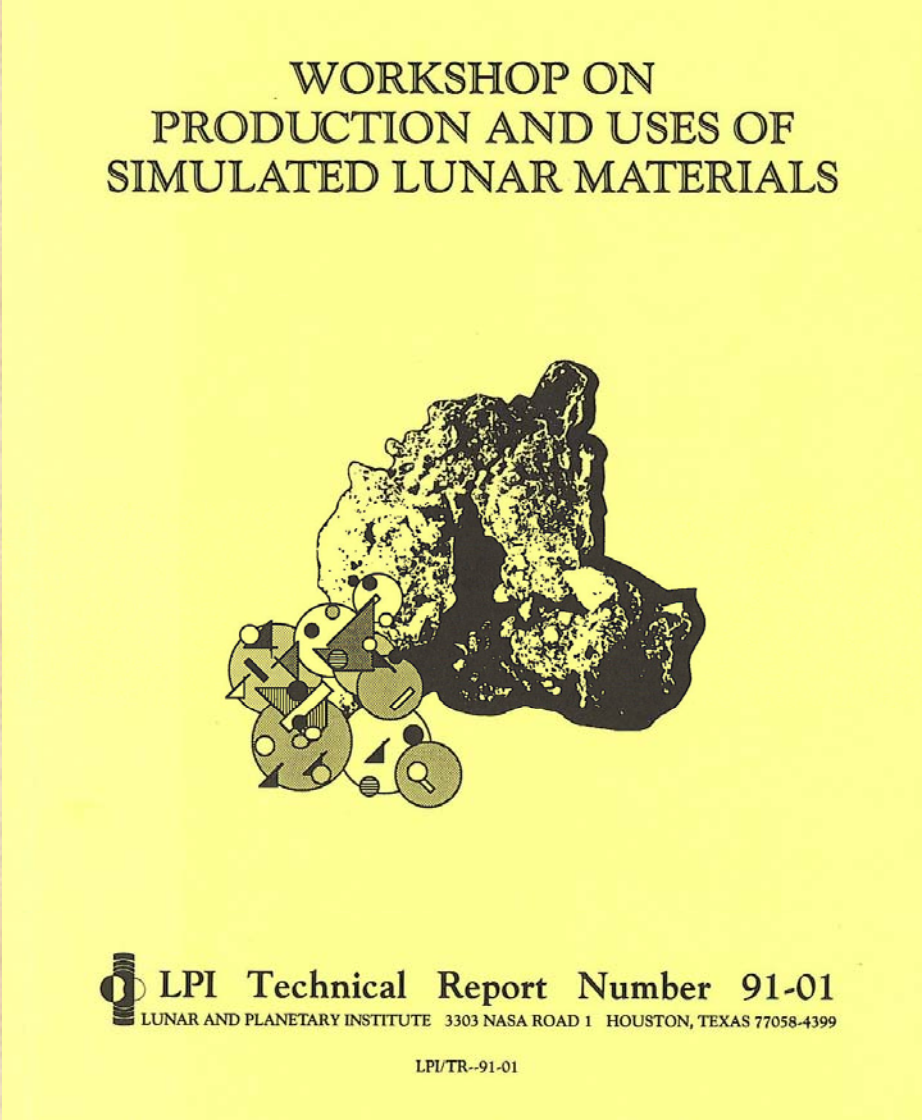
Simulants—are we on the right path?

David S. McKay

Astromaterials Research and Exploration Science (ARES) Directorate

NASA Johnson Space Center

A simulant workshop was held 20 years ago; the report is available at LPI


WORKSHOP ON
PRODUCTION AND USES OF
SIMULATED LUNAR MATERIALS

LPI Technical Report Number 91-01
LUNAR AND PLANETARY INSTITUTE 3303 NASA ROAD 1 HOUSTON, TEXAS 77058-4399

LPI/TR--91-01

TABLE 3. Properties to be simulated.

1. Grain properties
   - a) Size distribution
   - b) Size/shape distribution
2. Electrostatic charging properties
3. Magnetic properties
4. Geomechanical properties
   - Mechanical
     - a) Fatigue
     - b) Strength
       - i. Tensile
       - ii. Compressive
       - iii. Shear
       - iv. Grain hardness
       - v. Coefficient of friction
     - c) Flexural strength - bending resistance
     - d) Fracture properties
     - e) Impact resistance
     - f) Rheology (aggregate flow properties)
     - g) Angle of repose
   - Physical
     - h) Thermal properties
     - i) Bulk density
     - j) Particle density
     - k) Porosity
     - l) Surface area
     - m) Permeability (gas)
5. Agglutinate-specific
   - a) Friability
   - b) With single-domain iron
6. Chemical reactivity
   - a) From surface damage
   - b) As volatile/soluble minerals
7. Chemical properties
   - a) Bulk
   - b) Mineral
   - c) Glass
8. Modal composition
   - a) Total
   - b) As a function of grain size
9. Texture
10. Implanted solar particle-specific (e.g., H, C, N)

A Key Table: Shows 10 Property Categories and 32 specific properties

Categories of Processes to be Reproduced in a Simulant:

- grain properties
- electrostatic charging properties
- magnetic properties
- geomechanical properties
- agglutinate-specific properties,
- chemical reactivity properties,
- chemical properties,
- modal composition properties,
- texture properties, and
- implanted solar particle-specific properties.

Categories that we have focused on:

- Chemistry
- Grain Size
- Modal (mineral) composition

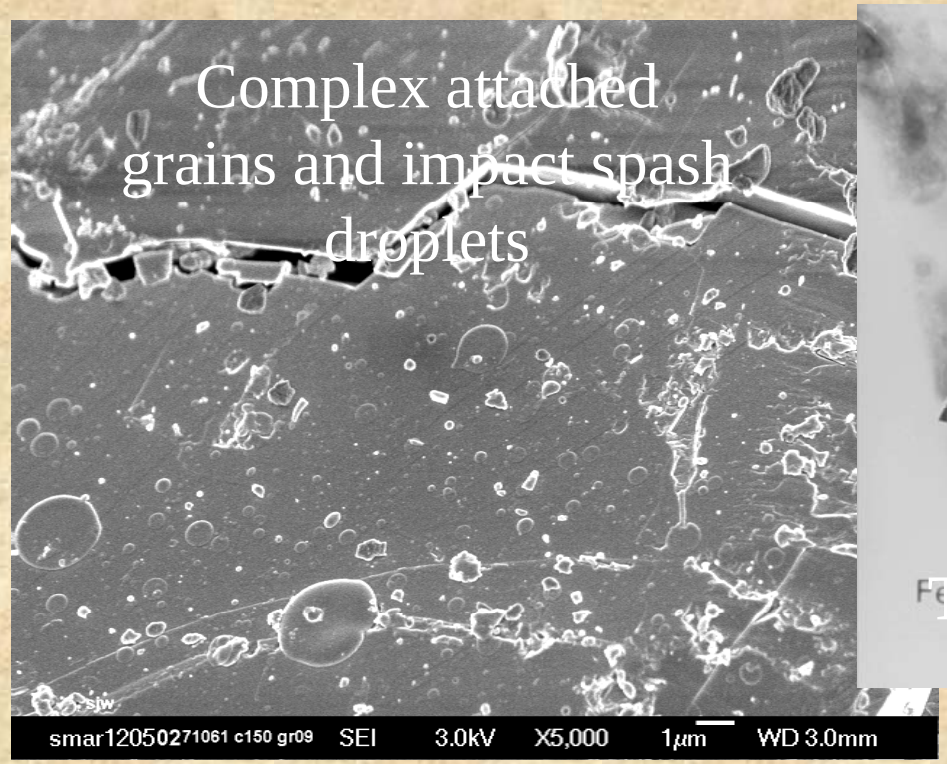
- ***These three are really the only properties that we have come close to reproducing out of the ten categories on the list.***

