SCIENCE PRIORITIES FOR LUNAR SAMPLE RETURN. B. L. Jolliff[1], S. J. Lawrence[2], M. S. Robinson[2], and J. D. Stopar, [1]Department of Earth and Planetary Sciences and The McDonnell Center for the Space Sciences, Washington University, St. Louis, MO, 63130, USA (blj@wustl.edu). [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA.

Introduction. The Moon is a geologically complex world in its own right. Numerous exploration programs have investigated the Moon over the past 50 years [1,2], including orbiters, landers, human and robotic exploration, and sample returns. Additionally, lunar rocks are found on Earth, delivered by impacts on the Moon [e.g., 3,4]. The results from lunar missions, Earth observations, and samples have enabled scientists to construct a history of Earth's companion as a strongly differentiated object (with a core, mantle, and crust), a natural laboratory for the evolution of a rocky planetary body through internal thermal and magmatic evolution and volcanism, and a record of the impact process, especially for information regarding the flux of impactors at Earth and throughout the inner Solar System. Years of study of the lunar samples led to the hypothesis that the Moon's primary anorthositic crust and mafic mantle formed from an early magma ocean hundreds of kilometers deep [5]. The lunar samples also contain evidence of an origin by accretion of hot material following a colossal impact into proto-Earth ~4.5 billion years ago [6,7]. Indeed, lunar samples provided the first hints that all bodies in the inner Solar System experienced a cataclysmic bombardment by asteroids some 500 million years after accretion [8], possibly due to migration of the giant planets and subsequent destabilization of the early asteroid belt [9,10]. Most of these discoveries, which form a fundamental underpinning of modern planetary science, stem from the direct investigation of lunar samples in laboratories on Earth, including highly accurate and precise chemistry and isotopic analysis, mineralogy, spectroscopy, and geochronology. Moreover, having samples from known localities on the Moon enabled the coupling of sample knowledge with remote sensing and geophysical data to extend our understanding of the distribution of materials globally around the Moon and throughout the Moon's depths [11].

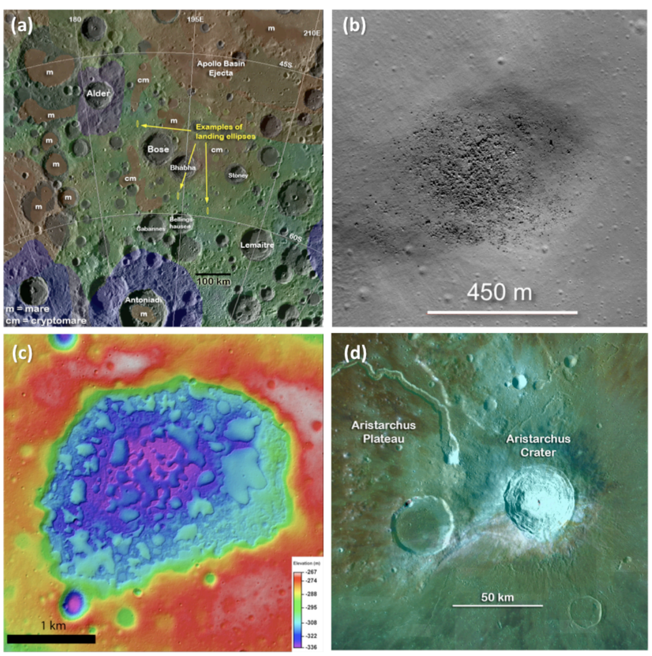

Figure 1: (a) Interior of SPA basin, showing geologic formations and example landing sites, LRO WAC base image; (b) Boulders on a small dome at the Compton-Belkovich silicic volcanic complex, LRO NAC; (c) Ina-D caldera topography, NAC digital topographic model; (d) Aristarchus region, Clementine mineral ratio map on LRO WAC 100 m base image.

New samples needed! Despite the early period of surface exploration and sample return (US and Soviet) much remains unknown about the Moon. Its polar regions, one of the truly unique environments in the Solar System, have been probed from orbit and with the LCROSS impact, and found to contain frozen volatile elements, trapped in extremely cold regions that receive little or no sunlight [12,13]. The farside contains a record of Moon's early primary anorthositic crust and one of the largest impact structures in the Solar System, South Pole-Aitken (SPA) basin (Fig. 1a). This mega-basin is our key to understanding the materials and conditions of the lunar interior and unlocking the timing of heavy impact bombardment (on the Moon and the inner Solar System as a whole). The Moon's many thousands of large, well-preserved impact craters record the history of impact bombardment in the Solar System and await future sample collection and analysis to decipher that history. The Moon's volcanic rock formations hold a record of internal thermal and chemical evolution, and timing of these events that have only begun to be unraveled with existing samples. Simply put, the Moon offers tremendous potential for addressing key questions of planetary history and evolution, and for untangling the impact record of the Solar System. These issues have fundamental implications for all of the planets and for the development and sustainability of habitable environments on Earth, Mars, and elsewhere.

Volcanism: Oldest, youngest, extents of chemical variations, petrogenetic relationships. Extensive basaltic volcanism occurred on the Moon 3.9-3.2 Ga, and continued, at a much lower rate, to as recently as ~1 Ga [14]. The mare basalts formed by melting in the Moon's mantle, thus they provide direct evidence of mantle compositions and conditions, from which the thermal history of the Moon has been inferred. Far less abundant are the petrologically and chemically "evolved" silicic volcanic materials. The silicic volcanics provide evidence of the extremes of internal chemical differentiation in the Moon's shallow interior and thus also provide key constraints on thermal and magmatic evolution. Basalts spanning the age range ~3.9-3.2 Ga were sampled by Apollo and Luna; however, areas of old buried basalts and the youngest basalts have not been visited; these need to be sampled and their ages and compositions determined. None of the silicic volcanics such as Gruithuisen and Mairan Domes, and Compton-Belkovich [15] (Fig. 1b) have been directly sampled, and only small pieces of silicic rocks are found in the lunar samples [16]. Enigmatic volcanic features such as the Ina-D caldera (Fig. 1c) and similar sites are not understood at all; samples are needed to determine their age and whether they represent sites of potentially recent outgassing [17].

