Science Concept 5: Lunar Volcanism Provides a Window into the Thermal and Compositional Evolution of the Moon

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Science Goals:

a. Determine the origin and variability of lunar basalts.

b. Determine the age of the youngest and oldest mare basalts.

c. Determine the compositional range and extent of lunar pyroclastic deposits.

d. Determine the flux of lunar volcanism and its evolution through space and time.

INTRODUCTION

Features of Lunar Volcanism

The most prominent volcanic features on the lunar surface are the low albedo mare regions, which cover approximately 17% of the lunar surface (Fig. 5.1). Mare regions are generally considered to be made up of flood basalts, which are the product of highly voluminous basaltic volcanism. On the Moon, such flood basalts typically fill topographically-low impact basins up to 2000 m below the global mean elevation (Wilhelms, 1987). The mare regions are asymmetrically distributed on the lunar surface and cover about 33% of the nearside and only ~3% of the far-side (Wilhelms, 1987). Other volcanic surface features include pyroclastic deposits, domes, and rilles. These features occur on a much smaller scale than the mare flood basalts, but are no less important in understanding lunar volcanism and the internal evolution of the Moon. Table 5.1 outlines different types of volcanic features and their interpreted formational processes.

TABLE 5.1 Lunar Volcanic Features

<table>
<thead>
<tr>
<th>Volcanic Feature</th>
<th>Interpreted Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroclastic deposit</td>
<td>violent eruption caused by the rapid exolusion of volatiles</td>
</tr>
<tr>
<td>Flood basalts</td>
<td>high volume of extrusive lavas</td>
</tr>
<tr>
<td>Domes</td>
<td>local build-up of extrusive or intrusive materials</td>
</tr>
<tr>
<td>Sinuous rilles</td>
<td>channels or collapsed lava tubes; uncertain if origin is erosional, constructive or both</td>
</tr>
<tr>
<td>Linear rilles</td>
<td>possible magmatic degassing of a stalled, subsurface dike; possible lava tube or channel following morphology of pre-existing structure; possible tectonic feature; possibly multiple</td>
</tr>
</tbody>
</table>

Volcanic materials are surficial expressions of subsurface magmatism and can be used as tools for understanding large-scale internal and external lunar processes, links between the Earth and the Moon, and planetary evolution within the inner solar system. Volcanic processes on Earth are comprised of a series of related, complex volcanic and tectonic systems that are not fully understood (Head and Coffin, 1997). A general understanding of volcanic processes on both the Earth and the Moon is required to fully understand each planetary body individually as well as the relationships between the closely coupled Earth-Moon
System. Moreover, each terrestrial planet in the solar system has unique compositional, thermal, and resurfacing properties. It is imperative to understand how the evolution of volcanic processes through space and time vary between terrestrial planets. Such information provides necessary supplemental data for completing our understanding of the thermal evolution of our own planet.

FIGURE 5.1 Global albedo map of named mare regions.

Beyond describing the thermal evolution of terrestrial planets, a complete investigation of Science Concept 5 can provide ancillary information for other NRC (2007) Science Concepts, enhancing our knowledge of not only the Moon as a whole, but of the entire solar system. For example, accurately dating volcanic resurfacing events will help refine crater size-frequency calculations with the result of advancing our understanding of the impact flux in the early and recent solar system (Science Goals 1a and 1d). Also, understanding the depths and locations of source regions for volcanic materials provides information on the thermal, structural, and compositional evolution of the crust (Science Goals 2a, 3c, and 3d), upper mantle (Science Goal 2b), and heat-producing regions within the lunar interior (Science Goal 2d). Sampling different types of volcanic rocks, including KREEP component samples, high-aluminum basalts, high titanium basalts, and low titanium basalts within their geologic context will supplement the lunar rock database with new samples of previously unsampled rocks types (Science Goal 3b) and will provide new and essential information on planetary differentiation properties (Science Goal 3a). Describing lava ascent mechanisms will give insight into the structure of the regolith and mega-regolith layers (Science Goal 3e). Surface-covering lava layers from different depths and ages can provide insight into the scales on which weathering occurs on the lunar surface (Science Concept 7). Sampling cryptomare regions reveal mechanisms and extent to which impact events mix layered materials in ejecta (Science Goal 6d). Finally, studying the magma ascent through impact-induced fracture fields and extrusion through crater floors will advance our knowledge of impact processes, which is the most frequent geological resurfacing process within the solar system (Science Concept 6).
Volcanic materials are also useful as resources for in-situ mineral resource extraction for both rocket propulsion and life-support systems and as shielding materials from the hostile space environment (e.g. uncollapsed lava tubes or loose pyroclastic deposits). Thus, sampling and studying lunar volcanic deposits should be a prime scientific goal for future missions to the Moon.

DATASETS AND METHODS

To achieve the objective of determining the global coverage of all possible locations where individual goals of Science Concept 5 Science Goals can be addressed, the following steps were used:

1. Detailed literature review of previous studies of lunar volcanism;
2. Digitizing, geo-referencing and combining datasets where volcanic deposits, structures and features can be identified and categorized:
   a. Maps from previous studies.
   b. Tables from previous studies.
   c. Maps/images of the lunar surface from orbiting spacecraft.
3. Where applicable, further mapping using current datasets to achieve global distribution coverage.

A summary of the various datasets used in this study is presented in Table 5.2 (the mare basalt and glass database compiled by Clive Neal at Notre Dame University was also utilized). Compositional, age, pyroclastic deposits, volcanic features, stratigraphic features, and other global maps were compared to identify locations where multiple features were located within 10 and 20 km of each other, reflect the current walk-back safety limits for crews during Extra-Vehicular Activities (EVAs). This method enabled suggestion of landing sites where the maximum number of Science Concept 5 Science Goals may be addressed. We separate these sites into Group 1 and Group 2 sites based on diversity of volcanic features, complexity of geology, accessibility to these features, and importance to addressing individual goals.

TABLE 5.2 Table of datasets used to identify Science Concept 5 candidate landing sites.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>Instrument</th>
<th>Data Description</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar Orbiter I-V</td>
<td>05/1967–10/1967</td>
<td>Camera</td>
<td>Individual frames and digitized and orthorectified image mosaics</td>
<td>1–154 m/pixel</td>
</tr>
<tr>
<td>Apollo 8-17</td>
<td>03/1968–12/1971</td>
<td>Camera</td>
<td>Panoramic and single frame images</td>
<td></td>
</tr>
<tr>
<td>Clementine</td>
<td>01/1994–06/1994</td>
<td>Laser Image Detection and Ranging (LIDAR) system</td>
<td>Topographic data</td>
<td>Horizontal: ~1.9 km/pixel, Vertical: ~140 m/pixel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ultra-violet/Visible Camera (UVVIS)</td>
<td>5 bands between 415 and 1000 nm</td>
<td>60–160 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Near-infrared camera (NIR)</td>
<td>6 bands between 1100 and 2780 nm</td>
<td>135–240 m</td>
</tr>
</tbody>
</table>
SCIENCE GOAL 5A: DETERMINE THE ORIGIN AND VARIABILITY OF LUNAR BASALTS

Introduction

Lunar volcanism covers approximately 17% of the Moon’s surface (Head, 1976). The majority of this volcanism erupted on the lunar near-side, suggesting a fundamental difference between the near-side and far-side in terms of the thermal and compositional evolution of the Moon (e.g., Wasson and Warren, 1980; Lucey et al., 1994; Shearer et al., 2006). The lunar magma ocean hypothesis, based on data provided by lunar basalts (e.g., Neal and Taylor, 1992), does not completely explain this asymmetry but continues to guide our understanding of the differentiation and evolution of the Moon. Since the Moon and the early Earth have closely linked compositional and thermal histories during formation, understanding the origin and evolution of the Moon will provide insight into the early magmatic evolution of the Earth.

The integration of petrographic, chemical, isotopic and age studies of basalts guides our understanding of the origin and processes involved in the generation of basaltic lavas. Due to this multifaceted nature of studying basalt petrogenesis, a spatially and chemically diverse set of samples is needed to resolve discrepancies between petrogenetic models.

Samples returned by the Apollo and Luna missions include several types of basalts, but global remote sensing data from the Clementine and the Lunar Prospector missions that a much broader range of compositions exist on the lunar surface. Therefore, a strategic assessment of potential landing sites suitable for sampling additional basalts is needed.

Methodology

The following steps were applied to address Science Goal 5a:

1. Determine chemical criteria for locating unsampled basalt units from literature and available compositional datasets;
2. Compile detailed global compositional information in a spatial context using ArcGIS;
3. Quantitatively combine compositional global maps with possible stratigraphic features, volcanic features, pyroclastic deposits, and surface age into global maps;
4. Find an example location where multiple compositionally diverse and interstratified basalt flows may be studied.

