIS global map and a detailed view of the Tycho landing site. From these images, it is apparent that the ejecta directly surrounding the crater is of a different composition than that farther out. Astronauts can easily sample both types of material from our chosen landing site.

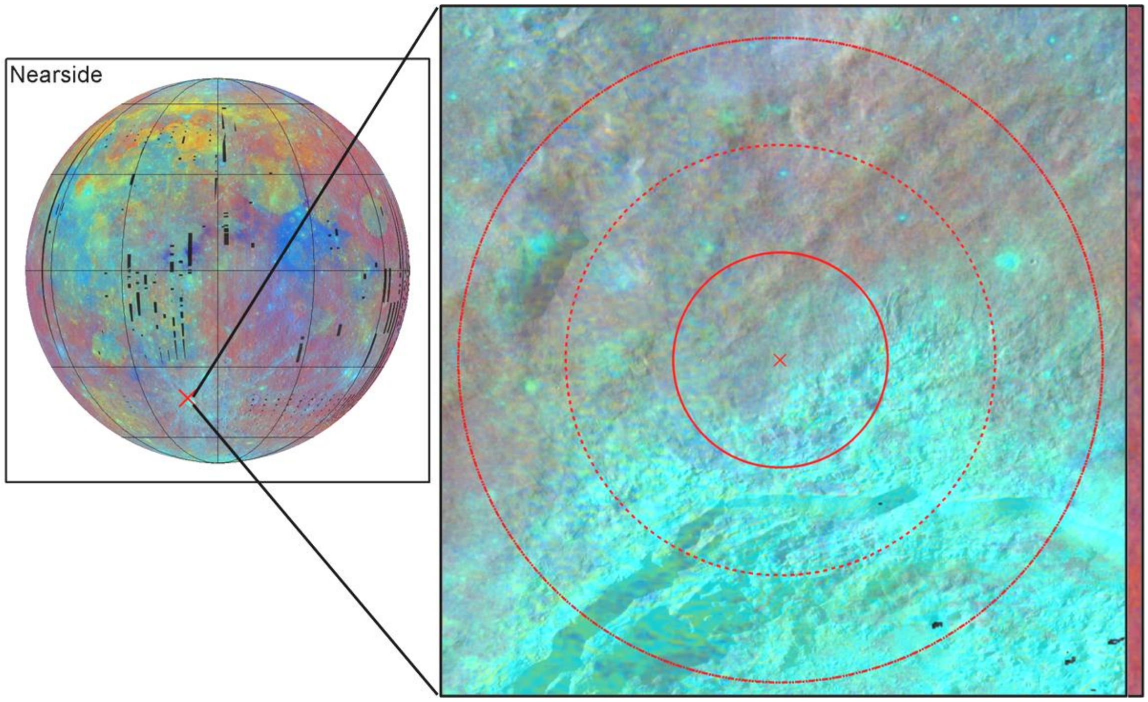

FIGURE 7.50 Clementine mosaic showing the nearside hemisphere and a detailed view of the Tycho landing site. The region has material of two different compositions, and both are accessible to our proposed landing site.

Science Goal 7a

The Tycho landing site is located outside the crater on the continuous ejecta blanket, but is within 20 km of the crater rim. Possible layered deposits can be found just inside the crater rim within 30 km of the landing site (Fig. 7.51). NAC coverage for Tycho is not complete, so additional layered deposits within 20 km of the landing site may still be unidentified. Tycho is located in the highlands in highly cratered pre-Imbrian terrain, so layers in Tycho's walls may expose regolith of pre-Imbrian age. Slopes for the upper edges of the Tycho rim exceed 25° only in some locations; a navigable path to access layered deposits may be possible to find. Preserved pre-Imbrian regolith should also be present beneath Tycho's continuous ejecta blanket, but no smaller craters penetrate through this layer in the region of the landing site, so the older regolith beneath it may be inaccessible. The thickness of the ejecta blanket at the landing site can be calculated using Equation 7.1. Using this equation, we find that the thickness of the ejecta blanket at the landing location is approximately 153 m, decreasing to 43 m at the outermost edge of a 30 km traverse away from Tycho from the landing site. Apollo drill cores reached only 3 m into the regolith; at best, a drill core on a future mission might reach 10m into the regolith. However, the ejecta could be sampled at intervals of varying distances from the crater rim, producing a stratigraphic column as described in the introduction to this case study. The ejecta could also be age dated precisely to better determine the potential for finding ancient regolith in the layers of the crater.

