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Constraining Particle Variation in Lunar Regolith for Simulant Design

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Outline

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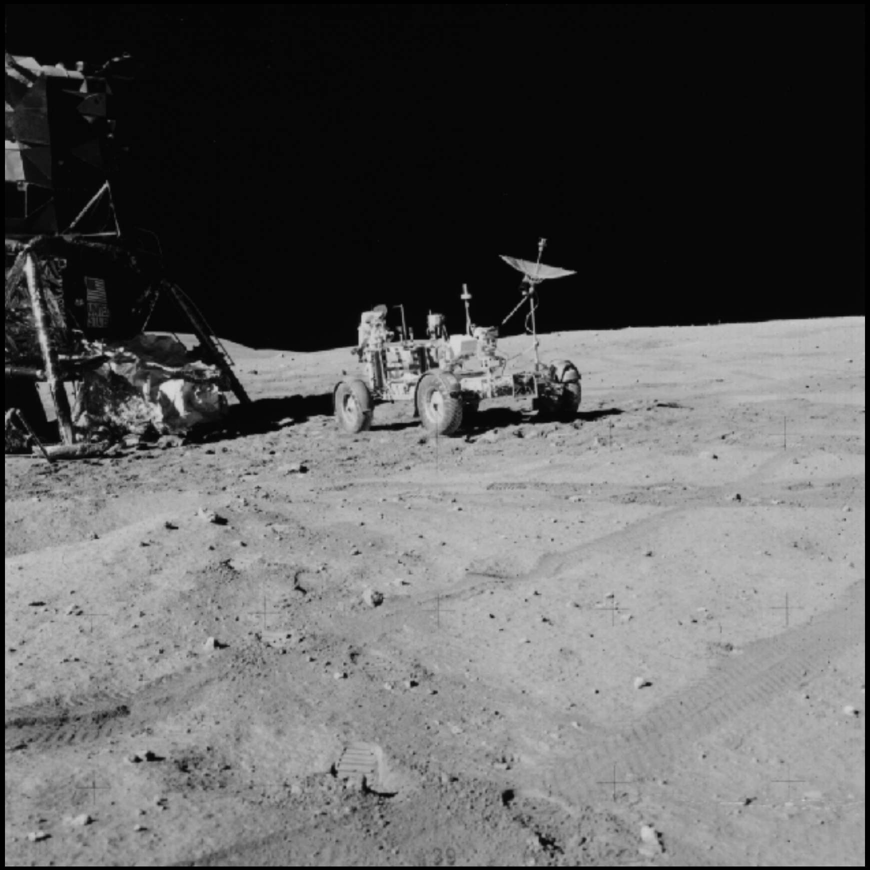


Background: Figure of Merit

The FoM is a set of algorithms designed to quantitatively compare two granular materials.

1) particle type/composition
2) particle size distribution (PSD)
3) particle shape distribution
4) bulk density characteristics

Figure of Merit

- The FoM was developed to compare lunar regolith simulants to lunar reference materials, such as an Apollo sample.
- However, we use it here to compare Apollo 16 samples to one another.
- This stage of work addresses compositional, or particle type, variance only.

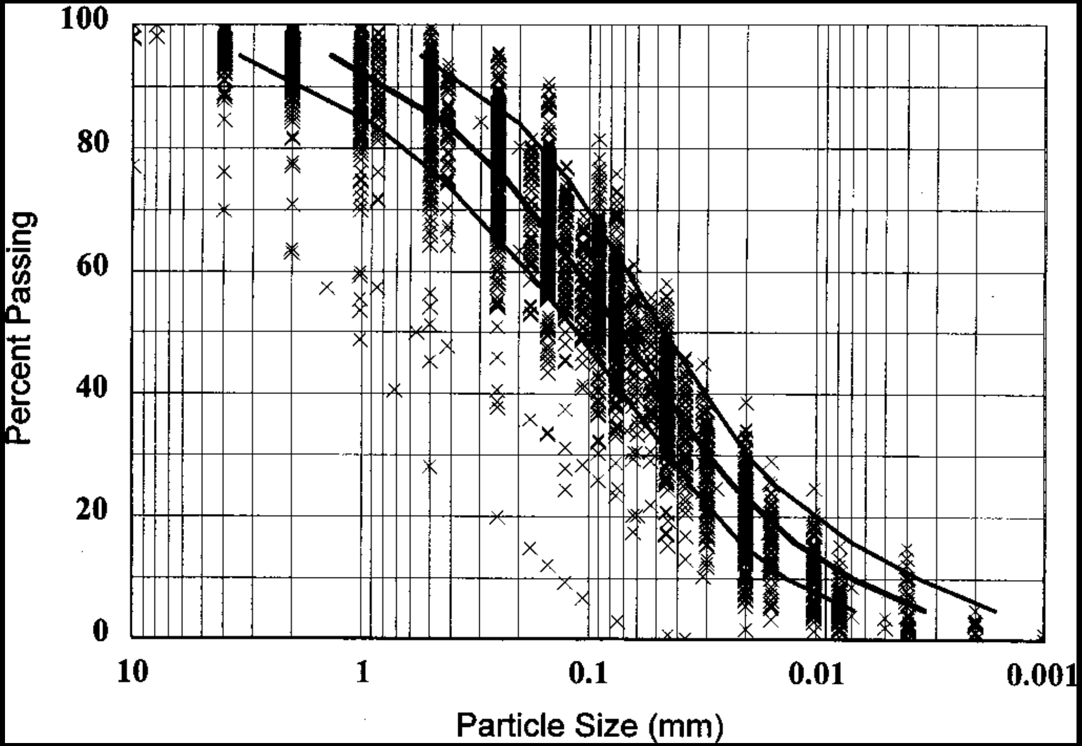
Variance

Assessing compositional variance of lunar regolith is necessary to provide constraints and “worst case scenarios” for ISRU and hazard mitigation planning.

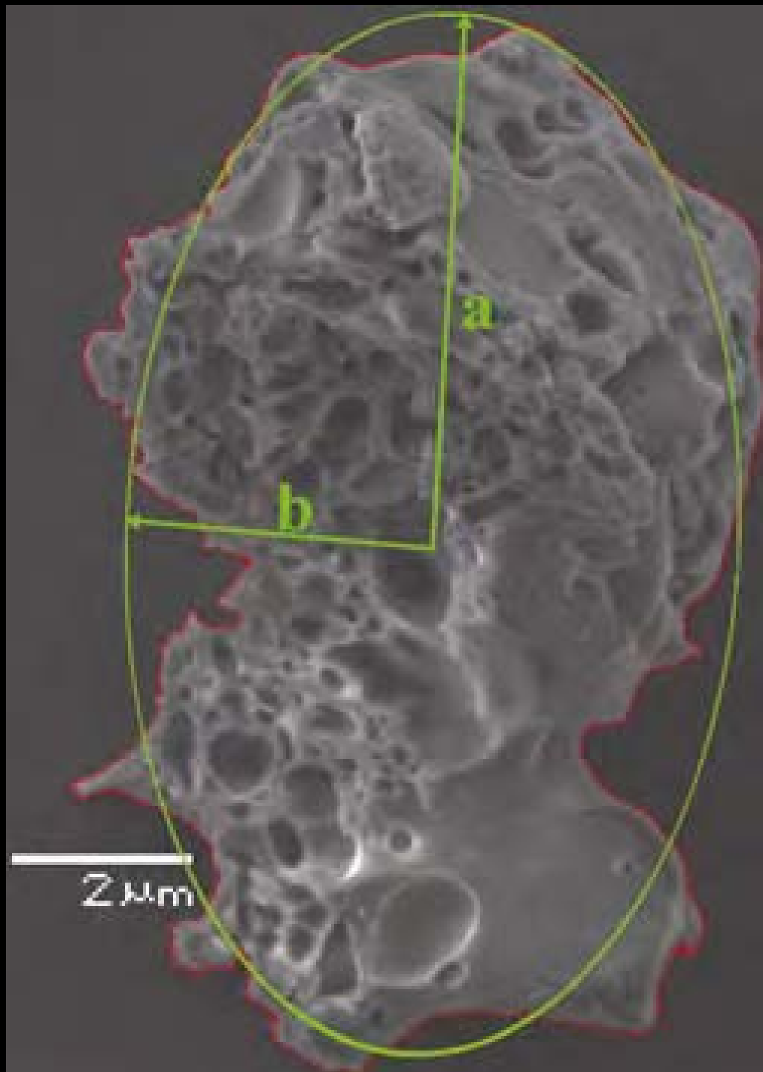
Variance: Particle Size (Carrier, 2003)