Mare Volcanism

Mare volcanism on the Moon was mapped by the USGS (Wilhelms and McCauley, 1971; Wilhelms and El-Baz, 1977; Scott et al., 1977; Stuart-Alexander, 1978; Lucchitta, 1978; Wilhelms et al., 1979) based on their dark color and surface morphology (Wilhelms, 1987). Figure 5.2 shows the distribution of mare volcanism, which clearly exhibits the nearside-farside asymmetry.
Lunar Basalt Types

Lunar basalt compositions range in major and trace element abundances (BVSP, 1981). Returned lunar samples are geochemically classified primarily based on Ti content for mare basalts (e.g., Neal and Taylor, 1992; Papike et al., 1998). In addition to the flood basalts of mare volcanism, KREEP volcanism is thought to represent pre-mare volcanism and has been collected in mostly highlands terrain (Papike et al., 1998). Figure 5.2 shows four examples of basalts returned from the Apollo missions. The recognition of both sampled and unsampled basalt types will be important for the return to the Moon, because most likely there will be a restriction on the amount of sample permitted to return to Earth for study. Identifying and ultimately collecting a variety of basaltic samples will aid in our understanding of the bulk Moon composition. The bulk Moon composition is essential for determining the igneous evolution of the Moon as well as how the Moon and Earth can be compared (Lunar And Planetary Sample Team, 1985).

FIGURE 5.2 Map of USGS Mare Units. E = Eratosthenian, I = Imbrian, m = mare. Data: US Geological Survey.
Chemical Compositions of Lunar Basalts

The returned lunar basaltic lavas have provided a wealth of compositional information and provide important input for the magmatic evolution of a differentiated Moon. However, these models are poorly constrained by existing samples of limited quantity and diversity of sample locations on the lunar surface. Therefore, more samples from chemically diverse regions need to be collected. The present returned-sample chemical data provide a solid foundation for establishing the chemical criteria to be used in selecting future sample sites where basalts with variable compositions are located.

The compositional diversity of lunar basalts is revealed in major and trace element geochemistry, and has been reviewed in detail by Papike et al. (1976), BVSP (1981), Taylor et al. (1991), Neal and Taylor (1992), and Papike et al. (1998). Three basalt type groups are revealed in MgO variation diagrams, especially MgO versus TiO$_2$: a high TiO$_2$ group (~8–14 wt. %), a low TiO$_2$ group (~1–6 wt. %), and a very-low-Ti group (<1 wt. %). The majority of the returned lunar basalts range from ~15–24 wt. % FeO, while the highlands material, including anorthosite, range from ~1–4 wt. % FeO (Spudis and Bussey, 2003). This difference allows for identification of basalts using Fe remote sensing data. The pre-mare KREEP basaltic lavas also have a distinct FeO content of ~10 wt. %. The combination of the Fe content, enriched incompatible elements, and Th abundances allow for remote recognition of these rarely sampled basalts.

Remote Sensing Data

Chemical remote sensing data from the Clementine and Lunar Prospector missions has provided global geochemical information from the surface of the Moon. Three datasets used to select possible landing sites are FeO and TiO$_2$ weight percent from the LPI Clementine Mapping Project using the Lucey et al. (2000) method and a resolution of 0.5 km/pixel and +/- 1wt. %, and Th abundances derived by the Lunar
Prospector mission in half degree intervals and with less than 1 ppm margin of error (Lawerence et al., 2000). Maps of the global variations of these quantities are shown in Figs. 5.4–5.6.

FIGURE 5.4 Clementine FeO concentration Map of Possible Lunar Basalts. The FeO weight percent ranges include the margin of error for tentative mare and non-mare compositions.

FIGURE 5.5 Global Clementine TiO₂ Composition Map. Showing the possible compositional range of lunar basalts. Compositional ranges include the margin of error.
Fe-Ti-Th Ratio Maps

The combination of Fe, Ti, and Th concentrations provides more comprehensive constraints on the global distribution and variability of lunar basalts. Ratio maps of these quantities reveal regions of potentially unsampled basalt compositions. Figure 5.7 shows a map of Clementine FeO/TiO$_2$ ratio in each pixel. Major areas of potentially unsampled basalts include Mare Frigoris, northern Mare Imbrium, Oceanus Procellarum, Aristarchus, and a cryptomaria region south of Mare Humorum. Compared to the Apollo and Luna landing site compositions, these unsampled regions have different compositional values of FeO and TiO$_2$.

A Fe/Th ratio map (Fig. 5.8) shows potential locations where KREEP basalts might be found, as well as presenting a more comprehensive comparison for determining locations with additional chemical diversity. The majority of unsampled Fe/Th compositions are located in Oceanus Procellarum, southern Mare Imbrium, Mare Serenitatis, Mare Nubium, and Mare Humorum. Some of the regions with unsampled Fe/Th and Fe/Ti overlap, which make them particularly interesting targets for exploration. Ultimately, combining many high resolution datasets will provide the best constraints on potentially unsampled basalt types.

FIGURE 5.6 Global Th Abundance Map. Color scale represents relative concentrations.
FIGURE 5.7 Fe-Ti Ratio Map for Tentative Mare and Non-Mare Compositions. Color scale represents relative compositions.

FIGURE 5.8 Fe-Th Ratio Map for Tentative Mare and Non-Mare Compositions. Colors represent relative compositions.
A Potential Landing Site

A candidate site with multiple flows in temporal context is located in the northern Mare Imbrium region. The northern portion of the area contains two separate flows: a younger flow on top of an older flow, based on crater ages, photogeologic methods such as albedo and flow margins, and remote sensing data (e.g., Heisinger et al., 2003; Wilhelms and McCauley 1971; Chevrel et al., 2002). After a detailed survey of this region, we determined that the crater Carlini D (diam. ~9 km; 33°N, 16°W) provides the best location for astronauts to sample potentially three different basalt flows in stratigraphic context, either by sampling exposed layers in the crater wall (rim to floor depth of crater is 1170 m) or by sampling the ejecta in a radial traverse towards the crater rim (Fig. 5.9). The compositions within the center of Carlini D are similar to an older northern Mare Imbrium flow and Mare Frigoris; therefore, Carlini D may provide samples similar to both of these major unsampled regions. These samples have KREEP features (like those at Apollo 15 landing site), but are chemically distinct.

As higher resolution spectral data is collected and more precise chemical data become available, the techniques outlined here can be expanded to provide detail for determining additional potential landing site locations.
SCIENCE GOAL 5B: DETERMINE THE AGE OF THE YOUNGEST AND OLDEST MARE BASALTS

Introduction

The timing and duration of lunar mare volcanism is poorly constrained because mare basalts are incompletely sampled. Resolving the duration of mare volcanism will greatly improve models for the thermal evolution of the Moon and has, thus, been identified as a key scientific goal during the next phase of lunar exploration (NRC 2007).

Dating Mare Basalts

Relative ages of mare basalts are assigned based on stratigraphic relationships and the superposition of geologic units. Figure 5.10 shows the lunar geologic timescale, ranging from the oldest, pre-Nectarian period to the youngest, Copernican period. Quantitative ages have been assigned to lunar rocks and surfaces using a variety of methods. Radiometric age dating is the only unequivocal way to quantify the age of a mare basalt. In contrast, ‘model ages’ of mare surfaces have been estimated based on crater-frequency measurements. This crater-based method for estimating ages for lunar surfaces is based on the simple principle that older surfaces will contain a higher density of craters than will younger surfaces. It is a powerful technique for determining the relative ages of planetary surfaces and has been widely applied to the mare surfaces of the Moon (e.g., Schultz and Spudis, 1983; Hiesinger et al., 2000, 2003, 2006, 2008; Haruyama et al., 2009). Quantitative ages can be confidently assigned to undated surfaces only if several surfaces of known crater-frequency have been radiometrically dated and span a wide interval of time.

