USING TECHNOLOGY TO BETTER CHARACTERIZE THE APOLLO SAMPLE SUITE: A RETROACTIVE PET ANALYSIS AND POTENTIAL MODEL FOR FUTURE SAMPLE RETURN MISSIONS. R. A. Zeigler, NASA – Johnson Space Center, Astromaterials Curation and Acquisition, 2101 NASA Parkway, Mail Code XI2, Houston TX 77058. ryan.a.zeigler@nasa.gov.

Background: From 1969-1972 the Apollo missions collected 382 kg of lunar samples from six distinct locations on the Moon. Studies of the Apollo sample suite have shaped our understanding of the formation and early evolution of the Earth-Moon system, and have had important implications for studies of the other terrestrial planets (e.g., through the calibration of the crater counting record) and even the outer planets (e.g., the Nice model of the dynamical evolution of the Solar System). Despite nearly 50 years of detailed research on Apollo samples, scientists are still developing new theories about the origin and evolution of the Moon. Three areas of active research are: (1) the abundance of water (and other volatiles) in the lunar mantle [e.g., 1,2], (2) the timing of the formation of the Moon and the duration of lunar magma ocean crystallization [3], (3) the formation of evolved lunar lithologies (e.g., granites) and implications for tertiary crustal processes on the Moon [4]. In order to fully understand these (and many other) theories about the Moon, scientists need access to "new" lunar samples, particularly new plutonic samples. Over 100 lunar meteorites have been identified over the past 30 years [5], and the study of these samples has greatly aided in our understanding of the Moon. However, terrestrial alteration and the lack of geologic context limit what can be learned from the lunar meteorites. Although no "new" large plutonic samples (i.e., hand-samples) remain to be discovered in the Apollo sample collection, there are many large polymict breccias in the Apollo collection containing relatively large (~1 cm or larger) previously identified plutonic clasts, as well as a large number of unclassified lithic clasts. In addition, new, previously unidentified plutonic clasts are potentially discoverable within these breccias. The question becomes how to non-destructively locate and identify new lithic clasts of interest while minimizing the contamination and physical degradation of the samples.

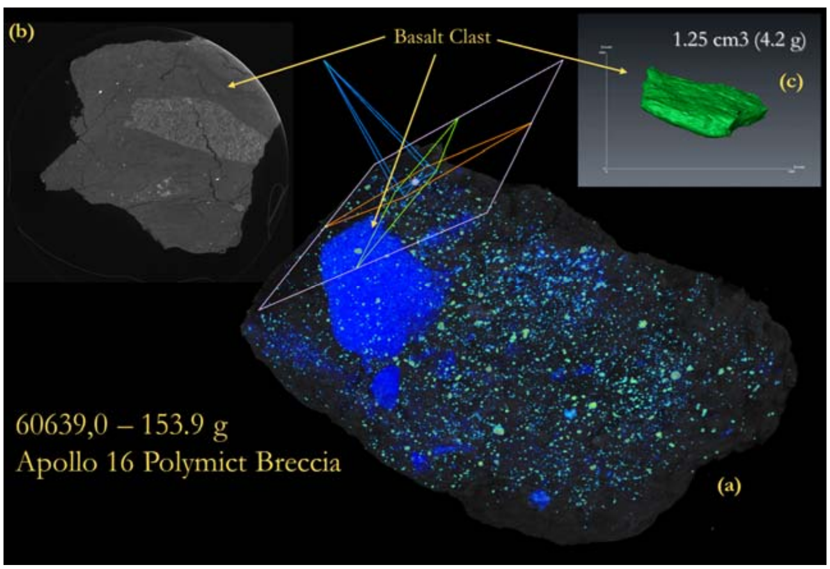

Figure 1: (a) A 3-dimensional view of a micro-CT scan of the main mass of Apollo 16 polymict breccia 60639. The colors within the scan correspond to materials with high x-ray attenuation values, and highlight lithic and mineral clasts rich in Fe-bearing minerals (e.g., pyroxene, olivine, ilmenite). The blue clasts are basalt clasts within the breccia. The whole sample is ~8 cm in the longest dimension. **(b)** A close-