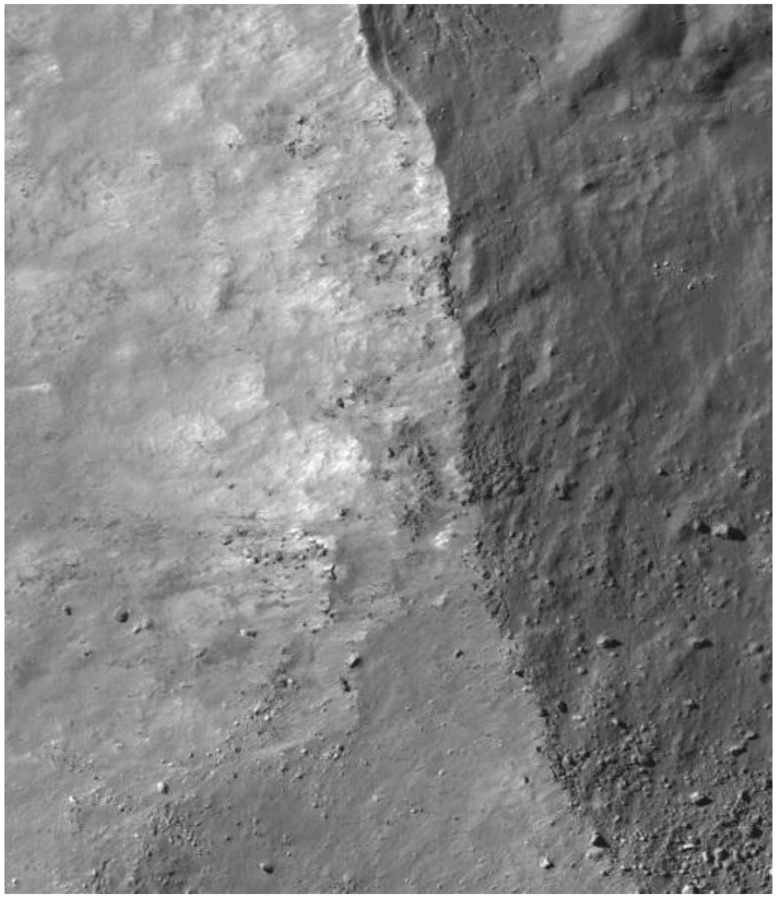

FIGURE 7.51 LROC NAC Image #M144708853 showing layered deposits in the wall of Tycho.

Science Goal 7b

The priority of Science Goal 7b is to measure regolith's properties at many different locations. Tycho is a large crater, and taking into account also the area covered by its rays it is very large feature indeed. In 1968 Surveyor 7 landed on the ejecta blanket, approximately 30 km to the north of Tycho, and in 1972 Apollo 17 landed on one of the rays about 2000 km away from Tycho.

Our suggested landing site is closer to the rim of Tycho and may let us compare measurements from previous missions (Fig. 7.52). In addition, we can study regolith not only surrounding Tycho, but also covering its rim and slopes, allowing us to better understand the regolith properties at depth in the region. None of the previous missions were situated in highlands so far away from PKT Mare. Another very important advantage of this site is that it offers an opportunity to measure the heat flow in lower latitudes. Measuring heat flow at Tycho and comparing it to measurements from the equatorial zones will give us a better understanding of how the day/night and diurnal heat flow changes with increasing latitude. For future human missions, knowledge of the global heat flow will aid in determining how deep a structure must be buried to avoid extreme lunar temperature fluctuations.