- We have done this for one chemistry (similar to Ap14 soil) and are about to do it for another (Ap16 Highlands)

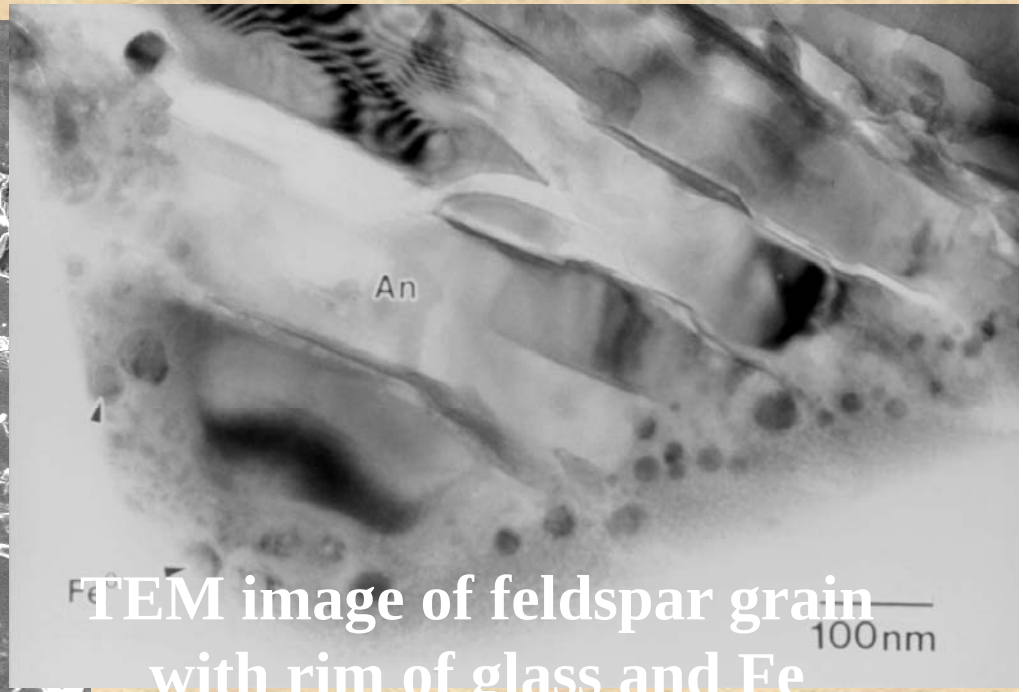
To a much lesser extent, we have reproduced nanophase iron, texture of some grains, and possibly some other properties

But mainly we have not reproduced the other 29 properties in our wish list

For example, we have nothing close to the intricate surface textures showing pancakes, microcraters, attached nanosize grains, or thin coating of glass with nanophase iron

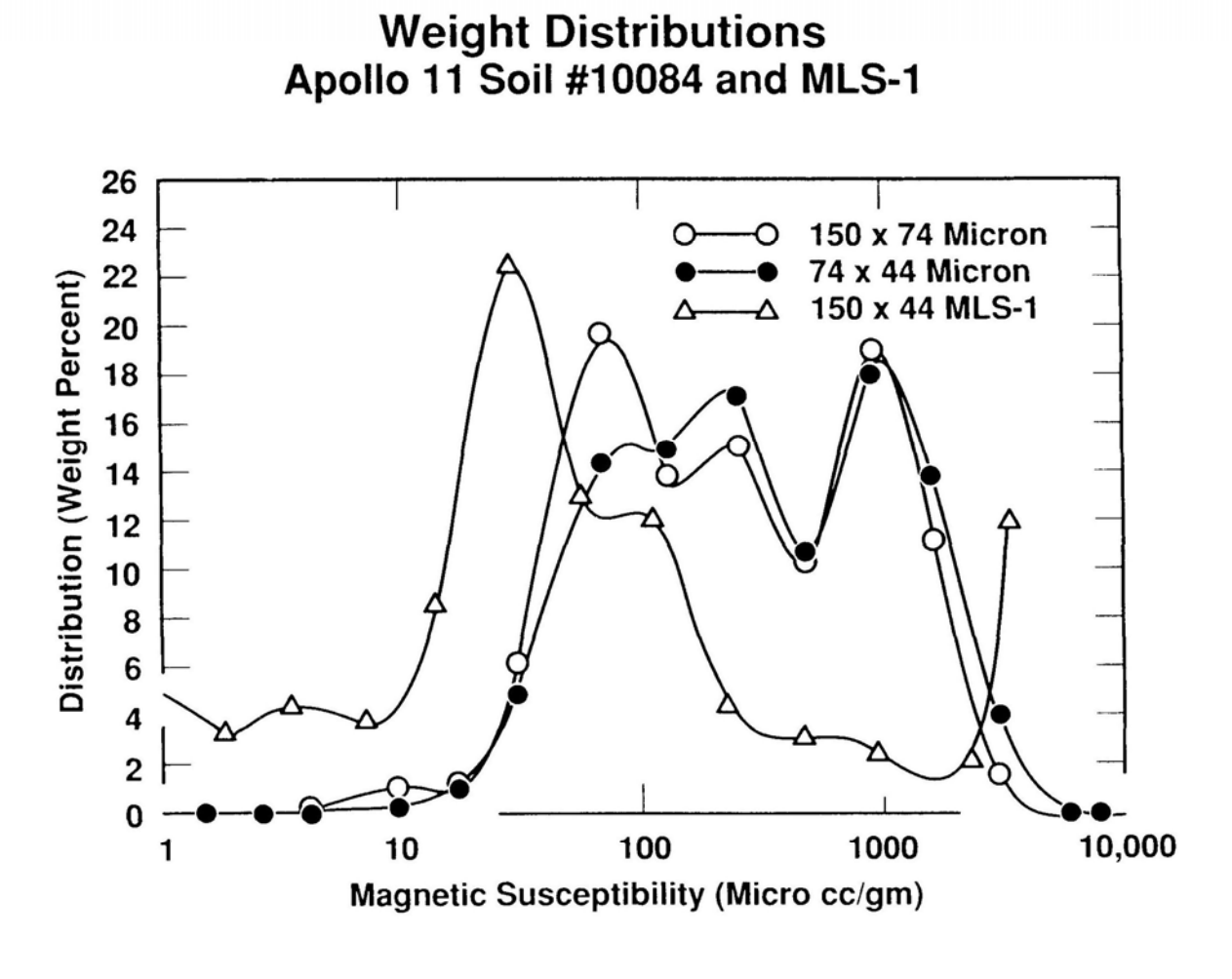


Complex attached grains and impact spash droplets



TEM image of feldspar grain with rim of glass and Fe

Nor do we have anything like the magnetic properties of actual lunar soil.



