Unexplored Areas of the Moon: Nonmare Domes

A White Paper submitted to the
Planetary Science Decadal Survey 2013-2022

Primary Author

Sarah E. Braden
School of Earth and Space Exploration
Arizona State University
sebraden@asu.edu
(480) 727-8899

Co-Authors

Samuel J. Lawrence, Arizona State University
Mark S. Robinson, Arizona State University
Bradley L. Jolliff, Washington University
Julie D. Stopar, Arizona State University
Lillian R. Ostrach, Arizona State University
Lisa R. Gaddis, U.S. Geological Survey
Justin J. Hagerty, U.S. Geological Survey
Steven B. Simon, The University of Chicago
B. Ray Hawke, University of Hawaii

Endorsers

Carlton C. Allen, NASA Johnson Space Center
David T. Blewett, Johns Hopkins University Applied Physics Laboratory
Richard C. Elphic, NASA Ames Research Center
Bernard H. Foing, European Space Agency and ILEWG
Vera A. Fernandes, Berkeley Geochronology Center
Timothy D. Glotch, Stony Brook University
Jim Head III, Brown University
David J. Lawrence, Johns Hopkins University Applied Physics Laboratory
Thomas Magna, Westfälische Wilhelms-Universität Münster
David S. Mckay, ARES Office, NASA Johnson Space Center
Clive R. Neal, University of Notre Dame
Lawrence A. Taylor, University of Tennessee
David T. Vaniman, Los Alamos National Laboratory
Lionel Wilson, Lancaster University

I. Introduction

The Moon is a relatively close and invaluable source of information about planetary evolution and the history of the inner solar system. Forty years ago, returned samples from the Apollo missions enabled a series of discoveries that revolutionized our knowledge of the Earth-Moon system [*Spudis*, 1999]. While the Apollo missions sampled a range of volcanic materials, including glasses from fire fountains, mare basalts, and crustal rocks, these samples represent only a small portion of the lunar crust. Results from past remote sensing missions (Lunar Prospector and Clementine) show that lunar samples returned during the Apollo and Luna missions are not representative of the entire lunar surface and that other rock chemistries exist [*Giguere et al.*, 2000]. Sample return missions from unexplored and unsampled volcanic terranes, such as nonmare domes, can contribute to our knowledge of lunar magmatic evolution. Nonmare domes are morphologically and spectrally distinct non-basaltic extrusive volcanic features. The Gruithuisen Domes site, discussed later in this paper, would be a scientifically valuable site for a human mission, which would allow for interpretation and sampling of the surrounding mare and underlying highlands in addition to the domes. However, even an automated robotic sample return, such as a regolith scoop similar to the Luna missions, would provide invaluable information. However, an automated sample return mission cannot replace the level of detail and contextual information that would be gathered by human explorers. Analysis of samples returned from unexplored areas of lunar volcanism such as the Gruithuisen Domes will (1) increase our knowledge of the history of the Earth-Moon system, (2) advance theories of lunar magmatic evolution, especially our understanding of the conceptual lunar magma ocean (LMO), and (3) provide valuable points of comparison with other terrestrial planets, including Mercury, Earth, and Mars.

The National Research Council's 2007 "Report on the Scientific Context for Exploration of the Moon" (SCEM) targeted key concepts and summarized scientific objectives for lunar exploration in the coming decades [*National Research Council*, 2007]. This document is comprehensive and concise in defining lunar science objectives. The SCEM Committee concluded that "a diversity of lunar samples is required for major advances," and recommended that a "landing site should be selected that can fill in the gaps in diversity of lunar samples." Remote sensing results from recent and current robotic orbiter missions, SELENE (Japan), Chang'e (China), Chandrayaan-1 (India), and the Lunar Reconnaissance Orbiter (United States), will change our current understanding of the distribution of minerals on the lunar surface, and detailed topographic data will improve our ability to analyze geologic features.