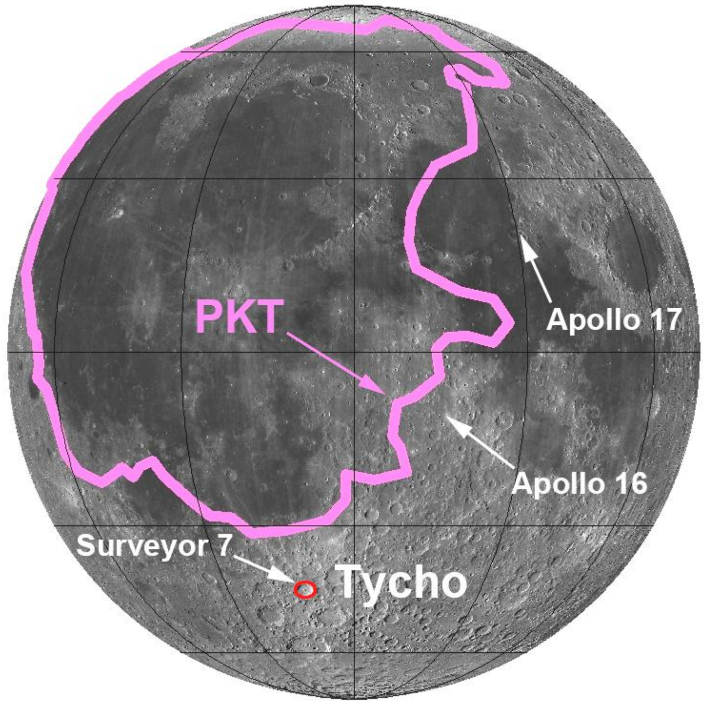

FIGURE 7.52 LROC WAC view of the Tycho landing site location on a global scale. The PKT region is outlined in pink, and the Apollo 16 and 17 sites are shown with arrows. Tycho is well outside the PKT region, and at much lower latitudes than have been sampled before.

Science Goal 7c

For Science Goal 7c, the Tycho landing site is appealing for a variety of reasons. Most importantly, Tycho is a very fresh crater located in the ancient highlands. From remote sensing maturity maps developed by Lucey *et al.* (2000b), it is apparent that the landing site contains both very immature and intermediately mature soil. Astronauts have not been able to sample such immature material, so we may be able to better understand the space weathering process by studying material around the Tycho landing site.

Another important feature of the Tycho landing site is that the Surveyor 7 spacecraft is within accessible distance of our proposed landing site: approximately 20 km away, as shown in Figs. 7.53 and 7.54. Surveyor 7 offers a chance to study the effects of space weathering on a known surface for a known amount of time, a goal which is specifically stated in the NRC 2007 report. Additionally, because Surveyor 7 is located about 20 km away from the proposed landing site, it should not suffer sandblasting effects of lander decent engines, as Surveyor 3 experienced when Apollo 12 landed just 183 m away (Heiken *et al.*, 1991). Surveyor 7 should therefore provide scientists with a more pristine sample of space weathering on manmade surfaces.