- Particle size distribution (PSD) is an important factor in geotechnical behavior and the kinetics of chemical reactions.

- PSD is part of the Figure of Merit.



Shape (Liu, 2007)



Aspect ratio

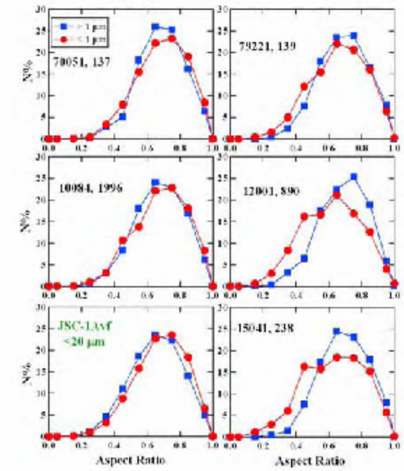


Fig. 3. Aspect ratios of five lunar soils and a simulant JSC-1Avf.

Complexity (related to angularity)

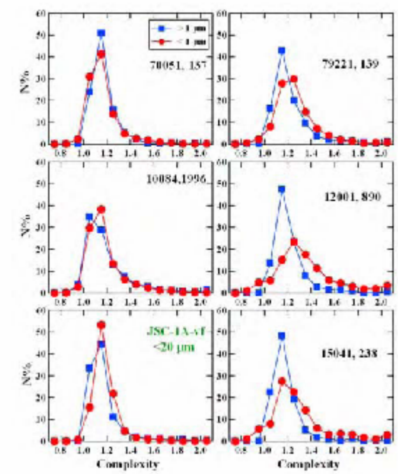
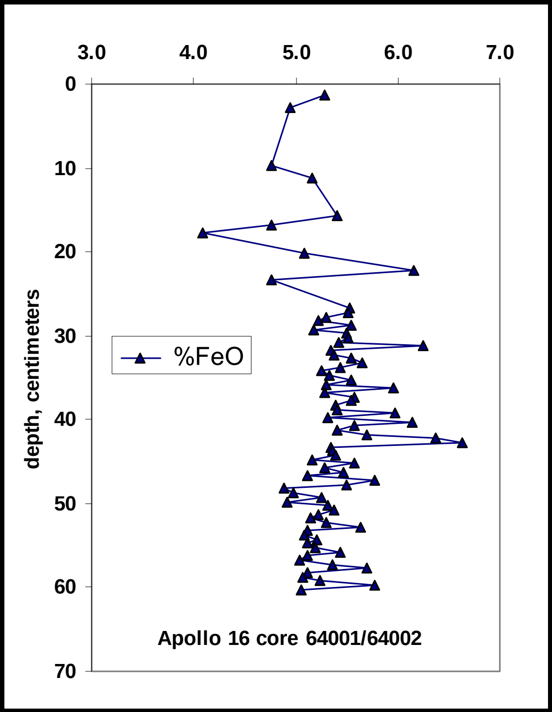
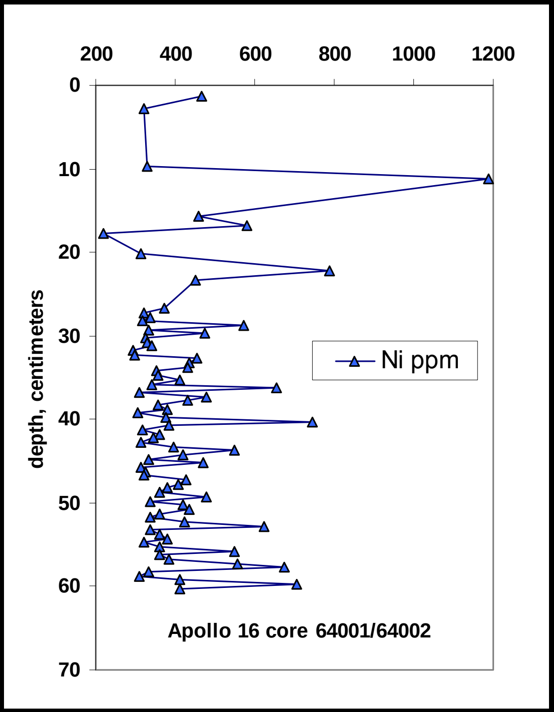


Fig. 4. Complexity of five lunar soils and a simulant JSC-1Avf.

Variance: Major and trace element chemistry
(Korotev, 1982 and Korotev et al., 1984)

- Regolith chemistry is key to ISRU and to health hazard mitigation.
- Regolith mineralogy is largely derivative of chemistry.
- Mineralogy is part of the particle type composition Figure of Merit.