Impact cratering flux and the question of a cataclysm. In addition to evidence from samples, recent remote sensing and numerical models suggest various hypotheses about the early large-impactor flux [10,18]. The issue of cataclysmic bombardment at ~4 Ga, when life on Earth was first establishing a foothold, has garnered public interest [19]. It is time for a new suite of targeted samples to be collected from the Moon to determine in detail the early flux, beginning with SPA basin and other key basins such as Nectaris [20], as well as the timing of large and stratigraphically important craters that occurred later in Solar System history, including the intermediate aged craters (Eratosthenian) and younger craters (Copernican). Such craters can be dated directly by sampling their impact melt sheets. Moreover, direct ages of the volcanic rocks that formed throughout the Moon's full active volcanic period will cement the lunar cratering stratigraphy, which is still the primary evidence for timing of crustal modifications on the terrestrial planets. Samples are needed for the required very high-precision chemical and isotopic analyses.

Volcanic pyroclastic deposits: Samples of the deep lunar interior. Among the most scientifically significant of the lunar samples were the green and orange volcanic glasses, collected at the Apollo 15 and Apollo 17 sites, respectively [1]. These glasses are important because they erupted from hundreds of kilometers deep in the mantle with little or no modification enroute to the surface. Their ages, compositions, isotopic characteristics, and volatile-element contents are keys to the origin and evolution of the Moon and to our understanding of early Earth and how it originated and evolved. Many pyroclastic deposits occur on the Moon that could be targeted for simple sample returns, but the most interesting one is the Aristarchus Plateau deposit because of its proximity to Aristarchus crater (Fig. 1d), which excavated a suite of diverse and uncommon lunar rock types.

Polar volatile deposits. Thanks to low obliquity, the Moon's poles are hosts to deposits of volatile elements, sequestered in polar cold traps that reach as low as several tens of Kelvins. The origin, extents, and detailed makeup of these deposits are unknown. Much could be learned in-situ, with both scientific and resource potentials. However, the ultimate scientific goal is the return of a cryogenic sample for detailed chemical and isotopic analysis to determine the origins and ages of the volatile element deposits.

Sample return: How? The best way to explore and collect samples with full contextual information is with boots on the ground and mobility, with well-trained astronauts using all of their senses and with rapid assessment and decision-making capabilities, as demonstrated by the Apollo experience. Sampling with very specific objectives, however, can be done robotically [21], with potential advantages by having astronaut presence in orbit or at Earth-Moon Lagrange point L2 [22], especially in terms of return mass and conducting farside mission operations.

References: **[1]** *Lunar Sourcebook* (1991) Cambridge; **[2]** Harland (2008) *Exploring the Moon*, Springer; **[3]** Warren (1994) Lunar and martian meteorite delivery services. *Icarus* **111**, 338; **[4]** Korotev (2005) Lunar geochemistry as told by lunar meteorites. *Chemie der Erde* **65**, 297; **[5]** Shearer et al. (2006) Lunar Interior. In *New Views of the Moon*, *RiM-G* **60**, MSA; **[6]** Canup and Asphaug (2001) Origin of the Moon in a giant impact... *Nature* **412**, 708; **[7]** Touboul (2007) Late formation and prolonged differentiation of the Moon... Nature 450, 1206; **[8]** Tera et al. (1973) A lunar cataclysm at ~3.95 AE and the structure of the lunar crust. *Lunar Planet Sci.* **4**, 723; **[9]** Levison et al. (2001) Could the lunar "Late Heavy Bombardment" have been triggered by the formation of Uranus and Neptune? *Icarus* **151**, 286; **[10]** Bottke et al. (2007) Can planetesimals left over from terrestrial planet formation produce the lunar late heavy bombardment? *Icarus* **190**, 203; **[11]** *New Views of the Moon* (2006) RiM-G 60, MSA; **[12]** Colaprete et al. (2010) Detection of water in the LCROSS ejecta plume. *Science* **330**, 463; **[13]** Speyerer and Robinson (2012) Persistently illuminated regions at the lunar poles. *Icarus* **222**, 122; **[14]** Hiesinger et al. (2003) Ages and stratigraphy of mare basalts... *J. Geophys. Res.* **108**; **[15]** Jolliff et al. (2011) Non-mare silicic volcanism on the lunar farside at Compton-Belkovich. *Nat. Geosci.* **4**, 566; **[16]** Seddio et al. (2013) Petrology and geochemistry of lunar granite …and implications for … petrogenesis. *Am. Min.*, in press; **[17]** Robinson et al. (2010) High resolution imaging of Ina: Morphology, relative ages, formation. *Lunar Planet. Sci.* **41**, #2592; **[18]** Fassett and Minton (2013) Impact bombardment of the terrestrial planets and early history of the Solar System. *Nat. Geosci.* **6**, 520. **[19]** Irion (2013) Our wild, wild Solar System. *National Geographic* **224**, 42; **[20]** Norman (2009) The lunar cataclysm: Reality or "Mythconception"? *Elements* **5**, 23; **[21]** Jolliff et al. (2012) Sampling South Pole-Aitken basin: The MoonRise Approach. LEAG Annual Meeting; **[22]** Alkalai et al. (2012) Orion/MoonRise: Joint human-robotic lunar sample return mission concept. LEAG Annual Meeting.