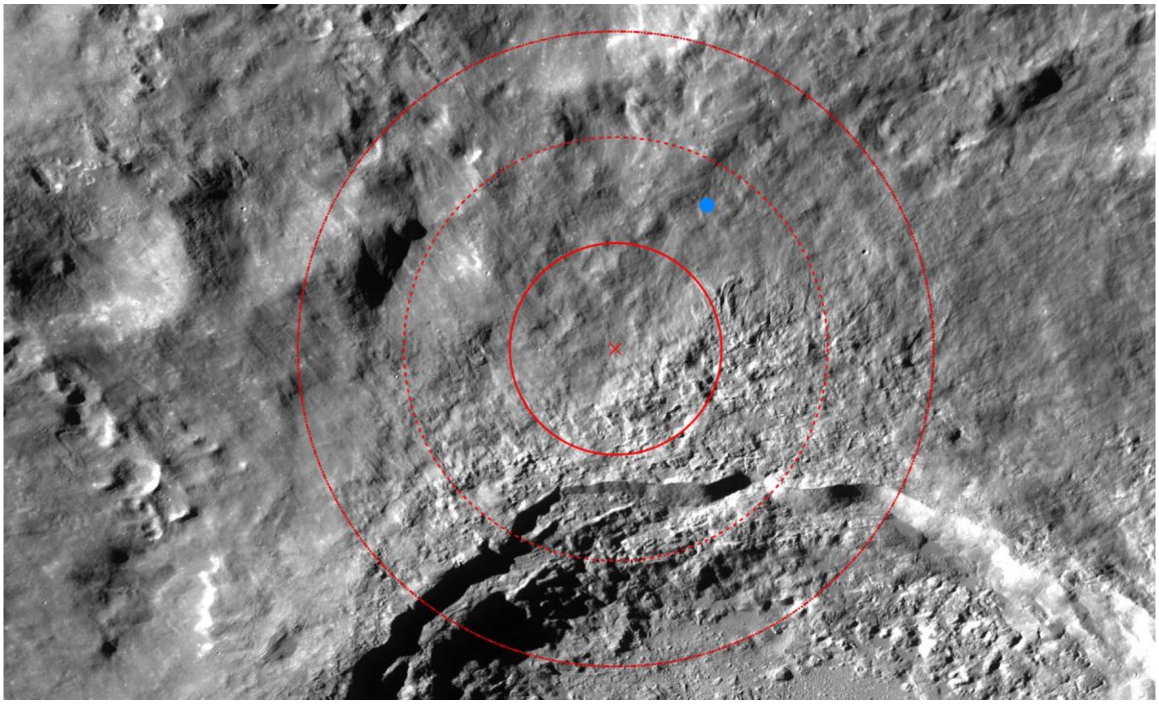

FIGURE 7.53 Tycho landing site location, and Surveyor 7 (denoted by a blue dot) shown just inside the 20km mark.

FIGURE 7.54 LROC NACIimage #M119936760LE of the Surveyor 7 landing site, roughly 20km from our proposed landing site.

Finally, the Tycho landing site is not near a lunar magnetic anomaly, so all space weathering processes are expected to be normal and representative of the lunar highlands. Thus, the Tycho landing site is an especially good site for Science 7c because of the access to Surveyor 7, the ability to sample material of a variety of maturities and the site's lack of magnetic anomalies to alter space weathering effects.

Science Goal 7d

Tycho is a relatively young crater and this increases the chances of finding meteoritic material in its deposits. Second, Tycho has many secondary craters and crater clusters, making it possible to identify ejected material from craters in more distant regions. Moreover, the fact that Tycho is not located in the equatorial zone covered by the Apollo missions gives us the possibility of studying and sampling a potentially very different area. Another interesting aspect of Tycho is the presence of a layered structure in its walls that may expose meteoritic material trapped in the layers. There is also the possibility to find samples of the original Tycho impactor within impact melt in and around Tycho. The chosen landing site is within a small melt pond and will provide immediate access to impact melt material.

Figure 7.55 summarizes the case study for the Tycho rim landing site. Tycho could potentially be a two-mission site. If it were deemed possible, a mission could also land inside Tycho to sample the floor, central peak, and or some of the crater's walls. At this point, it is unknown whether a mission to Tycho's floor is possible because of possible surface roughness. However, if possible we suggest a landing site at approximately 42.98° S, 10.78° W. The slope of this region is 3.66°. The landing location compared to our rim location, as well as a NAC image of the landing site, are shown in Figs. 7.56 and 7.57.

