SAMPLING THE AGE EXTREMES OF LUNAR VOLCANISM: THE YOUNGEST AND OLDEST LUNAR BASALTS

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SUMMARY

Understanding the timing and compositional range of basalts on the lunar surface is vital for interpreting the origin and geologic evolution of the terrestrial planets. Here, we discuss the importance of automated sample return missions to the mare basalts considered to be the youngest (Procellarum) and oldest (cryptomaria) on the lunar surface. These targets can be easily sampled using automated sample return missions to help improve our absolute chronology for the inner Solar System by providing the timing for the beginning and end of lunar basaltic volcanism. Sampling these basaltic materials can be cost-effectively performed using small spacecraft missions in a manner which complements future human exploration.

INTRODUCTION

As outlined in numerous documents over the past four decades (e.g., Taylor and Spudis 1990), the Moon plays a key role in planetary science, providing a unique window into Solar System history and preserving ancient processes that have been erased on the Earth and Venus, and largely erased on Mars. The Moon's origin is intimately connected with that of Earth. The Moon preserves a record of the early impact rate and a detailed record of its early evolution. The Moon is the only extraterrestrial body from which we have samples from known locations, providing a more quantitative understanding of its history. There remain many unanswered questions. For example, we do not know the details of the Moon's early igneous history, a key period in the history of all the solid planets. We do not know the full compositional and age ranges of lunar volcanic rocks, so we lack vital information about the mantle and thermal history of the Moon, which hinders our understanding of terrestrial planet formation. We do not know the full range of compositional variations in the crust, and we know even less about the bulk composition of the lunar mantle.

Automated landers similar to the Soviet Luna 24 spacecraft can be sent to specific locations to return samples for analysis to address these questions. Such missions can be executed for a relatively low cost compared to other planetary missions, yet still address key questions. Precursor sample return missions could complement future human lunar exploration by addressing science questions that do not require the flexibility and capability of human explorers, as well as possibly prospecting for useful resources (NASA 2005; NASA Advisory Council 2007). *Here, we advocate executing low-cost automated sample return missions to the oldest (the cryptomaria) and youngest (Procellarum) lunar basalts in order to answer key questions about the origin and evolution of the Moon and the rest of the terrestrial planets.*

RELEVANCE TO COMMUNITY OBJECTIVES

Sampling the oldest and youngest lunar basalts is directly responsive to several science goals outlined in the 2007 National Research Council Report on the Scientific Context for the Exploration of the Moon, especially Goal 5b: Determine the age of the youngest and oldest mare basalts (Space Studies Board 2007). Sample return from the oldest and youngest lunar basalts is also relevant to other goals established in that report, including:

1b: Establish a precise absolute chronology for the Moon;
2d: Characterize the thermal state of the interior and elucidate the workings of the planetary heat engine;
3d: Quantify the local and regional complexity of the current lunar crust;
5a: Determine the origin and variability of lunar basalts; and
5d: Determine the flux of lunar volcanism and its evolution through space and time

NOTIONAL MISSION STRATEGY

Figure 1. Artist's concept of sample return mission lifting off from the lunar surface with its precious cargo.

For the purposes of this white paper we advocate automated lunar sample return missions functionally similar to the Soviet Luna 24 mission. The Moon's proximity to Earth makes this kind of focused "grab-and-go" lunar sample return mission both feasible and scientifically productive. To reduce cost, our spacecraft would consist solely of a single landed spacecraft element with sampling capabilities and a sample return system. The spacecraft would be minimally instrumented, foregoing most in-situ analyses. After landing, a robotic arm would automatically collect and store a scoop of bulk regolith, then collect a kilogram of 1 - 4 cm rocks by raking. Following collection, the samples would be returned to Earth (Figure 1). The mission duration would be less than a lunar day; no long-duration survival for the landed element is contemplated.

THE IMPORTANCE OF SAMPLE RETURN

Experience demonstrates the importance of returning planetary samples to Earth (e.g., Taylor et al. 1991). To achieve the important science objectives discussed here, detailed analyses of chemical and isotopic compositions, mineralogy, rock textures, and physical properties are required. While important measurements could be made using in-situ instrumentation, terrestrial laboratories will offer more capability for the foreseeable future. In addition, collected samples become resources that can be utilized for years, so new measurements can be made as analytical techniques improve. For a sample return mission to be successful, NASA and the science community must maintain key capabilities, including lunar sample curation, lunar remote sensing data analysis, and appropriately-equipped laboratories staffed with experienced planetary scientists. Sample return missions will also play an important complementary role towards human lunar return by giving the next generation of lunar scientists experience analyzing new lunar samples before the seventh human lunar landing, as most Apollo-era veterans will probably be inactive by the middle of the next decade.