Have we chosen the right priority? Have we reproduced the right 3 categories? (chemistry, grain size, and mineral mode) Why have we ignored the other 7 categories and 29 specific properties?

Are mechanical properties like compressive strength or angle of repose or rheology or bulk density perhaps equally important for future surface operations? What about thermal conductivity, porosity, and permeability? What properties most affect trafficability, excavation resistance,ditch digging, tunneling, mechanical abrasion, and toxic reactions of humans to lunar dust?

I do not argue that we have made the wrong choice. But I do argue that we have ignored some possibly very important properties.

What to do?

We need to look at overall need for simulants from the standpoint of mass. Why do we need 100 tonnes of simulant? What is the driving requirement? Is it mainly to test rovers, excavators, regolith transport devices, construction techniques, and radiation hardening technologies? Are not these requirements more closely related to physical and mechanical properties than they are to chemistry and mineralogy? If so, maybe we should concentrate more on reproducing these physical and mechanical properties rather than the chemistry or mineralogy, which may not have much effect on the critical properties required for engineering design.

What other potential application has a requirement for 10s or 100s of tonnes of simulant?

Maybe ISRU

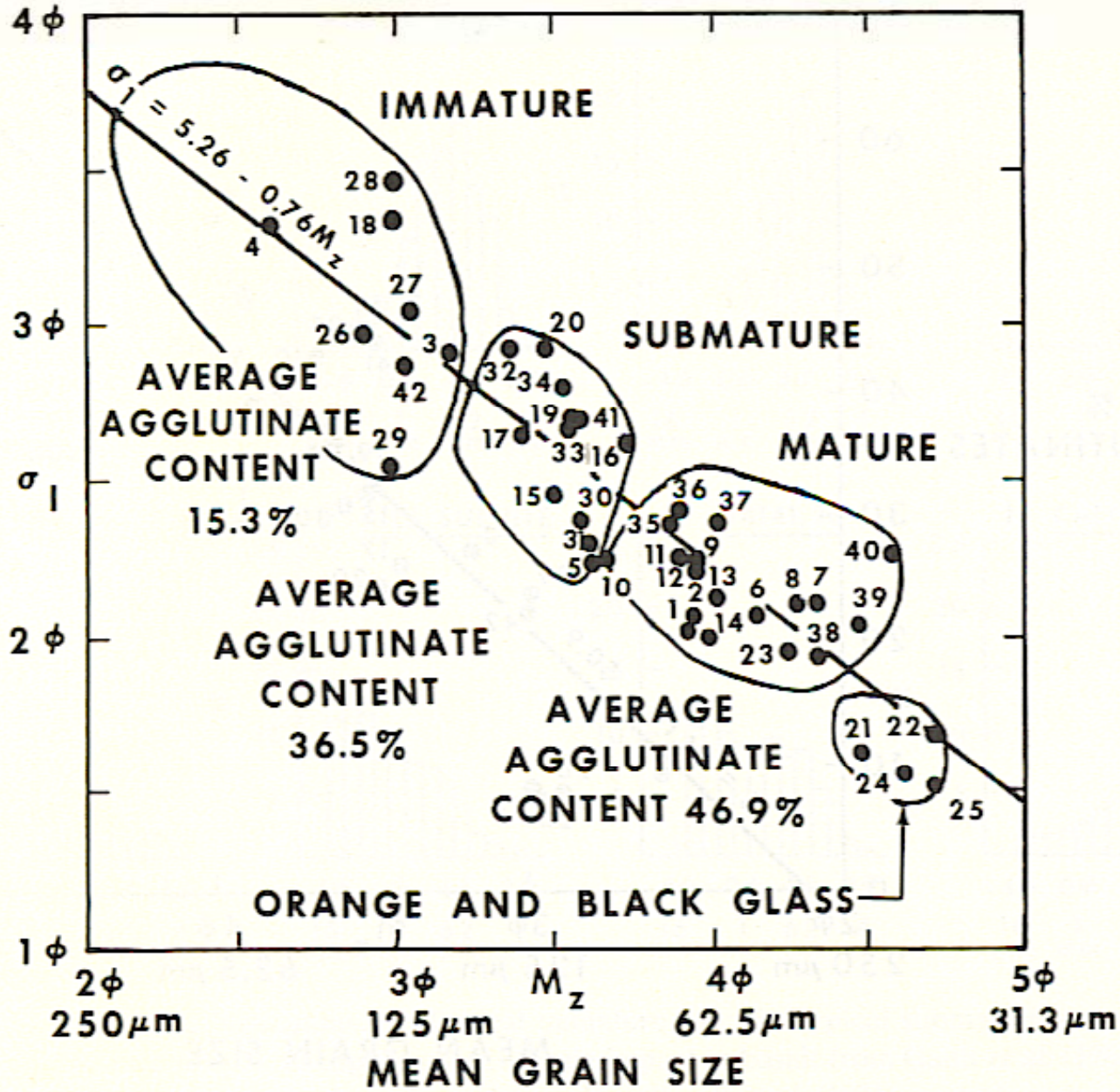
But some ISRU processes have no special requirement for specific chemistry or specific mineralogy. An example is plasma processing to liberate oxygen. Other processes such as hydrogen reduction, can be adapted to most any composition and only depend on total iron content. Maybe the ISRU process should be adaptable enough to work anywhere on the moon, in which case most any terrestrial rock could be used to test systems.

