SCIENTIFIC EXPECTATIONS FROM A SAMPLE OF REGOLITH AND ROCK FRAGMENTS FROM THE INTERIOR OF THE LUNAR SOUTH POLE–AITKEN BASIN.

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The South Pole–Aitken Basin Sample-Return mission concept (SPA-SR) was highly ranked by the NRC-NAS Decadal Survey [1] because the science objectives address Solar-System issues as well as the Earth-Moon system and Moon, specifically. Key objectives relate to (1) the timing and nature of post-accretional bombardment in the inner Solar System by very large objects and subsequent effects on planetary evolution and processes, and (2) planetary differentiation and crustal evolution in general [see also 2,3].

The impact process is among the most fundamental processes in shaping and altering the early-formed surfaces and atmospheres of planets in the inner Solar System. Direct dating and isotopic modeling of Apollo rocks and meteorites has revealed much of the early chronology, yet the timing of the largest and oldest impact structures remains poorly constrained. Constraining the age of SPA either by direct dating of a remnant of its impact melt or by establishing the range of ages of smaller, subsequently formed basins within SPA, will increase knowledge of how, when, and why these massive impacts occurred and how they affected early surfaces and surface environments of the terrestrial planets.

The Moon is key to understanding the early history of planet formation and differentiation into crust, mantle, and core because its rocks and minerals retain a direct record of its primary crust. It cooled quickly, so crust-mantle processing has not been extensive. The Moon is the well-studied small-planet endmember that allows us to understand relationships between a planet's size and composition, and how it cooled, differentiated, and was subsequently modified by internally generated igneous and volcanic processes. Much of what is well known about the Moon stems from the analysis of samples and data collected from a relatively small area and fraction of the Moon's Earth-facing side. Recent global remote sensing shows the Moon to be significantly more diverse than is reflected by the samples now in hand. The SPA basin lies far from the sampled near-side locations, and the impact that produced it excavated materials from deep in the crust or upper mantle. Thus, we expect samples from SPA basin to provide significant new insight into early planetary differentiation.

Additional specific objectives of SPA-SR are pivotal for lunar science [1] and foundational for understanding processes important during early planetary differentiation. These include, but are not limited to, the following: determine composition and mineralogy of lower crust directly from samples (test models for differentiation of the Moon's crust and mantle); determine composition and mineralogy of the mantle beneath SPA; calibrate/validate compositional and mineralogic remote sensing over a major part of the Moon (SPA) where existing data are ambiguous or otherwise not well understood and for which no samples are known to exist in Apollo, Luna, or meteorite collections (enabling improved understanding of the lunar surface and bulk composition); obtain materials that are less likely than existing samples to be biased by the youngest and largest near-side impact basins (e.g., Serenitatis, Imbrium); determine sources of anomalous concentrations of thorium and other heat-producing elements to understand lunar differentiation and thermal evolution, including volcanism; determine ages and compositions of basalts to reveal if the mantle source regions on the far side of the Moon and timing of volcanism differ from regions previously sampled.

In this abstract we discuss approaches and measurements to be made on returned samples to address these objectives. Over thirty years of experience exist for the analysis of lunar materials; in some cases, however, new equipment now permits analyses that were not possible during much of that time. Noteworthy are capabilities for microanalysis that have been and continue to be developed for the investigation of small planetary samples and cosmic dust [e.g., 4 and refs therein]. Much can be done with small rock samples that was not possible or routine until recently, such as in-situ micro-isotopic and geochemical analyses using new/improved methods such as SIMS, LA-ICPMS, MC-ICPMS, SXRF, PIXE, and others [see 4]. Furthermore, much of what can now be done has not been done extensively with existing small rock fragments from the lunar regolith because of the availability of the large Apollo rock samples. Well-established analytical approaches have nevertheless been used effectively for many years on small lunar rock fragments (e.g., SIMS, EMP, INAA, XRF, SEM, TEM), and those results are just as pertinent to samples from an SPA-SR.

Geochronology. Fundamentally important to SPA-SR science goals is the capability to determine ages of small and in most cases complex (breccia) samples. The goal of assigning an absolute age to the SPA event can be attained with varying degrees of confidence by direct and indirect means. This goal would be achieved directly by dating a sample of the original crystallized impact melt; such a sample is not necessary to obtain this goal, however. Clasts of crystalline impact melt that were incorporated into later-formed breccias can be extracted and dated [5]. Crystalline impact melt produced by proximal post-SPA basins can be dated to provide constraints. If multiple basin-forming events are dated, SPA would logically be at least as old as the oldest one. Post-SPA volcanic rocks will also contribute to

SPA-basin chronology. Petrologic and geochemical information will help to confirm that the oldest event in a distribution of ages is indeed the SPA event.