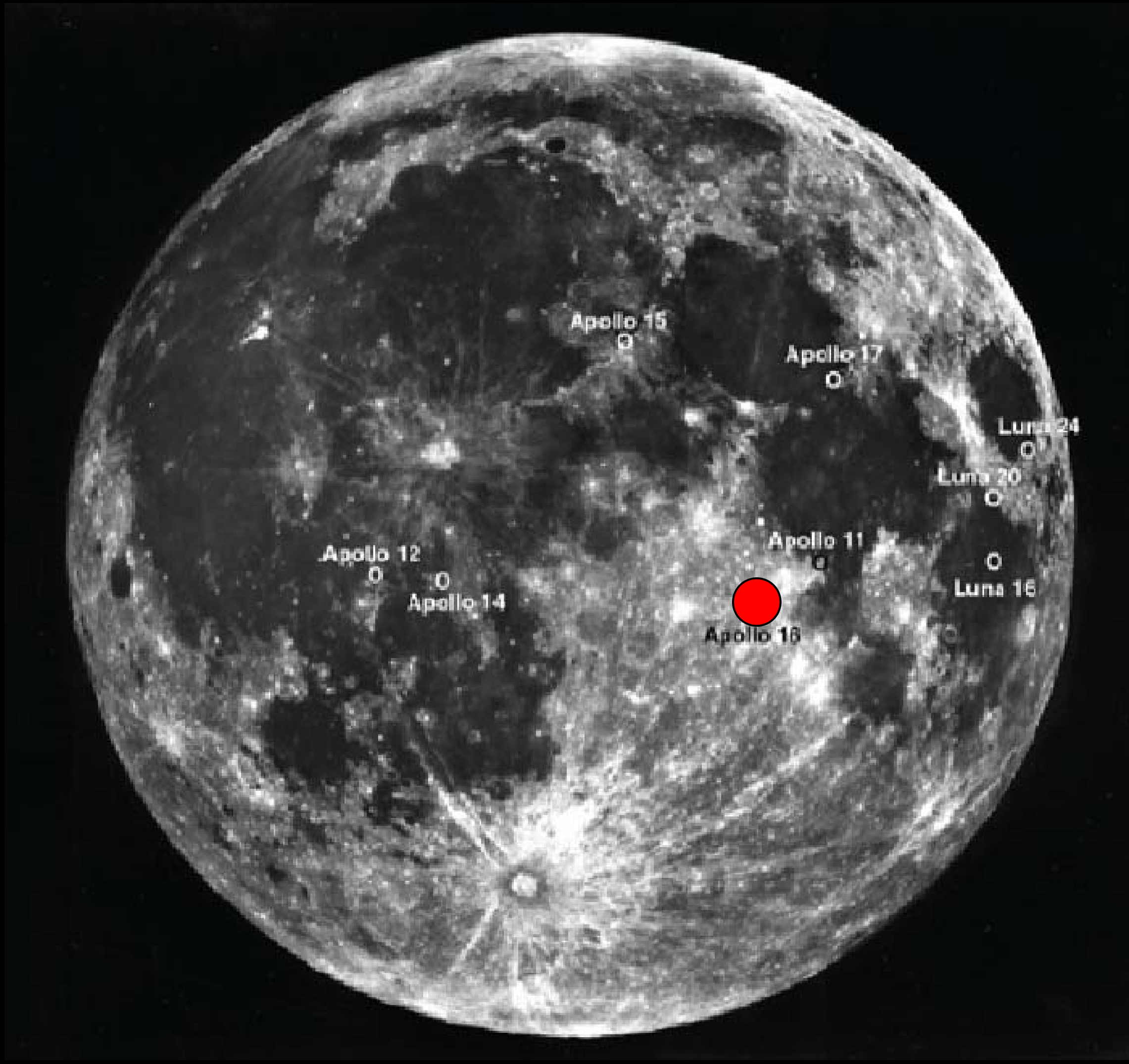
Sampled Sites – Apollo 16

Regolith composition and the simulant project

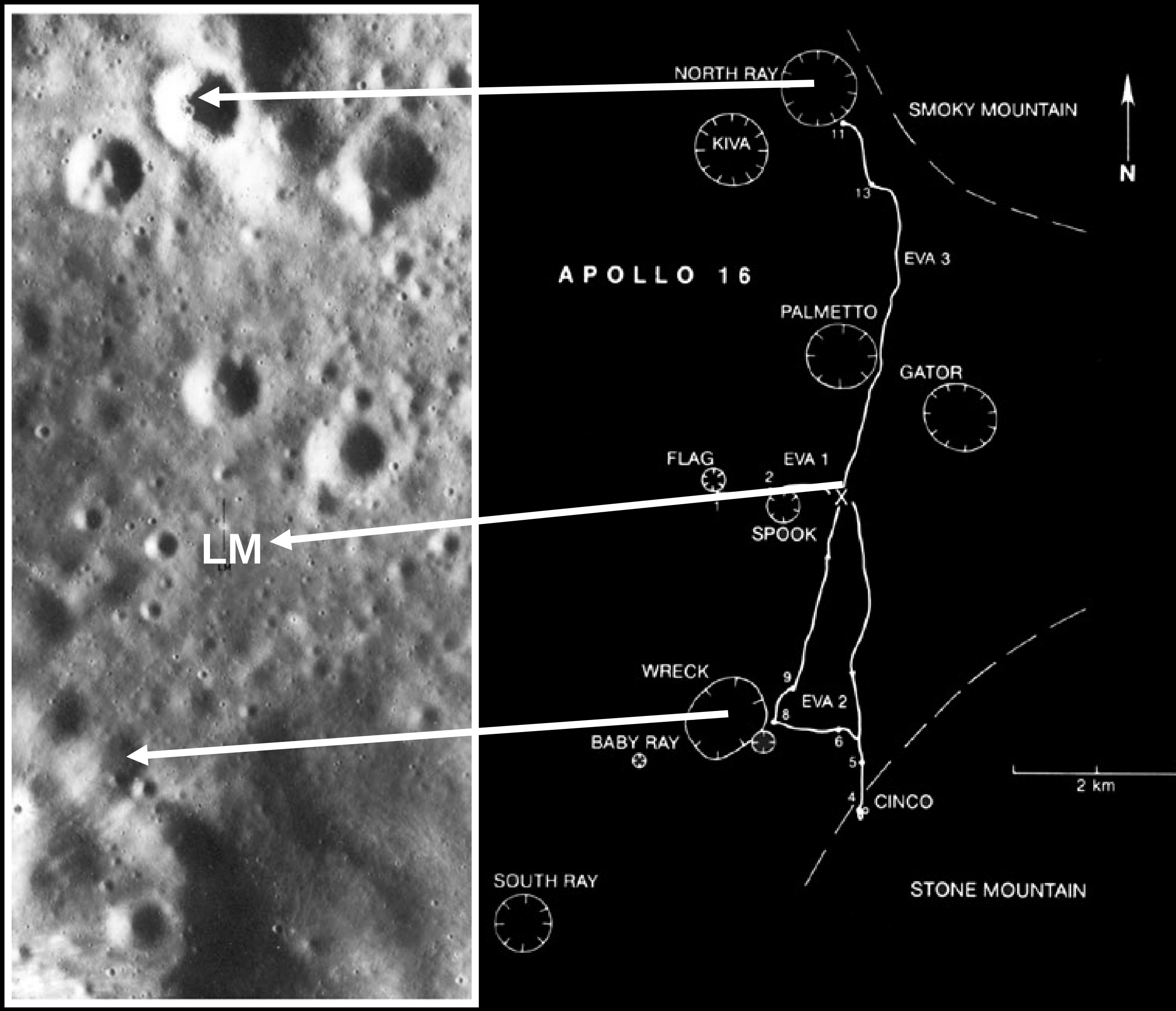
We investigate Apollo 16 regolith because it it is the only highlands material available.

We use core samples as reference material for simulant development and evaluation.

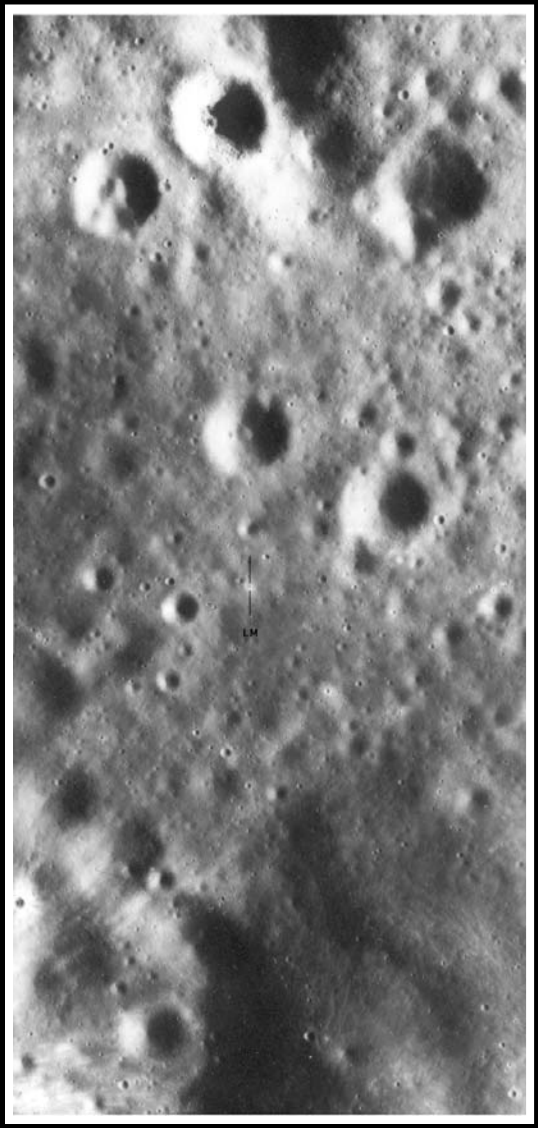
Here, we evaluate variance in regolith composition laterally and vertically using core and surface samples.