In the wake of these new observations plans should be made for sample-return missions to investigate specific science objectives in areas where a) remote sensing cannot provide sufficient answers to scientific questions and b) sample-return missions are the only way to make new discoveries or contribute to existing knowledge. Obtaining lunar samples for analysis on Earth is important for determining ages, detailed elemental compositions including isotopes, and the dissemination of samples to a variety of research institutions. While stressing the importance of obtaining samples that represent the full suite of lunar volcanic material, this paper focuses specifically on the scientific rationale for a sample return mission to a nonmare lunar dome. A Luna-style sample return mission (Discovery-class) to a nonmare lunar dome would provide invaluable insights into the diversity and mechanisms of lunar volcanism. An automated sample return from the Moon could be performed at lower cost than developing the instrumentation to do detailed elemental analyses in-situ. Moreover, sample return to Earth is required for age-dating. In addition, the proximity of the Moon provides the opportunity for human exploration of high-priority sites such as the Gruithuisen or Mairan domes. Astronauts can sample a wider range of rocks at a particular locale than a "grab and go" Luna-style automated sample return mission, which would increase the diversity and quality of lunar samples returned.

II. Lunar Magmatic Evolution and the Diversity of Lunar Rock Types

The SCEM put forth a list of top-level scientific objectives pertaining to lunar magmatic evolution and the diversity of lunar rock types, based on the conclusion that "key planetary processes, such as thermal state and compositional evolution, are manifested in the diversity (duration, age, composition, petrology, and morphology) of lunar rocks:"

a. Determine the origin and variability of lunar basalts.
b. Determine the age of the youngest and oldest mare basalt.
c. Determine the composition range and extent of lunar pyroclastic deposits.
d. Determine the flux of the lunar volcanism and its evolution through space and time.
e. Determine the extent and composition of the KREEP layer and other products of planetary differentiation.
f. Inventory the variety, age, distribution, and origin of lunar rock types.

Our present view of lunar magmatic evolution is limited because our sampling of the Moon is limited. We lack global sample coverage, and many details of lunar history are controversial. Samples of ferroan anorthosite and other non-basaltic pristine rocks are rare. The few such samples that are believed to be pristine have been subjected to extensive study because of the clues they provide to understanding the origin and early history of the Moon. Investigating regions with unknown rock types, such as nonmare domes, is an excellent way to advance studies.

Many workers have considered lunar magmatic evolution, including *Warren* [1985], *Shearer and Papike* [1999], and *Shearer et al.* [2006]. A generalized framework of lunar magmatic evolution includes the formation of (1) an anorthositic crust, (2) Mg-rich rocks, (3) KREEP-rich rocks, and (4) mare basalts. However, petrogenetic relationships between major lunar igneous rock suites are not well understood. Exploring unsampled regions of the Moon with robots and human explorers is required to address this deficiency. The chemistry of pristine highlands rocks (e.g., ferroan anorthosites) indicates that extensive melting occurred in the outermost part of the Moon, forming a silicate magma ocean. If such an ocean cooled and crystallized, the physical separation of crystals (the floating of lower-density plagioclase feldspar, following extensive crystallization of olivine and pyroxene at depth) produced the original lunar crust between 4.6 and 4.3 b.y. ago. Eventually late-stage cumulates, rich in Fe-bearing minerals including ferropyroxene and ilmenite ($FeTiO_3$) sank to form the source areas for high-Ti mare basalts. Negative Europium (Eu) anomalies (deficiencies) in mare basalts indicate that they formed by partial melting of these cumulates, which developed from the magma ocean after plagioclase (took up the Eu) crystallization.

Between the formation of the anorthositic crust (> 4.3 Ga) and the mare basalts (mostly < 3.8 Ga), another group of igneous rocks formed, including the Magnesian-suite (Mg-suite), and related, more chemically evolved rocks with KREEPy or alkali-rich compositions. The KREEPy rocks are highly enriched in potassium (K), rare earth elements (REE), and phosphorus (P). Both Mg-suite magmas and some mare basalt magmas seem to have been affected by KREEP, either as a component in their source area or as an assimilated component. Whereas the ferroan anorthosites appear to be flotation cumulates from solidification of the magma ocean, the Mg-suite rocks have the characteristics of layered mafic intrusive rock bodies, and their relationship to the ferroan anorthosites, geologic and petrologic, remains poorly understood. The Mg-suite rocks most likely formed by partial melting of magma-ocean-derived mantle cumulates that intruded and variably reacted with early crustal rocks. These ages are mostly ancient (> 4.0 Ga), but some samples have been dated that have considerably younger ages, extending their parent magmatic activity in some parts of the Moon to perhaps as young as 3.0 Ga. A volumetrically minor group of rock types known as the alkali suite (granite, alkali anorthosite, alkali norite, and monzogabbro) may be related to the Mg-suite by extreme fractionation of residual melts, but the sample set is too sparse to prove geologic relationships. KREEP-rich basalts may also be related to the Mg-suite rocks by similar parent magmas and lines of descent. What is not at all known is if the chemically and petrologically evolved KREEP-rich basalts and alkali-suite rocks exist only as small, insignificant late stage separations of residual melt, or if they actually form large intrusive or extrusive bodies in some parts of the Moon [e.g., *Hagerty et al*., 2006] These rock types, rich in silica and feldspar, including K-feldspar, and in some cases phosphates and rare Zr-Ti minerals, are not easily detected by remote sensing methods, but they may actually be concentrated in some locations, including the nonmare domes.