Thus far, the only lunar surfaces that have been confidently assigned radiometric ages are the Apollo and Luna landing sites where rock samples were returned and radiometrically dated. Based on the crater frequencies of the Apollo and Luna sample return sites and their determined radiometric ages, a relationship has been empirically derived between crater frequency and quantitative age called the ‘lunar cratering chronology curve’ (Fig. 5.11) (Neukum, 1983; Neukum and Ivanov, 1994). This curve has served as the basis for most of the model ages determined by various authors whose work is presented in this report. The plotted points, corresponding to the Apollo and Luna landing sites, are the empirical basis of the curve. Note that most of these points fall into a tight time period of approximately 4.3–3.2 Ga, and indeed this area of the curve is considered to be the most accurate and well-calibrated portion of the curve (Greeley et al., 1993). Thus, most model ages outside of the time period of ~4.3–3.2 Ga are poorly calibrated.
FIGURE 5.10 Lunar stratigraphic column showing the geologic periods for the Moon with the tentative quantitative age boundaries for each period (Ryder et al., 2000). Also displayed are the radiometric ages of representative mare basalts that have been sampled from the lunar surface, along with the tentative ending point of mare volcanism (~1.0Ga) based on crater frequency measurements performed on potentially young basalts (Schultz and Spudis, 1983; Hiesinger et al., 2003, 2008). All Apollo and Luna samples date to within the age range of ~3.9-3.1Ga, possibly meaning approximately two billion years of mare volcanic history are not represented in our sample collections. Figure modified from Ryder et al. (2000). Age data for basalts samples from BVSP (1981), Fagan et al. (2002), and Terada et al. (2007). (Note: the time periods now called the Nectarian and pre-Nectarian were once lumped into the single time period simply called ‘pre-Imbrian’.)
FIGURE 5.11 The lunar cratering chronology curve (Neukum, 1983; Neukum and Ivanov, 1994) representing the empirically-derived relationship between crater frequency and age. Note the poor calibration of the curve beyond the age range of ~4.3–3.2 Ga. Figure from Neukum and Ivanov (1994).

Youngest Mare Basalts

The youngest directly dated mare basalts obtained from the Apollo and Luna sample return missions have radiometric ages no younger than ~3.08 Ga (BVSP, 1981). The youngest basalt sample obtained from the Moon thus far is lunar meteorite Northwest Africa 032 (an unbrecciated basalt), which has a radiometric age of ~2.8 Ga (Fagan et al., 2002). However, model surface age estimates suggest that some mare basalt flows may be as young as ~1 Ga (Schultz and Spudis, 1983; Hiesinger et al., 2000, 2003, 2008).

Figure 5.12 shows the model ages for most of the visible mare basalt surfaces on the Moon, which have been compiled from the work of several investigators (Tyrie, 1988; Greeley et al., 1993; Neukum and Ivanov, 1994; Hiesinger et al., 2000, 2003, 2008; Haruyama et al., 2009). According to these model ages, the very youngest mare basalt flow appears to embay the southernmost margin of the Aristarchus Plateau (AP in Fig. 5.12) and has an estimated surface age of ~1.2 Ga (Schultz and Spudis, 1983). This locality lies in close proximity to volcanically complex locales (i.e., the Aristarchus Plateau and Harbinger Mtns.), and is, thus, in a region that can be used to address several other exploration objectives (e.g., Korteniemi et al., 2010).

A few small areas may have slightly younger mare basalts (e.g., the nearby and potentially ~0.9 Ga oldmare embaying the eastern rim of the crater Lichtenberg, LC [Schultz and Spudis, 1983]), but these estimated ages are less certain. For that reason, these areas may be good secondary targets. Based on the crater-count work of Hiesinger et al. (2000, 2003, 2008), which stands as the most thorough and comprehensive study of the relative ages of nearside mare basalts to date, and the crater-count work done on the lunar farside mare by other investigators represented in Fig. 12 (Tyrie, 1988, Greeley et al., 1993, Haruyama et al., 2009), the basalt flow embaying the southern margin of the Aristarchus plateau is the
least-densely cratered mare on the lunar surface and, thus, the best candidate for collecting samples of the youngest mare.

Oldest Mare Basalts

Basalt samples found among lunar meteorites and as clasts within Apollo impact breccias have radiometric ages as old as ~4.3 Ga (e.g., Terada et al. 2007; Taylor et al. 1983). In contrast, crater-frequency-based model ages of exposed mare surfaces do not appear to be greater than ~4.0 Ga (Fig. 5.12). It thus appears that the oldest mare basalts may be buried and relatively inaccessible. The buried mare basalts, termed cryptomare (Fig. 5.13), are generally considered to be the oldest mare basalts (e.g., Schultz and Spudis, 1983; Antenenko et al. 1995), and, thus, their locations and accessibility on the lunar surface will be the focus here.

Most cryptomare have been identified by the presence of dark-halo impact craters (DHCs) and mafic geochemical anomalies in the highlands revealed by remote spectral data (Schultz and Spudis, 1983; Antenenko et al. 1995; Hawke et al. 2005). Light plains topography has also been considered an indicator of cryptomare as their smooth texture might indicate buried mare basalt plains (Antenenko et al. 1995). Figure 5.14 shows an overlay of the global distribution of DHCs, a Lunar Prospector Gamma Ray (LP-GRS) spectrometer Fe-abundance map (which reveals mafic geochemical anomalies in the highlands), and light plains across the lunar surface. Most regions where these features overlap (outlined in Fig. 5.14) are major regions of cryptomaria where the oldest mare basalts may occur.

DHCs are impact craters where low albedo material has been excavated from beneath higher albedo material by an impact event, producing a ring of dark ejecta material surrounding the impact crater (Antenenko et al. 1995), and have long been recognized to be indicators of buried mare deposits (Schultz and Spudis, 1979). Because DHCs have excavated buried, potentially ancient basalts directly onto the lunar surface in the form of their dark haloes, the dark haloes are ideal locales for sampling such basalts.

Most regions outlined in Fig. 5.14 contain abundant DHCs. Examples of DHCs that might have excavated the oldest cryptomare may be found in the Balmer-Kapteyn (B-K) and Lomonosov-Fleming (L-F) regions. These DHCs include the crater Kapteyn-B in B-K (Hawke et al. 2005) and the craters named 3 and 11 by (Giguere et al. 2003) in L-F. Kapteyn-B is by far the largest DHC (diameter = 39km) in the B-K.
region (Hawke et al. 2005), and because craters with larger diameters excavate material from greater depths, the dark halo around Kapteyn B might contain some of the deepest (and, thus, oldest) cryptomare in the region. Craters named 3 and 11 in the L-F region excavate material from beneath Nectarian to pre-Nectarian aged terrae mantling material (Giguere et al. 2003), excavating basalt material older than any exposed mare surfaces.

FIGURE 5.13 Schematic diagram illustrating a cryptomare and some of the features that could potentially be used to identify it. Order of major events: (1) basin forms in anorthositic crust via large impact event; (2) basin filled with mare flood basalt unit via dikes, some basaltic regolith develops at surface of mare due to space weathering; (3) basin ejecta from distal impact event in anorthositic crust obscures mare flood basalt unit forming a cryptomare. As ejecta is emplaced over mare, mare material is mixed and incorporated into anorthositic ejecta forming light plains of intermediate albedo (according to the ballistic sedimentation and erosion model; intermediate albedo also symbolizes the mafic content that can be detected spectrally); and (4) relatively small impact events form dark halo impact craters (DHCs) in light plains where underlying cryptomare has been partially excavated due to the small impact event. The diagram also illustrates the point that DHCs can excavate different types of cryptomare, i.e., either the mare flood basalts directly or regolith that has developed on top of the mare flood basalts. Figure modified after Antonenko et al. (1995).
Summary of Recommended Sampling Locations

Presented in Table 5.3 is a summary of the locations recommended here for sampling what are potentially the youngest and oldest mare basalts. The youngest mare basalt on the lunar surface appears to be embaying the southern margin of the Aristarchus Plateau in Oceanus Procellarum. The oldest mare basalts on the lunar surface appear to be the buried mare basalts termed cryptomare, which can be found most prominently in the Balmer-Kapteyn, Lomonosov-Fleming, Mendel-Rydberg, and Schiller-Schickard regions of the Moon. The cryptomaria in some of these regions are perhaps as old as pre-Nectarian in relative stratigraphic age.

TABLE 5.3 List of sites recommended here for sampling what are potentially the youngest and oldest mare basalts on the lunar surface.

