

**The Spectral Characteristics of Lunar Agglutinates: Visible–Near-Infrared
Spectroscopy of Apollo Soil Separates**

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Separation of agglutinates and non-agglutinates

Soil	Step 1: After magnetic separation (% mass)		Step 2: After manual refinement (% mass)	
	Low-aggl remnant (less magnetic)	Aggl-rich separate (highly magnetic)	Non-agglutinates	Agglutinates
67461	87	13	96	4
61141	80	20	93	7
62231	77	23	87	13
<i>62231</i>	--	--	79	21
14259	64	36	75	25
15041	57	43	66	34
79221	63	37	87	13

Table S1. Mass fractions of soil separates after each step of magnetic–manual separation. Italics indicate the 62231 sample that was only manually separated.

Soil	Non-agglutinate purity		Agglutinate purity	
	Ratio of correct to total particles	Percentage (nearest 5%)	Ratio of correct to total particles	Percentage (nearest 5%)
67461	43/46	95	45/50	90
61141	62/70	90	43/44	95
62231	51/58	90	43/45	95
<i>62231</i>	<i>60/67</i>	<i>90</i>	<i>50/65</i>	<i>75</i>
14259	66/78	85	46/48	95
15041	53/62	85	61/66	90
79221	45/54	85	55/58	95

Table S2. Purity of non-agglutinate and agglutinate separates. Purity estimates are based on counting a sample of particles in a microscope image of each separate and categorizing the particles as non-agglutinate or agglutinate. Italics indicate the 62231 sample that was only manually separated.

Spectroscopy apparatus: Reflectance Experiment Laboratory (RELAB)

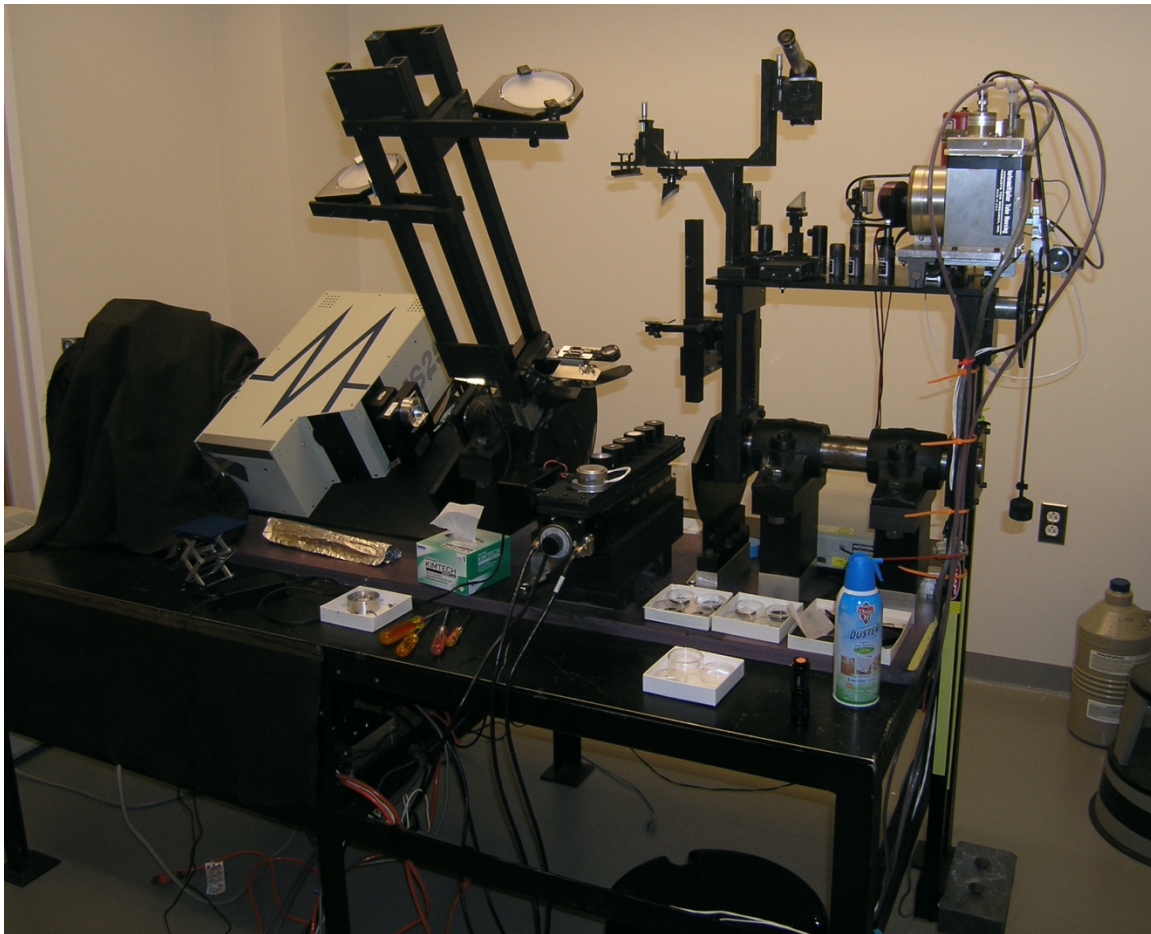


Figure S1. The RELAB bidirectional reflectance spectrometer system at Brown University.

Wavelength region (μm)	Lamp	Detector
0.32–0.44	Xenon	PMT
0.40–0.88	Halogen	PMT
0.86–1.80	Halogen	InSb
1.78–2.55	Halogen	InSb

Table S3. RELAB bidirectional reflectance spectrum wavelength regions. While spectra for the four regions are measured and calibrated against Spectralon separately, the spectra are then stitched together to form a single, continuous spectrum.

