A MULTI-DECADAL SAMPLE RETURN CAMPAIGN WILL ADVANCE LUNAR AND SOLAR SYSTEM SCIENCE AND EXPLORATION BY 2050.

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Introduction: There have been 11 missions to the Moon this century, 10 of which have been orbital, from 5 different space agencies. China became the third country to successfully soft-land on the Moon in 2013, and the second to successfully remotely operate a rover on the lunar surface [1]. We now have significant global datasets that, coupled with the 1990s Clementine and Lunar Prospector missions, show that the sample collection is not representative of the lithologies present on the Moon [2]. The M^3 data from the Indian Chandrayaan-1 mission have identified lithologies that are not present/under-represented in the sample collection [3,4]. LRO datasets show that volcanism could be as young as 100 Ma [5] and that significant felsic complexes exist within the lunar crust [6]. A multi-decadal sample return campaign is the next logical step in advancing our understanding of lunar origin and evolution and Solar System processes.

Current Decadal Survey (DS) [7]: South Pole-Aitken (SPA) Basin Sample Return has been a named New Frontiers class mission in the last two DSs [7,8]. [7] also states (p. 133) "*Other important science to be addressed by future missions include the nature of polar volatiles, the significance of recent lunar activity at potential surface vent sites, and the reconstruction of both the thermal-tectonic-magmatic evolution of the Moon and the impact history of the inner Solar System through the exploration of better characterized and newly revealed lunar terrains. Such missions may include orbiters, landers, **and sample return***." It is difficult to conduct a lunar sample return mission under the current Discovery cost cap; international cooperation and/or commercial partnersips are ways to propose a Discovery nearside lunar sample return.

Sample Return Targets: Given the wealth of orbital information now available for the Moon, we can propose targeted sample return missions beyond what is outlined in [7]. Multiple nearside and farside targets are proposed (**Fig. 1a,b**). Note that these locations are examples of locations for the the types of samples that would greatly advance our understanding of the Moon *and* the inner Solar System. **Figure 1** is not meant to be an all-inclusive compilation of potential sample return sites. These sites will need to be adjusted on the basis of landing safety, accessibility, etc. Here, science is the only driver for these locations.

Spinel- and Olivine/Orthopyroxene-rich lithologies were discovered using M^3 data [3,4]. These are not well represented in the current sample collection (Apollo and Luna, as well as lunar meteorites), although a small clast in ALHA81005 is spinel-rich [9]. Such lithologies are vital for understanding the composition of the lunar crust and possibly the upper mantle, and to test the lunar magma ocean (LMO) hypothesis.

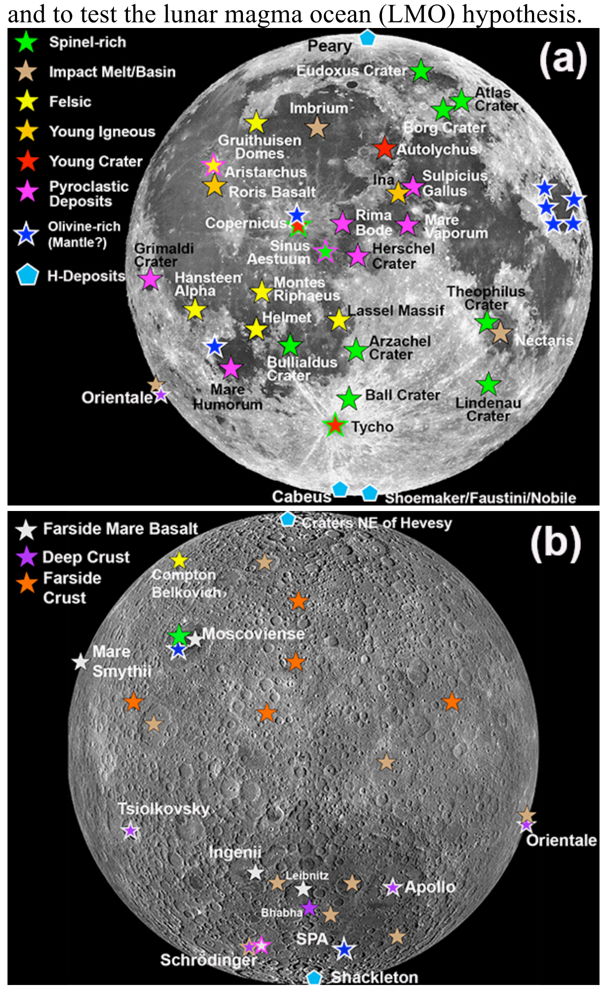

Figure 1: Examples of sample return locations: (a) nearside, (b) farside. Where >1 sample type can be obtained from a single site, symbols = multiple colors.

The locations for "**Impact Melt/Basin**" are intended to represent returning impact melts from such basins to constrain the impact history of the inner Solar System. This activity also includes "**Young Craters**" are also included in an attempt to constrain the impact flux at times older and younger than the 3.8-3.9 Ga ages of impacts that dominate the samples returned by Apollo.

"**Felsic**" locations are those that have been ideintifed from orbital datasets to be silica-rich (and contain high Th abundances and a distinct peak in the Moon's thermal emission near 8µm, the Christiansen feature, associated with Si-O stretching vibration [10,11]). Felsic lithologies are present in the sample collection, but are relatively small (a few grams at the most). Orbital data demonstrate the presence of massifs at the Gruithuisien Domes, Hansteen Alpha, Aristarchus, Lassell, Compton Belkovich [6,12]. Sampling these massifs will enable tests of granite/rhyolite petrogenesis through silicate liquid immiscibility [13] and/or LMO processes.