<table>
<thead>
<tr>
<th>Region</th>
<th>Rationale</th>
<th>To Be Sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanus Procellarum (Aristarchus Plateau)</td>
<td>Youngest mare basalt</td>
<td>Basalt flow embaying southern margin of the Aristarchus Plateau</td>
</tr>
<tr>
<td>Balmer-Kapteyn</td>
<td>Old mare basalt (possibly pN* in age)</td>
<td>Dark halo surrounding Kapteyn B</td>
</tr>
<tr>
<td>Lomonosov-Fleming</td>
<td>Old mare basalt (possibly pN* in age)</td>
<td>Dark halo surrounding DHICs 3 and 11</td>
</tr>
</tbody>
</table>

FIGURE 5.14 The global distribution of DHCs (black dots), light plains (faint grey outlines), and mafic geochemical anomalies in the highlands (revealed by the LP-GRS Fe-abundance map). Major cryptomare regions are darkly outlined (after Hawke et al., 2005): M-R = Mendel-Rydberg, S-S = Schiller-Schickard, B-K = Balmer-Kapteyn, L-F = Lomonosov-Fleming.
<table>
<thead>
<tr>
<th>Location</th>
<th>Terrane Description</th>
<th>Halo Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mendel-Rydberg</td>
<td>Old mare basalt (older than Orientale impact)</td>
<td>Dark halo surrounding any of the DHICs in the region (only one identified so far)</td>
</tr>
<tr>
<td>Schiller-Schickard</td>
<td>Old mare basalt (older than Orientale impact)</td>
<td>Dark halo surrounding any of the DHICs in the region</td>
</tr>
</tbody>
</table>

*pN = pre-Nectarian
SCIENCE GOAL 5C: DETERMINE THE COMPOSITIONAL RANGE AND EXTENT OF LUNAR PYROCLASTIC DEPOSITS

Introduction

Lunar pyroclastic deposits represent a composition closest to the lunar mantle and therefore provide the closest analog for understanding lunar mantle materials. The resource potential of pyroclastic deposits is vast and can provide materials such as oxygen, iron, and titanium among others that may be useful for establishing a permanent lunar base. Sampling new examples of pyroclastic deposits can be helpful in understanding the lunar mantle, the nature of mare basalt source regions, and information about the lunar magma ocean and lunar igneous processes (NRC, 2007).

Lunar pyroclastic deposits are believed to form from fire-fountain eruptions in which gas exsolution creates an explosive eruption with sprays of lava (Fig. 5.15). The magma is quenched in transport and cools as small droplets and ash before being deposited on the surface. These deposits do not form steep cones like some pyroclastic volcanism deposits on Earth because of the Moon’s lower gravity and the lack of a significant lunar atmosphere. The lack of atmosphere affects the velocity of the particles because they do not create a fluid or turbulent flow (Lucey et al., 2006; McGetchin et al., 1974). Due to these affects, pyroclastics cover an area roughly six times larger on the Moon than they would under similar eruption conditions on the Earth and do not form pyroclastic flows (Hawke et al., 1989). Lunar glasses are a form of lunar pyroclastic deposit and despite their relatively minor volume, their presence is indicative of lava fire-fountaining on the Moon (Lucey et al., 2006). High-Ti ultra-mafic glasses may represent the liquid formed by a re-melted cumulate material that had been displaced to greater depths due to gravitational overturn in the lunar magma ocean (Grove, 2009).

Surface Expressions of Pyroclastic Deposits

Pyroclastic deposits are often referred to as endogenic dark halo craters (EDHCs). Before the Apollo missions, all dark halo craters were thought to be of volcanic origin. Since the discoveries made on these
missions, especially Apollo 17 (Parker et al., 1973), which landed on a dark halo deposit, there has been a distinction between endogenic dark halo craters and dark halo impact craters (DHICs). Volcanic dark halo craters are usually non-circular, and have a low crater depth to diameter ratio compared to impact originated craters. EDHCs have no clear crater rims or rays and have un-textured smooth peripheral deposits. Spectral reflectance characteristics of volcanic glasses have lower strength of absorption features than dark halo impact deposits (Gaddis et al., 1985). These characteristics help in distinguishing and identifying the type of dark halo crater. The type locality for endogenic dark halo craters is Alphonsus crater (Fig. 5.16), a lower-Imbrium aged crater located in the Fra Mauro highlands of the central near-side East of Mare Numbium. Alphonsus has 11 EDHCs that are associated with linear rilles within the crater (Gaddis, 2008). These deposits are only 3–5 km in radial extent and the relationship between crater volume and the size of the deposits can help in calculating the amount of material that must make up the deposit (Head and Wilson, 1979; Hawke et al., 1989). The deposit has a mafic spectral signature rich in olivine and pyroxene (clinopyroxene) and is similar to the spectral signature of the nearby Mare Nubium basalt (Hawke et al., 1989). Spectral studies show that there are intra-deposit composition variations (Gaddis, 2008). The dark mantling deposits at Oppenheimer crater, which will be discussed later, are similar to the endogenic dark-halo craters at Alphonsus.

Pyroclastic deposits are also referred to as Dark Mantling Deposits (DMDs) which are divided into two groups, localized dark mantle deposits (LDMDs) and the larger scale regional dark mantle deposits (RDMDs). LDMDs are usually <2500 km² in size, typically between 250–550 km² and are usually associated with EDHCs. They are usually concentrated on crater floors in association with small pit craters aligned along linear rilles in large Imbrian to pre-Imbrian impact craters/basins. They are composed of mafic materials dominated by olivine and pyroxene. The eruption style of LDMDs is suggested to be similar to that of terrestrial vulcanian eruptions in which large blocks or bombs of cooled cap material are ejected at high speeds during short-lived eruptions (Hawke et al., 1989).

RDMDs are usually >2500 km² in size, typically several 1000 km², cover large areas with deposits superimposed on the older mare and/or highland substrate, and are often adjacent to major basins.
Pyroclastic deposit thickness can range from very thin (Orientale pyroclastic deposit less than about 2 km thick [Gaddis et al., 2003]) to tens of meters thick. They are composed of picritic (high-Mg olivine rich) glasses and ilmenite-rich (FeTiO\textsubscript{3}) black spheres and glass beads. RDMDs originate from a source vent suggested to be at the head of a sinuous rille or associated with other irregular depressions. The eruption style of RDMDs is most like the terrestrial strombolian style of eruption in which relatively viscous lava is ejected in bomb and lapelli sized fragments to typically form scoria cones. On the Moon however, due to the lower gravity and lack of atmosphere, the dispersal of erupted clasts is over a much larger area with extreme sorting and no topographically significant cones are formed (Lawrence et al., 2008; Weitz et al., 1998; Hawke et al., 1989).

Pyroclastic deposits can have a range of textures including pure glass beads, fractured glass beads, glasses mixed with fine regolith fragments, beads mixed with sublimes, and crystalline beads (with crystals of ilmenite, olivine, spinel, and metal) (Papike et al., 1998). Most pyroclastic deposits consist of fragmented basalt, iron-bearing minerals like olivine and pyroxenes and small amount of volcanic glasses (Gaddis et al., 2001). Figure 5.17 shows the site where the Apollo 17 orange glasses were collected and also shows the sample 72240 in thin section. The thin section is shown in 40× plane polarized light and exemplifies the different textures of volcanic glasses that are an average of 40 to 60 microns in diameter. Some of the beads are pure orange glass while others have olivine crystals that nucleated and grew during slower cooling with or without small ilmenite grains on the outside of the olivine. Some are almost completely black and are composed of more completely with crystallized minerals. For a further description of the sample and the minerals within see Meyer (2003).

![Figure 5.17](http://minerva.union.edu/hollochkl/c_petrology/moon_rocks/74220.htm)

Pyroclastic deposits can be distinguished from mare basalts using multispectral remote sensing because of the glass-rich nature of the high-Ti black spheres. Recognizing low-Ti pyroclastic deposits, however, can be problematic. Through compositional analyses of mare basalt and picritic glass samples it is evident that mare basalts and volcanic glasses are in fact distinct. It has been hypothesized that picritic glasses are derived from the parental magmas of the evolved mare basalts (Longhi, 1987) but more samples are needed to better understand the relationship between mare basalt compositions and volcanic glass compositions and their corresponding source regions.
Cooling rate calculations for pyroclastic debris have been made from experimental studies (e.g., Arndt and von Englehardt, 1987; Arndt et al., 1984; Kring and McKay, 1984). These studies suggest cooling rates that are considerably lower than those predicted for ‘free-flight’ conditions. The cooling rates for the Apollo 17 orange glasses are estimated as ~100°C/s (Arndt and von Englehardt, 1987) and 1°C/s for the Apollo 15 green glasses (Arndt et al., 1984). This slow cooling has been suggested to be caused by a hot vapor cloud in which the glass beads were insulated by either the gas vapor or the cloud of radiating droplets themselves. Arndt et al. estimate that the green glass droplets stayed in the gas cloud for ~10 minutes and cooled slowly allowing for different degrees of crystallization as can be seen in return sample petrography and mineralogy studies. This suggests that the flight times of sampled pyroclastic debris are not what would be theoretically expected, illustrates the complexity and clear difference between lunar and terrestrial eruptions and how information about volatile content and volatile interaction can constrain eruption style.

