PRODUCING TRANSFORMATIVE LUNAR SCIENCE WITH GEOLOGIC SAMPLE RETURN: A NOTE ABOUT SAMPLE MASS. David A. Kring[1,2], [1]Center for Lunar Science and Exploration, Lunar and Planetary Institute, Universities Space Research Association, 3600 Bay Area Blvd., Houston TX 77058 USA (kring@lpi.usra.edu), [2]NASA Solar System Exploration Research Virtual Institute.

Introduction: The big ideas to emerge from Apollo are a product of sample return: (1) The chemical composition of lunar samples forced the community to reconsider the origin of the Earth-Moon system, spawning the giant impact hypothesis. (2) A few bright-white clasts in Apollo 11 soils, deftly interpreted to be impact-excavated debris from the distant highlands, led to the lunar magma ocean hypothesis. (3) A bevy of ~3.9 to 4.0 Ga impact ages in samples from several Apollo sites prompted the lunar cataclysm hypothesis, which is now more broadly understood to be a Solar System-wide event, although the magnitude and duration of bombardment continue to be debated. (4) The coincidence of the end of that bombardment with the earliest evidence of life on Earth is an important observation behind the impact–origin of life hypothesis. (5) A large number of magmatic zircon ages in Apollo samples of the approximate age of the impact event that produced the 2,500 km-diameter South Pole-Aitken basin has generated the lunar magmatism hypothesis. (6) And, as analytical capabilities improved and water was detected in Apollo 15 and 17 samples, we were provided an independent measure of the accretion of volatiles to the Earth-Moon system. That work also increased the probability that significant reservoirs of water ice exists in permanently shadowed regions (PSRs) of the polar regions. Without sample return, we would be ignorant of those important findings.

Despite the success of Apollo, most of the Moon remains unexplored. Importantly, armed with the knowledge Apollo sample analyses provide, we can target specific landing sites to address existing questions and resolve uncertainties that have vexed the scientific community for five decades. The key investigations are well known. They are articulated in an NRC (2007) report *The Scientific Context for Exploration of the Moon* [1] and echoed in a number of additional documents (e.g., [2]). Several of those investigations, if they are supported by sample return, will be truly transformative [3]. Case studies of landing sites, traverses, and stations for crew-facilitated sample return missions have been completed for Malapert, Shackleton, Schrödinger, Antoniadi, SPA, and Kepler [4-7] among others. Here I explore the generic capabilities that an exploration architecture must provide to make sample return a success from those and any other locations on the Moon.

Potential Mass of the Investigation: There are three components to the mass required for a sample return investigation.

Geologic tools (to surface). Tool kits including hammers (est. 1.3 kg), tongs (est. 0.2 kg), scoops (est. 0.6 kg), rakes (est. 1.5 kg), and extension handles (est. 0.8 kg) will be needed on the descent manifest, but will not be returned to Earth. Cameras will also be needed for sample documentation and interaction between crew and a supporting science operations staff.

Geologic samples (from surface). Estimating sample return mass can be done using (1) historical data from the Apollo missions [8] and (2) recommendations for individual sample masses as a function of rock type (lithology) [9].

Apollo missions returned 382 kg of geologic samples, ranging from 21.5 kg collected by Apollo 11 crew to 110.5 kg collected by the Apollo 17 crew. Sample mass increased with each mission and as a function of EVA time (**Fig. 1**). Importantly, there is a near constant sample return mass per EVA hour per crew member. The exception is Apollo 11 when the Commander famously filled the sample box with nine scoops of additional soil, providing an invaluable sample (10084; ~10 kg) for a broad range of scientific and *in situ* resource utilization (ISRU) studies. The near constant average value is 2.3 kg/EVA hr/crew member, although, if one scrutinizes the data, one detects a 20% increase in the sampling rate between the Apollo 15 and 17 missions. The near-constant sampling rate occurred regardless of the terrain; e.g., mare (Apollo 12), highland (Apollo 14, 16), and a juxtaposition of mare and highland materials (Apollo 15, 17). That average value can be usefully applied to estimate the sample mass of future missions.

For example, a 6.5 day surface mission with two astronauts (e.g., [10]) conducting 24 hours of EVA will have an estimated sample mass of 110.4 kg, comparable to that from the Apollo 17 mission. This method [8] was incorporated into a recommendation by the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM; [9]).