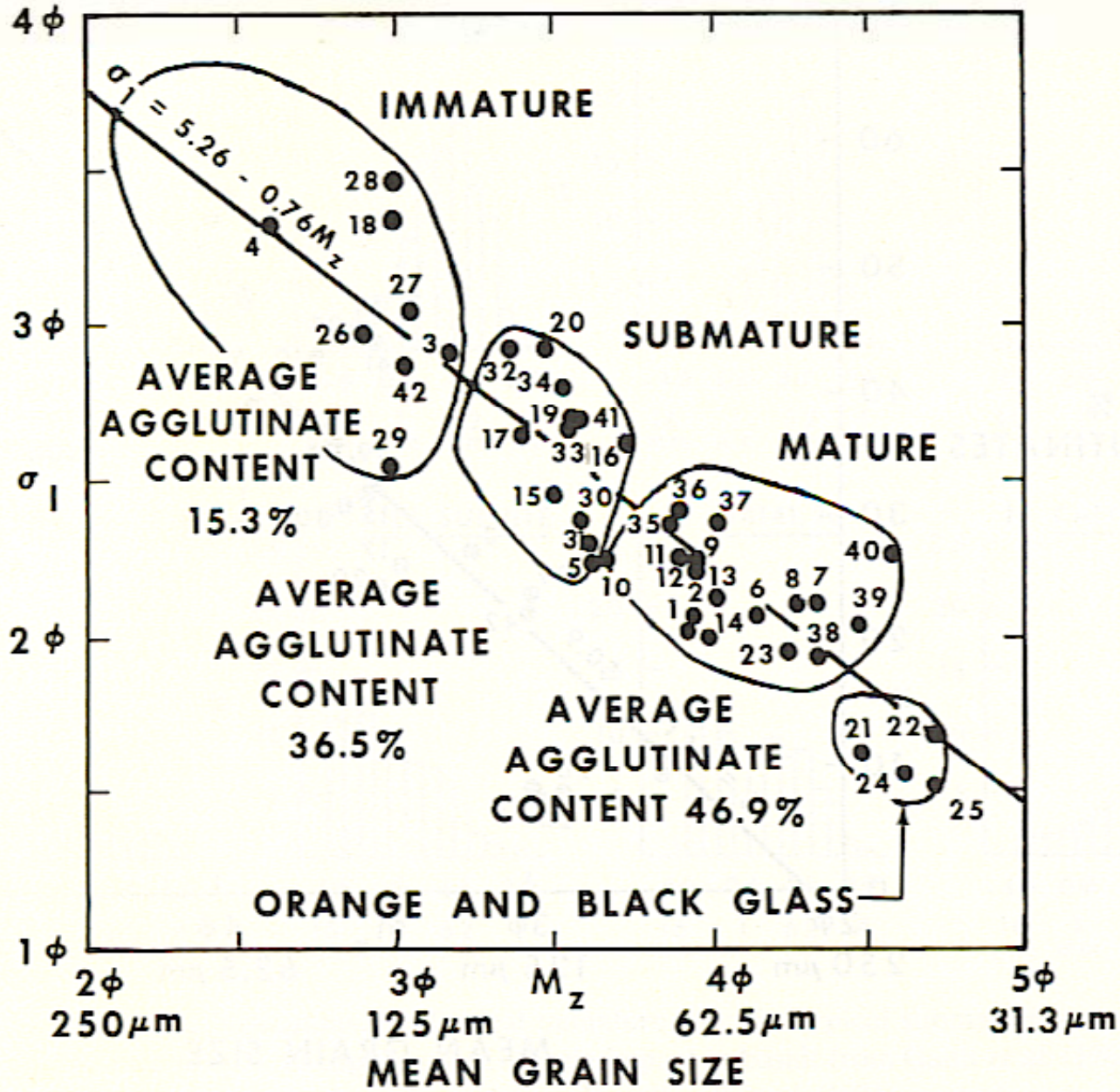
Summary

While we have done a good job of producing two different simulants, it may be time to rethink the priorities and evaluate if we are really reproducing the properties that will be most critical to the upcoming surface operations and to the construction and activity at a lunar outpost. I suggest that we may be ignoring some of the key properties that will be critical in excavation, regolith moving, construction of roads, radiation shielding, protection from rocket blast effects, and other applications that may be insensitive to chemistry and mineralogy and even to grain size distribution. It may be time to revisit our priorities look at the other 7 categories of properties that we have mostly neglected while concentrating on our favorite 3.

The End

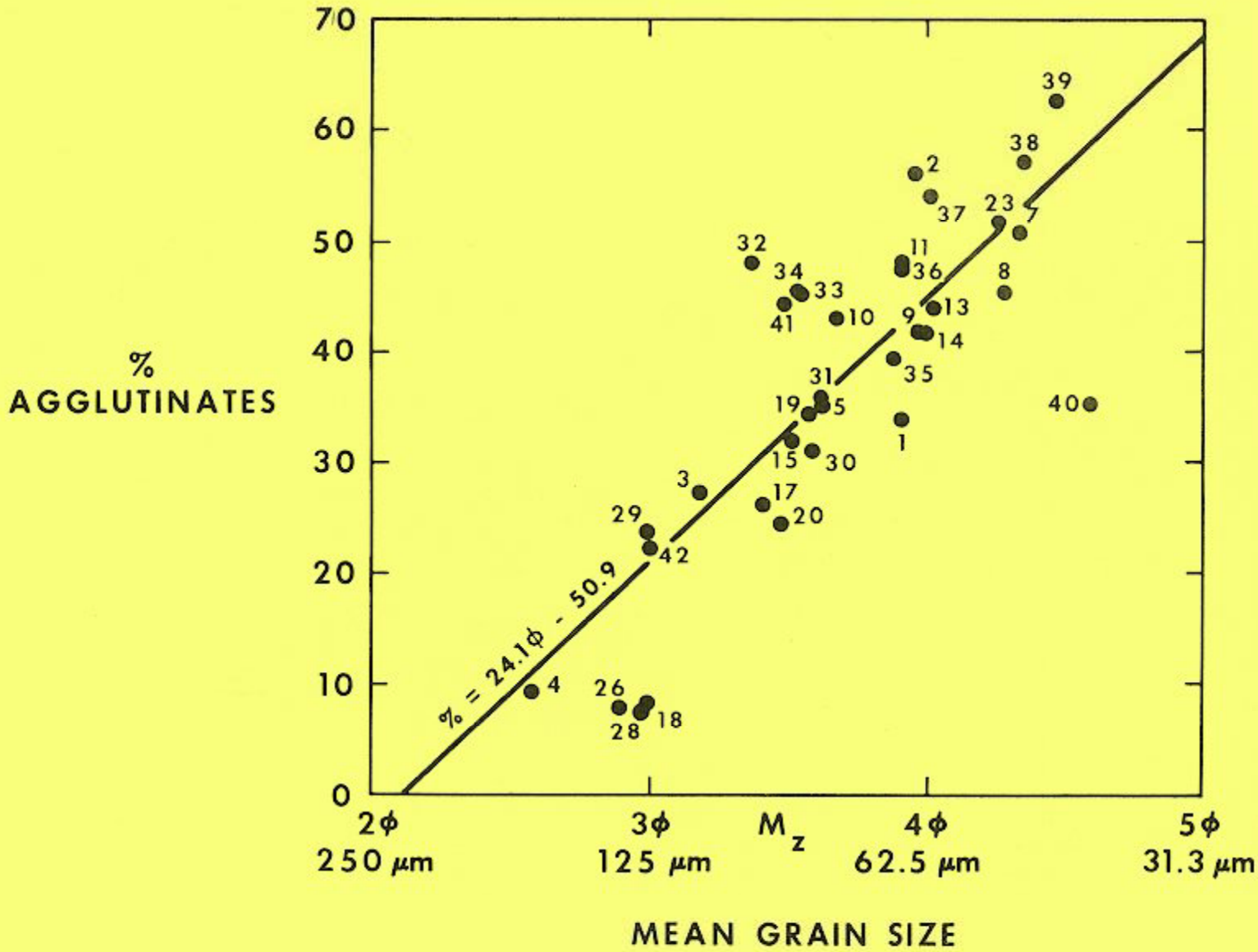
Extras


4ϕ
3ϕ
2ϕ
1ϕ
σ1
σ1 = 5.26 - 0.76Mz
IMMATURE
SUBMATURE
MATURE
AVERAGE AGGLUTINATE CONTENT 15.3%
AVERAGE AGGLUTINATE CONTENT 36.5%
AVERAGE AGGLUTINATE CONTENT 46.9%
ORANGE AND BLACK GLASS
2ϕ 250μm
3ϕ 125μm
Mz
4ϕ 62.5μm
5ϕ 31.3μm
MEAN GRAIN SIZE


