ON THE IMPORTANCE OF APOLLO REGOLITH SAMPLES FOR SCIENTIFIC EXPLORATION OF THE MOON. B. L. Jolliff and R. L. Korotev, Department of Earth & Planetary Sciences and The McDonnell Center for the Space Sciences, Campus Box 1169, Washington University in St. Louis, One Brookings Dr., St. Louis, MO 63130; [bjolliff@wustl.edu]

Introduction: Samples of regolith brought to Earth by the Apollo missions have proven to be one of the great treasures of the Apollo sample program. Regolith samples represent *the critical ground truth* for remote sensing and have been used to calibrate major remote compositional, mineralogical, and maturity data sets. Although well mixed locally by small- and large-scale impact processes, lunar regolith samples exhibit a great dynamic range of chemical compositions, reflecting the "bedrock" composition(s) at the locality where they occur [1,2]. All of the Apollo regolith samples contain rock fragments, and these small, very abundant rocklets have proven to represent well the diversity of large rocks at a given site [3-6]. The regolith samples provide context for the interpretation of lunar meteorite regolith breccias and enable us to extend what is known from Apollo samples and exploration to the entire globe via the ever-growing lunar meteorite collection and dataset [e.g., 7-8]. As current and future missions explore the lunar surface, we can and should leverage the knowledge gained from 5 decades of studies of lunar soils to maximize the efficiency of continued scientific exploration of the Moon.

Landing Site Data: Within a given Apollo landing site, the variations in regolith "bulk compositions" reflect local geology and enable the use of regolith samples as ground truth for orbital remote sensing that is of sufficiently high resolution to sense the area in close proximity to individual sample stations, e.g., the "Lucey method" of FeO estimation [9], the calibration of TiO_2 [10,11], and most recently, LROC NAC photometry [12,13]. As an example, the systematic study of Apollo 17 soils by [14] showed the range of these components to be substantial (FeO: 7-22 wt.%, TiO_2: 0.9-10 wt.%) and this variation has been used to advantage to calibrate the remotely sensed data [11,15-17]. They [14] also showed, through the use of a mixing model with known endmember components, how soils collected at each of the sample stations and Lunar Roving Vehicle (LRV) stops record the percentages of Taurus Littrow Valley basalts, pyroclastic glass, massif impact-melt components, KREEP-rich materials, anorthositic highlands materials, meteoritic contaminants, and exotic components such as very low-Ti (VLT) basalts that are not found among the large rocks at the site. As additional information is gained from remote sensing, such as testing for the occurrence of impact melt from Tycho deposited on South Massif [18], the soils remain available for study to search for evidence of such materials because they have been carefully curated for continued study by future generations with improved analytical methods.

Rock Components in Apollo Soils. Owing to studies of the Apollo soils, the effects and scales of mixing caused by impacts large and small are understood. For example, a basaltic site such as Apollo 11, located 50 km from the nearest highlands, actually contains some 28% nonmare components [19]. At Apollo 12, the percentage varies depending on the soil sample, but on average, the soils contain 27% KREEP-rich impact-melt breccia and over 8% feldspathic material, including alkali-rich anorthosite [6]. Among the rock components found only in the soils are high-Th impact-melt breccia (Apollo 12) and incompatible-element-rich impact-melt breccia at Apollo 17 [4] that are unlike the large sampled impact breccias. New and improved analytical methods make these small samples amenable to age determination by multiple techniques and such studies will be increasingly important to further assess the ages of large impacts to test the lunar cataclysm hypothesis [e.g., 20].

On the basis of knowledge gained from studies of rock fragments in Apollo soils, we can have increased confidence that regolith samples from any location on the Moon will contain representative suites of the rock types that have broken down to make the soils in those locations, and that they will be well correlated with local geology. Components delivered from distant impact craters can be tied with confidence to a known origin if impact crater rays cross the site. The best example among Apollo sites is Apollo 12 where material ejected by Copernicus 360 km to the north was sampled. As an example of a future mission that would benefit from this experience, sampling young basalts south of Aristarchus crater [21,22] will, with a high degree of certainty, sample ejecta materials from Aristarchus crater, enabling direct radiometric dating of this prominent Copernican cratering event and providing a key calibration point for the lunar chronology.

Apollo Soils and Lunar Meteorites: Because of the great diversity of components contained in lunar soils and the fact that their component makeup so well represents the area where they occur, regolith breccias, which are essentially lithified soils, also contain a wealth of information in their clast components as well as matrix. The matrix, commonly glassy, provides a good estimate of the bulk composition. Besides being relatively random samples of the lunar surface, many of the lunar meteorites are regolith breccias, containing demonstrable regolith components. Accordingly, they represent some area of the lunar surface, and depending on geologic relationships, they can represent a large area. From the abundance of highly feldspathic lunar regolith breccia meteorites with very low incompatible element contents, it has been inferred that as a class, this group of meteorites must sample the northern farside's highly feldspathic highlands [23-28]. Although there have been no sample collection missions to the farside highlands, we arguably have quite a few representative samples from there in the meteorite collection. By matching regolith breccia compositions for elements that are well determined from orbit such as FeO and thorium [29,30], the meteorites, which all have geologically young ejection ages from the Moon, can be tied to certain locations on the Moon [e.g., 31]. As remote sensing methods continue to improve, this technique will become increasingly more valuable for relating all kinds of lunar meteorite breccias that have sampled near-surface or surface materials, including mare basalts [e.g., 32]. Because we know how to interpret the soils in terms of mixing, additional ground-truth measurements such as those accomplished by the Chang'E-3 mission [33] will further improve the connection between samples and remote sensing.