SCIENTIFIC BACKGROUND

Mare basalts cover about 17% of the lunar surface, primarily filling topographic lows on the nearside (Head 1976). Since lunar basalts formed through partial melting of the mantle, they are the only direct window into the composition of the interior. Mare basalt classification is based on three distinguishing geochemical indices (Ti, Al, and K), which also reflect crystal fractionation trends in an evolving magma (Neal and Taylor 1992). However, workers analyzing remote sensing datasets have shown that the full range of mare basalt composition and ages has not yet been sampled (Giguere et al. 2000; Hiesinger et al. 2003), and additional samples are required. Knowledge of the duration of mare volcanism comes from (a) radiometric dating of meteorites and samples from the Apollo and Luna missions, and (b) crater counting statistics of mare surfaces from remote sensing data. Mare volcanism reached its maximum volumetric output between 3.8 and 3.2 Ga (Shearer and Papike 1999), but began as early as 4.3 Ga (Taylor et al. 1983; Dasch et al. 1987; Shih and Nyquist 1989a, b) and may have persisted until as recently as 1.2 Ga (Schultz and Spudis 1983; Hiesinger et al. 2003). The uncertainty associated with these timing estimates requires clarification, not only to improve our understanding of lunar geology, but facilitate interpretation of all terrestrial planet geology.

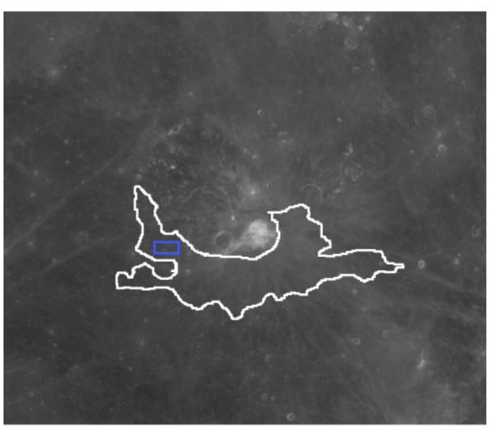

Figure 2. Image showing the P60 area of Hiesinger et al., 2003, along with the crater counting region used to derive the model basalt age (in blue). Collection of basalts from this region would provide a much-needed calibration of crater-derived age dates.

SAMPLING TARGET: THE YOUNGEST PROCELLARUM BASALTS

It has long been recognized that some of the basalt flows on the Moon might have formed more recently than the youngest Apollo basalts (Schultz and Spudis 1983). Hiesinger et al. (2003) mapped 60 spectrally homogenous basalt units in Oceanus Procellarum. Using crater counting methods, they determined that five of these units have model ages ranging from ~1.5-1.20 Ga. Unit P60 (Figure 2) is the most interesting. Directly south of the Aristarchus Plateau, Unit P60 has the youngest model age (1.20 Ga) of all the basalt units in Oceanus Procellarum. The nearside location makes this an ideal location for an automated sample return.

SAMPLING TARGET: CRYPTOMARIA

The oldest mare basalts, cryptomaria, are basalt deposits that were subsequently buried by highlands materials of higher albedo by basin-forming events (Head and Wilson 1992). Numerous workers have studied cryptomare using remotely sensed data (Schultz and Spudis 1979; Hawke and Bell 1981; Davis and Spudis 1985, 1987; Head and Wilson 1992; Giguere et al. 2003; Hawke et al. 2004, 2005; Lawrence et al. 2008; Blewett et al. 1995; Bell and Hawke 1984). In the current lunar sample collection, the oldest basalts are from the Apollo 14 site, dated at 4.3 Ga±0.1 (Taylor et al. 1983; Dasch et al. 1987; Shih and Nyquist 1989a, b). More recently, it has been suggested that the lunar meteorite Kalahari 009, which is a very-low-Ti mare-basalt breccia dated to 4.35±0.15 Ga, is from a cryptomare (Terada et al. 2007; Sokol et al. 2008).