Young Igneous samples include the young basalts defined by crater counts [14], as well as irregular mare patches [4]. The composition of these young basalts has important implications for understanding the composition of the mantle as well as the thermal evolution of the Moon. Sampling of **Farside Mare Basalts** will also address these science issues.

Pyroclastic Deposits are critical for understanding the volatile budget of the deep lunar interior. Experimental petrology on the glasses returned by Apollo suggest they are derived from greater depths than the crystalline mare basalts [15]. The presence of volatiles in the Apollo 17 orange and Apollo 15 green glasses [16,17] make pyroclastic deposits important for science and exploration (i.e., *in situ* resource utilization - ISRU).

Hydrogen (volatile) Deposits are identified from orbit to be present in and around some permanently shaded regions (PSRs) (e.g., [18]). We know very little about these deposits and landed missions such as Resource Prospector and far more capable follow-on missions are required. Sample return of such materials could contain ancient materials that address Solar System science questions (building blocks of life, source signature of inner solar system volatiles, etc.). Understanding the nature, distribution, and accessibility will be important for ISRU and human exploration.

Deep Crust and possibly lunar mantle can potentially be sampled around central peaks and deep areas within SPA. Having a sample of the deep crust or even the upper mantle will help constrain the Apollo geophysical data as well as the more capable and globally distributed Lunar Geophysical Network, a named New Frontiers mission for the NF-5 call later this decade.

Farside Crust (highlands): example locations are given (Fig. 1b). Comparing these samples with Apollo, Luna and lunar meteorite highlands lithologies is important for understanding crustal heterogeneity. It will also test if ferroan anorthosites are the dominat crustal lithology, as predicted from the LMO hypothesis.

Outcrop Sampling: None of the samples in the collection were collected from unequivocal in situ outcrops. Properly oriented samples are required from various terrains and of different ages to truly test the whether the Moon ever established a core dynamo [19].

Technology Development. Sample return has become a next step for studying many planetary bodies (Moon, Mars, asteroids). For the return of rock and regolith samples, very little technology development is needed. However, cryogenic sampling, return, and curation will require investment. If this is started now by 2050 such sample return will be possible.

Human vs. Robotic Sample Return: The United States has not yet robotically returned a sample from a planetary surface, but has returned samples successfully 6 times from the Moon with humans. The Soviet Union is the only country to have achieved robotic sample return from a planetary surface and did this successfully 3 times. These 3 missions brought back a total of 0.3 kg of regolith. The 6 Apollo missions returned a total of 382 kg of rocks, regolith, and core tubes. The trained human eye on the surface allows significant dscoveries to be made (e.g., Genesis Rock (15415) and Seatbelt Rock (15016) from Apollo 15; the Orange Glass (74220) from Apollo 17). Having humans involved in sample collection is critical for maximizing the return mass and sample types (Fig. 2). By 2050, we assume a permanent human presence on the Moon that will facilitate extensive sample return possibilities. We have potential to advance both lunar and Solar System science and exploration in this way.

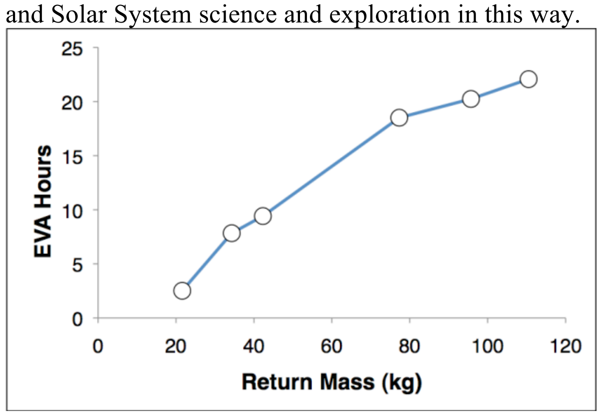

Figure 2: Human returned sample mass is positively correlated with EVA hours [20].

References: [1] Xiao L. et al. (2015) *Sci. 347*, 1226. [2] Giguere T.A. et al. (2000) *MaPS 35*, 193. [3] Pieters C. et al. (2011) *JGR 116*, doi:10.1029/2010JE 003727. [4] Pieters et al. (2014) *Am. Min. 99*, 1893. [5] Braden S. et al. (2014) *Nat. Geosci., 7*, 787. [6] Jolliff B. et al. (2011) *Nat. Geosci., 4*, 566. [7] Vision & Voyages for Planetary Science in the Decade 2013-2022 (2013) 399 pp. [8] New Frontiers in the Solar System (2003) 248 pp. [9] Gross J. et al. (2011) *JGR, 116*, 10.1029/2011JE003858. [10] Murcray F. et al. (1970) *JGR, 75*, 2671. [11] Salisbury J. et al. (1970) *JGR, 75*, 2671. [12] Glotch T. et al. (2010) *Sci. 329*, 1510. [13] Rutherford M.J. et al. (1976) *PLSC 7*, 1723. [14] Hiesinger H. et al. (2010) *JGR 115*, 10.1029/ 2009JE003380. [15] Green D. et al. (1975) *PLSC 6*, 871. [16] Saal A. et al. (2008) *Nat. 454*, 192. [17] Hauri E. et al. (2011) *Sci. 333*, 213. [18] Mitrofanov I.G. et al. (2010) *Sci. 330*, 483. [19] Garrick-Bethell I. et al. (2009) *Sci. 323*, 356-359. [20] CAPTEM-LEAG Analysis of Sample Acquisition and Curation (2011).