The second method uses recommendations of sample masses needed to extract the best results using current analytical capabilities. The sample types anticipated are sieved soils, rake-separated clasts in regolith, trench samples, isolated rock samples, and rock chips from boulders. (Drive tube and drill core

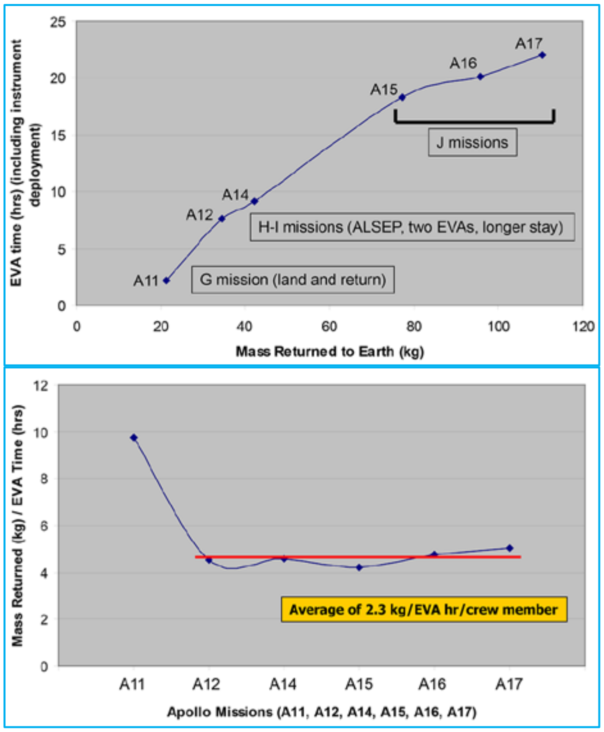

Figure 1. (top) Geologic sample mass returned to Earth for analyses as a function of EVA time. (bottom) Average sample mass returned as a function of EVA time. Because Apollo missions had two astronauts on the surface, the average is 2.3 kg/EVA hr/crew member. From [8].

samples are also likely on some missions, but that discussion is beyond the scope of this paper.) The types of rocks sampled will vary, depending on the geologic context of a landing site. Based on analytical experience with Apollo samples, CAPTEM recommends [9] 0.5 kg for large hand samples of homogeneous rocks such as basalts and clast-free impact melt rocks; 5 kg for impact breccias; 2 kg for unsieved regolith samples; and multiple 0.0005 kg clasts in rake samples through the lunar soil. Landing in the vicinity of the lunar south pole on the rim of Shackleton crater will likely provide [11] brecciated samples of impact ejecta from Shackleton and several other impact craters (5 kg each), homogeneous impact melts (0.5 kg each), homogeneous crystalline rocks of anorthosite and other crustal litholoies (0.5 kg each), and at least three varieties of soil samples (2 kg each), including samples from small PSRs, and additional rake samples from those soils. Similar types of mass assessments can be performed for robotic sample return missions (e.g., [12,13]).

Geologic sample containers (to and from surface). I defer to the Johnson Space Center curation staff and CAPTEM for these mass estimates.

Estimates of the Cost to Develop and Operate the Investigation: Costs include a pre-mission geologic assessment of each landing site, training of crew and supporting mission operations staff, manufacture of tools (that may not be reusable), manufacture of one or more rovers (which are potentially reusable), continuous communication capability between crew and a science operations center during EVA, manufacture of sample containers, curation, preliminary sample examination, and research and analysis by the lunar sample community.

Amount of Crew Interaction Needed: The crew will need to collect samples during EVA. It will be important for astronauts to be well-trained and have clearly-defined objectives to maximize the efficiency of sample collection. The initial destination of the Artemis program is the lunar south pole, which is a heavily impact-cratered terrain that will require training of astronauts [14] in terrestrial analogues (Meteor Crater, Ries Crater, Sierra Madera, and, potentially, Sudbury). During Apollo, crew had a training cycle of ~1 geologic field trip per month.

Requirements for Landing Site(s): Sample return will be an element of any landed mission, regardless of the landing site. The need to handle volatile-rich and icy samples may depend on the landing site.

Rocky *versus* Volatile Samples: Because rocky lunar samples and soils are notoriously complex, the Moon has a relatively small gravity well, and the Moon is only three days from Earth, returning samples to Earth will be preferred to attempts to analyze materials *in situ* or on an orbiting platform. Volatile samples, however, are relatively simple to analyze and lend themselves to *in situ* analyses, particularly when transport may alter important physical and chemical properties.

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