COMPOSITIONAL VARIATION IN LUNAR REGOLITH SAMPLES – LATERAL.
R. L. Korotev, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130 (rlk@levee.wustl.edu).

The composition of samples of lunar regolith collected on the Apollo and Luna missions are highly variable; the lunar meteorites, most of which are breccias of lithified regolith from unknown locations on the Moon, extend the compositional range (Fig. 1). Here I discuss some aspects of regolith composition as inferred from studies of samples that are relevant for interpretation of data obtained remotely.

Database: During the Apollo and Luna missions, regolith samples were obtained with scoops and coring equipment. Apollo scoop samples were taken from near the surface (<10 cm depth) as well as from the bottom of trenches dug as deep as 30 cm. Some nominal "soil" samples are fines derived largely from a single rock (e.g., 12057, 67700, 73130, 76320) [1].

Most Apollo scoop samples were passed through sieves of 10 mm, 4 mm, 2 mm, and 1 mm mesh size in the curatorial facility at the NASA Johnson Space Center. Most chemical and physical measurements on samples of "lunar soil" have been made only on bulk samples of material that passed through a 1-mm sieve, i.e., the "<1-mm fines." For the Luna samples and some Apollo cores, compositional data are for <0.25-mm fines. With a few important exceptions, material in the 1–2 mm and 2–4 mm grain-size fractions has been largely unstudied.

The number of samples of surface and trench soils ranges from 7 at Apollo 11 to 68 at Apollo 17. Remarkably, a number samples of Apollo surface and trench soils are not well characterized compositionally. The dataset is poorest for the Apollo 12 samples.

Classes of Lithologic Material: From the compositional perspective, regolith samples are composed mainly of three classes of material each representing a distinct geologic environment (Fig. 1a):

1) mare basalt and volcanic glass
2) mostly-feldspathic rocks of the lunar highlands
3) mafic, KREEP-bearing impact-melt breccias and KREEP basalt

Each of these classes of material encompasses a variety of lithologies. For example, there are many compositionally distinct types of mare basalt and volcanic glass; the distinction between soils dominated by low-Ti and high-Ti mare basalts is evident on Fig. 1b.

A few regolith samples consist predominantly (>90%) of a single class of material. For example, some soils from Apollos 15 (Hadley Rille) and 17 (Taurus-Littrow, Central Valley) and that from Luna 24 (Mare Crisium) contain mainly mare basalt or volcanic glass. The most feldspathic of the lunar meteorites consist almost entirely of feldspathic highlands material with a bulk composition that correspond to that of noritic anorthosite although the meteorite regolith breccias are mixtures of a variety of rock types (granulitic and impact-melt breccias, plutonic anorthosite, noritic and troctolitic anorthosite, rare mafic lithologies). It is likely that these meteorites best represent typical feldspathic upper crust distant from the nearside basins [e.g., 2]. Presumably because all the Apollo missions landed near the High-Th Oval Region [3]

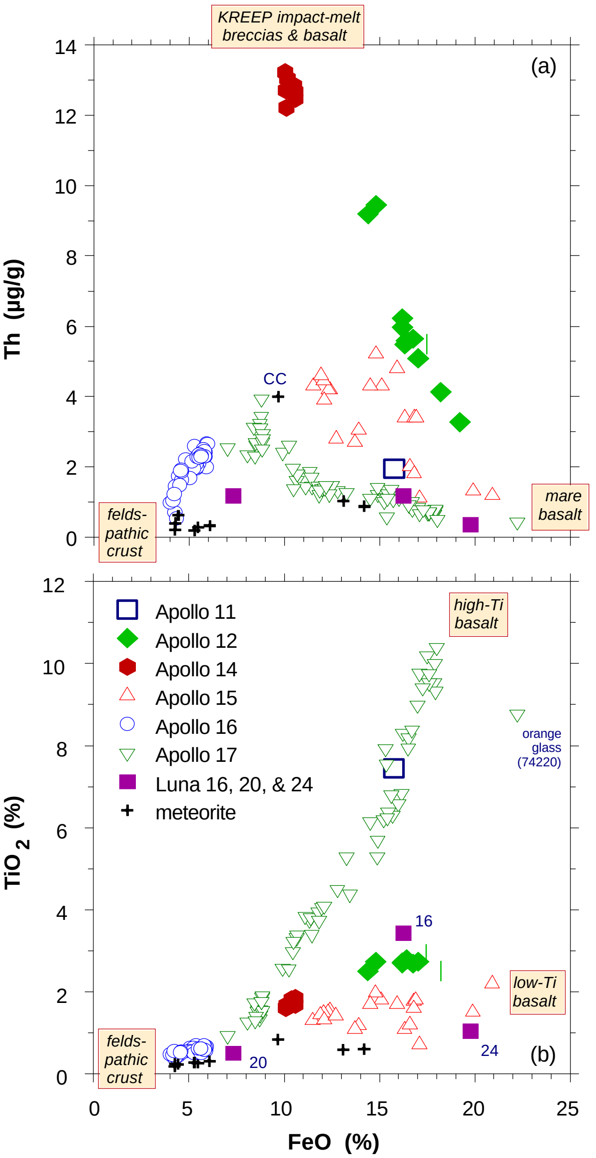

Figure 1. Concentrations of FeO, TiO_2, and Th in samples of lunar regolith. For the Apollo missions, each point represents the composition of a numbered (e.g., 64221) surface or trench soil (<1 mm). For the Luna missions, a single point for each mission is plotted. "Meteorite" points each represent one of the regolith-breccia lunar meteorites (e.g., MAC88105).

surrounding the Imbrium basin, all nonmare Apollo regoliths contain a substantial component of Th-rich, mafic impact-melt breccias (a component often misleadingly designated “LKFM.”). The Apollo 14 regolith (Fra Mauro) is derived mainly from such material. The mafic melt breccias are the principal carrier of incompatible elements like Th in Apollo highlands regoliths, although igneous KREEP basalt is probably an important component of the Apollo 15 regolith. With ~10% FeO, the mafic melt breccias are also the principal carrier of Fe in those Apollo regoliths that contain little mare material (e.g., 44% of the Fe at Apollo 16 [4]).