Key Unknowns. In terms of relating soil, meteorite, and remote sensing compositions, one of the critical needs for remote sensing and an issue for which the soils and meteorites are essential is in the assessment of surface MgO content. The Mg/(Mg+Fe) of anorthositic highlands is needed to assess the efficiency and timing of separation of plagioclase from the magma ocean [34]. X-ray spectrometry from orbit with an "active" Sun is needed. Another key unknown is the surface composition and lithologic makeup of the South Pole-Aitken (SPA) basin terrane. Compositional and mineralogical remote sensing [35-38] provide important information, but a ground-truth composition from the basin interior, nonmare deposits will reveal which of the lunar meteorites likely come from SPA and will lead to a rapid gain in understanding the deposits of the largest and oldest impact basin on the Moon.

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References: [1] Papike, J., et al. (1982) *Rev. Geophys. Space Phys.* **20**, 761-826. [2] Korotev, R. (1987) *Proc Lunar Planet. Sci. Conf. 17th, Pt. 2, in J. Geophys. Res.* **92**, E411-E431. [3] Jolliff, B., et al. (1991) *Proc. Lunar Planet. Sci. Conf.* **21**, 193-219. [4] Jolliff, B., et al. (1996) *Meteor. Planet. Sci.* **31**, 116-145. [5] Zeigler, R., et al. (2006) T *Geochim. Cosmochim. Acta* **70**, 6050-6067. [6] Korotev, R., et al. (2011) *Geochimica et Cosmochimica Acta* **75**, 1540–1573. [7] Korotev, R., (2005) *Chemie der Erde* **65**, 297–346. [8] Korotev, R., and Zeigler, R. (2015) in: Righter et al. (Eds.), *35 Seasons of US Antarctic Meteorites (1976-2010)*, Spec. Pub. 68. AGU, John Wiley & Sons, Inc., 101-130. [9] Lucey, P., et al. (1995) *Science* **268**, 1150-1153. [10] Lucey, P., et al. (1998) *J. Geophys. Res.* **103**, 3679-3699. [11] Sato, H., et al. (2017) *Icarus* **296**, 216-238. [12] Watkins, R., et al. (2017) *Icarus* **285**, 169-184. [13] Hahn Jr., T., et al. (2018) *Lunar Planet. Sci.* **49**, #2637. [14] Korotev, R., and Kremser, D. (1992) *Proc. Lunar and Planet. Sci. Conf.* **22**, pp. 275-301. [15] Blewett, D. (1997) *J. Geophys. Res.* **102**, 16319-16325. [16] Robinson, M., and Jolliff, B. (2002). *J. Geophys. Res.* **107**, DOI 10.1029/2001 JE001614. [17] Coman, E., et al. (2018) *Icarus* **306**, 243-255. [18] Hahn Jr., T., et al. (2019) *Lunar Planet. Sci.* **50**, #1963 [19] Korotev, R., and Gillis, J. (2001) *J. Geophys. Res.* **106**, 12,339-312,354. [20] Liu, D., et al. (2012) *Earth Planet Sci. Lett* **319-320**, 277–286. [21] Hiesinger, H., et al. (2003) *J. Geophys. Res.* **108**, DOI 10.1029/2002JE001985. [22] Stadermann, A., et al. (2018) *Icarus* **309**, 45-60. [23] Fukuoka, T., et al. (1986) *Proc. 10th Symp. Antarct. Meteorit. Mem. Natl. Inst. Polar Res. Spec. Iss*. **41**, 84-95. [24] Koeberl, C. (1988) *Proc. NIPR Symp. Antarct. Meteorit*. **1**, 122–134. [25] Lindstrom, M., et al. (1986) *Proc. 11th Symp. Antarct. Meteorit. Mem. Natl. Ins. Polar Res. Spec. Iss.* **41**, 58-75. [26] Ostertag, R., et al. (1986) *Proc. 10th Symp. Antarct. Meteorit. Mem. Natl. Inst. Polar Res. Spec. Iss.* **41**, 17-44. [27] Warren, P., and Kallemeyn, G. (1986) *Proc. 10th Symp. Antarct. Meteorit. Mem. Natl. Inst. Polar Res. Spec. Iss.* **41**, 3-16. [28] Korotev, R., et al. (2003) *Geochim. Cosmochim. Acta* **67**, 4895-4923. [29] Lawrence, D., et al. (1998) *Science* **281**, 1484-1489. [30] Prettyman, T. et al. (2006) *J. Geophys. Res.* **111**, doi:10.1029/2005 JE002656. [31] Wittmann, A., et al. (2018) *Meteoritics and Planet. Sci.*, 1-22. [32] Carpenter, P. et al. (2019) *Lunar Planet. Sci.* **50**, #2125. [33] Ling, Z., et al. (2015) *Nature Comm.* **6**, 1-9. [34] Charlier, B., et al. (2018) *Geochim. Cosmochim. Acta* **234**, 50-69. [35] Pieters, C., et al. (1997) *Geophys. Res. Lett.* **24**, 1903-1906. [36] Pieters, C., et al. (2001) *J. Geophys. Res.* **106**, 28001-28022. [37] Lucey, P., et al. (1998) *J. Geophys. Res.* **103**, 3701-3708. [38] Moriarty III, D., and Pieters, C. (2018) *J. Geophys. Res.* **123**, 729–747.