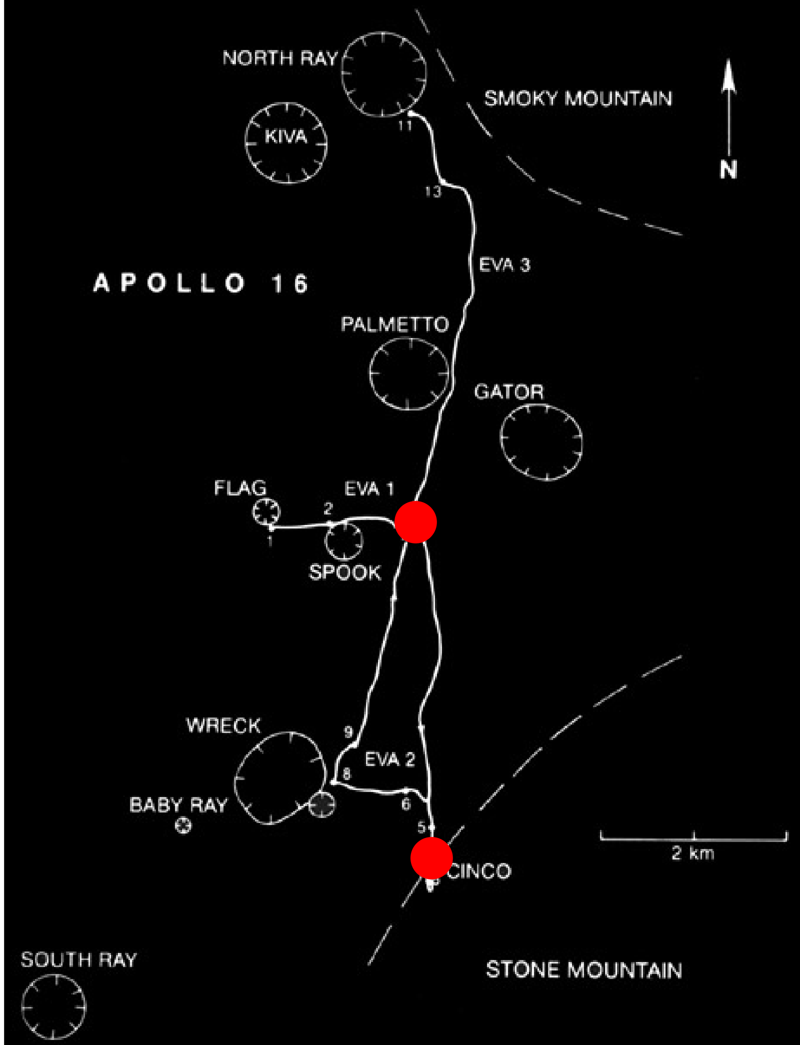


Apollo 16 stations



Apollo 16 stations

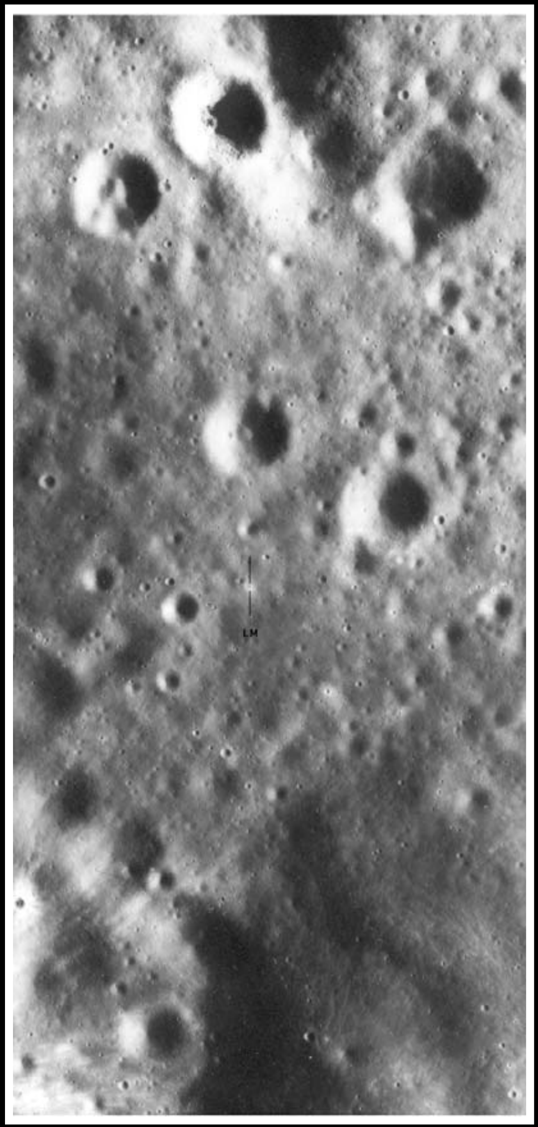


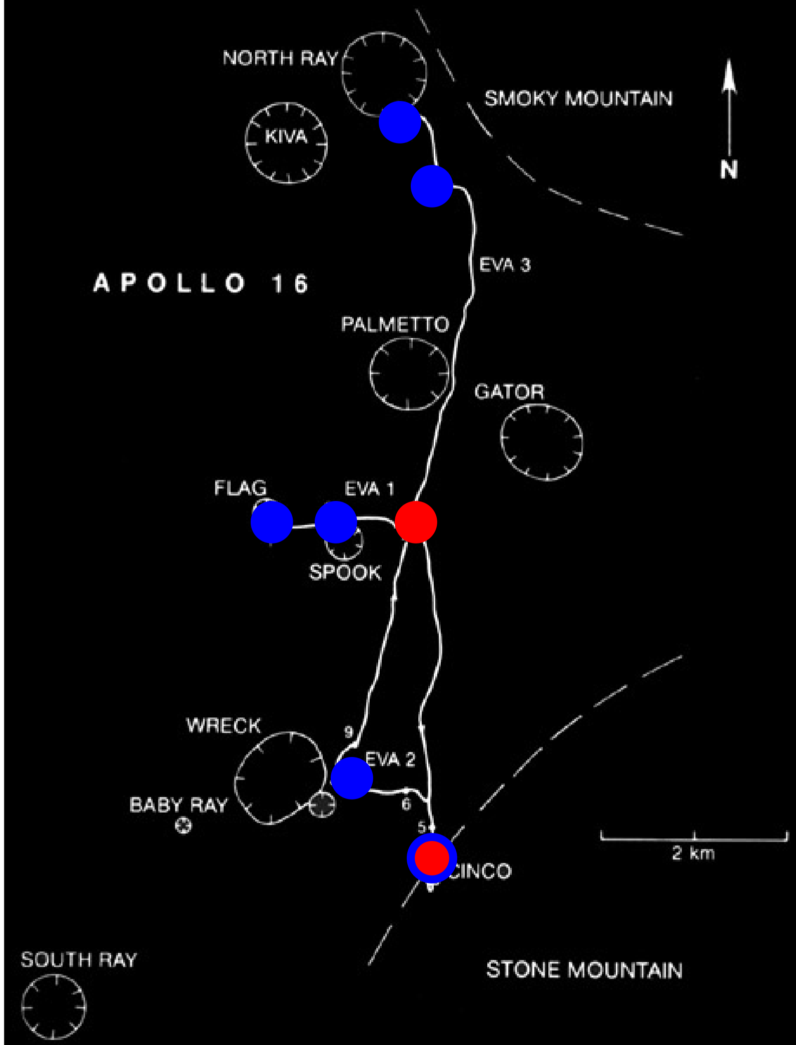


Station 4:
64001/64002 (n = 12)