**Compositions of Pyroclastic Deposits**

The chief chemical distinction between pyroclastic volcanic glasses and mare basalts is the greater concentration of compatible elements in the glasses (elements such as Mg and Ni that fit into olivine, pyroxene, and other common minerals of the lavas). Volcanic glasses have on average higher MgO values than the mare basalts, suggesting that the magmas that erupted to produce volcanic glasses underwent less crystallization (removal of crystals from the melt) during their ascent to the lunar surface than did the magmas that gave rise to the mare basalt lavas (Lunar Sourcebook). This composition suggests that the glasses are more likely to represent a primitive magma as compared with crystalline mare basalts because as basalts crystallize, the Mg/(Mg+Fe) ratio decreases due to the crystallization of olivine and pyroxene. They are depleted in alkali, volatile, and siderophile elements and contain no water (Papike et al., 1998; Delano, 1986; Longhi, 1987). This suggests that volcanic glasses have higher liquidus temperatures than mare basalts (Delano, 1986; Longhi, 1987). The source depth of pyroclastic glasses has been estimated to be ~400 km by Delano (1986) and experimental studies show source depths ranging from ~250 km to ~500 km (Grove and Krawczynski, 2009) to ~1000 km (Longhi, 1992).

The bulk compositions of picritic glasses are more similar to terrestrial komatiites (compositions with low SiO₂, low K₂O, low Al₂O₃, and high to extremely high MgO) than terrestrial basalts (Lucey et al., 2006). Volcanic glasses have higher MgO, Ni, and Mg/(Mg + Fe) concentrations and values of Mg # (MgO/(MgO/FeO)) and lower Al₂O₃ and CaO values than most fine grained non-cumulate mare basalts. Understanding the chemical differences between mare basalts and pyroclastic glasses can help in identifying them using remotely sensed chemical data. Pyroclastic glasses have, on average, lower Al₂O₃ content than do mare basalts. Pyroclastic deposits have a wide range of TiO₂ contents, from 0.20–17.0 wt % (Papike et al., 1998 pp 5.80-5.82, 5.213-5.215) while the Mg/(Mg+Fe) ratio only varies from 0.76–0.85 (Delano, 1986). Hagerty et al. (2006) split the glasses into groups based on Ti content into the following groups: very low-Ti (VLT) = 0.2–1.0 wt% TiO₂, low-Ti = 1.0–3.4 wt% TiO₂, intermediate-Ti = 3.4–6.9 wt% TiO₂, high-Ti = 8.6–14.0 wt% TiO₂, and very high-Ti (VHT) = 14.0–17.0 wt% TiO₂. The color of the glass varies with TiO₂ content (Fig. 5.18), although color alone is not always indicative of TiO₂ content. Longhi (1987) suggested that the discrepancy between basalt compositions and volcanic glass compositions is due to a lack of sufficient sample numbers, and with more samples this discrepancy will be resolved. volcanic glasses and mare basalts may represent different mantle source-regions (Delano 1990). More samples of volcanic glasses and associated mare basalts from in-situ field collection could help in constraining the relationship between the two and their influences on each other.
FIGURE 5.18 Simplified figure showing that lunar volcanic glasses change color with Ti content. Note, however, that black beads from the Apollo 17 orange soil have the same composition as the orange glass beads (Delano, 1986; Papike et al., 1998 and references therein). The degree of nucleation as well as Ti content can affect the visible color of the glasses and glasses with the same chemical compositions have been identified with different colors.

Box 5.1
Pyroclastic Deposits as Lunar Resources

Lunar resources are any element that can be extracted from the lunar surface and used as fuel, energy, or building materials. Useful and likely to be utilized elements include Ti, Fe, and O from ilmenite, Mg from olivine, Na, K, Sr, and Ba from plagioclase and potassium feldspars, and Mn and Cr from pyroxenes. Solar wind atoms (He, He3, C, H, N and other noble gases) that are implanted in mineral grains of the regolith are also a potential source for resource materials.

Pyroclastic deposits are one of the most numerous and easily accessible lunar resources (Lawrence et al., 2008 and references therein). Regional-scale deposits are relatively thick and consist of loose, unconsolidated material high in Ti and relatively unmixed with other low-Ti materials. Ilmenite is also abundant in high-Ti mare basalt soils but may prove to be more difficult to utilize because basalts are often still intact in flows or in large blocks and therefore more difficult to process. The range of compositions of lunar glasses must be more fully understood in order to assess their resource potential.

Volcanic glasses have surface coatings of volatile elements from gas exsolution during eruption including S, Ag, Cd, Zn, and Br which can potentially be used as resources. Oxygen is one of the most important materials needed and can be extracted from ilmenite by reduction (Duke et al., 2006). High-Ti pyroclastic deposits have a high potential for resource extraction. He3, identified as an important resource element found in mature high-Ti deposits, would be expected to be found in more concentrated amounts on the lunar farside because it has more nearside solar wind fluence due to magnetotail shielding (Johnson et al., 1999). Ilmenite preferentially retains solar wind volatiles including H, He, C, N, and S and is known to preferentially retain He3 which can be used as nuclear fission fuel using a Deuterium-He3 reaction. Ilmenite is abundant in lunar soils and is often found in volcanic glasses, especially in black beads like the ones found in the Apollo 17 orange ‘soil’. These beads have a TiO2 content of 9–10% and are similar in composition to Apollo 17 high-Ti mare basalts (Hawke et al., 1990).
Potential Sampling Sites

Figure 5.19 shows a map of pyroclastic deposits with the Clementine TiO₂ global map as a base map. The white circles represent over 120 identified pyroclastic deposits, about 100 of which have been confirmed and published in lists of compiled data (see Gaddis et al., 1985, 2000, 2003 and references therein). The deposits have diameters of ~2–330 km. The red symbols are floor-fractured craters, indicated with their appropriate sizes. Floor-fractured craters are often found in association with pyroclastic deposits and some are partially or entirely filled by mare-type smooth dark-albedo lacus (lakes) or smaller ponds, suggesting that the fractures provide vents for flood lavas (Gaddis et al., 2000; Head, 1974; Korteniemi et al. 2010). Pyroclastic deposits are also often associated with sinuous rille morphologic features, however are not represented on this map.

Four regions of overlapping high-Ti, floor-fractured craters, and pyroclastic deposits are identified as regions suggested for further investigation and/or sampling. These locations are Mare Moscoviense, Oppenheimer, Grimaldi, and Mare Smythii. Mare Moscoviense (Fig. 5.20), which is located on the northern far-side, is suggested to have a He³ abundance of 8–17 ppb (Johnson et al., 1999) which is high compared to average maria abundance of 8–10 ppb (Duke et al., 2006). This location also has the largest variation in Ti within an enclosed deposit on the farside and may have particularly high glass contents based on very red spectra (Gillis and Spudis, 1998). Oppenheimer (Fig. 5.21) is located within the South Pole-Aitken basin (SPA) and has seven pyroclastic deposits located along floor-fractures that are concentric to the crater rim and associated with the linear part of a rille and several small rille-related craters. Although these deposits visually resemble the deposits at Alphonsus, they have been identified as having a different composition than both the Alphonsus deposits and two other deposits within SPA (Petro and Gaddis, 2001; Head, Wilson and Pieters, 2000). Mare Smythii (Fig. 5.22), located on the equatorial eastern limb of the Moon, has some of the most diverse geologic units including pyroclastic deposits in minable...
quantities (Spudis and Hood, 1992). These deposits are suggested to contain a large amount of basaltic glass (Gillis and Spudis, 1998) and the site was suggested for a lunar base by Spudis and Hood (1992). The Grimaldi region (Fig. 5.23) consists of two pyroclastic deposits: one about 10 km northwest of the inner ring of the Grimaldi crater and the other covering ~90 km² on the floor of Grimaldi F (~50 km east of Grimaldi crater). They are associated with irregularly shaped endogenic source vents and floor-fractures. Coombs and Hawke (1992) suggest that both the pyroclastic deposits and the nearby mare basalts originate from the same source vent.

All four of these locations can provide important samples to help understand lunar volcanism. At all locations, high-resolution images, detailed spectral data, and sample return would help in understanding lunar volcanism from the perspective of pyroclastic glass deposits. Because these deposits are loose and at the surface they can be sampled with simple scoop techniques, as exemplified by Apollo 17 EVA station 4 (see in Fig. 5.17). Pyroclastic deposits can also be sampled from within an exposed unit in geologic strata if such a place of exposed geologic cross section is found (in a crater wall or exposed fault block, etc.).

FIGURE 5.20 Left: Clementine image mosaic of Moscoveinse crater. Right: a sketch map of Moscoveinse crater. From Craddock et al. (1997). Based on analyses of UV/VIS Clementine data, these pyroclastic deposits may have 7.7–11.1 wt % TiO₂.
FIGURE 5.21 Left: Clementine image mosaic of Oppenheimer crater. Right: a sketch map of Oppenheimer crater. From Head et al. (2000). Based on analyses of UV/VIS Clementine data, these pyroclastic deposits may have 5.5–11.1 wt % TiO$_2$.