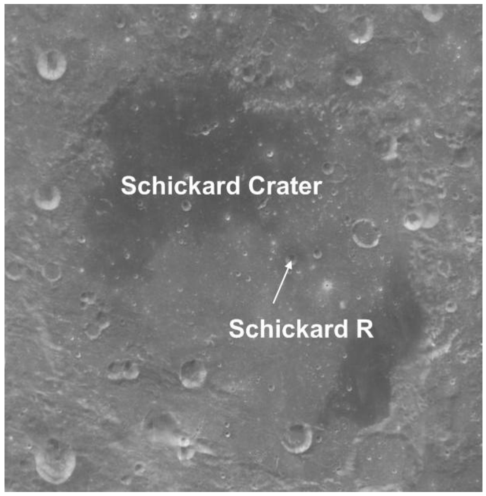

Figure 3. Clementine 750nm mosaic showing the position of Schickard R crater. Schickard R would be an ideal location to collect a sample using an automated reconnaissance sample return mission; its nearside location eliminates the need for a relay satellite.

The Schiller-Schickard Region contains several enigmatic features that have long been the subject of interest and debate (Schultz and Spudis 1979, 1983; Hawke and Bell 1981; Bell and Hawke 1984; Head et al. 1993; Blewett et al. 1995; Antonenko et al. 1995; Antonenko and Yingst 2002). In addition to containing the highest density of dark-haloed impact craters, other peculiarities of the region include Orientale secondary craters, and the crater Wargentin, the floor of which is topographically higher than the surrounding terrain. Utilizing an automated sample return spacecraft to collect a sample from a nearside dark halo crater such as Schickard R (Figure 3) would result in a contextualized sample from a known cryptomare surface, providing an important calibration of age dating and important geochemical information about the early lunar mantle.

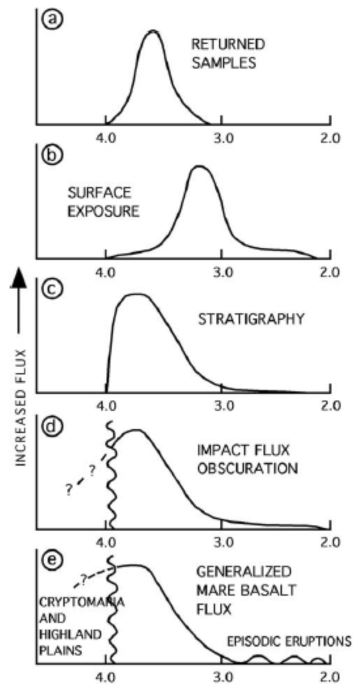

Figure 4. Notional schematic diagram reproduced from Head and Wilson (1992). Sampling the oldest and youngest lunar basalts would provide important information to more accurately constrain these models.

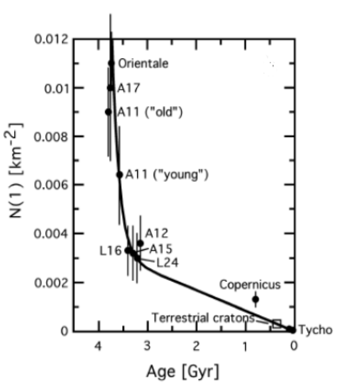

Figure 5. Radiometric age dates as a function of cratering density, reproduced from Stöffler et al. (2006). Sampling the youngest and oldest lunar basalts will provide more data points and a much-needed absolute age calibration for all of the terrestrial planets (© Mineralogical Society of America)

IMPLICATIONS

Collecting samples of these extremes of lunar basaltic volcanism offers a low-risk, high-reward pathway to address important questions in planetary science, including understanding the lunar interior, understanding the flux of mare volcanism, and improving the absolute chronology for the Moon.

UNDERSTANDING THE LUNAR INTERIOR

Mare basalts originate through partial melting in the Moon's mantle. The basaltic Apollo samples and lunar meteorites only sample a limited range of lunar basalt compositions and ages, which limits our understanding of the lunar interior and the full extent in space, time, and composition of lunar basaltic volcanism. Returning samples from the oldest and youngest lunar basalts would increase our knowledge about isotopic and trace element variations in lunar basalts, and in principle would help to distinguish prospective differences in basalt source regions/reservoirs over time.

UNDERSTANDING THE FLUX OF MARE VOLCANISM

An important measure of the thermal history of a planetary body is the rate of lava eruption and its change with time. Our knowledge of this parameter for the Moon is limited. Age determinations of samples from the maria indicate that most mare volcanism took place between 3.7 and 3.1 Ga, but photogeologic evidence suggests that volcanism may have begun as early as 4.3 Ga and continued to as recently as 1.2 Ga (Figure 4). The characterization of the oldest and youngest mare basalts would help to unravel how eruption rates varied with time.