Station 10:
60009/60010 (n = 11)

Apollo 16 stations





Station 4:
64001/64002 (n = 12)
64501

Station 10:
60009/60010 (n = 11)

Station 1:
61161, 61181, 61221, 61241

Station 2:
62281

Station 8:
68501

Station 11:
67481, 67601, 67701, 67711, 67941

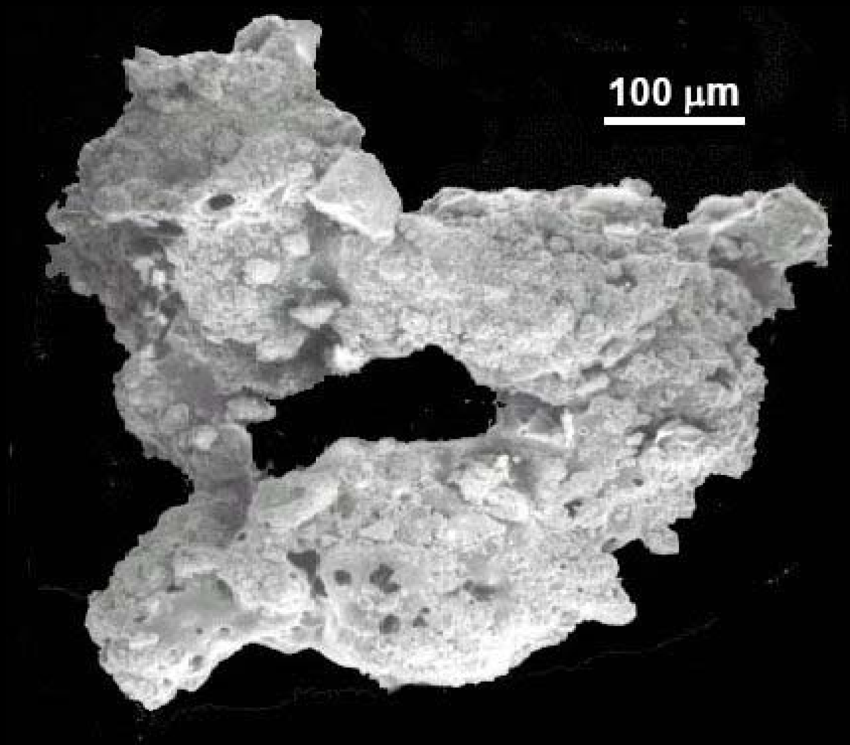
Station 13:
63321, 63341, 63501

Data: Modal data used in this exercise

- All data is "particle type" modal data, i.e., a count by volume of grain types.
  - this can be gathered by optical microscopy and a large database on Apollo samples exists
  - total volume% data is preferable in some cases but the image analysis necessary has not long been in use

- All data is of the 90-150 μm fraction.
  - some sources contain analyses of multiple size fractions, but all contain at least the 90-150 μm
  - this fraction is often studied as representative of the regolith distribution

Modal data



- The data used here would classify this particle as an agglutinate.
- Image analysis routines on SEM images would parse the constituent glass and minerals.

Modal data used in this exercise, cont.

- All data uses a classification system of Basu and McKay (1981), or is convertible to it (e.g., McKay et al., 1977)
  - much data is available in the literature but is not directly comparable, due to differing emphasis of attention or particle definition

- The following sources are used:
  - McKay et al., 1976 and 1977: 60009/60010 core
  - Houck, 1982a: Apollo 16 surface soils from multiple stations
  - Houck, 1982b: 64002 core section
  - Basu and McKay (1984): 64001 core section

Average Modal% of Apollo 16 Regolith Samples

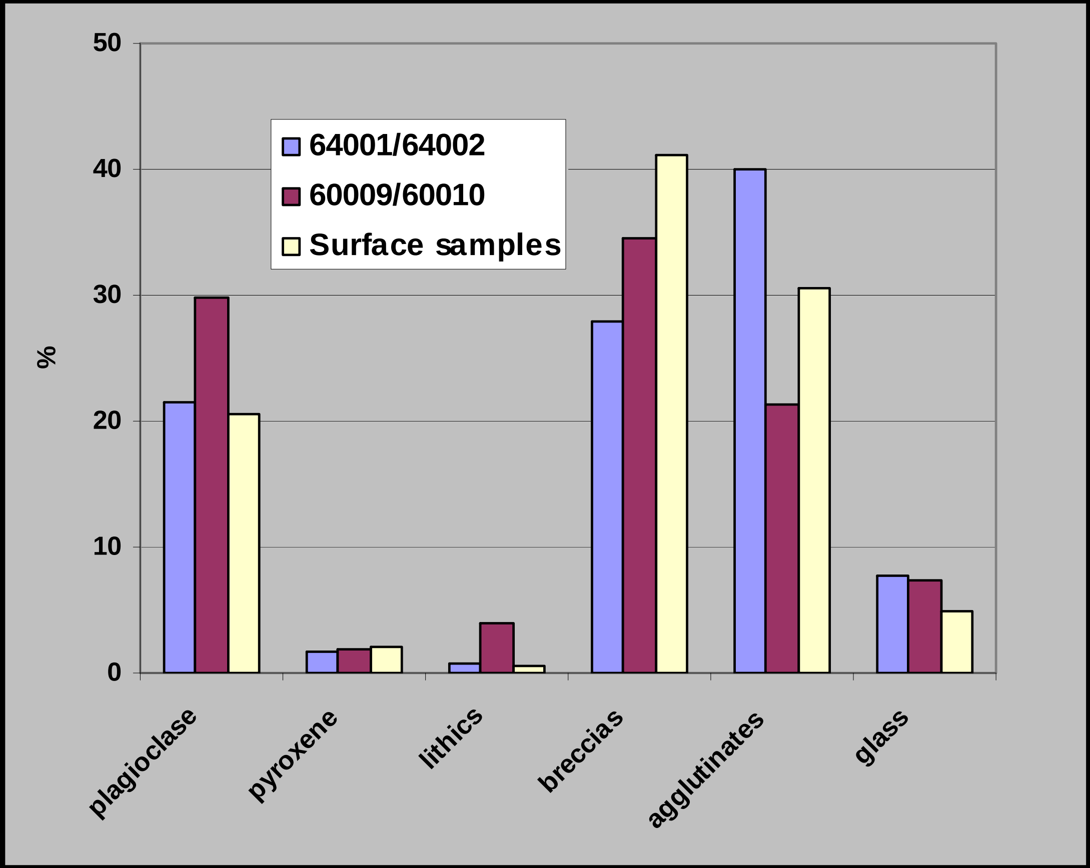
Monomineralic grains
- Plagioclase
- Pyroxene
- Olivine
- Opaques

Crystalline Lithics (undifferentiated)
- basalts (mare, KREEP)
- anorthosites, etc.