4ϕ
3ϕ
2ϕ
1ϕ
σ1
σ1 = 5.26 - 0.76Mz
IMMATURE
SUBMATURE
MATURE
AVERAGE AGGLUTINATE CONTENT 15.3%
AVERAGE AGGLUTINATE CONTENT 36.5%
AVERAGE AGGLUTINATE CONTENT 46.9%
ORANGE AND BLACK GLASS
2ϕ 250μm
3ϕ 125μm
Mz
4ϕ 62.5μm
5ϕ 31.3μm
MEAN GRAIN SIZE

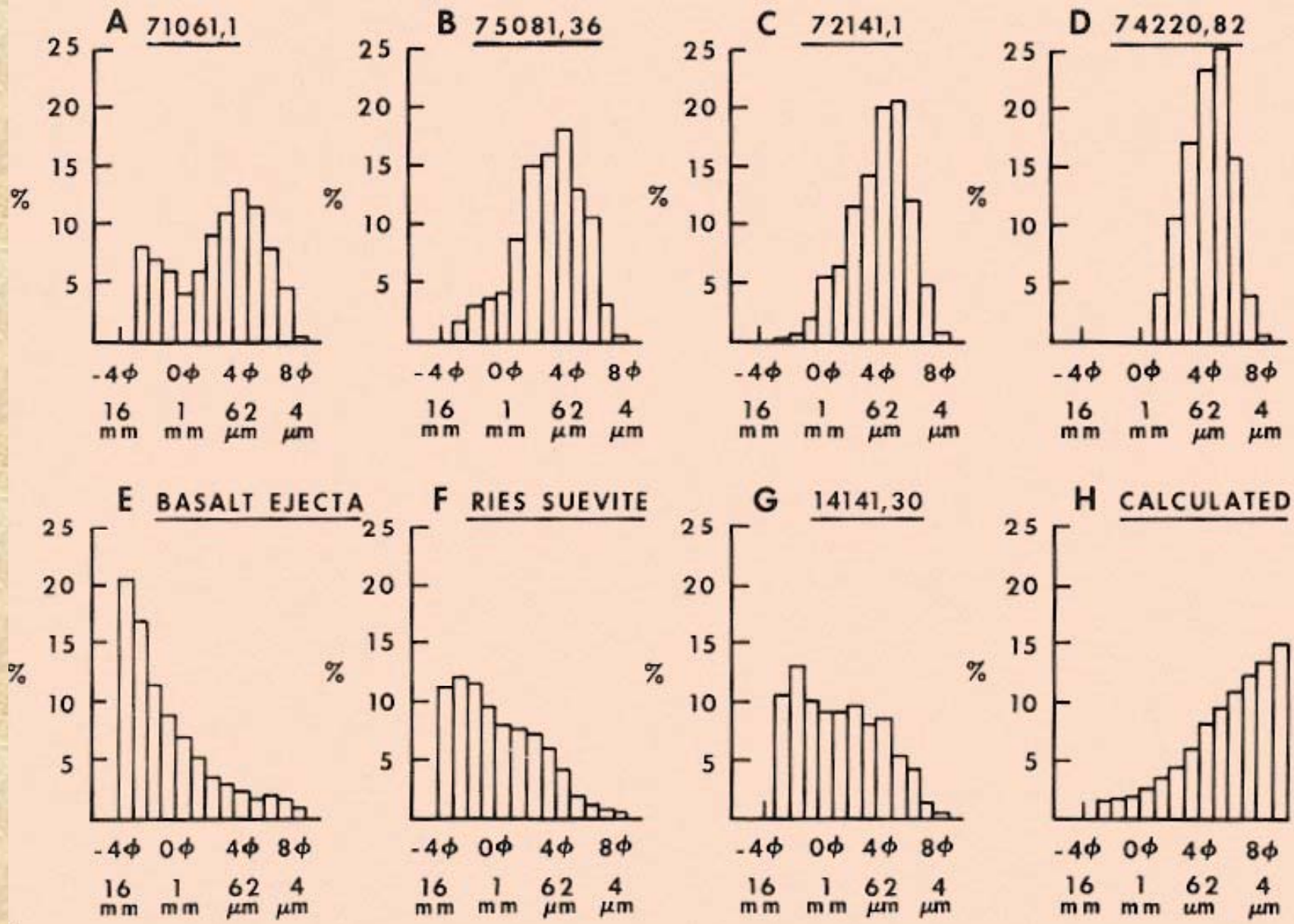
What happens as lunar soils mature?

- The mean grain size decreases
- The standard deviation decreases
- **Agglutinates increase**