IMPROVE THE ABSOLUTE CHRONOLOGY FOR THE MOON

The fieldwork and samples from the Apollo and Luna missions yielded an absolute chronology which has been extended to the rest of Solar System (Stöffler and Ryder 2001; Stöffler et al. 2006; Neukum et al. 2001; Hartmann and Neukum 2001; Hartmann et al. 2000). Collecting samples from the notionally oldest and youngest mare basalts will have important ramifications for planetary science (Crawford et al. 2007; Space Studies Board 2007). Current cratering flux calibration curves for the Moon are anchored by dates from mare surfaces near Apollo landing sites (3.8-3.2 Ga) with very few young dates to establish the more recent (<2 Ga) cratering flux (Figure 5). For example, if the Procellarum samples have older or younger absolute ages than expected, then we would get a new calibration that would significantly alter or improve knowledge of surface ages on the Moon and other terrestrial planets.

SUMMARY

Returning samples from the temporal extremes of lunar basalts will provide key constraints on important questions in lunar and planetary science. Robotic sample return missions provide the ability to sample locations on the Moon in advance of future human exploration.

REFERENCES

Antonenko I, Yingst RA (2002) Mare and Cryptomare Deposits in the Schickard Region of the Moon: New Measurements Using Clementine FeO Data. In: Lun. Plan. Sci. Conf. XXXIII. Lunar and Planetary Institute, Houston, TX, abstract 1438.

Antonenko I, Head JW, Mustard JF, Hawke BR (1995) Criteria for the Detection of Lunar Cryptomaria. Earth Moon Planets 69:141-172.

Bell JF, Hawke BR (1984) Lunar Dark-Haloed Impact Craters: Origin and Implications for Early Mare Volcanism. J. Geophys. Res. 89:6899-6910.

Blewett DT, Hawke BR, Lucey PG, Taylor GJ, Jaumann R, Spudis PD (1995) Remote sensing and geologic studies of the Schiller-Schickard region of the Moon. J. Geophys. Res. 100:16959-16978.

Crawford IA, Joy KH, Fagents SA (2007) Full Moon exploration. Astron. Geophys. 48:3.18-3.21.

Dasch E, Shih C, Bansal B, Wiesmann H, Nyquist L (1987) Isotopic analysis of basaltic fragments from lunar breccia 14321: Chronology and petrogenesis of pre-Imbrium mare volcanism. Geochim. Cosmochim. Acta 51:3241-3254.

Davis PA, Spudis PD (1985) Petrologic province maps of the lunar highlands derived from orbital geochemical data. In: Proc. Lun. Plan. Sci. Conf. 16. Houston, TX, p 61.

Davis PA, Spudis PD (1987) Global petrologic variations on the moon - A ternary-diagram approach. J. Geophys. Res. 92:387.

Giguere TA, Hawke BR, Blewett DT, Bussey DBJ, Lucey PG, Smith GA, Spudis PD, Taylor GJ (2003) Remote Sensing Studies of the Lomonosov-Fleming Region of the Moon. J. Geophys. Res. 108:CiteID 5118.

Giguere TA, Taylor GJ, Hawke BR, Lucey PG (2000) The titanium contents of lunar mare basalts. Meteorit. Planet. Sci. 35:193-200.

Hartmann WK, Ryder G, Dones L, Grinspoon D (2000) The Time-Dependent Intense Bombardment of the Primordial Earth/Moon System. In: Canup RM, Righter K (eds) Origin of the earth and moon. University of Arizona Press, Tucson, AZ, pp 493-512.

Hartmann WK, Neukum G (2001) Cratering Chronology and the Evolution of Mars. Space Science Reviews 96:165-194.

Hawke BR, Bell JF (1981) Remote sensing studies of lunar dark-halo impact craters - Preliminary results and implications for early volcanism. In: Proc. Lun. Plan. Sci. Conf. 12. pp 665-678.

Hawke BR, Gillis JJ, Giguere TA, Blewett DT, Lawrence DJ, Lucey PG, Smith GA, Spudis PD, Taylor GJ (2004) Remote Sensing and Geologic Studies of the Balmer Region of the Moon. In: Lun. Plan. Sci. Conf. XXXV. p 1190.

