

Systematic global mixing and melting in lunar soil evolution

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[1] We present a revised model of soil evolution constrained by the recent LSCC data for lunar soils. In addition to an observed universal increase in feldspathic components in the finer fractions of soils [Taylor *et al.*, 2001, 2003a, 2003b], both differential melting and lateral mixing processes appear to be required during the evolution of lunar soils. We propose mare-highland mixing of a significant glass component along with a preferential melting sequence for agglutinitic glass formation of: glass > plagioclase > pyroxene \gg ilmenite.

INDEX TERMS: 3655 Mineralogy and Petrology: Major element composition; 3672 Mineralogy and Petrology: Planetary mineralogy and petrology (5410); 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5470 Planetology: Solid Surface Planets: Surface materials and properties; 6250 Planetology: Solar System Objects: Moon (1221). **Citation:** Pieters, C. M., and L. A. Taylor, Systematic global mixing and melting in lunar soil evolution, *Geophys. Res. Lett.*, 30(20), 2048, doi:10.1029/2003GL018212, 2003.

1. Introduction

[2] Since return of the first lunar samples it has been well known that lunar soils are quite different from pulverized lunar rocks and breccias in both optical and compositional properties [e.g., McKay *et al.*, 1991; Pieters, 1993]. Soils were found to accumulate distinctive glass-welded aggregates (agglutinates) as the result of multiple processes active in the space environment, many of which are driven by micrometeorite impacts. Using modern analytical techniques, coordinated detailed chemical, petrographic, and spectral analyses of a suite of mare and highland soils and their agglutinate constituents have been prepared and analyzed by the Lunar Soil Characterization Consortium (LSCC) [Taylor *et al.*, 2001, 2003a, 2003b]. The LSCC studies confirmed that the proportion of agglutinates (as measured by agglutinitic glass content) increases with increasing exposure to the space environment but identified nanophase reduced iron (npFe⁰) deposited on the surface of grains as the principal carrier of optical alteration effects [Keller and McKay, 1997; Taylor *et al.*, 2001; Noble *et al.*, 2001]. For an individual soil the LSCC studies also showed that the proportion of agglutinitic glass as well as the feldspathic component as seen in the bulk chemistry increases systematically with decreasing particle size for all soil types.

[3] For the LSCC soil suite of mare basalts, the composition of the glass within agglutinates mimicked the composition of the very finest fraction of the soils [Taylor *et al.*,

2001], implying that the glass was derived from melting of the finest fraction, a concept proposed by Papike *et al.* [1981] from initial analyses of lunar soils. However, when LSCC highland soils from Apollo 14 and 16 were studied with the same detail [Taylor *et al.*, 2003a, 2003b], agglutinitic glasses did not follow the compositional trend seen for mare soils. This required additional models for soil evolution to be considered [Pieters and Taylor, 2003]. We discuss a revised model of soil evolution that is constrained by these data and requires both fractionation through differential melting as well as lateral transport mixing processes.

2. LSCC Compositional Data for Lunar Soils

[4] The LSCC soil suite consists of nine mare soils (from Apollo 11, 12, 15, and 17) and ten highland soils (from Apollo 14 and 16) that span a range of exposure history, or maturity [Taylor *et al.*, 2001, 2003a, 2003b]. Since it had been shown that the optical properties of lunar soils were controlled by the smaller size fractions [Pieters *et al.*, 1993], the LSCC concentrated on detailed analysis of these size fractions, so that the data would be applicable to remote analyses. Each soil was prepared at the NASA Johnson Space Center under the direction of D. McKay into three size fractions (20–45, 10–20, and <10 μm) as well as a “bulk” <45 μm sample. Representative splits were sent to each consortium member for coordinated analyses. Typical reflectance spectra for the size separates of two soils are shown in Figure 1, illustrating principal differences between mare and highland soils (see Pieters *et al.* [1993] for discussion of diagnostic features).