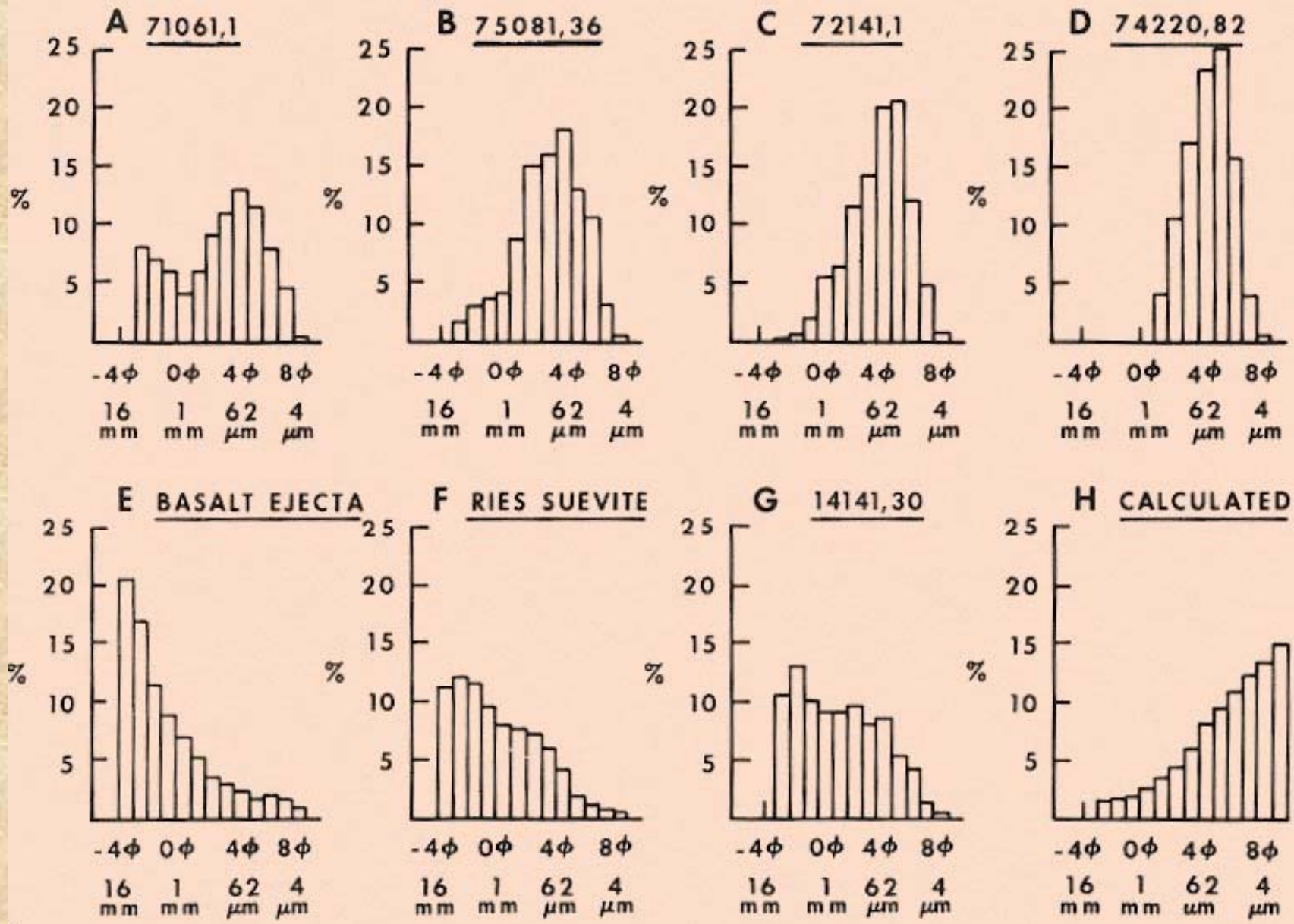

70
60
50
40
30
20
10
0
% AGGLUTINATES
% = 24.1φ - 50.9
2φ
250 μm
3φ
125 μm
M_z
4φ
62.5 μm
5φ
31.3 μm
MEAN GRAIN SIZE

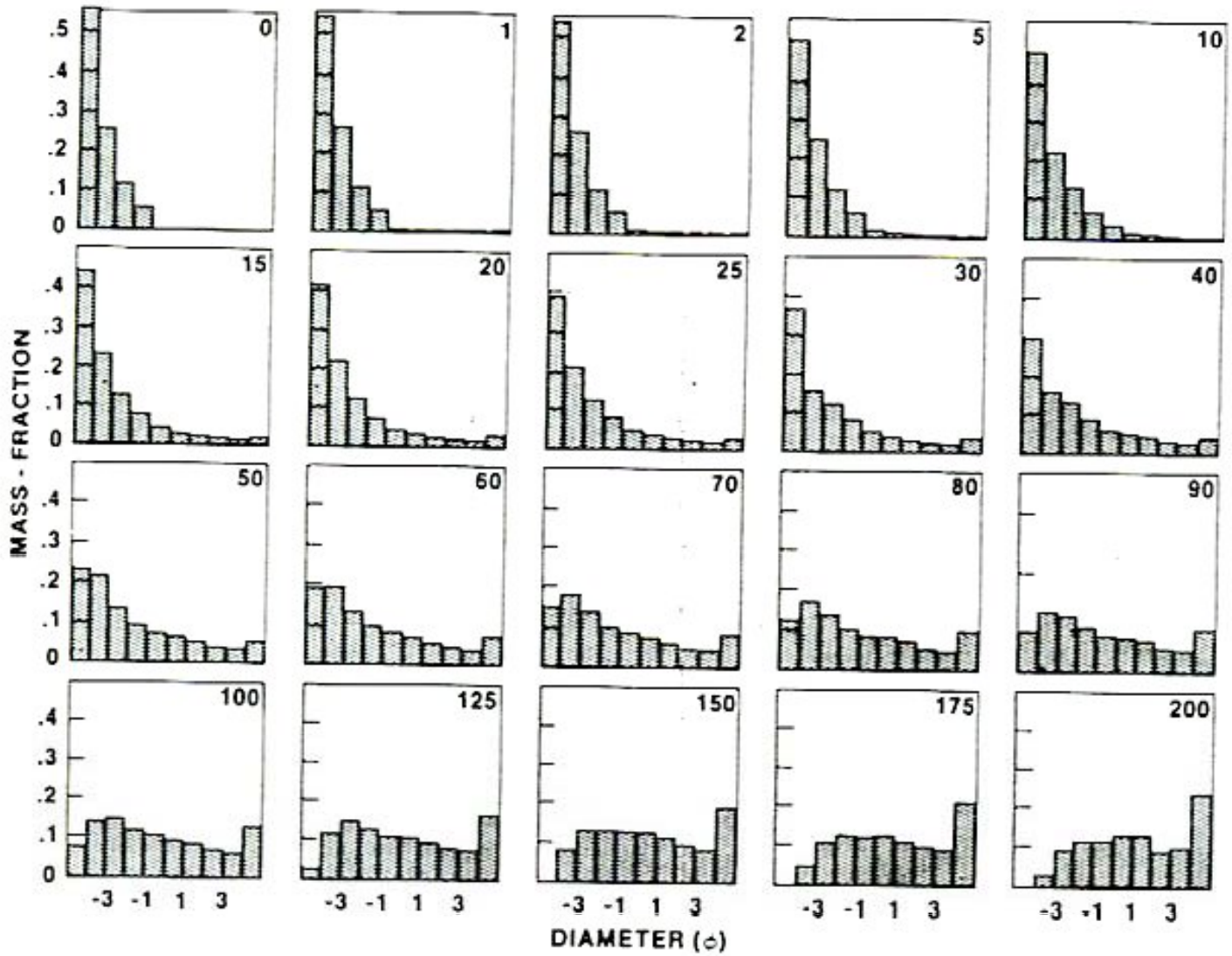
What happens as lunar soils mature?