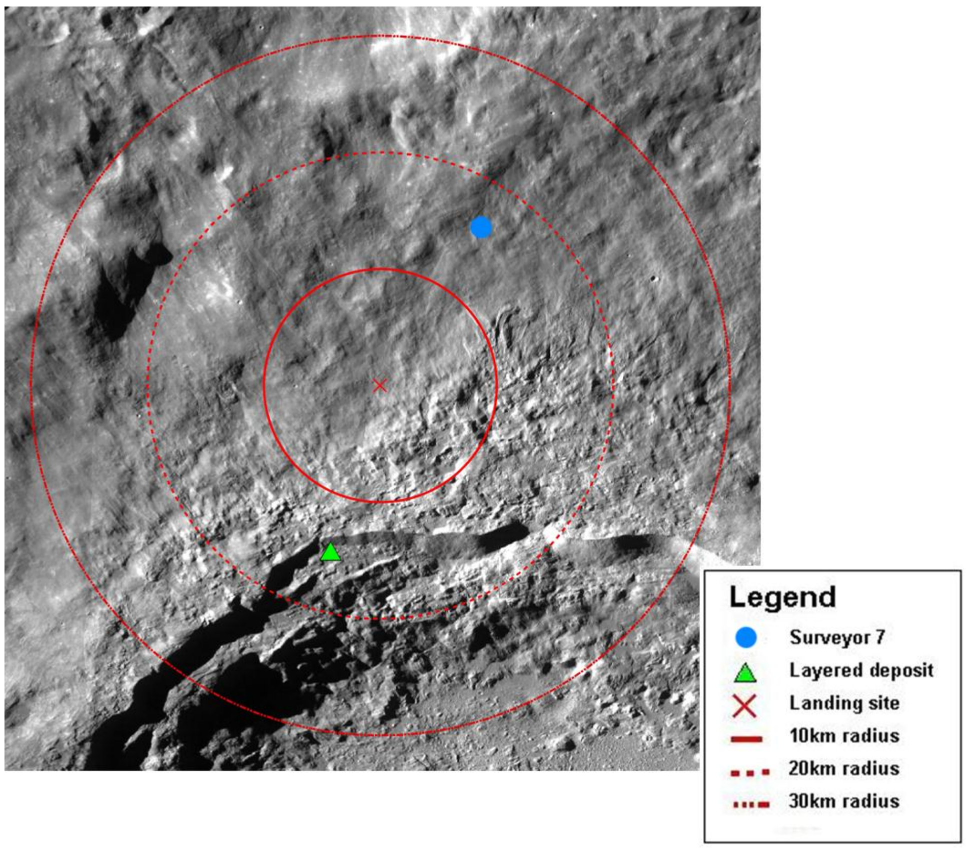

FIGURE 7.55 An LROC WAC image of the suggested landing site on Tycho's rim, located at approximately 41.4° S and 11.8° W. The circles represent areas of exploration at 10km, 20km, and 30km radii from the landing site. Stations of interest within the 20km exploration area include the Surveyor 7 and layered deposits within the crater walls. These are marked on the map and explained in the legend. Additionally, Tycho's ejecta could be sampled at increasing distances from the crater rim, providing a stratigraphic column of the excavated depth of the crater. This information could be useful to the floor landing, as it may provide a better understanding of the layering found within the crater. Overall, the Tycho rim landing site provides an excellent opportunity to sample regolith of varying ages from Tycho's ejecta and possibly its walls. The lower latitude and highland material is useful for understanding the regolith in the area. Finally, Surveyor 7 provides an opportunity to sample a known material that has been on the surface for a known amount of time.