Dish diameter (mm)	Detector aperture size (mm)	Detector field of view (mm) ^a	Estimated sample mass (mg)
5	5	4	14–19 ^b
9	9	7.2	-- ^c

Table S4. RELAB measurement parameters corresponding to each sample dish size. Spectra were gathered using the 5 mm sample dish for all samples, while for a few samples (non-agglutinate separates of soils 14259, 61141, 67461, and 79221) additional spectra were gathered using the 9 mm sample dish.

^aDetector field of view is 80% of aperture size.

^bThe range of sample masses in the 5 mm dish for separates of soils 14259, 15041, 61141, and 79221. Other sample masses for the 5 mm dish were not measured.

^cSample masses for the 9 mm dish were not measured.

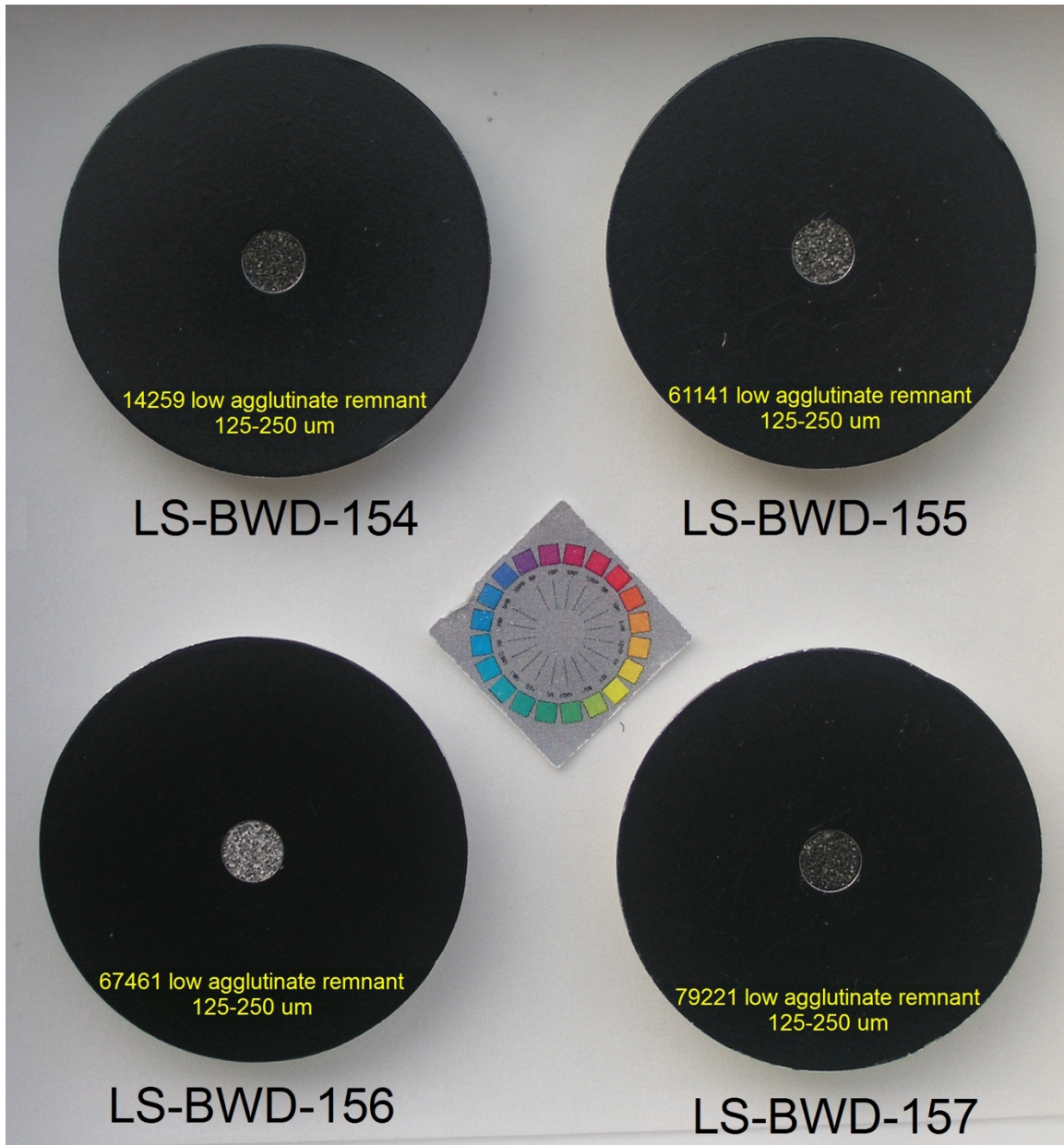


Figure S2. RELAB sample dishes (**5 mm diameter**) filled with 125–250 μm non-agglutinate separates (described in the image as “low agglutinate remnant”) of soils 14259, 61141, 67461, and 79221. Sample dishes are coated with black Teflon.