Breccias (undifferentiated)

Agglutinates

Glass (undifferentiated)



Composition Figure of Merit

$$FoM = 1 - \frac{\left\| \mathbf{w}\left(\mathbf{c}_{material\ A} - \mathbf{c}_{material\ B}\right)\right\|_1}{\left\|\mathbf{w}\,\mathbf{c}_{material\ A}\right\|_1 + \left\|\mathbf{w}\,\mathbf{c}_{material\ B}\right\|_1}$$

$$= 1 - \frac{\sum_i \mathbf{w}_i \left|\left(\mathbf{c}_{material\ A_i} - \mathbf{c}_{material\ B_i}\right)\right|}{\sum_i \mathbf{w}_i \mathbf{c}_{material\ A_i} + \sum_i \mathbf{w}_i \mathbf{c}_{material\ B_i}}$$

$C_{material\ A}$:

the composition vector of the "reference", whose elements (minerals, grain types, etc.) must sum to 1

$C_{material\ B}$:

the composition vector of the material to be compared (a simulant, lunar sample, etc.) to the reference material

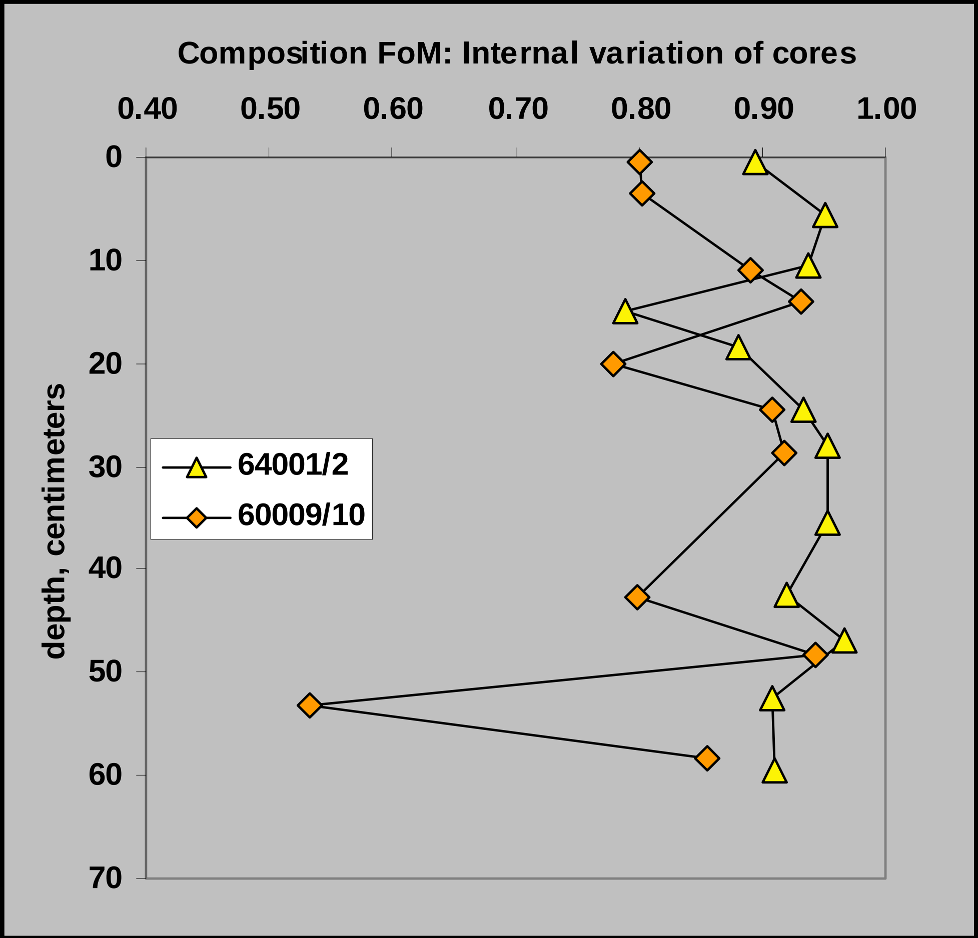
W:

weighting factor (here it = 1)

Internal Variance of two Apollo 16 Cores

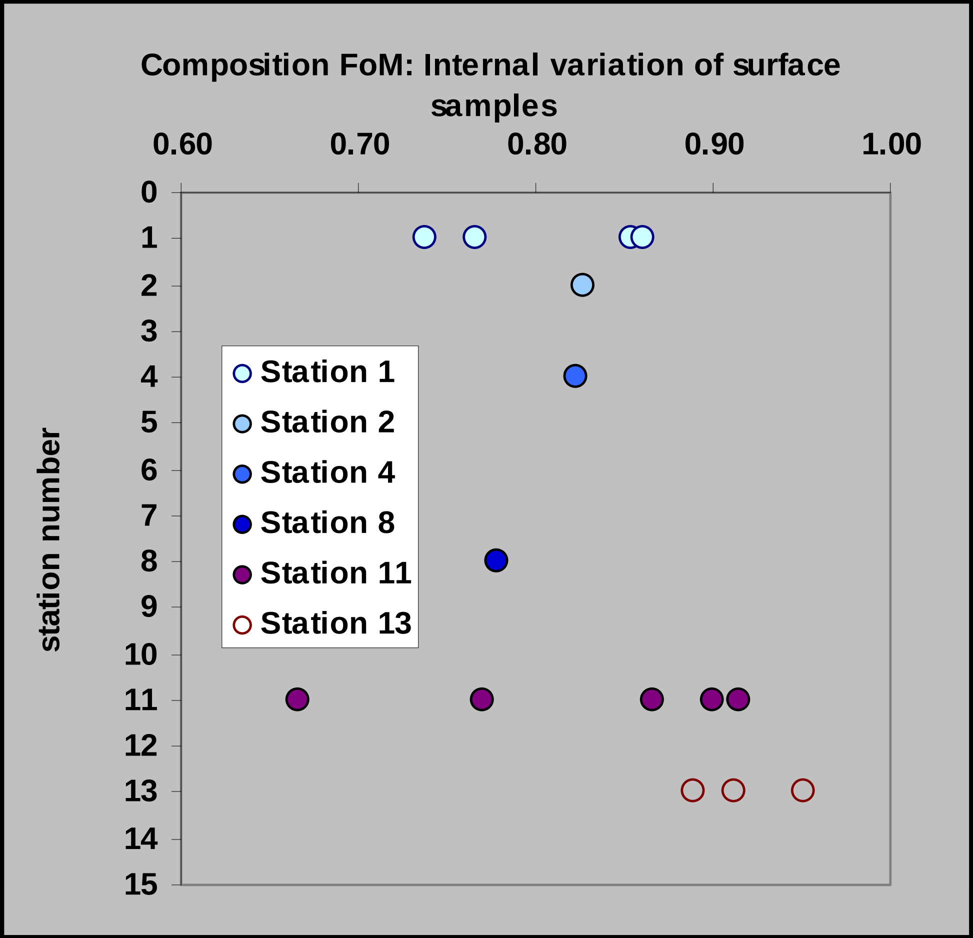
<u>64001/64002</u>
FoM composition: 0.79-0.97
mean: 0.92