[5] LSCC measurements for each sample included bulk major- and minor- element composition, mineral abundance and composition (for the three discrete size fractions), the “maturity parameter” I_{g}/FeO [Morris, 1976, 1977, 1978], and spectral reflectance (0.3 to 2.6 μm). The data allow the bulk composition of each soil size fraction to be compared with the composition of the glass phase within the agglutinates produced during the soil forming process (note that mineral fragments within agglutinates are counted as such for the modal abundance determinations). See Taylor *et al.* [2001] for details of consortium procedures. An overview of compositional trends with particle size for soil separates and agglutinitic glass is shown in Figure 2. For ease of comparison, all data are scaled to the composition of the bulk <45 μm soil.

2.1. Mare Soils

[6] The feldspathic component of all mare soils studied increases with decreasing particle size and the composition

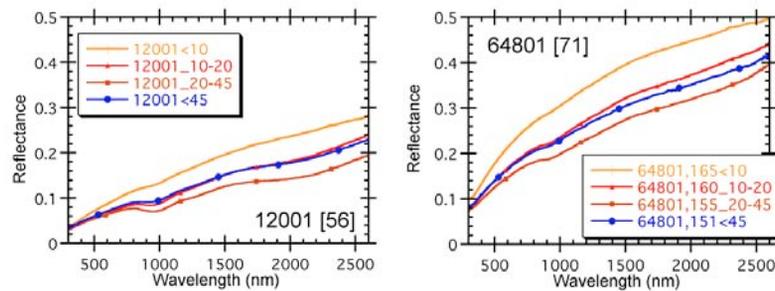


Figure 1. Typical bidirectional reflectance spectra of the size separates and “bulk” $<45 \mu\text{m}$ sample for a mare (12001) and a highland (64801) soil. See color version of this figure in HTML.

of agglutinitic glass is closest to that of the smallest size fraction ($<10 \mu\text{m}$) [Taylor *et al.*, 2001]. This compositional relationship is illustrated by the variations of FeO and Al_2O_3 shown in Figure 3 for the particle size separates of mare soils along with the average composition of agglutinitic glass from the same separates. The observed trend is very regular for all lunar soils from different Apollo sites. It should be noted that even though agglutinitic glass is heterogeneous [e.g., Basu *et al.*, 2002] and standard deviation of their composition about the mean for any sample is quite large, agglutinitic glass average compositions for mare soils clusters near the composition of the finest fraction of the bulk soil. This observation originally led us to conclude [Taylor *et al.* [2001] that the data appeared to support the fusion of the finest fraction (F^3) model of agglutinate formation by Papike *et al.* [1981].

[7] A perplexing aspect of the data, however, was TiO_2 of mare soil size separates compared to that of the agglutinitic glass, especially for Ti-rich soils. Although ilmenite is present in the finest fraction in proportions correlated to the type of basalt [Taylor *et al.*, 2001], the agglutinitic glass is observed to be depleted in TiO_2 by more than a factor of two (see 10084 and 79221 in Figure 2), strongly suggesting ilmenite did not enter the glass in proportion to its abundance [Pieters, 2002].

2.2. Highland Soils

[8] Similar detailed analyses for a suite of soils from Apollo 14 and 16 are presented in Taylor *et al.* [2003a, 2003b]. As shown in Figures 4 and 5, the feldspathic component also increases with decreasing particle size for all the Apollo 14 and Apollo 16 soils. This trend parallels