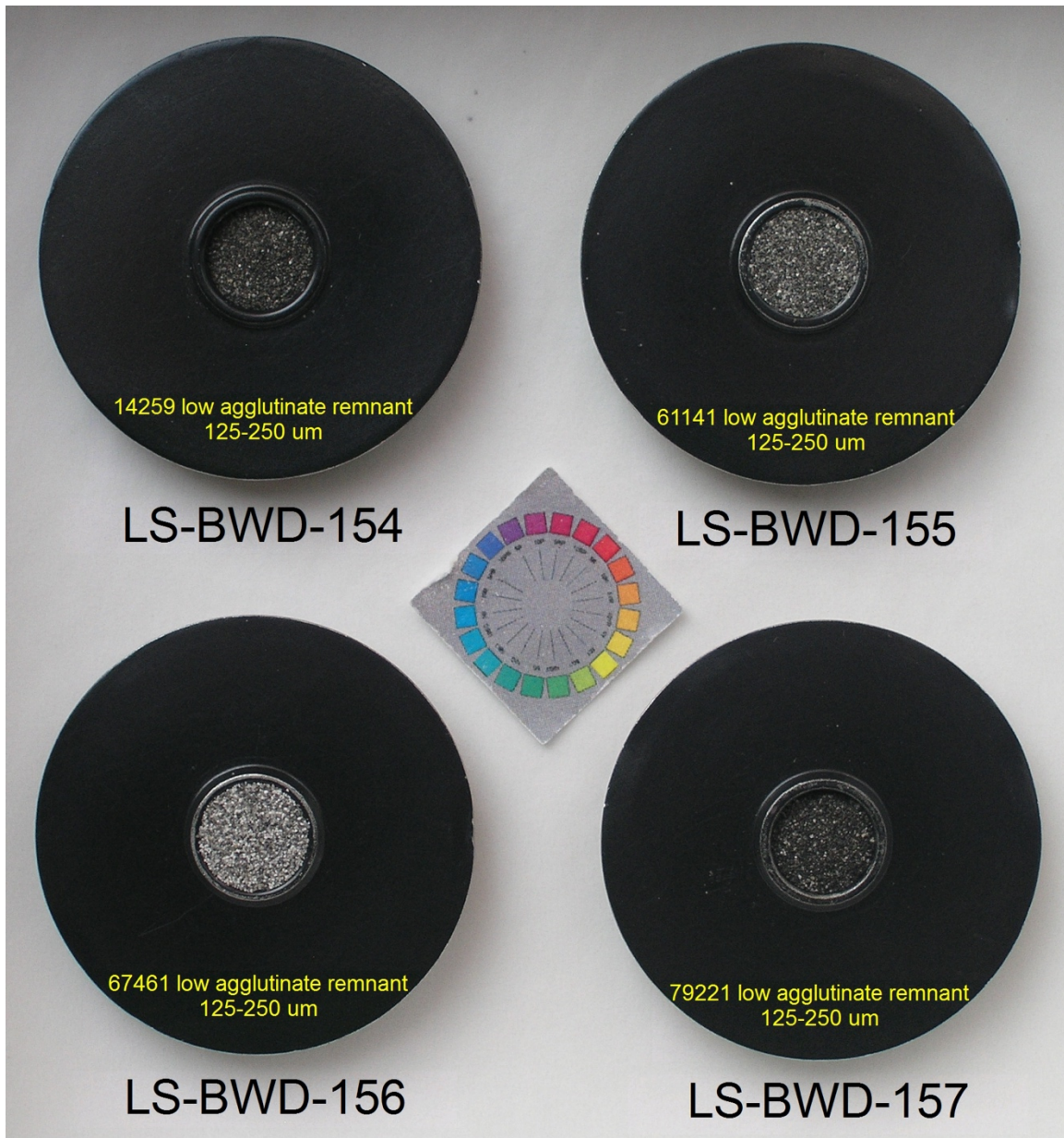


Figure S3. RELAB sample dishes (**9 mm diameter**) filled with 125–250 μm non-agglutinate separates (described in the image as “low agglutinate remnant”) of soils 14259, 61141, 67461, and 79221. Sample dishes are coated with black Teflon.

Sources of RELAB spectral variability

Text S1.

In this work we are primarily interested in how spectral properties of lunar soils vary according to separate type (unsorted, non-agglutinates, agglutinates) and maturity. However the reflectance spectra we obtained using RELAB's bidirectional reflectance spectrometer could also be affected by additional factors related to the measurement process:

- (1) the use of a depolarizer on the illumination source,
- (2) the size of the sample dish,
- (3) the width of the illumination beam, and
- (4) the specific soil particles that end up at the measured sample surface (i.e., sample heterogeneity).

Most of our measurements use a consistent set of the first three factors: a calcite depolarizer over the wavelength range of 0.32–1.80 μm , a 5 mm wide sample dish, and a 9 mm wide beam. However there are potential tradeoffs in these choices (e.g., using a 9 mm wide beam with a 5 mm wide sample dish ensures that all of the sample surface is illuminated, but does the light reflected off of the area around the sample dish add an unwanted signal to the measured reflectance spectrum?). Moreover, we cannot control for the fourth factor of sample heterogeneity, which may impact reproducibility of the measured spectra.

To test these tradeoffs and assess the reproducibility of our findings, we measured reflectance spectra of the same samples with different sets of measurement factors. Although it was not feasible to measure a sufficient number of spectra for a rigorous statistical assessment (due to the time-intensive nature of the spectral measurements), we were able to broadly assess the relative spectral impact of each measurement factor. We find that, of these four measurement factors, sample heterogeneity is generally the dominant source of spectral variability for our samples.

Given that the spectral variability due to sample heterogeneity seems to overshadow variability due to the other three measurements factors, our analyses in the main text use spectral averages that are calculated based on almost all the measured spectra (i.e., spectra with different depolarizer setups (except the no depolarizer setup), sample dish sizes, and beam widths).

Our assessment of the four measurement factors is described in further detail below.

(1) Depolarizer setup

The RELAB bidirectional spectrometer (wavelength range 0.32–2.55 μm) uses a monochromator that polarizes light. To better simulate (unpolarized) sunlight, a calcite depolarizer was placed between the monochromator and the sample over the wavelength range of 0.32–1.8 μm . However, the depolarizer was removed over the range of 1.8–2.55 μm due to calcite's absorption features in this wavelength regime. This depolarizer setup (which we henceforth call LowDep to indicate the low wavelength coverage of the depolarizer) was used when gathering nearly all spectra presented in the main text.

