ON THE MATURITY OF LUNAR REGOLITH. Randy L. Korotev[1] and Richard. V. Morris[2], [1]Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130 (rlk@levee.wustl.edu), [2]Code SN, NASA Johnson Space Center, Houston, TX 77058 (richard.v.moris1@jsc.nasa.gov).

Spectral reflectance properties of the lunar regolith change as the regolith "matures" with exposure to the space environment; a regolith composed of fragments from freshly disaggregated rock is lighter, less red, and has more spectral contrast than the same regolith after it has received lengthy exposed to the solar wind, cosmic charged particles, and micro-meteorite impact [e.g., 1–3]. In this work we discuss some aspects of lunar regolith maturity based on the study of Apollo regolith samples that may be important to interpretation of data obtained remotely.

Background: The changes that occur to regolith exposed at the surface are collectively called *maturation*. These changes include decrease in mean particle size, increase in the concentration of those elements derived largely from the solar wind (H, He, C, N, noble gases) and micrometeorites (Ir, Au), increase in the abundance of nanophase Fe metal grains produced by reduction of lunar Fe by solar wind hydrogen, increase in the abundance of agglutinate particles (small glass-bonded soil aggregates produced by micrometeorite impact), and increase in the fraction of particle surfaces with amorphous rims and coatings. (See [4] for a discussion of these topics and many references.)

Most information about the relative maturity of lunar regolith samples, particularly with depth (e.g., [5–15]), has been obtained by measuring the relative concentration of nanophase metallic iron (I_s) with ferromagnetic resonance (FMR) in <1-mm fines. Division of I_s by the concentration of total iron, expressed as FeO, gives the maturity index I_s/FeO [e.g., 16]. It is necessary to divide I_s by the FeO concentration in order to obtain a maturity index because the concentration of nanophase metal is proportional to both the amount of surface exposure (i.e., maturity) and the amount of iron available for reduction in the soil.

Most lunar regolith cores were "double drive tubes" (e.g., 15010/11) that obtained material down to a depth of 50–60 cm, although a few single drive tubes were taken (~30 cm, e.g., 76001). One each "deep drill core" was taken on the Apollos 15, 16, and 17 missions (Fig. 1).

Results from Apollo: Most impact-derived soil (as opposed to volcanic-ash soils) collected at the surface of the Apollo sites is mature (I_s/FeO > 60, e.g., [16] and Fig. 1). However, based on the Apollo cores, the maturity of lunar regolith, as measured by I_s/FeO, decreases by about a factor of 2, on average, over the first half meter. Clearly, I_s/FeO must approach zero at some depth. However, based on the deep drill cores, maturity