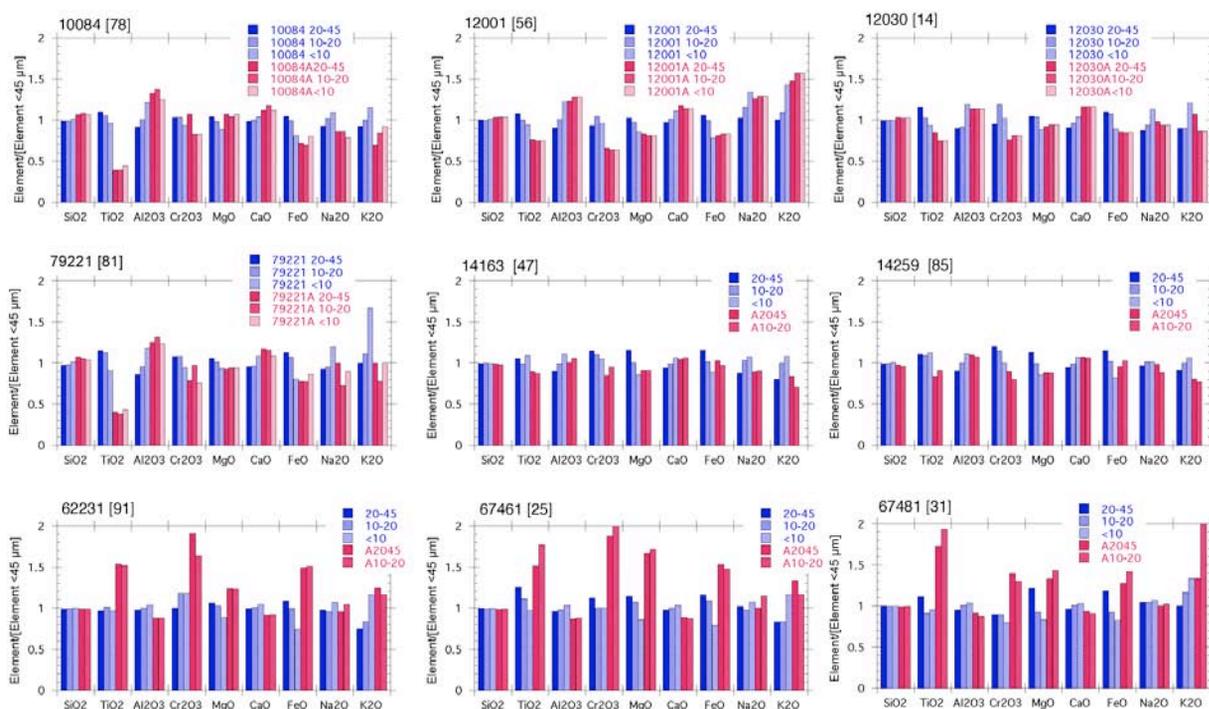


Figure 2. Chemistry of soil components relative to the chemistry of the bulk soil ($<45 \mu\text{m}$) for representative LSCC soils. The first three bars (blue shades) are the composition of three soil size separates (see legend). These are followed by the average composition of agglutinitic glass (red shades) present in the indicated size separate. The number in brackets is the I_g/FeO value for the bulk soil. See color version of this figure in HTML.

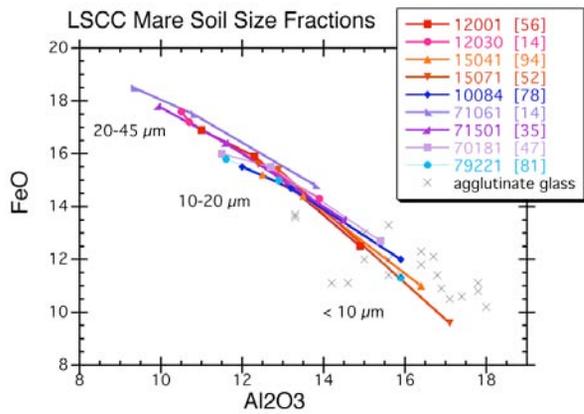


Figure 3. Composition of LSCC mare soils and agglutinitic glass (agg) for different size fractions. See color version of this figure in HTML.

that observed for mare soils and is consistent with the expected differential comminution of plagioclase during soil formation that concentrates plagioclase components into the finer fractions [e.g., Hörz *et al.*, 1984].

[9] The mean composition of the agglutinitic glass for these highland soils, however, is clearly not associated with the composition of the finest fraction. This is most obvious for Apollo 16 where the glasses are more FeO-rich than even the bulk soil. Although the standard deviation of the average agglutinitic glass compositions are also large, the data for highland soils are systematic.