To assess the spectral impact of using the depolarizers, we compared reflectance spectra gathered for four samples with four different depolarizer setups (Figures S4, S5). These depolarizer setups were as follows:

- **NoDep**: no depolarizer was used
- **LowDep**: the calcite depolarizer was used over the wavelength range of 0.32–1.80 μm
- **FullDep**: the calcite depolarizer was used over 0.32–2.55 μm
- **2Dep**: the calcite depolarizer was used over 0.4–1.8 μm while a quartz depolarizer was used over 0.32–0.4 μm and 1.8–2.55 μm .

The 2Dep setup is RELAB's most recently implemented depolarizer setup. The quartz depolarizer was added to the setup because it better transmits UV light than the calcite depolarizer and also has no absorption band in the 1.8–2.55 μm wavelength regime (but is less effective at depolarizing light in the 0.4–1.8 μm regime where the calcite depolarizer is still used). However we started gathering spectra before the 2Dep setup was implemented and when the LowDep setup was the norm so, to maintain consistency, almost all of our spectra were gathered using the LowDep setup.

Among our measured spectra for different depolarizer setups (Figures S4, S5), some are repeat measurements between which the sample was poured out and back into the sample dish. With these repeat measurements we assess whether spectral differences can be attributed to the depolarizer setup or might simply be variance arising from sample heterogeneity (i.e., due to different soil particles being at the measured sample surface).

Comparing these spectra, there is significant overlap in the spread of individual spectra using each depolarizer setup (e.g., for the spectra of the 79221 agglutinates separate, the set of two FullDep spectra and the set of two LowDep spectra show more differences within each set rather than between them). Given this, the sensitivity of the measured spectrum to the depolarizer setup seems to be negligible compared to the sensitivity to sample heterogeneity. Therefore in the main text, when we speak of mean spectra, we are averaging together the spectra that used the LowDep setup alongside

the ones that used the 2Dep and FullDep setups (but omitting spectra gathered with the NoDep setup, as it is not a typical measurement setup used by RELAB).

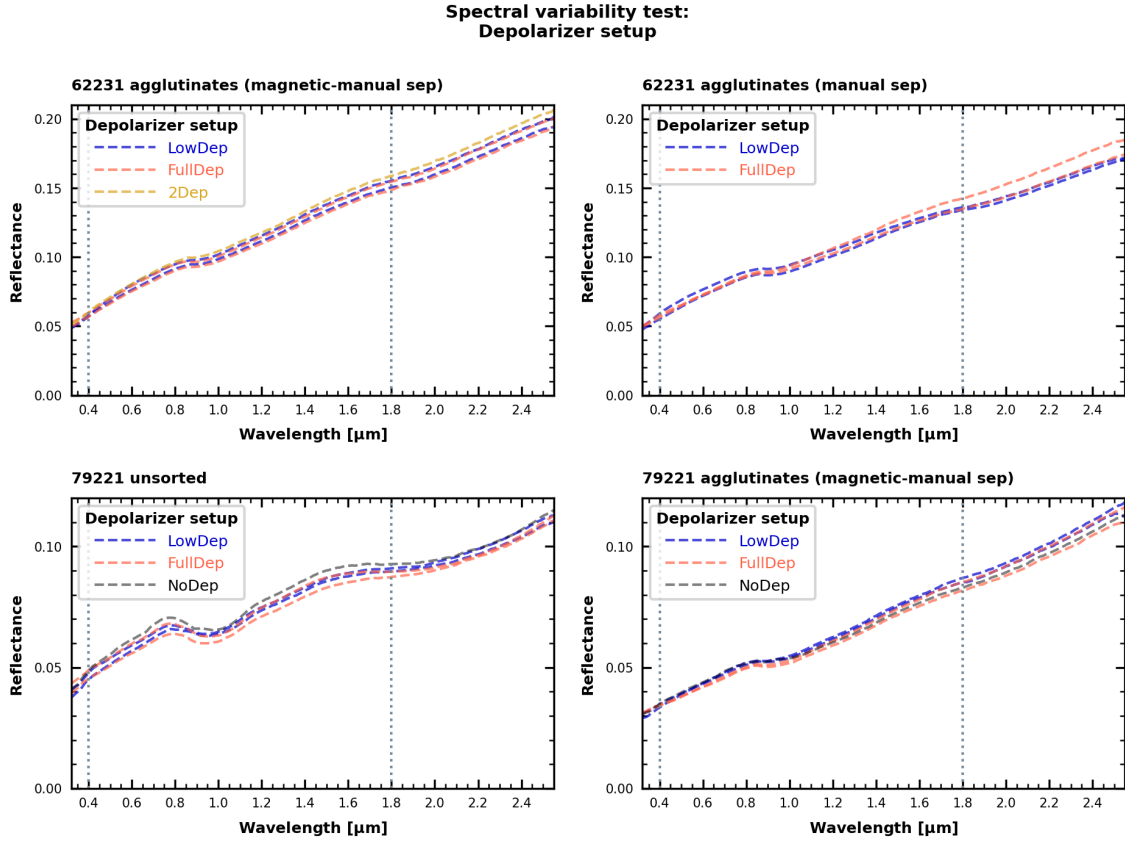


Figure S4. Reflectance spectra of four soil separates using four depolarizer setups: (LowDep) calcite depolarizer for 0.32–1.80 μm; (FullDep) calcite depolarizer for the full wavelength range of 0.32–2.55 μm; (2Dep) calcite depolarizer for 0.4–1.8 μm and quartz depolarizer for 0.32–0.4 μm and 1.8–2.55 μm; and (NoDep) no depolarizer.