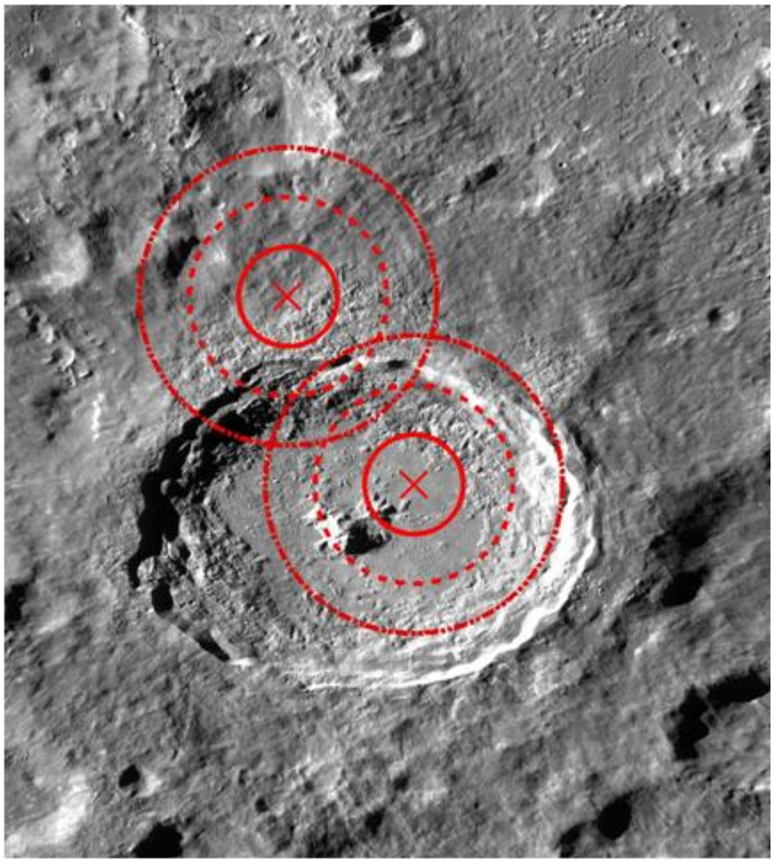

FIGURE 7.56 Both our proposed landing sites: the Tycho rim and the Tycho floor sites.

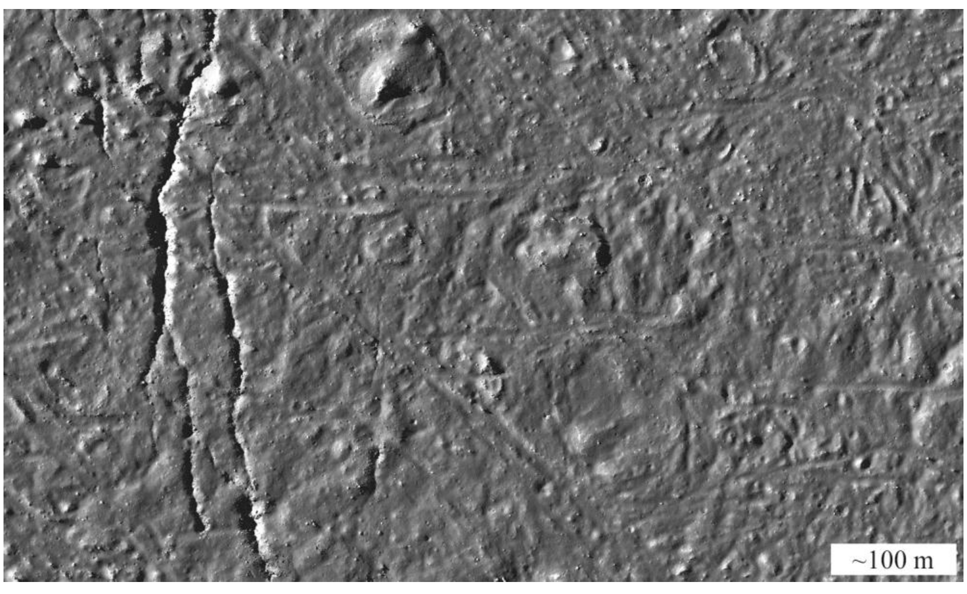

FIGURE 7.57 LROC NAC image M135257592L of the Tycho floor proposed landing site. We believe it may be possible to land on the floor of Tycho, but further study into the roughness of the area is needed.