FIGURE 5.22 Left: Clementine image mosaic of Mare Smythii. Right: a sketch map of Mare Smythii in which DMDs are the striped units. From Yingst and Head (1998). Based on analyses of UV/VIS Clementine data, these pyroclastic deposits may have 2.7–7.7 wt % TiO$_2$ (2.5–3.5 wt % [Spudis and Hood, 1992]).
SCIENCE GOAL 5D: DETERMINE THE FLUX OF LUNAR VOLCANISM AND ITS EVOLUTION THROUGH SPACE AND TIME

Introduction

Lunar volcanism can be used to examine the thermal and chemical evolution of the Moon and, by proxy, terrestrial-type planets. One of the principal ways to address that concept is to determine the flux of volcanism and its evolution in time. Calculating volcanic flux requires constraints on age, chemistry, thickness, and area of volcanic deposits. The lunar surface, unaffected by plate tectonics and erosion from wind and water, offers a pristine setting to study volcanic flux early in a planet’s history. Although past and current lunar missions, as well as Earth-based observations, have provided a framework for understanding the physical and chemical properties of lunar volcanic activity, significant uncertainties in the history of lunar volcanism remain (Shearer and Papike, 1999).

Thus far, it appears lunar mare volcanism peaked in the upper Imbrian, producing about $9.3 \times 10^6$ km$^3$ of lava at an average rate of 0.015 km$^3$/yr (Hiesinger and Head, 2006). During the Eratosthenian and Copernican periods, the rate of volcanism decreased to about $1.3 \times 10^4$ km$^3$/yr and $2.4 \times 10^6$ km$^3$/yr respectively (Hiesinger and Head, 2006). These estimated eruption rates can be misleading, because they are global averages over hundreds of millions of years. Some volcanic features, like sinuous rilles, are volumetrically minor on a global scale, but require large volumes of rapidly emplaced lava – sometimes eruption rates must be on the order of 1000 km$^3$/yr (Hiesinger and Head, 2006). Consequently, a global average estimate of volcanic flux does not accurately represent the magma source region of a localized...
eruption. It will be important to evaluate the global volcanic production rate and those reflecting regional magmatic conditions. Moreover, detailed analyses of some magmatic regions will be needed to properly evaluate the links between extrusive volumes, source regions, and the delivery of magma to the surface (Shearer et al., 2006).

Ascertaining changes in volcanic activity through time will require a continuum of samples from multiple time periods for a given location. Similarly, ascertaining changes in volcanic activity across space requires a continuum of samples from a given time period across a series of locations. To maximize the scientific return of missions, it will be best to identify locations where volcanic material from multiple time periods can easily be sampled on virtually any mission.

Criteria for Site Selection

We focus on locations where volcanic material from multiple time periods are within close proximity to one another, and where volcanic plumbing may be exposed, establishing the relationships between surface volcanic features and the underlying magmatic systems.

Craters

Craters can expose multiple units (e.g., cryptomaria or subsurface dikes) in one location that would not otherwise be accessible, allowing for the measurement and sampling of multiple events through time (Pike, 1977; Carter et al., 1980). Ideally, a target crater will penetrate all basalt layers and bottom in anorthositic crustal material to provide total basalt thickness. A detailed analysis of high resolution orbital data around a crater of interest will reveal the approximate number of flow and/or crustal units exposed in a crater wall and help delineate preferred traverse paths.

Area

Area measurements deal with large-scale features and, thus, orbital data is the most practical way to continue refining area estimates. Margins of individual lava flows can be visually outlined using remote sensing data and/or crater statistics and fill properties (e.g., Neukum et al., 1975; Hartmann et al., 1981; Stöffler et al., 2006; Hiesinger et al., 2000). As higher-resolution data becomes available, flow margins should be reexamined and refined.

Thickness

Flow thickness is difficult to estimate uniquely through aerial investigations because of uncertainties in the effects of downwarping caused by the extrusion of large masses of lava, uncertainties in pre-flow topography, and assumptions made among different methods of thickness calculation (e.g., Head, 1976; Yingst and Head, 1977; Wieczorek et al. 2006). In-situ sampling and accurate thickness measurements taken from exposed flow stratigraphy or geophysical techniques such as ground penetrating radar will reveal the amount of error associated with orbital estimates.

Cryptomare

Cryptomare deposits represent some of the oldest volcanic deposits on the Moon and remain largely, if not entirely, unsampled (Shearer et al., 2006). Measuring their volume, composition, and age is essential to understanding early lunar flux. An initial step in constraining their volume is to use high-resolution spectral data to identify and catalogue all Dark Halo Impact Craters (DHCs). These craters potentially reveal the areal extent and thickness of old mare deposits subsequently covered by regolith. Because no ground truth data exists for any cryptomare deposits, sampling any DHC will provide new information about the volcanic flux. Those in pre-Nectarian plains have the highest priority.

Composition

Composition plays an important role in determining source depth, amount of crystallization, and amount of assimilation of crustal rock in the erupting lava. We have only sampled a very small portion of the lunar crust, leaving entire crustal suites unsampled. Regions of unsampled composition have been identified with Clementine and Lunar Prospector data (e.g., Lucey et al., 2006) and re-evaluated with high-resolution compositional data from current and upcoming missions (e.g., M’ on Chandryaan-1).
Groundtruthing

Groundtruthing is an essential step in remote sensing analysis, which can address many NRC scientific priorities. Without groundtruthing, absolute ages and compositions of hypothesized geologic units cannot be known. Groundtruthing can only be accomplished by analyzing lunar samples and their geologic and stratigraphic context. As the library of lunar sample types grows, so does our ability to accurately interpret remote sensing data and analyze relative dates based on crater size-frequency distributions.

Example Landing Sites

We used the above criteria to identify four example landing sites, listed below.

**Buch B crater (~38°S, 17°W)**

Buch B is an example of a crater that may expose a basaltic dike (Hawke *et al.*, 2002). Lunar Orbiter mosaic images of Buch crater show dark-albedo, mafic material radiating away from the crater rim. Corresponding iron-oxide ratio maps of Buch B crater reveal this mafic material has a higher iron-oxide content than the surrounding anorthositic highland material. Age and compositional analysis of the mafic material could provide insight into the parameters that determine whether a dike propagates to the surface, or stalls in the crust.

**Carlini Crater (33.7°N, 24.1°W)**

Carlini (Fig. 5.24) is only 10 km in diameter, but is the largest unburied crater in the Imbrium region and offers a window into the deepest portion of the flow. Although it does not penetrate through mare into crust, the crater contains materials with at least three different titanium contents. This suggests it has penetrated at least three mare flows. From the crater rim, astronauts may conduct thickness and compositional measurements on the inside of the crater wall. Also, Carlini Crater may be located within the central ring of Imbrium Basin; this is an ideal location to verify differing thickness estimate and measurement techniques (*e.g.*, DeHon, 1974; Hörz, 1978; Head, 1982).

![Titanium map](image)

FIGURE 5.24 Titanium map (right) of the area surrounding Carlini Crater suggests that it has penetrated at least three mare flows.
**Lomonosov region (~24°N, ~109°E)**

The Lomonosov region (Fig. 5.25) contains two proposed DHCs that contain exposed pre-Nectarian cryptomaria (Giguere et al. 2003). Because these two DHCs are covered with pre-Nectarian material, they could represent some of the earliest basalt flows on the Moon. Sampling the basaltic ejecta of one or both of the craters would constrain the age and composition of these unique deposits. Geophysical work would penetrate through the regolith blanketing the cryptomaria and give the thickness of the basalt unit. These measurements, coupled with spectral studies to determine the arial extent of the cryptomare deposit, would help constrain the melt volume and source depth of some of the earliest lunar volcanism.

**FIGURE 5.25** Location of two proposed DHCs that contain exposed pre-Nectarian cryptomaria (Giguere et al., 2003). Both images are on a Clementine 750 base map.

**Apollo Crater (70°S, 172°W)**

Apollo (Fig. 5.26) contains high-titanium and high-aluminum regions with at least two units of hypothesized, unsampled mare units. A small unnamed impact crater located at 70°S, 172°W penetrates through a region of high titanium into a region of low titanium. This crater provides a good opportunity to sample at least two layers of material. The unnamed crater is located in Apollo Crater’s inner-ring and, like Carlini Crater, provides a good opportunity to test models of mare fill derived from orbital data and test excess mass-induced downwarping models with geophysical equipment.
SUGGESTED LANDING SITES AND CASE STUDIES

Below is a list of the most interesting and diverse volcanic sites that have been identified to achieve Science Concept 5 Science Goals. The ten locations (Fig. 5.27) have been split up into two groups based on the apparent complexity of the site and the proximity of the features to one another. We include recommended investigations to better understand the geology of each site, including pre-landing analyses of orbital high-resolution spectral and topographic data to pinpoint exact landing locations and traverse paths. The Science Concept 5 Science Goals that are addressed at each site are listed at the beginning of each site description.