**Spectral variability test:
Depolarizer setup**

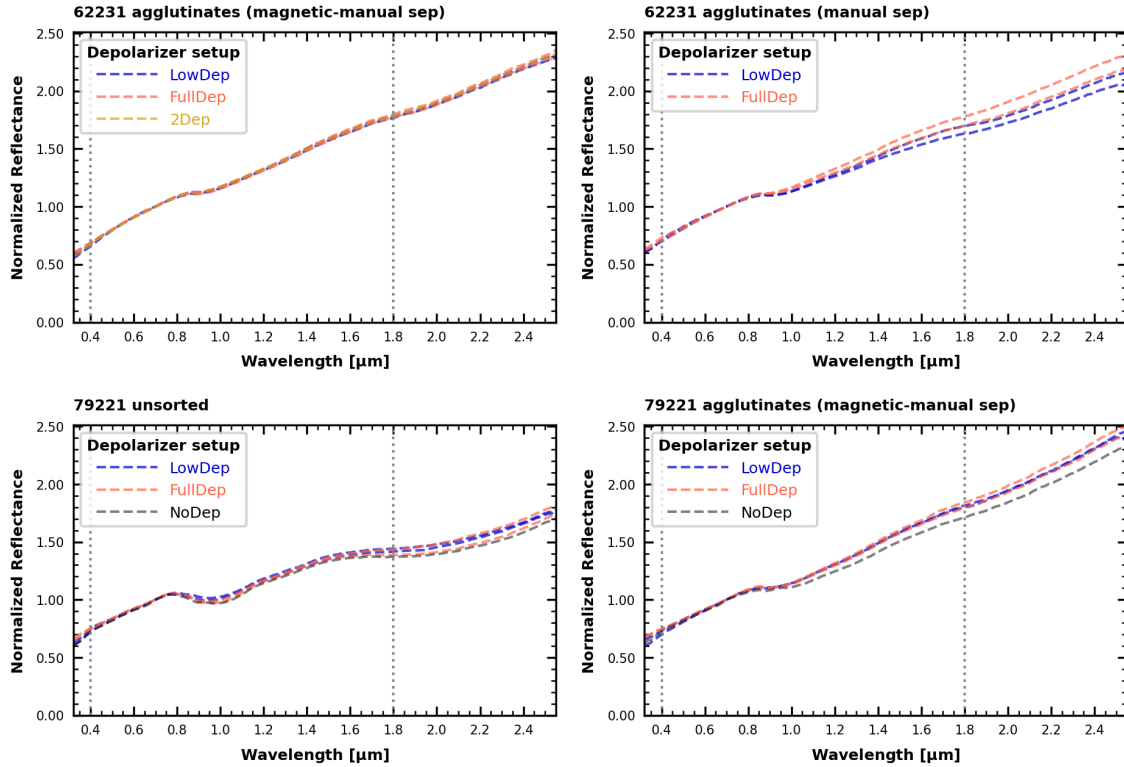


Figure S5. Same as [Figure S4](#), but with reflectance normalized to its value at 0.7 μm .

(2) Sample dish size

RELAB offers multiple sample dish sizes for spectral measurements, with larger dishes offering more sample surface (and therefore more soil particles contributing to the measured spectrum), but requiring more sample mass to fill. We used the 5 mm diameter sample dish ($\sim 14\text{--}19$ mg) as our standard dish size for measurements, as it was the largest dish that could be filled with the agglutinate separates. However, for four of the non-agglutinate samples we also used a 9 mm diameter dish and compared the resulting spectra to the spectra measured when using a 5 mm diameter dish.

In comparing the spectra ([Figures S6, S7](#)), we find that the measurements made using the 9 mm dish are comparable to those made using the 5 mm dish. This suggests that the spectral variability due to dish size is negligible compared to the variability due to sample heterogeneity. Therefore in the main text, when we speak of mean spectra, we are averaging together the spectra that used the 5 mm dish size alongside the ones that used the 9 mm dish size.