- The mean grain size decreases and the agglutinate abundance increases
- Agglutinates increase
- **The shape of the grain size distribution changes**


A 71061,1
B 75081,36
C 72141,1
D 74220,82
E BASALT EJECTA
F RIES SUEVITE
G 14141,30
H CALCULATED
%
25
20
15
10
5
-4ϕ 0ϕ 4ϕ 8ϕ
16 mm
1 mm
62 μm
4 μm

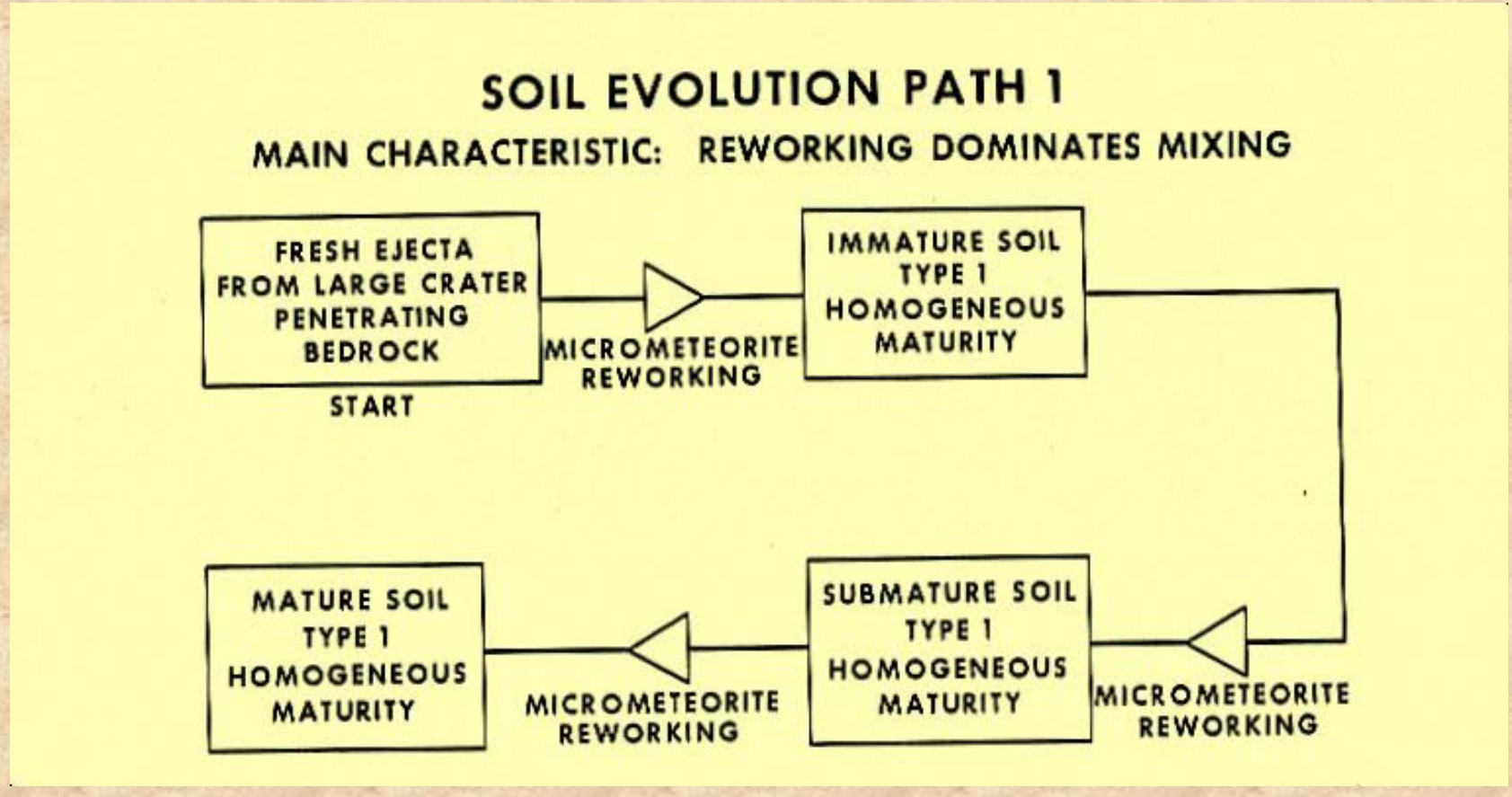
How do lunar size distributions compare to experimental data?


A 71061,1
B 75081,36
C 72141,1
D 74220,82
E BASALT EJECTA
F RIES SUEVITE
G 14141,30
H CALCULATED
%
25
20
15
10
5
-4ϕ 0ϕ 4ϕ 8ϕ
16 mm
1 mm
62 μm
4 μm