<u>60009/60010</u>
FoM composition: 0.53-0.93
mean: 0.83



Internal Variance of Apollo 16 Surface Samples

<u>All Samples</u>
FoM composition: 0.67-0.95
mean: 0.83

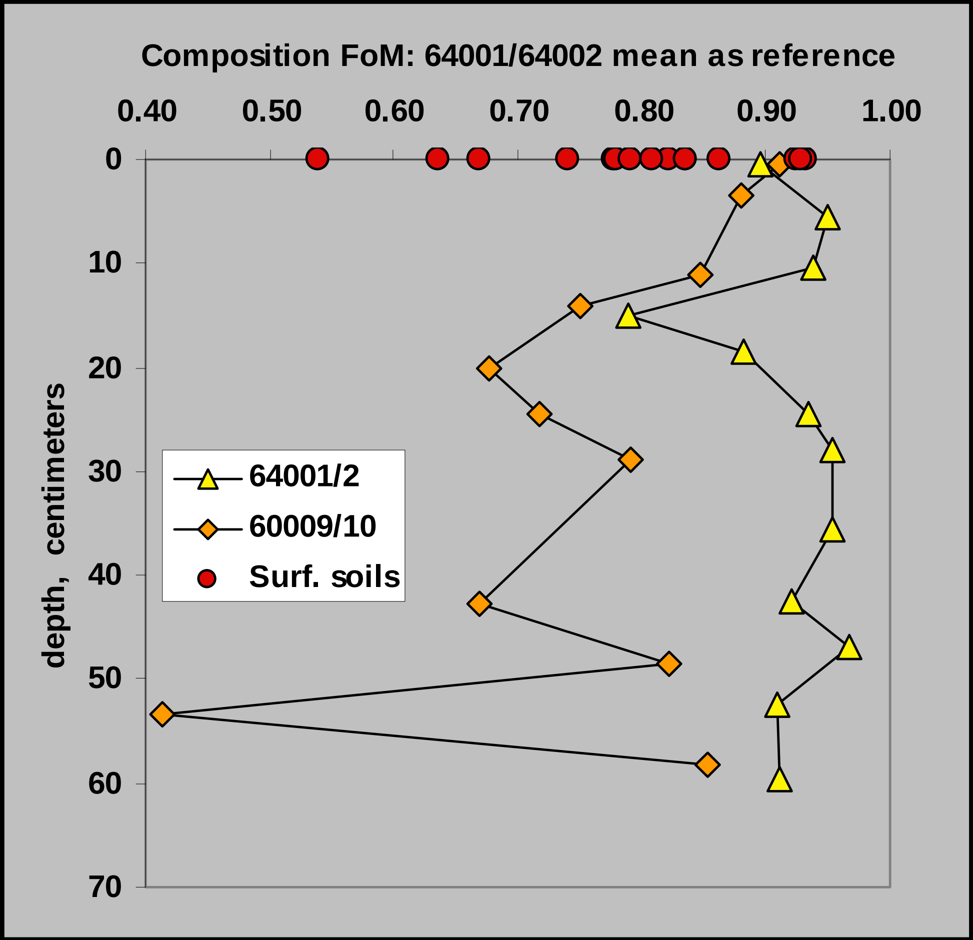


64001/2 mean as Reference: Apollo 16 Cores and Surface Samples

<u>64001/64002</u>
FoM composition: 0.79-0.97
mean: 0.92

<u>60009/60010</u>
FoM composition: 0.41-0.91
mean: 0.76

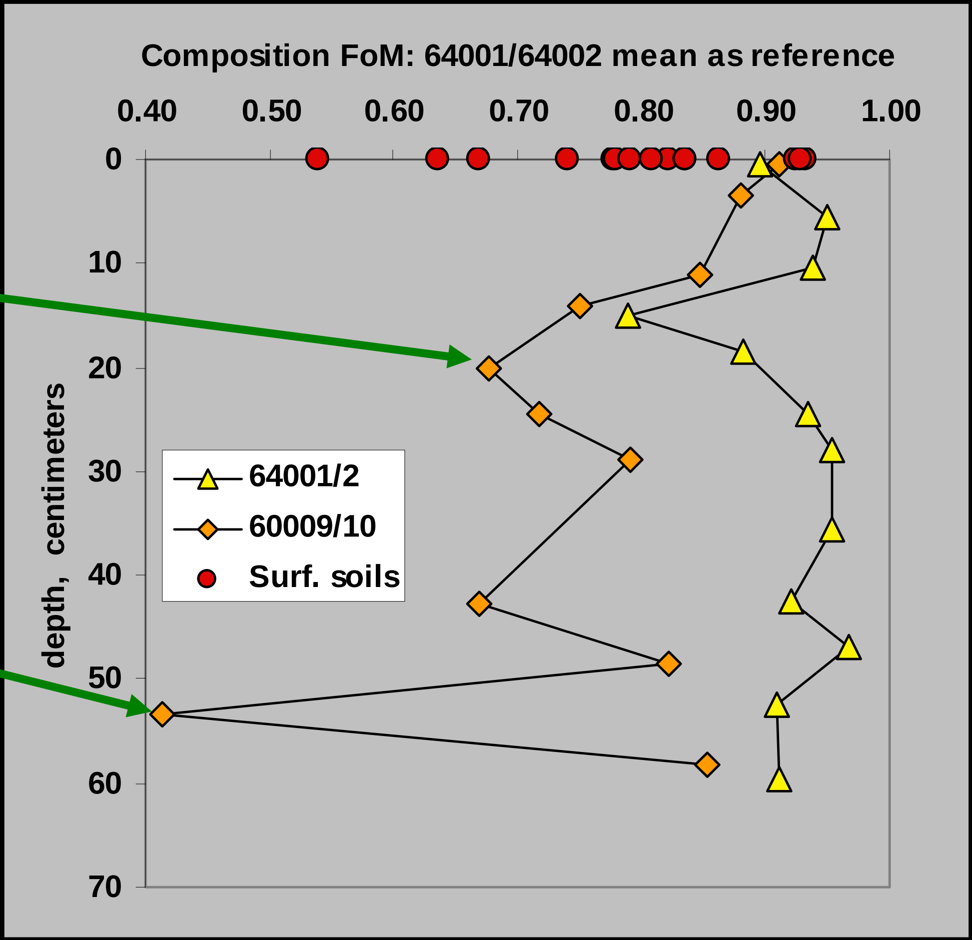
<u>Surface Samples</u>
FoM composition: 0.54-0.93
mean: 0.79



Numbers in parentheses are average of whole sample set

60010,3107: FoM 0.68
5% pyroxene (2% avg.)
47% breccia (35% avg.)
12% agglutinate (31% avg.)
High in Th and Sm; Fe and Cr

60009,457: FoM 0.41
76% plagioclase (24% avg.)
High in Al, Ca, low in Fe, Ni



FoM composition and maturity

- Chemical effects on regolith:
  - Fe reduction
  - implantation of solar wind particles

  This has no effect on the current particle type compositional FoM.