Results: The solution to the identification of new clasts within the Apollo samples while still keeping the samples pristine is micro-computed tomography (micro-CT). The technique uses high energy x-rays (typically 100-300 kV) to make 3-dimensional images of a sample (Figure 1). These images highlight materials with different x-ray attenuation values, which are determined by the density and composition of the materials. Thus, lithic clast materials can be differentiated from the breccia matrix, and different types of lithic clasts can often be differentiated from each other [6-8]. The scans can also be used to estimate the volume and mass of clasts, which is useful in determining which studies they are most suited for. The high-energy nature of the x-rays allow for scanning of relatively large samples (up to ~20 cm) while triply bagged in Teflon containing a dry-Nitrogen atmosphere. This protects the samples from potential contamination. Once the CT-scans have identified the location and approximate composition of the lithic clasts within the polymict breccia sample, this information can then be used to more precisely cut the samples into slabs, exposing the clasts of interest for sampling and further study. Although micro-CT provides x-ray attenuation data for a sample, it does not give direct compositional or mineralogical information (although making reasonable assumptions and using standards during analysis allows for good estimations). Micro

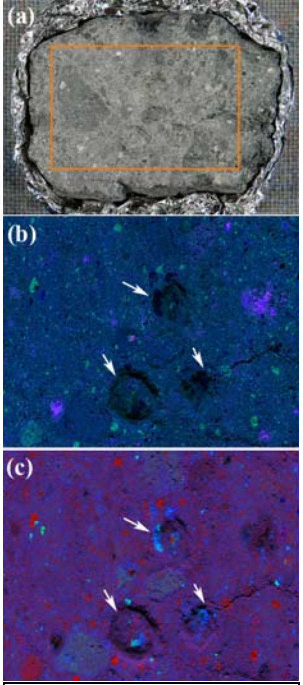

Figure 2: (a) Macroscopic image of 14305,483. Area in parts b + c outlined in orange

x-ray fluorescence (micro-XRF) uses a focused (~25 µm) high energy (up to ~50 kV) x-ray beam to produce semi-quantitative compositional maps of relatively flat surfaces (Figure 2). These maps can be used to better characterize clasts identified in micro-CT data, or to identify clasts that are compositional or textural outliers. Another technique, scanning laser-RAMAN analyses of cut slabs of breccias, has the potential to give direct mineralogical information that can be co-registered with the compositional data from the micro-XRF scans. Neither micro-XRF or laser-RAMAN scanning can be easily done on samples contained in Teflon bags, but it is likely that both scanning laser Raman and micro-XRF can be adapted to work in a standard Nitrogen glove box.

Future Missions: The original Apollo sample preliminary examination teams (PET) used primarily binocular microscopy as they made their initial descriptions and observations of the samples. This was in part due to the technology available at the time, and in part in an effort to keep the samples as pristine as possible. Subsequent missions have used progressively more sophisticated techniques for PET, e.g., FTIR for genesis or EDAX for Hayabusa. Future sample return missions like Osiris-Rex or South-Pole Aitken sample return are likely to incorporate micro-CT, micro-XRF, and other sophisticated techniques into their PET analysis.

References: [1] Anand M. (2014) *Phil. Trans. Roy. Soc. A*, Article ID 20130254. [2] Boyce J. W. et al. (2014) *Science*, **344**, 400-402. [3] Borg L. E. (2014) *MAPS*, doi: 10.1111/maps.12373. [4] Seddio et al. (2013) *Am. Min.*, **98**, 1697-1713. [5] http://meteorites.wustl.edu/lunar/moon_meteorites_list_alumina.htm. [6] Almeida N. V. et al. (2014) *MAPS*, Abstract #5033. [7] Smith C. L. et al. (201s) *MAPS*, Abstract #5323. [8] Hyde, B. C. et al. (2013) *MAPS*, Abstract #5301.