One approach to geochronology, then, will be to date many samples and thus infer SPA chronology from a distribution of ages. High-precision ^{40}Ar-^{39}Ar [e.g., 5-7] will be used to date samples with masses as little as 10 mg to <1 mg, which is ideally suited for rock fragments in the 2-4 mm range (typically 10 to 40 mg per fragment) or greater, and for clasts extracted from individual rock fragments such as has been done by [5]. Because the Ar system may effectively record many impact events subsequent to SPA, many analyses will be needed to establish ages of the major events.

Isotopic systems less easily reset, e.g., U-Pb, Rb-Sr, Sm-Nd, Re-Os, and Hf-W, may require microsampling, mineral separations, and samples of larger mass. These methods can be applied using the largest rock fragments or by combining samples that can be shown by geochemical or other means to be pieces of a single lithology. Judging by mature Apollo regolith samples, 1 kg of rock fragments greater than 2 mm would (conservatively) yield some 10,000 2-4 mm particles, over 3000 4-10 mm fragments, and a significant number of rocklets >1 cm. Coupling laser ablation with multicollector ICPMS will extend some of these systems to an in-situ micro-analysis capability [8].

Geochemistry and Petrology. Experience with Apollo samples has led to routine, precise, mineral and bulk chemical analytical procedures for small samples, including chemical analyses of sub-mg masses by highly precise methods such as INAA, ICP-MS, SIMS, SXRF, and others. Geochemical analysis of regolith rock fragments will provide much information about the regional geology and petrology. Studies of Apollo samples have shown that rock fragments in a single regolith sample typically match or exceed the lithologic diversity of large rocks at an entire landing site [9]. Lateral and vertical mixing by impacts extends lithologic diversity to a regional scale without necessarily mixing and destroying individual lithologies. Examples include the variety of nonmare rock types found at mare sites and the occurrence of volcanic glass and fragments of mare basalt at all the highland sites [9,10]. Some lithologies, e.g., volcanic glasses, are concentrated in fine size fractions, so some unsieved material is desired, but sieving and elimination of the finest material from part (most) of the return sample will select against the more friable regolith and fragmental breccias, and agglutinates, which are increasingly concentrated in the finest size fractions, e.g., 50% or more of the 1-2 mm fraction of mature soils [11].

We might expect lithologic diversity of regolith samples from SPA to resemble that of Apollo 14, which lies in a reworked basin-ejecta deposit. There, some 40% of the 2-4 mm fragments are crystalline impact-melt breccias and another 40% are fragmental or regolith breccias composed of multiple lithologies [12]. Compositions of melt breccias and the clasts they contain will, coupled with information from remote sensing, be used to determine provenance and to help establish relative chronology. Primary SPA impact-melt breccias are expected to incorporate deep-seated crust or upper mantle material and thus to have, on average, mafic compositions. Because of the size of the basin, the compositional diversity of SPA impact breccias may be substantial, but relationships will be recorded by chemical compositions and by mineral and lithic clast assemblages. Mineral compositions will record cooling rates and depths of origin of lithic clasts incorporated in SPA melt breccias from the lower crust or upper mantle. Lithic fragments from the mantle would be recognized by distinctive mineral chemistry. Trace-element compositions of mineral and lithic clasts will be used to relate components of potentially coarse-grained lithologies of deep origin and to determine their petrogenesis.

Volcanic glasses and basalt fragments distributed laterally by impacts into mare or cryptomare deposits should, on the basis of Apollo experience, be present in regolith everywhere in the SPA basin and will provide indirect (remelted) samples of the sub-SPA mantle. Geochronologic, geochemical, and petrologic investigations of these materials and comparison to Apollo, Luna, and lunar meteorite samples will reveal and help explain the causes of mantle heterogeneity and how/whether the SPA event influenced the course of volcanism.

Bulk samples of regolith will be studied by compositional and spectrographic methods. These studies will provide calibration for remote sensing over SPA for mineralogy and for major elements and Th. Trace-element signatures of key rock types will reveal the source(s) of the ~2 ppm Th "background" concentration of the basin, which is key to understanding the global distribution of KREEP and asymmetric development of the lunar crust.

In summary, much can be learned from integrated studies of individual lithic fragments. A 20 mg rocklet can be subdivided routinely for INAA, Ar-Ar dating, and sections for microbeam analysis. Impact mixing and lack of atmospheric weathering on the Moon provide greatly diverse samples, and a sieved regolith sample will provide literally thousands of specimens with which to understand the scientifically rich SPA Terrane.

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