Spectral variability test:
Dish size

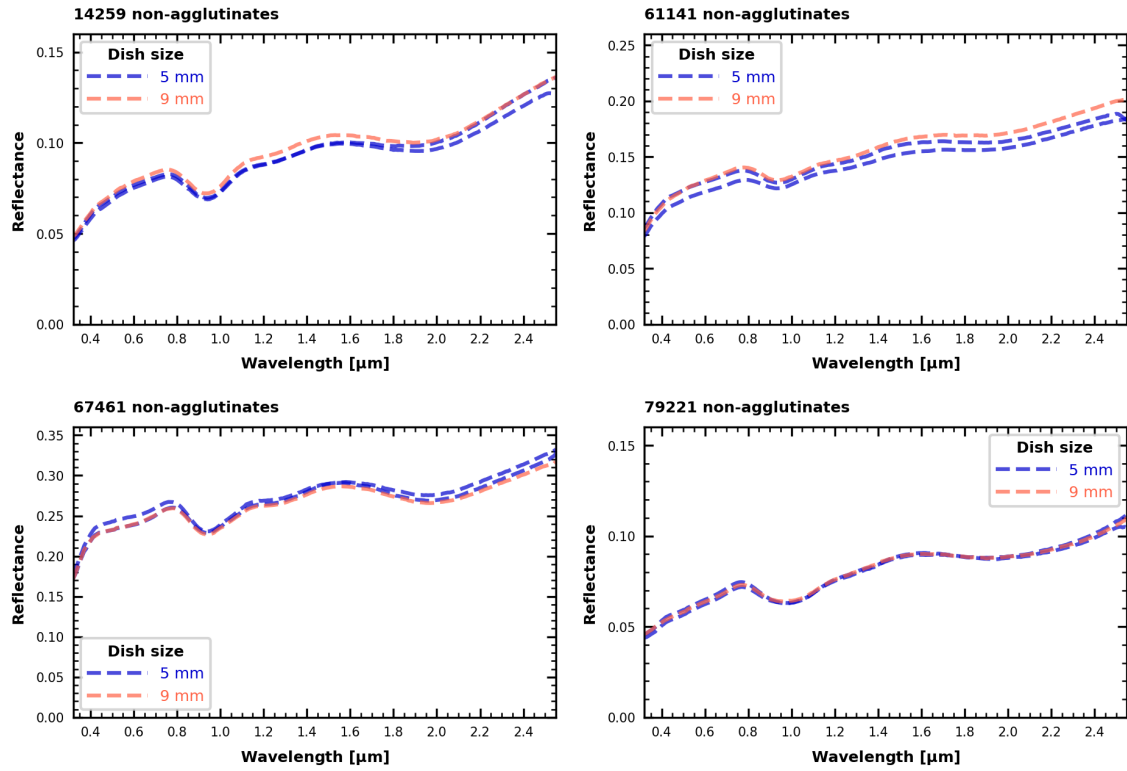


Figure S6. Reflectance spectra of four soil separates using two sample dish sizes: 5 mm and 9 mm diameter.

Spectral variability test:
Dish size

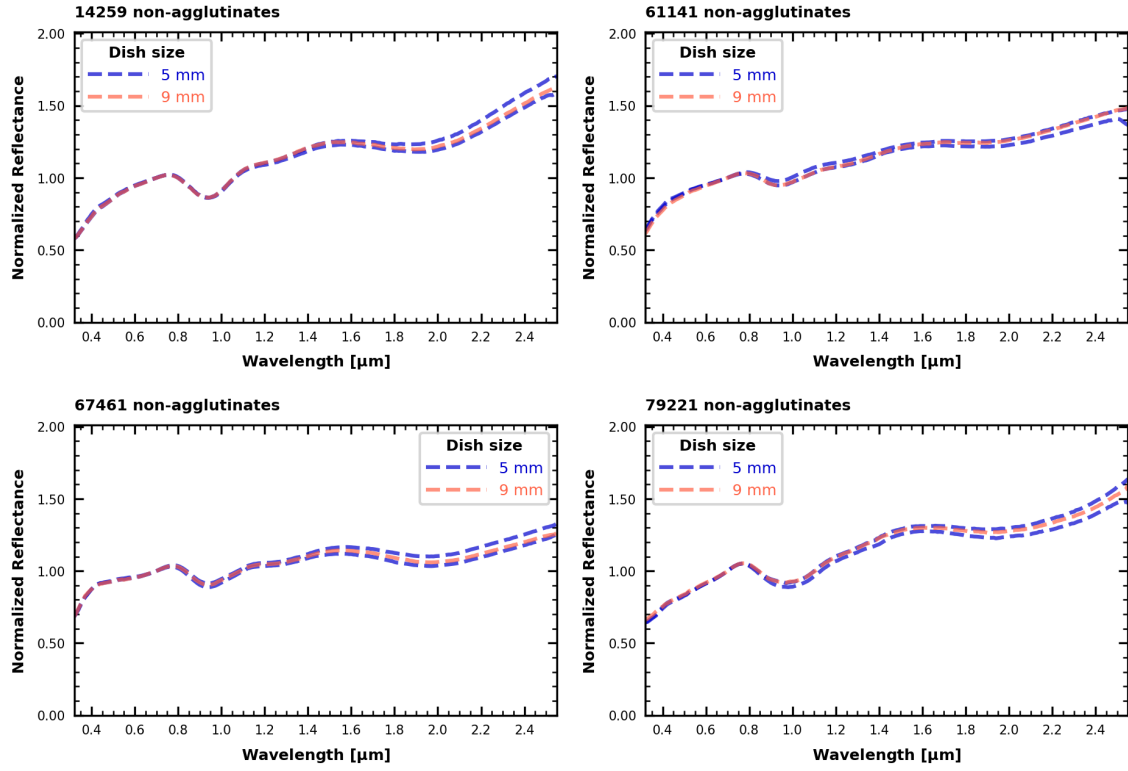


Figure S7. Same as [Figure S6](#), but with reflectance normalized to its value at 0.7 μm .

(3) Beam width

For most of our RELAB spectral measurements the sample was illuminated with a 9 mm diameter beam (but note that the spot size on the sample dish is elongated by a factor of $1/\cos(30^\circ) \approx 1.15$ due to the 30° incidence angle). This beam width, when used with the 5 mm diameter sample dish, ensures that the entire sample surface is illuminated. However this also means that the beam illuminates an area around the sample dish, which could add an unwanted signal of reflected light to the measured spectrum. The sample dish (and the area around it) is coated with black Teflon to minimize such reflected light (as seen in [Figures S2, S3](#)), but given the low reflectance of some of our samples we tested whether this additional signal substantially influenced the measured spectra. To do so, we compared spectra for three samples when measured using the 9 mm diameter beam versus the 4 mm diameter beam (which did not illuminate any area outside of the 5 mm sample dish).

In comparing the spectra ([Figure S8](#)), we find that the measurements made using the 4 mm beam are generally comparable to those made using the 9 mm beam. The exception is the 15041 unsorted sample, for which the spectrum measured using the 4 mm beam was noticeably higher in reflectance than the spectra measured using the 9 mm beam. Given the variance in the spectra due to sample heterogeneity—note the spread in the spectra measured using the 4 mm beam—it is conceivable that the spectral differences when using the 4 mm beam could be due to sample heterogeneity rather than due to the beam width. Moreover, if the beam width did affect the spectrum, we would have expected the reflectance when using the 4 mm beam to be *lower*, not higher (since there would be less signal contributed by the area surrounding the sample dish). This suggests that the spectral variability due to beam width is negligible compared to the variability due to sample heterogeneity. In the main text, when we speak of mean spectra, we are averaging together the spectra that used the 9 mm beam width alongside the ones that used the 4 mm beam width.

