MISSION OPTIONS TO EXPLORE THE FLUX AND EVOLUTION OF LUNAR VOLCANISM THROUGH SPACE AND TIME. T. Lough,[1] J. Korteniemi,[2] D. L. Eldridge,[3] K. Singer,[4] L. Werblin,[5] and D. A. Kring[6], [1]University at Buffalo, Buffalo, NY (talough@buffalo.edu), [2]Astronomy, Department of Physics, University of Oulu, Finland,[3]University of Colorado at Boulder, CO, [4]Planetary Geoscience Institute, University of Tennessee, Knoxville, TN, [5]Mount Holyoke College, South Hadley, MA, [6]Lunar and Planetary Institute, Houston, TX.

Introduction: One of the eight critical concepts the NRC identified for future lunar exploration [1] is that 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 [2].

Thus far, it appears lunar mare volcanism peaked in the upper Imbrian, producing about 9.3×10^6 km^3 of lava at an average rate of 0.015 km^3/yr [3]. During the Eratosthenian and Copernican periods, the rate of volcanism decreased to about 1.3×10^{-4} km^3/yr and 2.4×10^{-6} km^3/yr respectively [3]. 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 [3] 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 [4].

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 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 [5, 6]. 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 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., *7-10*]. As higher-resolution data becomes available, flow margins should be reexamined and refined.

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., 11-13]. 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 deposits represent some of the oldest volcanic deposits on the Moon and remain largely, if not entirely, unsampled [4]. 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 (DHIC). 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 DHIC will provide new information about the volcanic flux. Those in pre-Nectarian plains have the highest priority.

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., 14] and re-evaluated with high-resolution compositional data from current and upcoming missions (e.g., M^3 on Chandryaan-1).

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 CSFD.

Example Landing Sites. We used the above criteria to identify four example landing sites. We created maps of these landing sites in ArcGIS using Lunar Orbiter, Clementine, and Lunar Prospector data. The four landing sites are listed below.

Buch B crater (~38˚S, 17˚W) is an example of a crater that may expose a basaltic dike [15]. 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 propogates to the surface, or stalls in the crust.

Carlini Crater (33.7˚N, 24.1˚W) 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., 16- 18].

Lomonosov region (~24˚N, ~109˚E) contains two proposed DHICs that contain exposed pre-Nectarian cryptomaria [19]. Because these two DHICs 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.

Apollo Crater (70˚S, 172˚W) 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 unammed 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.

Summary: Landing sites that can addres lunar volcanic flux should contain 1) exposures of volcanic plumbing 2) accessible craters that penetrate multiple volcanic units 3) craters that penetrate through volcanic units into highland material 4) exposed cryptomaria and/or 5) unsampled rock compositions identified through remote sensing. Although locations that satisfy a maximum number of the above criteria provide the most information, any new volcanic sample will provide useful information.

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References: [1] NRC (2007) *The Scientific Context for Exploration of the Moon: Final Report*, http://www.nap.edu/catalog/11954.html, 120pp. [2] Shearer and Papike (1999) *Amer. Min., 84,* 1469-1494. [3] Hiesinger and Head (2006) *Rev. Min. Geochem.*, *60*, 1-67. [4] Shearer et al. (2006) *Review. Min. Geochem., 60,* 365-469. [5] Pike (1977) *Proc. Symp. Plan. Crat. Mech. 489-509.* [6] Carter et al., (1980) *Wear, 65,* 151-172. [7] Neukum, et al. (1975) *Moon, 12,* 2051-229. [8] Hartmann et al. (1981) *Basaltic Volcanism on the Terrestrial Planets,* 1,049-1,128. [9] Stöffler et al. (2006) *Rev. Min. Geochem.*, *60*, 519-596. [10] Hiesinger et al (2000) *JGR, 105*, 29,239-29,275. [11] Head (1976) *Rev. Geophys. Space Phys., 14,* 265-300. [12] Yingst, A. and J. Head (1997) *JGR*, *104*, 10,909-10,9301. [13] M. Wieczorek et al. (2006) *Review. Min. Geochem., 60,* 221-343. [14] Lucey et al. (2006) *Review. Min. Geochem., 60,* 83-220. [15] Hawke et al. (2002) *JGR, 107,* E12, doi:10.1029/-2000JE001494 [16] DeHon (1974) *Proc. Lunar Sci. Conf.5*, 53-59. [17] Hörz (1978) *Proc. Lunar Planet. Sci. Conf. 9*, 3311-3331. [18] Head (1982) *Moon Plan., 26,* 61-88. [19] Giguere et al. (2003) *JGR, 108*, E11, doi:10.1029/2003JE002069.