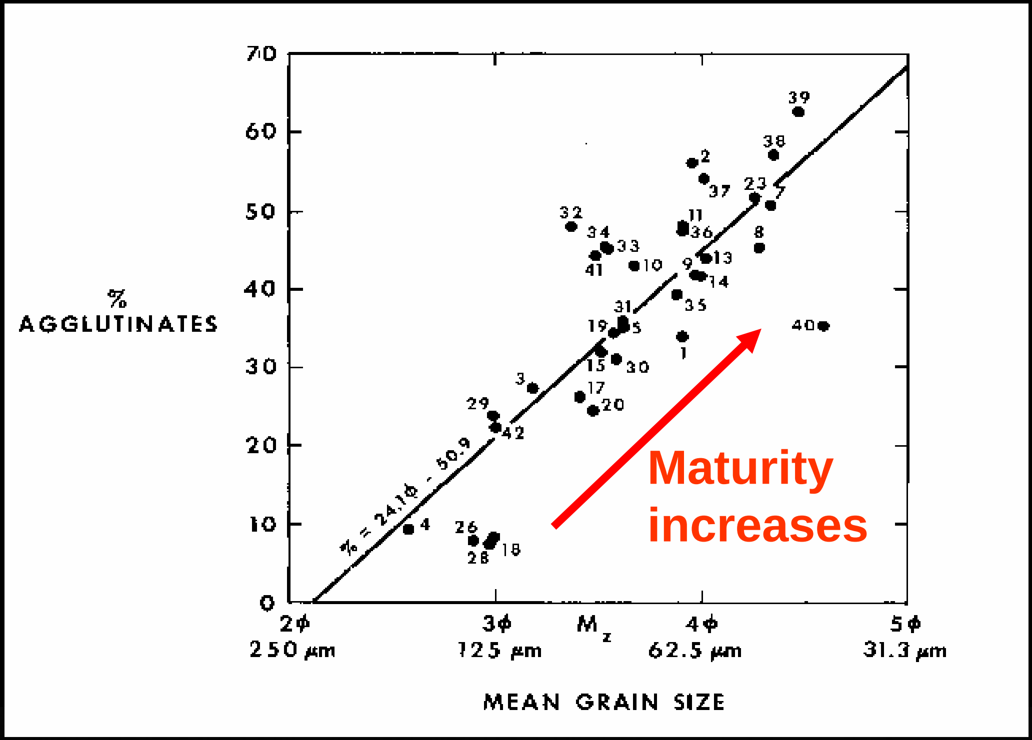
- Maturity has a larger effect on particle type composition.

Regolith maturity (McKay et al., 1974)

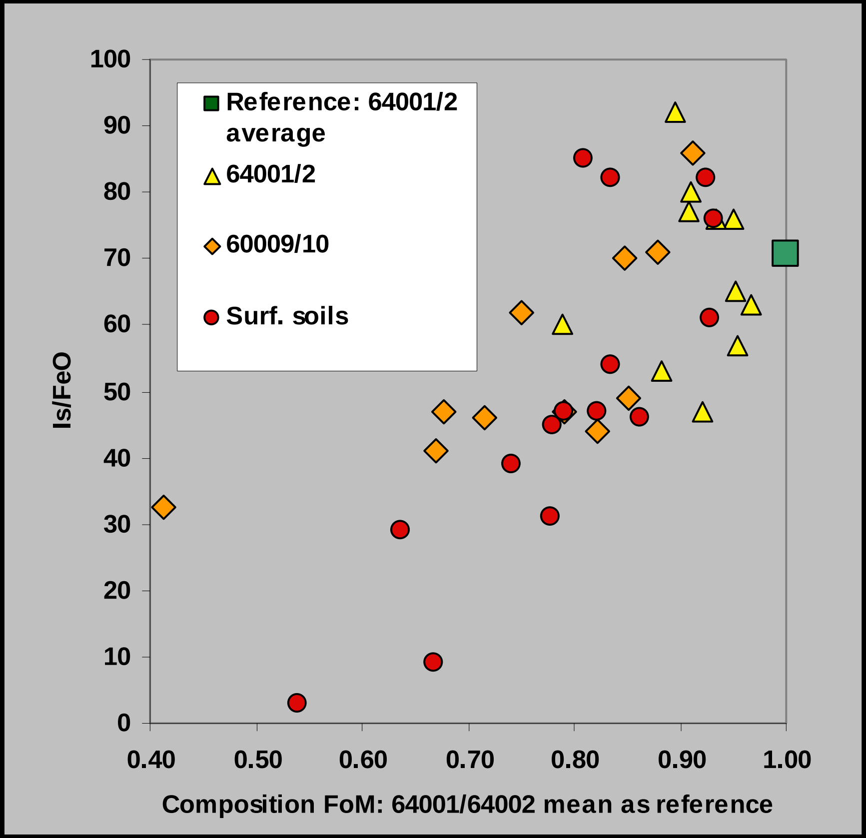
<u>Path 1 Regolith evolution</u>
comminution + agglutinization from micrometeorite impacts

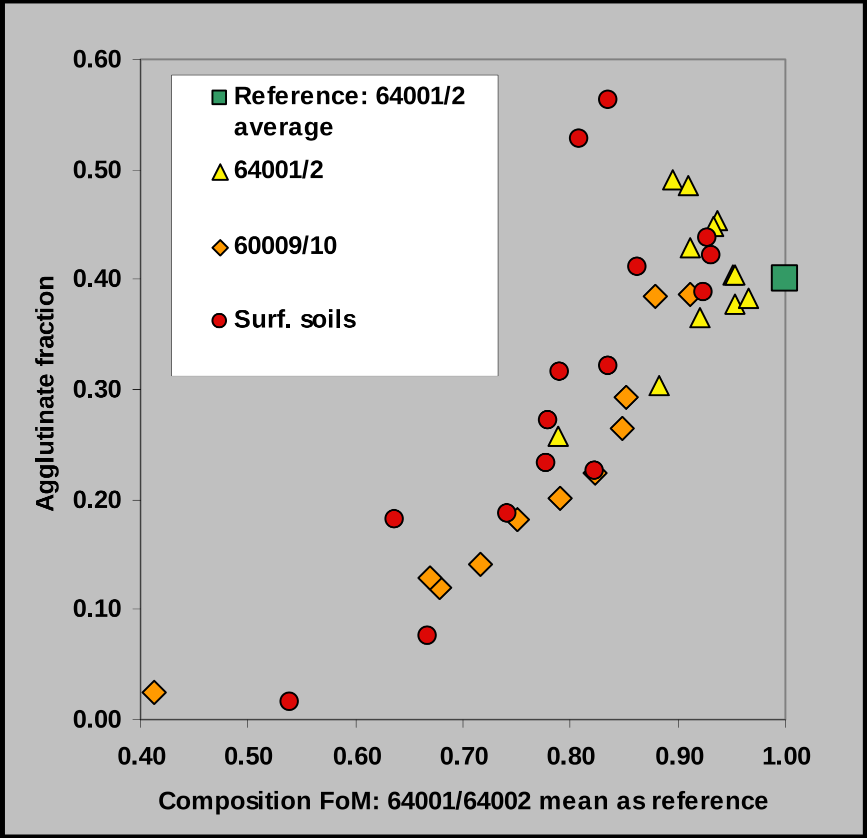
↓
↓

- **increased agglutinate%,**
- **reduced average grain size,**
- **decreased lithic%,**
- **increased glass% and monomineralic particle% in smallest size fractions**
- **increased nanophase Fe^0**



Compositional FoM variation by maturity





Some Conclusions

- The reference sample, core 64001/64002, has the lowest internal variance analyzed.
- Available particle type data yields FoM’s that are moderately to strongly dependent on sample maturity.
- Combining particle type with data with more detailed mineralogical and chemical data will improve variance assessment.

Further work already underway

- Incorporating PSD data
- Incorporating at least one more Apollo 16 core (60013/60014) into the dataset
- Incorporating more chemical data
- Gathering new detailed mineral/glass modal data from image analysis

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