3. Discussion

[10] The combined LSCC FeO vs Al₂O₃ data for both mare and highland soil size fractions and agglutinitic glass components are shown in Figure 6. The well-known compositional trend from mare to highland materials is evident, with mare soils being more iron-rich and highlands soils more aluminum-rich. In first appearances, the agglutinitic glass compositions seem to form a mixing line between mare and highland soils.

[11] Explanations for the compositional trends of agglutinitic glass observed in Figure 6 must be linked to the evolution of soils and the origin of the agglutinitic glass component. Possible processes involved include:

[12] a. Fusion of the Finest Fraction (F³) for agglutinitic glass, as originally proposed by Papike *et al.* [1981].

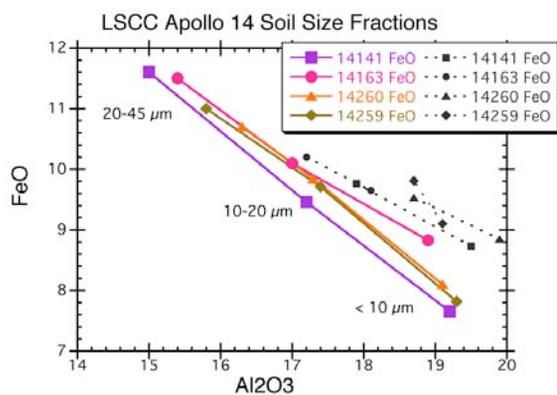


Figure 4. Composition of LSCC soils and agglutinitic glass (agg) for different size fractions of Apollo 14 soils. See color version of this figure in HTML.

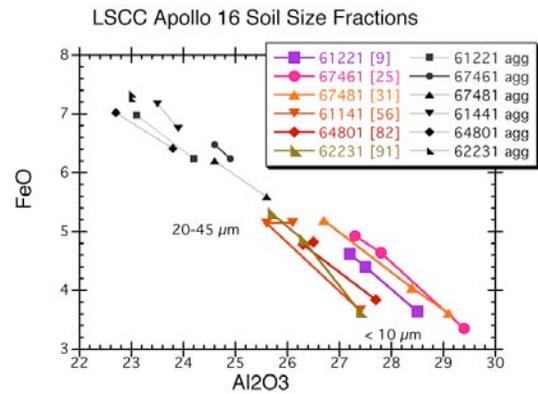


Figure 5. Composition of LSCC soils and agglutinitic glass (agg) for different size fractions of Apollo 16 soils. See color version of this figure in HTML.

[13] b. Mare - Highland physical mixing (e.g., impact excavation and redistribution) and incorporation into the glass component.

[14] c. Foreign (e.g., meteoritic) contamination of soils.

[15] d. Selective melting of soil species resulting in a glass composition different from bulk soil composition.

[16] e. A combination of the above.

[17] f. Something else (none of the above).

[18] There are serious flaws with the first four options. The compositional trends of highland soils in Figures 4 and 5 are *not* consistent with agglutinitic glass being formed by simple melting of the finest fraction. Although the agglutinitic glass data appear to form a separate mixing line between highland and mare soil compositions in Figure 6, this cannot result from a simple physical mixing of two lithologies because the mixing would have to affect *only the glass component* without influencing the host bulk soil by the same amount. This relation is especially notable with Apollo 14 glasses, where the soils themselves are below the mixing line. Global contamination of the agglutinitic glass by foreign material is viable, but there is no common meteorite composition that could produce the observed trends for the combination of soils. The depletion of TiO₂ in agglutinitic glass of Ti-rich mare soils (Figure 2) strongly suggests differential melting of mineral species during glass formation. Please note that this differential melting refers to cumulative products and statistical averages; individual

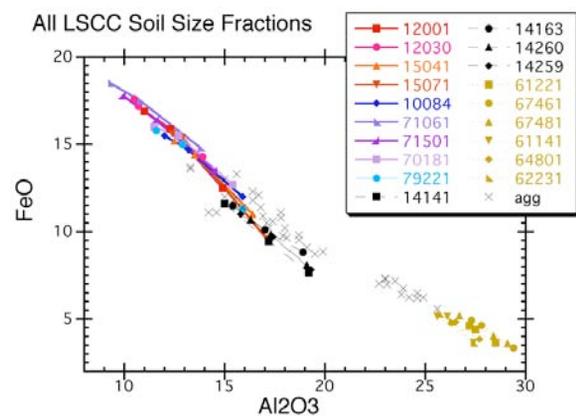


Figure 6. Composition of all mare and highland LSCC soil size fractions and agglutinitic glass (agg). See color version of this figure in HTML.