FIGURE 5.26 Apollo crater: high-titanium, high-aluminum region. Clementine 750 nm global base map in Mercator projection shows regions of potentially anomalously aluminum–rich basalts. The zoomed-in region shows a titanium map of the interior of Apollo crater.
Group 1: High Priority Sites (in no particular order)

Montes Harbinger (25.71° Lat., -44.47° Long.) Science Goals 5a, 5b, 5c, and 5d

Site Description: Montes Harbinger (Fig. 5.28) is a mountainous region located just east of the Aristarchus Plateau in Oceanus Procellarum. The region contains many of the same volcanic features of interest as the Aristarchus Plateau, except in a smaller area. Prinz Crater (25.5° Lat., -44° Long.) is filled and partially buried with a potentially young mare with model age ~1.2 Ga (Hiesinger et al., 2003), potentially the youngest mare flow on the lunar surface. The region is mantled by pyroclastic deposits, as is the adjacent Aristarchus Plateau. Aristarchus crater ejecta could potentially be sampled in the region (e.g., from within the mare-filled Prinz Crater). Several sinuous rilles are present in the area, two of which might be accessible from the ~1.2 Ga flow that fills Prinz Crater. Domes have been mapped in the area but are potentially remnant highland material surrounded by mare. Mare flows with relatively old model ages (3.48–3.74 Ga) bound the region to the north, east, and west (Hiesinger et al., 2003). The region is spectrally characterized by 16–18 wt-% FeO, intermediate Ti, and a high Th anomaly.

Site Recommendations:

- High-resolution images to determine:
  - Can stratigraphy be observed in Prinz Crater wall?
  - Distinguish between domes that are volcanic verses those that are highland material; target region bounded by 24.4°–25.7° Lat., -42.2°–40.6° Long.

- High-resolution topographic data:
  - Define the height and slope of the rim of the partially buried Prinz Crater to determine whether the rim can be traversed; if such a traverse is possible, can potentially examine sinuous rilles in high region
  - Determine sinuous rille morphology
- Determine dome heights
- Explore/Sample/Examine:
  - Inside Prinz Crater (potentially the young mare on the lunar surface)
  - North rim of Prinz Crater (stratigraphy, pyroclastic deposits)
  - Traverse up Prinz Crater rim to Vera crater (26.3° Lat., -43.7° Long.) if possible
  - Old mare units north of the southeast corner of Prinz rim
- It appears that the rille immediately east of Prinz Crater can be traversed, allowing access to the mountainous regions in the area

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**Oppenheimer (-34.30° Lat., -166.30° Long.) Science Goals 5a, 5c, and 5d**

**Site Description:** Oppenheimer (Fig. 5.29) is a farside basin (~208 km in diameter) within the larger South Pole-Aitken basin. The region contains mafic spectral signature (i.e., high FeO relative to surrounding region). Mare have not been mapped in the region (Wilhelms, 1987), although volcanic features inside Oppenheimer include concentric floor-fractures probably related to volcanic intrusions, smaller craters with floor-fractures (e.g., Oppenheimer U, -34.5° Lat., 68.2° Long.), pyroclastic deposits associated with fractures and high-Fe regions, a probable endogenic crater (-33° Lat., -156° Long.) within a dark mantle deposit and cut by linear feature, and a possible sinuous rille (-34.5° Lat., -168.48° Long.).

**Site Recommendations:**
- High resolution images to assess any possibility of the presence of mare material, look for:

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**FIGURE 5.28** Lunar Orbiter image mosaic of Montes Harbinger. The black point represents the recommended landing location surrounded by 10 km and 20 km radius circles. Dashed lines represent approximate flow boundaries as presented in Hiesinger et al. (2003). Model ages in figure are also from Hiesinger et al. (2003).
- Mare spectral signatures
- Flow scarps
- Ponded regions

- High resolution spectral images of Oppenheimer U to determine:
  - Does mafic anomaly represent mare?
  - Analyze possible lobate feature on northern rim
  - Map pyroclastic deposits
  - Analyze central peak; could contain material from ~55 km deep may reveal plumbing system under peak

- Detailed topographical information to determine:
  - Depth of possible rilles and fractures
  - Stratigraphy
  - Flow margins

**Marius Hills (14.68° lat., -55.65° long.) Science Goals 5a, 5b, and 5d**

**Site Description:** The Marius Hills region (Fig. 5.30) contains a high concentration of domes of probable volcanic origin and sinuous rilles associated with domes. The area has high Fe abundance (18–20 wt %), high Ti, and a range of Th values from lower in west to higher in east. Various aged flows surround the area ranging in model age from 1.73–3.74 Ga (Hiesinger et al., 2003). In the northern region there is a flow margin of two potentially young flows with model ages of 1.85 Ga and 2.01 Ga (Hiesinger et al., 2003).

**Site Recommendations:**
- Higher resolution imagery of the region:

![Figure 5.29](image-url) Clementine 750nm image of Oppenheimer basin. The white point represents the recommended landing location surrounded by a 10 km and 20 km radius circles.
Pinpoint exact locations of flow fronts
- Detailed dome and rille morphology
- Statistical analyses of dome distribution in order to understand timing of different eruptions to help decide which domes to sample
- Sample domes and rille materials
- Sample ejecta of several small impact craters occurring on the domes

**Site Description:** The Apennine Bench region (Fig. 5.31) is located in the southeast area of Imbrium basin, west of the Apollo 15 landing site. The area is dominantly characterized by the Apennine Bench formation, which is composed of light plains units that may uniquely be of volcanic origin (i.e., they may be high albedo lava flows rather than basin ejecta). Lobate margins have been observed within the plains. “Non-mare” volcanic material is present (the area is a ‘red spot’ [Malin, 1974]). Spectrally determined Fe, Th, and Ti compositions are consistent with ~3.9 Ga (radiometric age) Apollo 15 KREEP basalt samples (Nyquist et al., 1975; Carlson and Lugmair, 1979; Blewett and Hawke, 2001). Pyroclastic deposits are found at the northwestern edge of the region and south of the Apollo 15 landing site (Blewett and Hawke, 2001). Domes have been mapped along the western margin of the region near pyroclastic deposits, including a dome-like feature with a non-circular summit depression (at 23.4°, -5.1°). Sampling the adjacent mare units in Mare Imbrium is of secondary importance because the model ages of these flows (~3.3–3.55 Ga; Hiesinger et al., 2000) fall within the well-calibrated region of the ‘lunar cratering chronology curve’ (see Fig. 5.11). Beer crater (~8.5 km in diameter 27.1° Lat., -9.1° Long.) contains mare ponds, possibly visible stratigraphy, and possible fresh ejecta (including a secondary chain) from Timocharis crater, located ~100 km West.

**Site Recommendations:**
- High resolution images needed to find flow margins on plains unit
  - Particularly near Beer crater (at 27° Lat., -8° Long.) [see map in Blewett and Hawke, 2001]

**FIGURE 5.30** Lunar Orbiter image mosaic of Marius Hills. The black point represents our recommended landing location surrounded by a 10 km radius circle and a 20 km radius circle.

**Apennine Bench Region (26.67° lat., -8.52° long) Science Goals 5a, 5c, 5d**

Site Description: The Apennine Bench region (Fig. 5.31) is located in the southeast area of Imbrium basin, west of the Apollo 15 landing site. The area is dominantly characterized by the Apennine Bench formation, which is composed of light plains units that may uniquely be of volcanic origin (i.e., they may be high albedo lava flows rather than basin ejecta). Lobate margins have been observed within the plains. “Non-mare” volcanic material is present (the area is a ‘red spot’ [Malin, 1974]). Spectrally determined Fe, Th, and Ti compositions are consistent with ~3.9 Ga (radiometric age) Apollo 15 KREEP basalt samples (Nyquist et al., 1975; Carlson and Lugmair, 1979; Blewett and Hawke, 2001). Pyroclastic deposits are found at the northwestern edge of the region and south of the Apollo 15 landing site (Blewett and Hawke, 2001). Domes have been mapped along the western margin of the region near pyroclastic deposits, including a dome-like feature with a non-circular summit depression (at 23.4°, -5.1°). Sampling the adjacent mare units in Mare Imbrium is of secondary importance because the model ages of these flows (~3.3–3.55 Ga; Hiesinger et al., 2000) fall within the well-calibrated region of the ‘lunar cratering chronology curve’ (see Fig. 5.11). Beer crater (~8.5 km in diameter 27.1° Lat., -9.1° Long.) contains mare ponds, possibly visible stratigraphy, and possible fresh ejecta (including a secondary chain) from Timocharis crater, located ~100 km West.