As evident from Fig. 1, however, most regolith samples are mixtures containing two or more classes of material. In part this is an artifact of having deliberately chosen sample locations at major geologic boundaries (Apollos 15 and 17) where mare-highlands mixing trends are clearly evident in regolith compositions. However, geologically important mixtures also occur where not necessarily expected. Samples of Apollo 12 (Oceanus Procellarum) regolith reflect binary mixing between low-Ti mare basalt and some type of KREEP component (Fig. 1a,b). The low FeO concentrations of regoliths from Apollo 11 (Mare Tranquillitatis) and Luna 16 (Mare Fecunditatis) (Fig. 1b) compared to mare basalt (~20% FeO) result because the regoliths consist of only ~75% mare basalt; the rest is highlands material. Some soils from Apollos 15 and 17 as well as the Calcalong Creek lunar meteorite (a regolith breccia; CC in Fig. 1b) contain subequal amounts of all three classes of material, and three other meteorite regolith breccias (9–15% FeO, Fig. 1) are mixtures of mare and highland material. On average, the Apollo 16 regolith (Cayley Plains) is largely a mixture of feldspathic highland material similar to that of the feldspathic lunar meteorites (~64%, from chemical mass balance [4]) and Th-rich mafic melt breccias (29%); variation in the proportions of these components about the mean causes the trend of Fig. 1a. The Apollo 16 regolith is atypical of highlands distant from the Imbrium basin in containing such a high abundance of Th-rich melt breccias. Although not evident in Fig. 1, the Apollo 16 regolith also contains mare-derived (6%) and, like all mature regolith, meteoritic material (1%) [4].

Variations in Composition with Grain Size: Several studies have shown that the lunar regolith varies in composition and mineralogy with grain size. In soil dominated by mare basalt, the finest material (<10 µm or <20 µm grain-size fraction) is consistently more feldspathic and, therefore, richer in Al and poorer in Fe than the coarser fractions [5–7]. FeO concentrations in the <10-µm material are typically 70–95% of that in <1-mm material [6]. This effect has % of that in <1-mm material [6]. This effect has been largely attributed to preferential comminution of plagioclase compared to pyroxene during formation of the regolith by meteorite impact [5–7]. Thus the plagioclase/pyroxene ratio of the finest regolith is probably greater than that of the basalt from which it forms.

Also, in regolith composed of several lithologies, it is unlikely that all of them will have the same grain-size distribution. If the various lithologies have different compositions, then the composition of the regolith will vary with grain size. Older (mature) regolith is generally finer grained than younger (immature) regolith [8]. At Apollo 16, for example, the mature surface soil has a high proportion (29%) of Th-rich mafic melt breccia. Impacts that punched through this surface layer encountered anorthositic rocks and ejected coarse fragments onto the surface. Thus the ejecta of North Ray crater is a mixture of (1) mature, fine-grained Fe- and Th-rich material and (2) immature, coarse-grained Fe- and Th-poor material. Consequently, finer grain-size fractions are richer in Fe and Th than coarser fractions [4,6]. At the Apollo 17 South Massif, the 2–4-mm fines are richer in Fe and Th than the <1-mm fines because they contain a greater ratio of mafic melt breccia to feldspathic highland material (~12:1) compared to the <1-mm fines (~1:1), probably because the feldspathic material is more friable [9,10].

Implications for Remote Sensing: Lunar regolith is a mixture of several lithologies that are typically petrogenetically unrelated. Many to most mare surfaces are contaminated with some nonmare material. Although the bulk composition of Apollo 16 soil, for example, corresponds to anorthositic norite, the regolith is, in fact, composed mostly of unrelated noritic (melt breccias) and anorthositic lithologies. Systematic variation in composition across an interface may lead to correlations that extrapolate toward the composition of a rock type, as with the Apollo 17 samples in Fig. 1 [4]. Techniques sensitive to grain size may find literature data on <1-mm fines inadequate for establishing ground truth.

Acknowledgments: This work was funded by NASA grant NAG5-4172 to L. A. Haskin.

References: [1] Morris R.V. et al. (1983) *Handbook of Lunar Soils*, JSC 19069, NASA Johnson Space Center, Houston. 914 pp. [2] Korotev R.L. et al. (1996) *Meteoritics & Planet. Sci.*, ***31***, 909–924. [3] Haskin L.A. (1998), *JGR*, ***103***, 1679–1689. [4] Korotev R.L. (1997) *Meteoritics & Planet. Sci.*, ***32***, 447–478. [5] Korotev R.L. (1976) *Proc. LSC 7th,* 695–726. [6] Papike et al (1981) *Rev. Geophys. Space Physics,* ***20***, 761–826. [7] Laul J.C. et al. (1987) *GCA*, ***51***, 661–673. [8] McKay D.S. et al. (1974) *Proc. LSC 5th*, 887–906. [9] Jolliff B.L. et al. (1996) *Meteoritics & Planet. Sci.*, ***31***, 116–145. [10] Korotev R.L. & Kremser D.T. (1992) *Proc. Lunar Planet. Sci., Vol. 22*, 275–301.