(4) Sample heterogeneity

As already discussed in the three sections above, the choice of depolarizer setup, sample dish size, and beam width do not seem to have as much of an impact on the measured spectra as does sample heterogeneity.

Note that we assume all spectral variability that cannot be attributed to depolarizer setup, sample dish size, or beam width is attributable to sample heterogeneity. We assume this because we find no other potential source of the spectral differences that we see when measuring a sample, pouring it out of the sample dish and back in, and remeasuring it. For example, the instrumental error of the spectrometer is less than 0.25% in reflectance, which is too small to explain the variability we attribute to sample heterogeneity.

Spectral variability test: Beam width

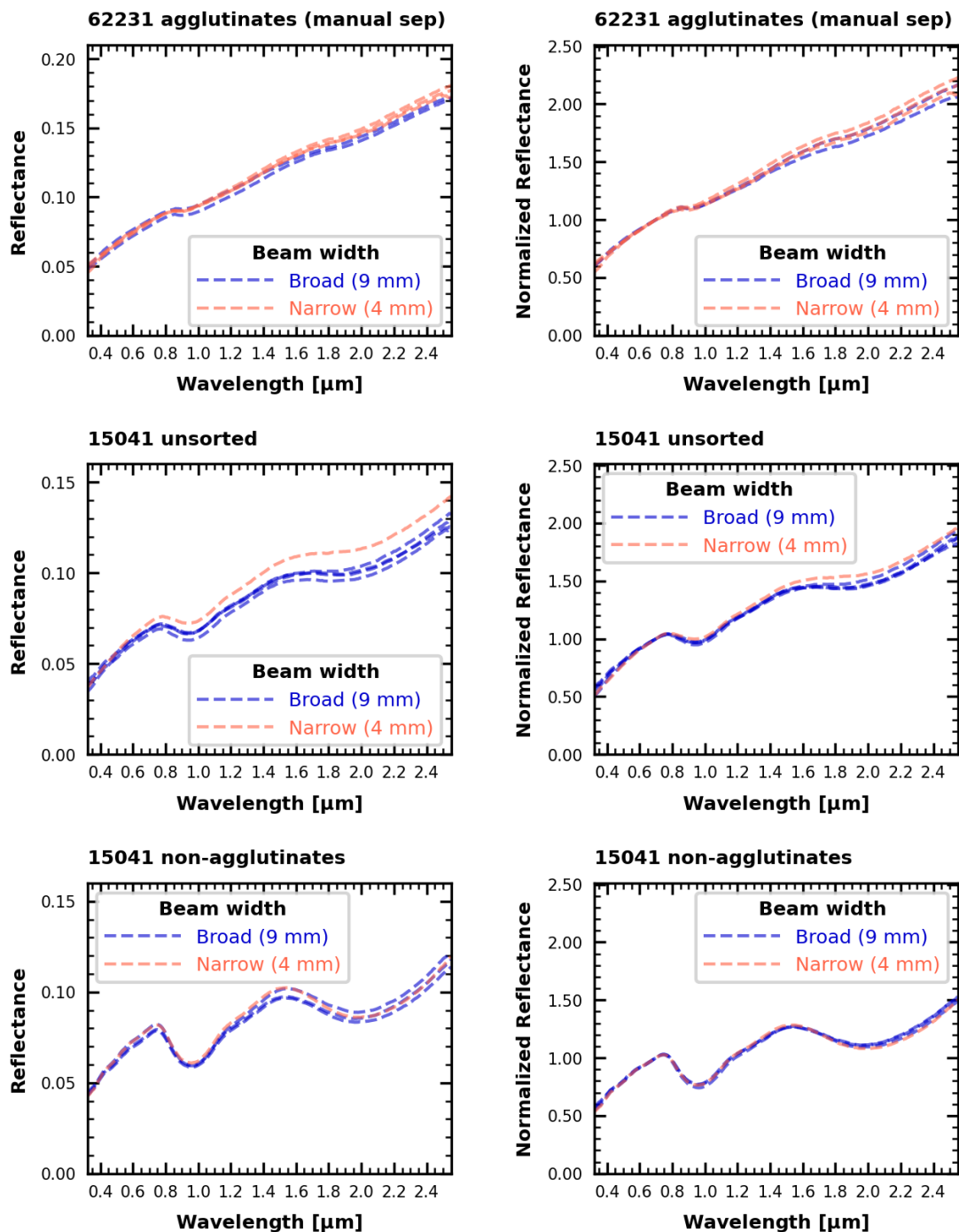


Figure S8. (left) Reflectance spectra of three soil separates using two beam widths: 9 mm and 4 mm. **(right)** The same spectra, but with reflectance normalized to its value at 0.7 μm.

Manual vs. magnetic–manual separation (reflectance spectra)

Text S2.

For two of the soils, 62231 and 14259, we have additional spectra for separates obtained using the manual separation method (as opposed to the magnetic–manual method used for all other spectra) (Figures S9, S10). For 62231 the manually separated agglutinate spectrum is bluer in slope and darker than the magnetic–manual separated agglutinate spectrum, while the manually separated non-agglutinate spectrum is brighter than the corresponding magnetic–manual separated spectrum. In contrast, for 14259, the manually separated and magnetic–manual separated agglutinate spectra are nearly identical.