grains are actually very heterogeneous. Impact experiments [Stöffler, 1971; Schaal et al., 1979; Hörz et al., 1991] indicated that plagioclase melts before pyroxene and olivine. On the other hand, the enrichment of TiO₂ and FeO, and to a lesser extent MgO and Cr₂O₃ in agglutinitic glass from Apollo 16 soils (see Figure 2) suggests at least one mafic material enters the melt before plagioclase. None of the specific mechanisms listed above can alone produce all the observed properties.

[19] This conundrum can be solved with a combination model (e) for mixing and melting during soil evolution. A summary of constraints from LSCC data for any model includes: 1) the feldspathic component of soil separates increases with decreasing particle size; 2) the agglutinitic glass component also increase with decreasing particle size; 3) the agglutinitic glasses form an apparent mixing line between bulk highland soil and bulk mare soil compositions; 4) agglutinitic glass in mare soils is depleted in TiO₂; 5) agglutinitic glass in highland soils is rich in basaltic components (FeO, TiO₂, MgO).

[20] Some form of differential melting during glass production appears to be necessary based on the apparent reluctance of ilmenite to enter the mare soil glasses (Figure 2). This observation combined with the results of impact experiments would predict a differential melting sequence during micrometeorite impact of plagioclase > pyroxene ≫ ilmenite. Such a sequence of bulk preferential melting could account for the composition of glasses in mare soils, but is inadequate for highland soils because they need a distinct mafic component to go into the melt before plagioclase.

[21] However, some form of mare-highland mixing is also likely based on Figure 6. Wholesale mixing of only lithic clasts will not produce the mafic trend of glasses in highland soils because plagioclase will still melt before pyroxene and the Apollo 16 glass composition will not be more mafic than the bulk soil.

[22] Our new model of soil evolution involves two additional, but justifiable, assumptions. First, the suspected large scale mixing between mare and highlands is real, but contains a significant glass component. This could be accomplished either from a cumulative history of impacts (with distant ejecta containing significant glass) or by electrostatic processes (which mobilize the finer, glass-rich particles) [e.g., Criswell, 1972; Lee, 1996; Sickafoose et al., 2002]. In either case, the minor but detectable mare-highland mixing is distinctly glass-rich. Secondly, the regolith differential melting sequence is actually glass > plagioclase > pyroxene ≫ ilmenite. The assumption that lunar glass melts before plagioclase in micrometeorite impacts is likely, but should be tested in the laboratory. Furthermore, there is a suggestion that lunar mafic-rich glass is more likely to melt than Al-rich glass since mare soils tend to accumulate a higher overall abundance of agglutinitic glass than highland soils [see Taylor et al., 2001, 2003b].

[23] We acknowledge that our soil evolution model is necessarily dependent on the small number of sites for which samples are available. For example, the model suggests the source of the mafic glass component in highland soils is the maria, but an alternate source for Apollo 16 might be the abundant “mafic impact melt breccias” thought to be derived from Imbrium [Korotev, 1997] if it can be shown that they enter Apollo 16

agglutinitic glass *preferentially*. Nevertheless, the soil evolution model presented above is consistent with data from all the Apollo sites, and LSCC analysis of Luna soils is underway.

4. Summary and Conclusions

[24] Detailed modal abundances and chemistry of the minerals and glasses in representative mare and highland soils have been measured by the LSCC with modern instruments. When all Apollo sites are considered, systematic trends observed between agglutinitic glass and the soils from which they are derived provide near global information about lunar soil formation and space weathering processes. Favored simple models for glass formation are discounted, but the data indicate that lateral mare-highland mixing and selective melting of soil phases are both significant parts of soil evolution.

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