Exploring an area such as the Gruithuisen Domes, which possibly are formed of KREEPy or Mg-suite rocks [*Hagerty et al.*, 2006], could represent a major new discovery for lunar rock types, leading to a more complete picture of lunar magmatic evolution.

III. Nonmare Domes

Exploration and sample return from an area of nonmare domes would fulfill a number of lunar science objectives. Examples such as the Gruithuisen and Mairan domes present an entirely new facet of lunar volcanism, which remains undiscovered or only weakly hinted at in the current sample inventory (Apollo, Luna, and meteorites). Most of the inferences on the compositional and mineralogic character of nonmare domes come from remote sensing instruments.

The Gruithuisen and Mairan domes represent morphologically and spectrally distinct nonmare extrusive volcanic features most likely of Imbrian age [*Wagner et al.*, 2002]. Gruithuisen Gamma, Delta, and NW domes occur at the western edge of Mare Imbrium, south of Sinus Iridum. The three Mairan domes are located west of Mairan crater [see figures 1, 2]. This area is also within the Procellarum KREEP Terrane (PKT), notable for the abundance of thorium and other heat-producing elements that are concentrated in late-stage melts [*Jolliff et al.*, 2000]. The presence of domes in the PKT hints a possible connection between these features and KREEPy rock chemistries or thorium. The morphology of the domes is consistent with silicic nonmare volcanic constructions [*Chevrel et al.*, 1999; *Wilson and Head*, 2003].

These domes are also members of a group of nonmare features known as red spots [*Whitaker*, 1972; *Malin*, 1974; *Head and McCord*, 1978; *Bruno et al.*, 1991]. Red spots are spectral anomalies on the near side of the Moon characterized by high albedo and strong ultraviolet absorption, which does not match spectral characteristics of common lunar samples [*Head and McCord*, 1978]. Figure 3 from Hagerty et al. [2006] shows the locations of multiple red spots. Red spots like the Gruithuisen Domes were produced by volcanism and suggest a connection with KREEPy basalts or even more evolved highlands compositions such as dacite or rhyolite [*Malin*, 1974; *Wood and Head*, 1975; *Head and McCord*, 1978; *Raitala et al.*, 1999; *Hagerty et al.*, 2006]. Red spots could be surface manifestations of pre-mare KREEP basalts [*Malin*, 1974]. In recent years, major controversies have been associated with highlands volcanism, the origin of KREEP, and the nature of red spots [*Raitala et al.*, 1999; *Hawke et al.*, 2001; *Chevrel et al.*, 1999; *Hagerty et al.*, 2006]. Many questions remain unanswered. A sample collected robotically from material excavated by impact craters on one of these domes would settle questions of their age, lithology, and origin, including their relationships to other major lunar rock types. Example science objectives for a mission to the Gruithuisen Domes include: a) unambiguous determination of the composition of the domes, b) identifying and measuring the distribution of any KREEP- and thorium-rich materials, c) placing materials in context with genetically related lithologies, and d) collecting samples for age dating of key units to investigate the geologic evolution of the region in which they are located.

Samples returned from the lunar domes will offer further clues in the story of lunar evolution and modifications to the LMO model. A high priority science objective from the SCEM study is to “determine the extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.” It is thought that lunar domes may be the result of extreme differentiation in the lunar crust or partial melting of compositionally evolved crust. The full extent of the distribution of the lunar dome rock type(s) is unknown, as are the ages, and origin. The rocks present in the lunar domes may lead to new conclusions about the lower crust of the Moon, and returned samples would help constrain our current estimates on the complexity of the lunar crust. Our understanding of the lunar crust will contain a deficit of knowledge until questions about the variety, age, distribution, and origin of rock types in the lunar domes are answered.