Site Recommendations:
- High resolution images needed to find flow margins on plains unit
  - Particularly near Beer crater (at 27° Lat., -8° Long.) [see map in Blewett and Hawke, 2001]
Sampling of the Appenine Bench formation, pyroclastic deposits, dome materials, complex crater ejecta materials (Timocharis crater), and “non-mare” KREEP material (of possible volcanic origin)

Site Description: The Lomonosov-Fleming region (Fig. 5.32) is located in the highlands northeast of Mare Marginis on the farside of the Moon. The region is characterized light plains units and is a well-known cryptomare region with multiple DHCs that have excavated potentially pre-Nectarian cryptomare from beneath (Giguere et al., 2003). The northernmost region contains dark mantling deposits of probable pyroclastic origin (e.g., along the southern side of Edison crater). Several craters (e.g., Dziewulski [21.2° Lat., 98.9° Long.], Edison [25.0° Lat., 99.1° Long.], Artamonov (25.5° Lat., 103.6° Long.), and Richardson [31.1° Lat., 100.5° Long.] contain pyroclastic deposits, expose cryptomare as DHCs, and/or contain unsampled mare units.

Site Recommendation:
- Obtain high-resolution images to define boundaries of volcanic units
- The nature of the low albedo material (as observed in Clementine 750nm images) between Dziewulski crater and the DHC numbered 11 by Giguere et al., (2003) is unclear; samples potentially from both pyroclastics from Dziewulski or dark halo material from DHC #11 could be collected in the area between these two craters. This material needs to be characterized before considering the area between the two craters as a potential landing site.
- Geophysical work would be useful for looking at the subsurface stratigraphy, potentially allowing the determination of:
the extension of cryptomare under ejecta
the thickness of cryptomare in the region in general

Gruithuisen Domes (36.43° lat., -40.18° long) Science Concept 5a, 5b, and 5d

Site Description: The Gruithuisen Domes site (Fig. 5.3) features a number of silicic composition, low-Ti and low-Fe domes. The region overall is a high-Th “red spot” (Malin, 1974). Unsampled materials here may be similar to those in Mare Frigoris, potentially KREEP sampling high-Ti, low-Ti KREEP materials. Maria in the region have an estimated model age of ~1.1 Ga (Schultz and Spudis, 1983). Gruithuisen Gamma includes a dome with a sinuous rille on its southern side (35.98°, 40.34°). The Luna 17 landing site is located ~100 km to the northeast, although it is located on different mare flow units.

Site Recommendations:
- High resolution topography data to identify flow fronts
- High resolution spectral data to identify compositions of the domes and basalt flows
  - High resolution imagery and spectral data of a crater (at 36.57°, -40.64°) on top of Gruithuisen Gamma; identify accessibility and if stratigraphy is present
- More accurate crater count model ages of the mare
- Sample the materials of all the domes and the adjacent mare, sinuous rille material, and flow margins

FIGURE 5.32 Clementine 750nm image of the Lomonosov-Fleming region. The black point represents the recommended landing location surrounded by 10 km and 20 km radius circles.
Mare Moscoviense (26.33 lat., 146.94 long) Science Concept 5a, 5b, 5c, and 5d

Site Description: Mare Moscoviense (Fig. 5.34) is a 277 km diameter mare-filled basin. At least two younger mare flows are present in the region, one in the east (model age ~2.57 Ga) and one in the west (model age ~3.50 Ga) (Haruyama et al., 2009); the western flow has higher Fe and Ti. Several floor-fractured craters are located on the central-western side of mare; Komarov on the southeast margin is partly flooded. A large pyroclastic deposit is located at the southern edge of the mare. An impact crater at 26.3°N, 147.7°E potentially penetrates through high-Ti and high-Fe material into low-Ti and low-Fe material, potentially penetrate through a mare flow to another flow beneath.

Site Recommendations:
- Higher resolution images and topography are needed to:
  - Delineate flow fronts
  - Determine stratigraphy in crater at 26.3° Lat., 147.7° Long.
- Sample crater at 26.3° Lat., 147.7° Long.
- Sample maximum number of flows
- Geophysical work to determine flow thickness

FIGURE 5.33 Lunar Orbiter image mosaic of Gruithuisen domes. The black point represents the recommended landing location surrounded by 10 km and 20 km radius circles.
Group 2: Lower Priority Sites

Aristarchus Plateau (25.17° lat., -54.69° long.) Science Concept 5a, 5b, 5c, and 5d

Site Description: The Aristarchus Plateau is a 200 × 230 km highland plateau in the middle of a mare unit. The southern margin of the plateau is embayed by what is potentially the youngest mare basalt flow on the lunar surface (model age ~1.2 Ga) (Hiesinger et al., 2003). Aristarchus crater may have excavated old low-Fe, very-high-Th highland material. A large regional pyroclastic deposit radiates outwards from the plateau center. Sinuous rilles are located on the north, east, and west sides of the plateau. There are flow margins of young and older flow units to the east and west adjacent to the plateau and several other potentially young mare flows surround the plateau (Hiesinger et al., 2003). This is considered to be a lower priority site because the nearby Montes Harbinger region appears to display the same level of volcanic complexity but in a much smaller area.

Site Recommendations:

- High resolution imagery and topography of young mare flow margins
- Define landing sites just outside the plateau
- East or west sides would be best to sample young-flow/old-flow margin, pyroclastic deposits, and sinuous rille materials within close proximity
- Samples of Aristarchus ejecta northeast of the crater may be volcanic material
- High resolution imagery of young flow south of the plateau to determine if there are underlying units exposed
- Sample plateau material anywhere where there is ejecta

Mairan Domes (41.7° Lat., -48.3° Long.) Science Concept 5a, 5b, and 5d

Site Description: The Mairam domes are located in a region flooded with a mare flow that potentially has a young age (~1.33 Ga) (Hiesinger et al., 2003). The northern group of two or more domes contains the Mairan T dome (identified as a “red spot”), 6.7 km in diameter and 930 m high with nested summit craters ~2-3 km in diameter. There are other nearby domes an rilles.

FIGURE 5.34 Lunar Orbiter image mosaic of Mare Moscoviense. The white point represents the recommended landing location surrounded by 10 km and 20 km radius circles.
Site recommendations:
- high-resolution images of Mairan T summit craters
  - map evolution of craters
  - look for visible plumbing
- sample young maria
- sample dome material
- geophysical work to determine flow thickness and possible shallow-crustal magma reservoirs

*Mare Smythii (1.3°, 87.5°)* Science Concept 5a, 5b, 5c, and 5d

Site Description: Mare Smythii is a ~373 km diameter mare-filled basin with floor fractured craters. Compositions of the mare units are similar to the Luna 24 site (low-Ti basalts). A young mare flow (model age ~1.1 Ga) potentially exists in the eastern portion of Mare Smythii (1.3°N, 91°E) around Dorsum Cloos (Schultz and Spudis 1983), however Hiesinger *et al.* (2008) suggest a much older model age for Mare Smythii (model age ~3.0 Ga). Pyroclastic deposits are present in the region and appear to have intermediate Ti contents.

Site Recommendations:
- Determine the relative age of the mare ponds south of the main mare
  - Dark halo impact craters and dark mantling deposits are in close proximity
- High resolution imagery, topography and spectral data
  - Determine the best single site to sample the dark halo impact craters, dark mantle deposits, and young mare unit

Other Sites of Interest

General Interest:
- Basin centers
- Cryptomaria
- Convergent flow margins
- Farside lava ponds

Sites of Interest for Individual Science Concept 5 Science Goals:
- Campbell crater
- Mare Marginis
- Goddard crater
- Schiller-Schickard region
- Buys-Ballot - Lacus Luxuriae
- Mare Nectaris
- Balmer-Kapteyn region
- Mare Australe
- Mare Humorum
- Maestlin crater (linear rilles, mare embayed craters, Kepler ejecta)
- Letronne region of Oceanus Procellarum (possibly young mare)
- Natasha/Euler region (domes w/ craters on top, rilles, mare)
- Mendel-Ryderberg region (orientale ejecta, cryptomare DHICs)
- Alphonsus crater (pyroclastic deposits inside FFC, domes)
- Northern Imbrium (domes, rilles)
- Grimaldi (northern part has domes, pyroclastic deposits, one mare flow model age estimated at ~3.0Ga, high-Ti, high-Fe)
- Flamsteed
- Mare Humboldtianum
- Mare Orientale
- Mons Hansteen