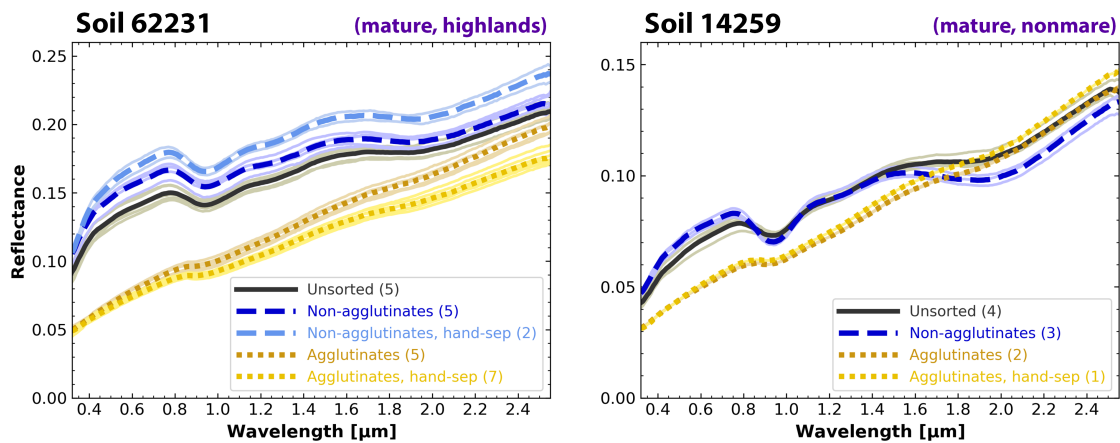


Figure S9. Reflectance spectra of the unsorted, non-agglutinate, and agglutinate separates for **(left)** soil 62231 and **(right)** soil 14259, including those yielded by manual separation. Each separate's mean spectrum (thick dark line) is the average of multiple individual measurements (thin faint lines). The number of measurements contributing to each mean is indicated in parentheses.

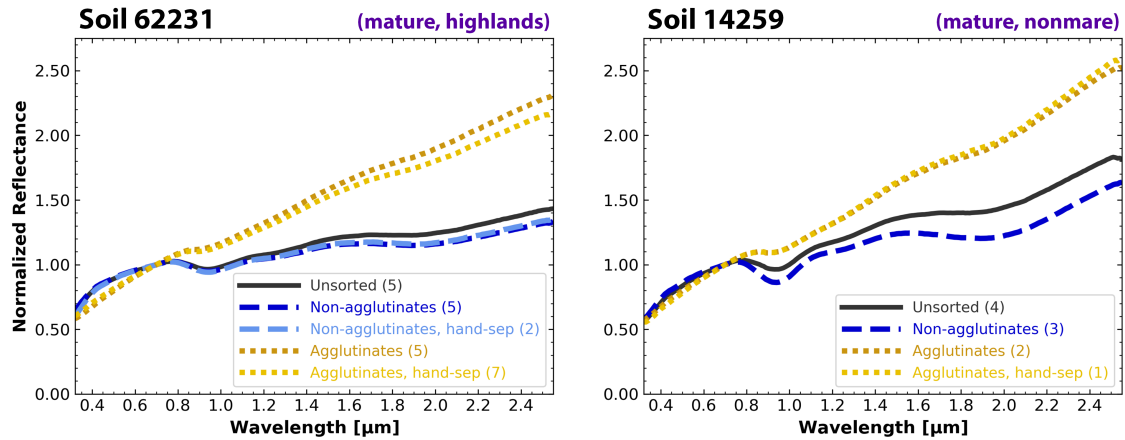


Figure S10. Same as Figure S9, but showing the mean reflectance spectra normalized to their values at 0.7 μm . The number of measurements contributing to each mean is indicated in parentheses, but these individual measurement spectra are not shown.

Soils of varying composition (reflectance spectra)

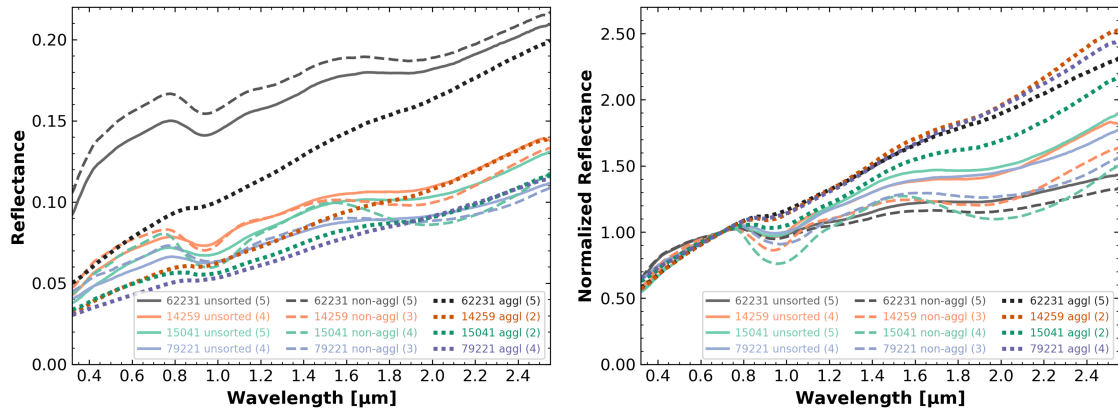


Figure S11. Reflectance spectra for the four mature soils: 62231 (highlands), 14259 (non-mare), 15041 (low-Ti mare), and 79221 (high-Ti mare). **(left)** Mean spectra and **(right)** the same spectra normalized to their values at 0.7 μm. The number of measurements contributing to each mean is indicated in parentheses, but these individual measurement spectra are not shown.