Within the lunar sample inventory there are silicic volcanic or intrusive materials that may be similar to the Gruithuisen Domes, but they are rare and only occur as small fragments of granite or felsite [*Jolliff*, 1991, 1998; *Korotev*, 1998; *Papike et al.*, 1998] and thus their provenance is unknown. Some of these samples have Th concentrations as high as 50-60 ppm. Spatial deconvolution of Lunar Prospector gamma-ray Th data of Gruithuisen Domes permit Th values that match the high measured sample concentrations [*Hagerty et al.*, 2006]. Knowledge of the petrogenesis of these rare fragments will be incomplete until the geologic setting of their origins is known.

IV. Conclusion

A sample return mission from a nonmare dome would fulfill many of the scientific objectives set out by the SCEM report. Sites for robotic and human exploration must be “science objective-driven” and explore poorly known areas. Instruments such as the Lunar Reconnaissance Orbiter

Camera will be returning images from thousands of geologically interesting lunar sites, which can be used for engineering analysis and in planning either a robotic sample return mission or a human return to the Moon. With either mission architecture we will be able to answer basic questions of lunar volcanism, but the different mission options offer a range of detail in the knowledge we will be able to obtain. Flexibility and innovation will work hand in hand to bring a sample return mission plan through to fruition, execution, and finally scientific results.

Figures

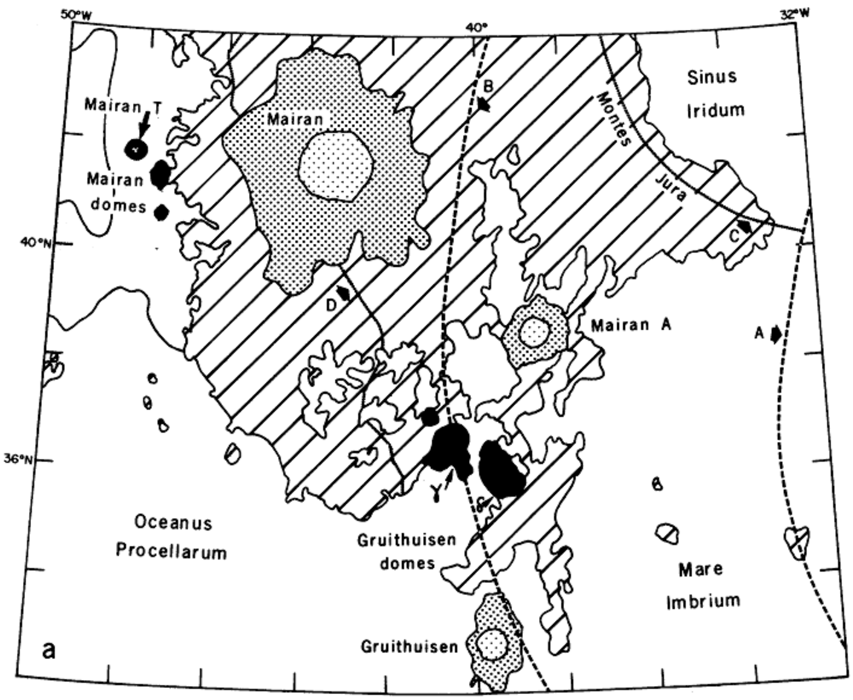

Figure 1. Location of the Gruithuisen and Mairan domes. From *Head and McCord*, 1978.