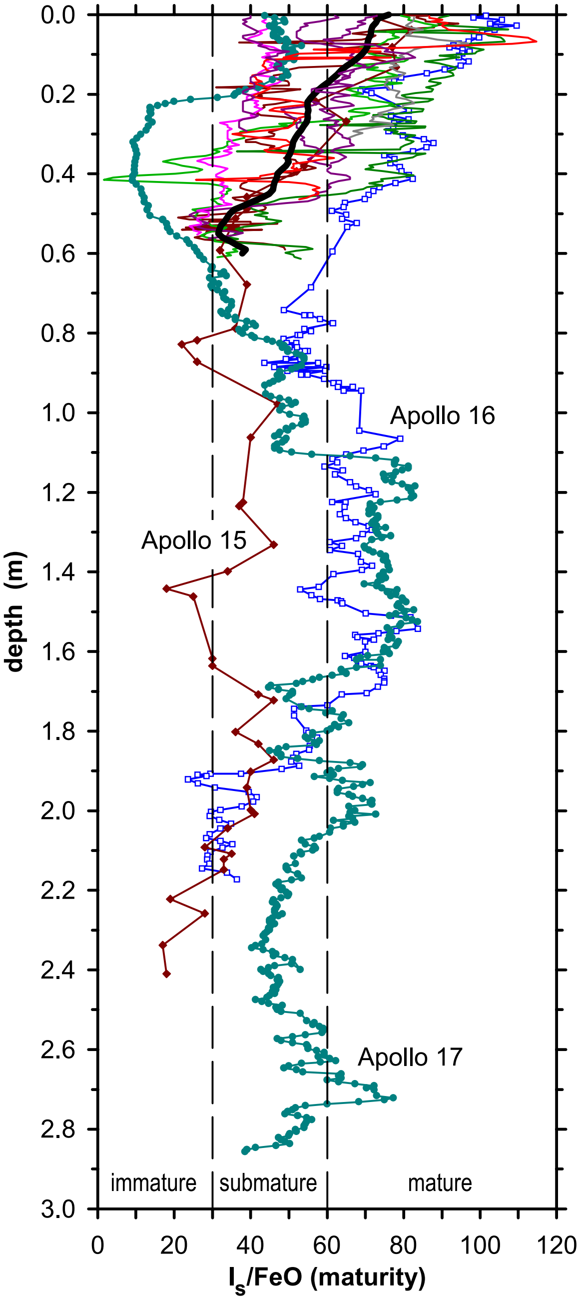

Figure 1. Variation of the maturity parameter I_s/FeO with depth in 12 lunar regolith cores (14210/11, 15001–6, 15007/8, 15009, 15010/11, 60001–7, 60009/10, 60013/ 14, 68001/2, 70001–9, 76001, 79001/2 [1-11]). The thick line above 60 cm depth is the smoothed average of all 12 cores. The labeled profiles are those of deep drill cores. The boundaries between immature, submature, and mature are those of Morris [12].

is not systematically less at 2 m depth than it is at 0.5 m (Fig. 1). If the upper half meter is taken as the average zone of *in situ* reworking, i.e., the region of "gardening" by small meteorites, then about 1 billion years of such gardening is required to extend the reworking zone to a depth of 0.5 m [17].

Interpretation: Soils of high maturity or very low maturity are the easiest to interpret. In a mature soil, much or most of the material has spent a relatively long time at the surface. Mature surface soil is the expected product in an area that has not been recently influenced by an impact large enough to penetrate the surface layer of mature regolith and deposit and mix ejecta of low maturity at the surface. In an highly immature soil, in contrast, very little of the material has had much exposure at the surface. Among Apollo samples, immature surface soils were only found near fresh craters or on steep slopes. Units of immature soil were found at depth in several cores, however (Fig. 1).

Soils of intermediate maturity are more difficult to interpret. If a fresh deposit of previously unexposed rock fragments is undisturbed by further large impacts, all particles at the surface experience the same degree of exposure and the soil matures uniformly. This is "soil evolution path 1" of [18], where "reworking dominates [large scale] mixing." I_s/FeO will increase with exposure time and during some range of time will pass through the submature zone of Fig. 1. In "soil evolution path 2," "[large-scale] mixing dominates reworking" [18]. If a mature soil of, e.g., I_s/FeO = 90 is mixed with an immature soil of the same composition but with I_s/FeO = 0, the resulting soil will be in the submature range, with I_s/FeO = 45. Thus, it is likely that the spectral reflectance properties will be different for a Path-1 soil and Path-2 soil, even if both have the same composition, mineralogy, and I_s/FeO, because of their different histories.

Effect of Grain Size: Spectral reflectance properties are strongly dependent on grain size [e.g., 19] and most quantities that increase with maturity also increase with decreasing grain size. For example, in the 60009/10 core, the value of I_s/FeO is typically a factor of two greater in the <20 µm grain-size fraction than in the 90–150 µm fraction [20,21]. More generally, log-log plots of the relative concentration of nanophase metallic iron versus soil-particle diameter are nearly linear [22]. The slopes of those plots varies in a regular way with maturity. For immature soils, the slope approaches –0.8. With increasing maturity, the slope flattens to a value of ~–0.2 for highly mature soils. The value of ~–0.8 represents the lower limit of production of nanophase metal as a function of particle diameter by micrometeorites. The value of ~–0.2 is a steady-state value and reflects a balance between the production of nanophase metal and the changes in particle size accompanying constructional (agglutination) and destructional (comminution) processes. The steady-state extreme represents Path-1 soils. For the Path-2 example given above, the mature component will have smaller average grain size, which leads to the same effect, i.e., the fine material will be more mature than the coarse material. As noted in a companion abstract on regolith composition [23], most measurements of bulk properties of lunar soils, such as I_s/FeO, have been made on <1-mm fines or <0.25-mm fines. Thus the statement, "sample 61121 is immature" applies strictly to the <1-mm grain-size fraction. The bottom line is that studies that compare maturity of Apollo soils as determined by spectral reflectance with tabulated values of I_s/FeO may encounter poor correlations that are related to grain-size and mixing effects. An additional complication is that spectra data may be more sensitive to the total concentration of nanophase metal (i.e., I_s) than to maturity [24].

Acknowledgment: This work was funded by NASA grant NAG5-4172 to L. A. Haskin and RTOP 344-31-10-21 to D. S. McKay.

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