Hawke BR, Gillis JJ, Giguere TA, Blewett DT, Lawrence DJ, Lucey PG, Smith GA, Spudis PD, Taylor GJ (2005) Remote sensing and geologic studies of the Balmer-Kapteyn region of the Moon. J. Geophys. Res. 110:E06004.
Head JW (1976) Lunar volcanism in space and time. Rev. Geophys. 14:265-300.
Head JW, Murchie S, Mustard JF, Pieters CM, Neukum G, McEwen A, Greeley R, Nagel E, Belton MJS (1993) Lunar impact basins: New data for the western limb and far side (Orientale and South Pole-Aitken basins) from the first Galileo flyby. J. Geophys. Res. 98:17149-17182.
Head JW, Wilson L (1992) Lunar mare volcanism - Stratigraphy, eruption conditions, and the evolution of secondary crusts. Geochim. Cosmochim. Acta 56:2155-2175.
Hiesinger H, Head JW, Wolf U, Jaumann R, Neukem G (2003) Ages and stratigraphy of mare basalts in Oceanus Procellarum, Mare Nubium, Mare Cognitum, and Mare Insularum. J. Geophys. Res. 108:5065.
Lawrence SJ, Hawke BR, Gillis-Davis JJ, Taylor GJ, Lawrence DJ, Cahill JT, Hagerty JJ, Lucey PG, Smith GA, Keil K (2008) Composition and origin of the Dewar geochemical anomaly. J. Geophys. Res. 113:02001.
NASA (2005) Exploration Systems Architecture Study. NASA-TM-2005-214062.
NASA Advisory Council (2007) Workshop on Science Associated with the Lunar Exploration Architecture. NASA, Tempe, AZ.
Neal CR, Taylor LA (1992) Petrogenesis of mare basalts: A record of lunar volcanism. Geochimica et Cosmochimica Acta 56:2177-2211.
Neukum G, Ivanov B, Hartmann W (2001) Cratering Records in the Inner Solar System in Relation to the Lunar Reference System. Space Science Reviews 96:55-86.
Schultz PH, Spudis PD (1979) Evidence for ancient mare volcanism. In: Proc. Lun. Plan. Sci. Conf. 10. Pergamon Press, Inc., Houston, TX, pp 2899-2918.
Schultz PH, Spudis PD (1983) Beginning and end of lunar mare volcanism. Nature 302:233-236.
Shearer CK, Papike JJ (1999) Magmatic evolution of the Moon. American Mineralogist 84:1469-1494.
Shih C, Nyquist LE (1989a) Isotopic Constraints on the Petrogenesis of Apollo 14 Igneous Rocks. In: Workshop on the Moon in Transistion: Apollo 14, KREEP, and Evolved Lunar Rocks. Lunar and Planetary Institute, Houston, TX, p 128.
Shih C, Nyquist LE (1989b) Isotopic and Chemical Constraints on Models of Aluminous Mare Basalt Genesis. In: Lunar and Planetary Institute Science Conference Abstracts. p 1002.
Sokol A, Fernandes V, Schulz T, Bischoff A, Burgess R, Clayton R, Münker C, Nishiizumi K, Palme H, Schultz L, Weckwerth G, Mezger K, Horstmann M (2008) Geochemistry, petrology and ages of the lunar meteorites Kalahari 008 and 009: New constraints on early lunar evolution. Geochim. Cosmochim. Acta 72:4845-4873.
Space Studies Board NRC (2007) The Scientific Context for Exploration of the Moon: Final Report. The National Academy Press, Washington, DC.
Stöffler D, Ryder G (2001) Stratigraphy and Isotope Ages of Lunar Geologic Units: Chronological Standard for the Inner Solar System. Space Sci. Rev. 96:9-54.
Stöffler D, Ryder G, Ivanov BA, Artemieva NA, Cintala MJ, Grieve RAF (2006) Cratering History and Lunar Chronology. Rev. Min. Geochem. 60:519-596.
Taylor GJ, Warren P, Ryder G, Delano J, Pieters CM, Lofgren G (1991) Lunar Rocks. In: Heiken GH, Vaniman DT, French BM (eds) Lunar Sourcebook. Cambridge University Press, Cambridge, pp 183-284.
Taylor GJ, Spudis PD (1990) Geoscience and a Lunar Base: A Comprehensive Plan for Lunar Exploration. NASA Conference Publication 3070.
Taylor LA, Shervais JW, Hunter RH, Shih C, Bansal B, Wooden J, Nyquist L, Laul L (1983) Pre-4.2 AE mare-basalt volcanism in the lunar highlands. Earth and Planetary Science Letters 66:33-47.
Terada K, Anand M, Sokol AK, Bischoff A, Sano Y (2007) Cryptomare magmatism 4.35 Gyr ago recorded in lunar meteorite Kalahari 009. Nature 450:849-852.