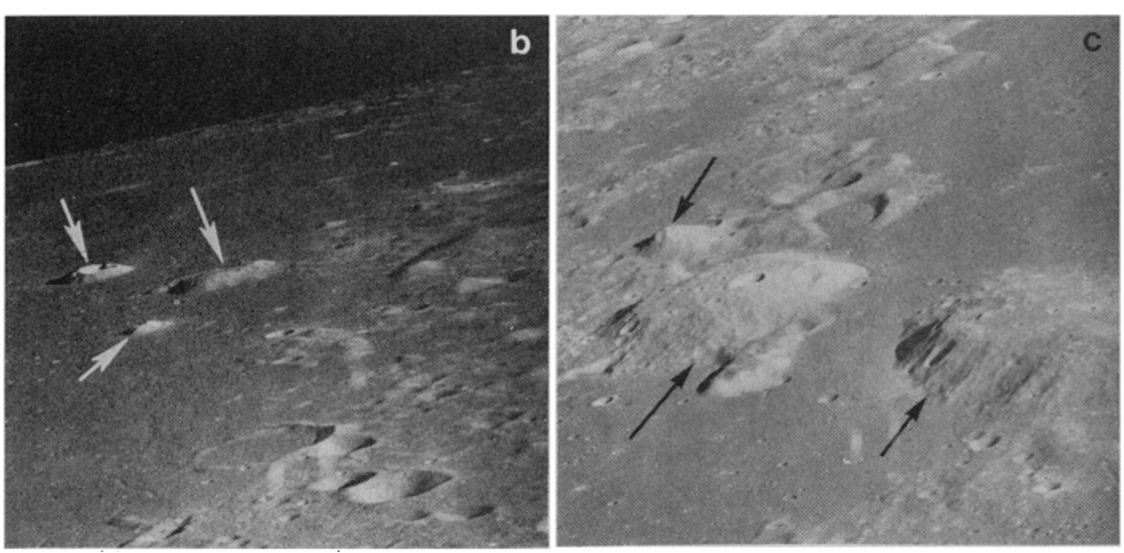

Figure 2. Left image shows Mairan dome (Apollo 15 image AS15-12730). The leftmost arrow is Mairan T, approximately 7 km in diameter and over 900 meters high. The right image shows Gruithuisen Domes, including the smaller northwest dome (Apollo 15 image AS15-12718). The smallest dome is known as “northwest” (NW) and is roughly circular, about 8 km in diameter and over 1100 m in height. Gruithuisen γ has a flat top and is about 20 km in diameter and over 1200 m in elevation. Gruithuisen δ is to the right, also with a flat top, and over 1500 m in height. From *Head and McCord*, 1978.

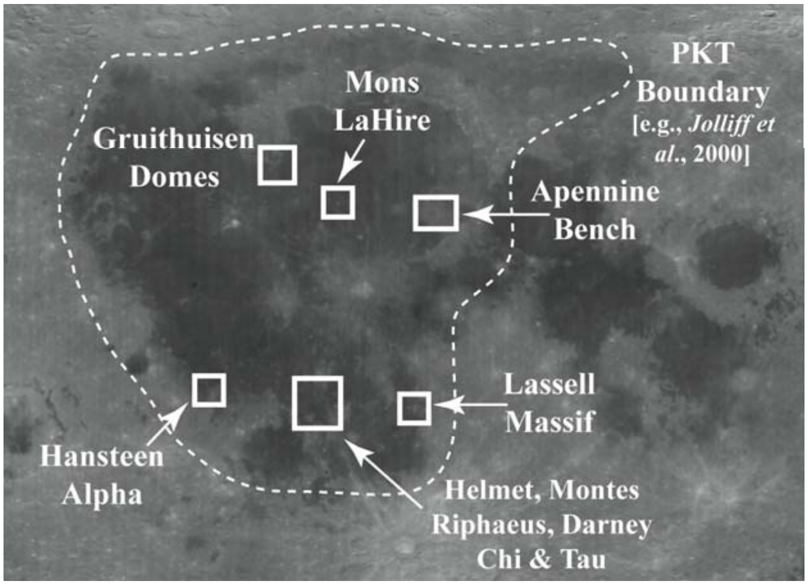

Figure 3. Locations of several near side red spot anomalies within the Procellarum KREEP Terrane. From *Hagerty, et al.*, 2006.

References

Bruno, B. C., P. G. Lucey, and B. R. Hawke (1991), High resolution UV-visible spectroscopy of lunar red spots, Proc. Lunar Planet. Sci. Conf. 21St, 405–415.

Chevrel, S. D., P. C. Pinct, and J. W. Head (1999), Gruithuisen domes region: A candidate for an extended nonmare volcanism unit on the Moon, J. Geophys. Res., 104(E7), 16,515–16,529.

Giguere, T., Taylor, G. J., Hawke, B. R., and Lucey, P. G. (2000), The titanium contents of lunar mare basalts. Meteoritics and Planetary Science, 35, p. 193-200.

Hagerty, J.J., Lawrence, D.J., Hawke, B.R., Vaniman, D.T., Elphic, R.C., Feldman, W.C. (2006), Refined thorium abundances for lunar red spots: Implications for evolved, nonmare volcanism on the Moon. J. Geophys. Res., 111, E06002, doi:10.1029/2005JE002592.

Hawke, B. R., D. T. Blewett, P. G. Lucey, G. A. Smith, G. J. Taylor, D. J. Lawrence, and P. D. Spudis (2001), Remote sensing studies of selected spectral anomalies on the Moon, Lunar Planet. Sci. [CD-ROM], XXXII, abstract 1249.

Head J. W. (1976), Lunar volcanism in space and time. Rev. Geophys. Space Phys., 14, 265–300.

Head, J.W., McCord, T.B. (1978), Imbrian-Age Highland Volcanism on the Moon: The Gruithuisen and Mairan Domes. Science 199, 1433-1436.
Heiken, G.H., et al., eds. (1991), The Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press.
Jolliff, B. L. (1991), Fragments of quartz monzodiorite and felsite in Apollo 14 soil particles, Proc. Lunar Planet. Sci. Conf. 21st, 101– 118.
Jolliff, B. L. (1998), Large-scale separation of K-frac and REEP-frac in the source regions of Apollo impact-melt breccias and a revised estimate of the KREEP composition, Int. Geol. Rev., 40, 916– 935.
Jolliff, B. L., J. J. Gillis, L. A. Haskin, R. L. Korotev, and M. A. Wieczorek (2000), Major lunar crustal terranes: Surface expressions and crust-mantle origins, J. Geophys. Res., 105(E2), 4197– 4216.
Korotev, R. L. (1998), Concentration of radioactive elements in lunar materials, J. Geophys. Res., 103(E1), 1691– 1701.
Malin, M. C. (1974), Lunar red spots: Possible pre-mare materials, Earth Planet. Sci. Lett., 21, 331– 341.
NASA/LPI (1999), Once and Future Moon. LPI Contribution No. 974.
National Research Council (2007), The Scientific Context for Exploration of the Moon.
Papike, J. J., G. Ryder, and C. K. Shearer (1998), Lunar samples, Rev. Mineral., 36, 5-1–5-189.
Raitala, J., M. A. Kreslavsky, Y. G. Shkuratov, L. V. Starukhina, and V. G. Kaydash (1999), Nonmare volcanism on the Moon: Characteristics from the Clementine data, Lunar Planet. Sci. [CD-ROM], XXX, abstract 1457.
Shearer CK, Papike JJ (1999) Magmatic evolution of the Moon. Am Mineral 84:1469-1494
Shearer, C.K. et al.(2006) Thermal and Magmatic Evolution of the Moon. Chapter 4, pages 365-518. In: Jolliff, B.L., et al., eds. (2006), New Views of the Moon, Rev. Min. Geochem., 60, 1-704.
Spudis, P.D. (1996), The Once and Future Moon, Smithsonian Institution Press
Wagner, R., J. W. Head, U. Wolf, and G. Neukum (2002), Stratigraphic sequences and ages of volcanic units in the Gruithuisen region of the Moon, J. Geophys. Res., 107(E11), 5104, doi:10.1029/2002JE001844.
Warren P. H. (1985), The magma ocean concept and lunar evolution. Annu. Rev. Earth Planet. Sci., 13, 201–240.
Whitaker, E. A. (1972a), Lunar color boundaries and their relationship to topographic features: A preliminary survey, Moon, 4, 348– 355.
Wilhelms, D.E. (1987), The Geologic History of the Moon, USGS Prof. Paper 1348.
Wilson, L., and J. W. Head (2003), Lunar Gruithuisen and Mairan domes: Rheology and mode of emplacement, J. Geophys. Res., 108(E2), 5012, doi:10.1029/2002JE001909.
Wood, C. A., and J. W. Head (1975), Geologic setting and provenance of spectrally distinct pre-mare material of possible volcanic origin, paper presented at Conference on Origins of Mare Basalts, Lunar Sci. Inst., Houston, Tex.