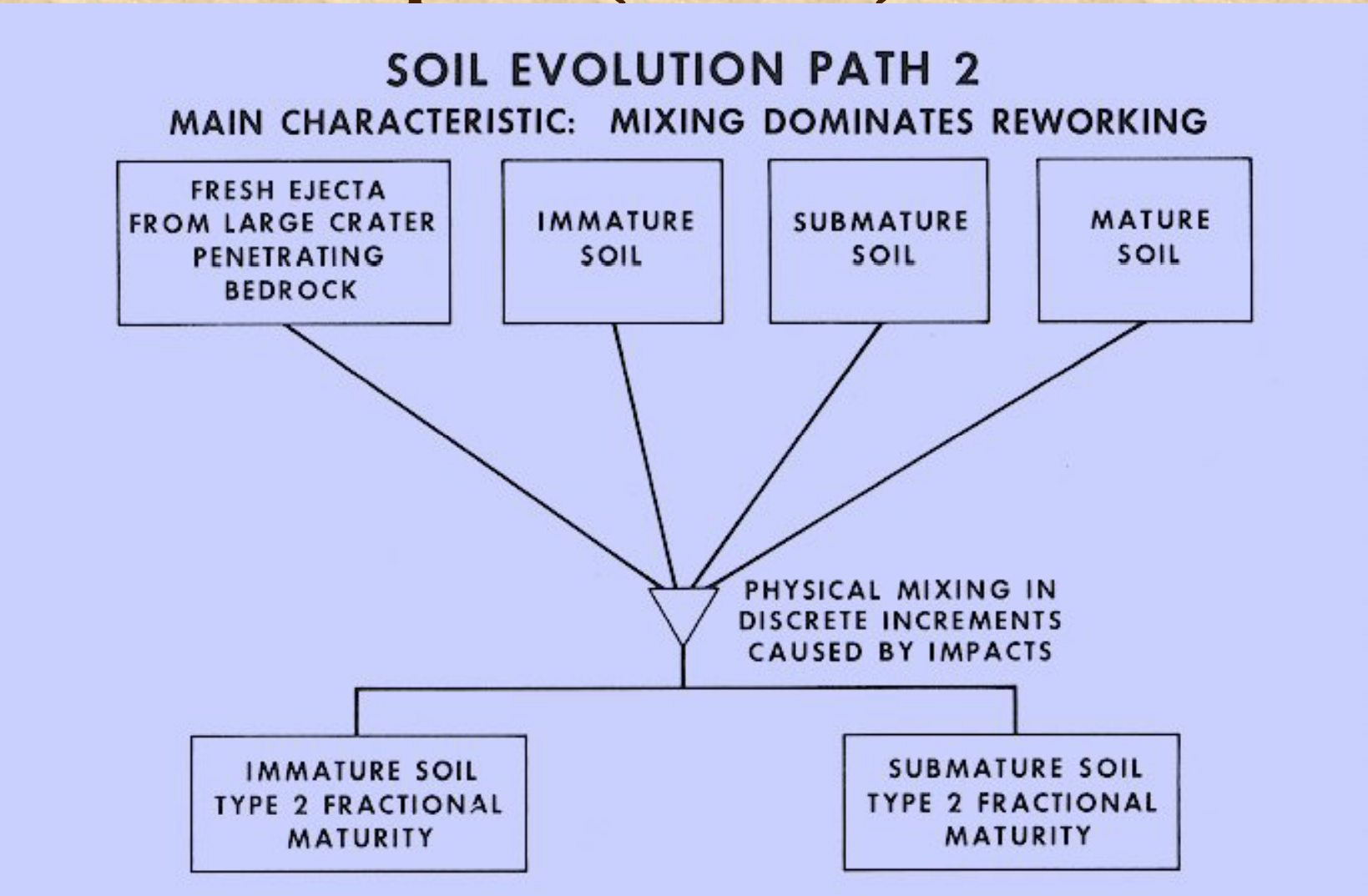


Differential grain-size distribution after select number of shots (shot number in upper right-hand corner). Note that ire population of >16–32 mm fragments, initially constituting 56% by weight, is ultimately destroyed and the grain-size ution changes from positively to negatively skewed.

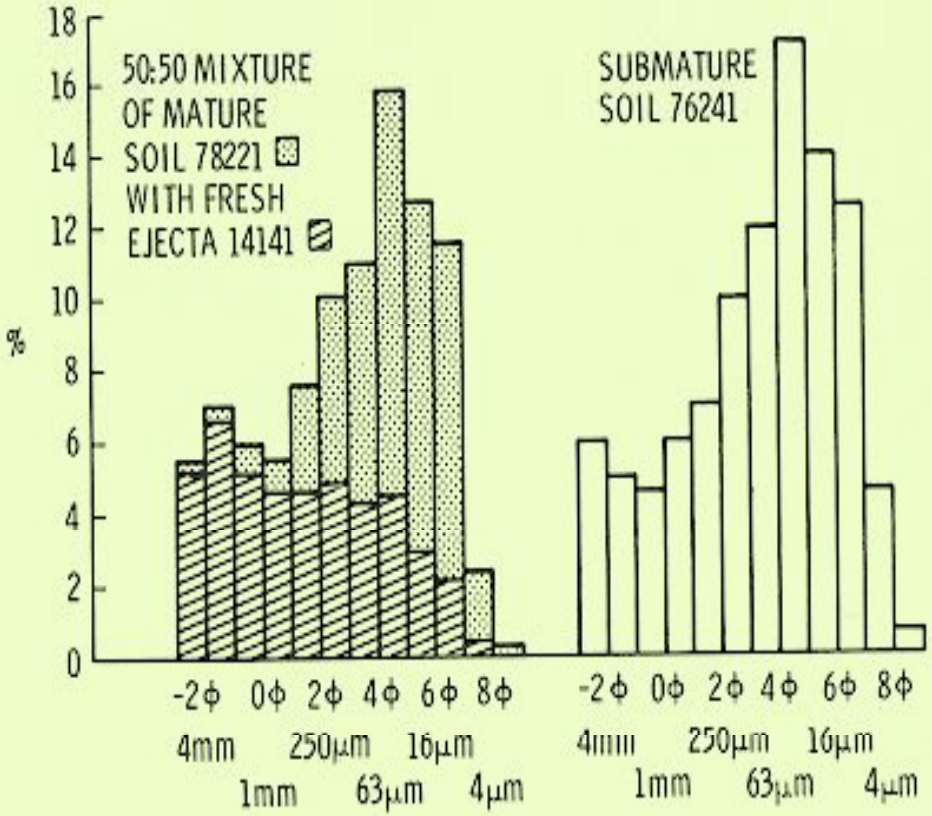
Soils follow an evolution path as they become more mature (Path 1)



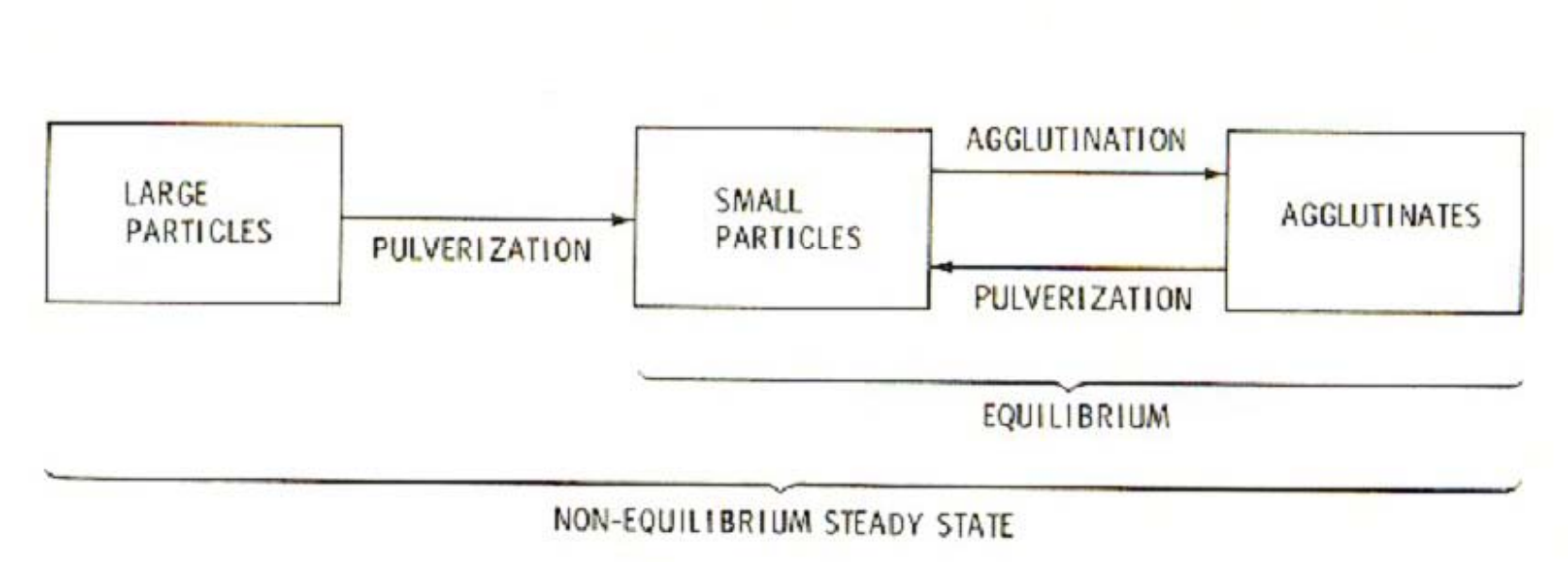
Soils may also follow a different evolution path (Path 2)



Mixed, path 2 soils may have unusual properties

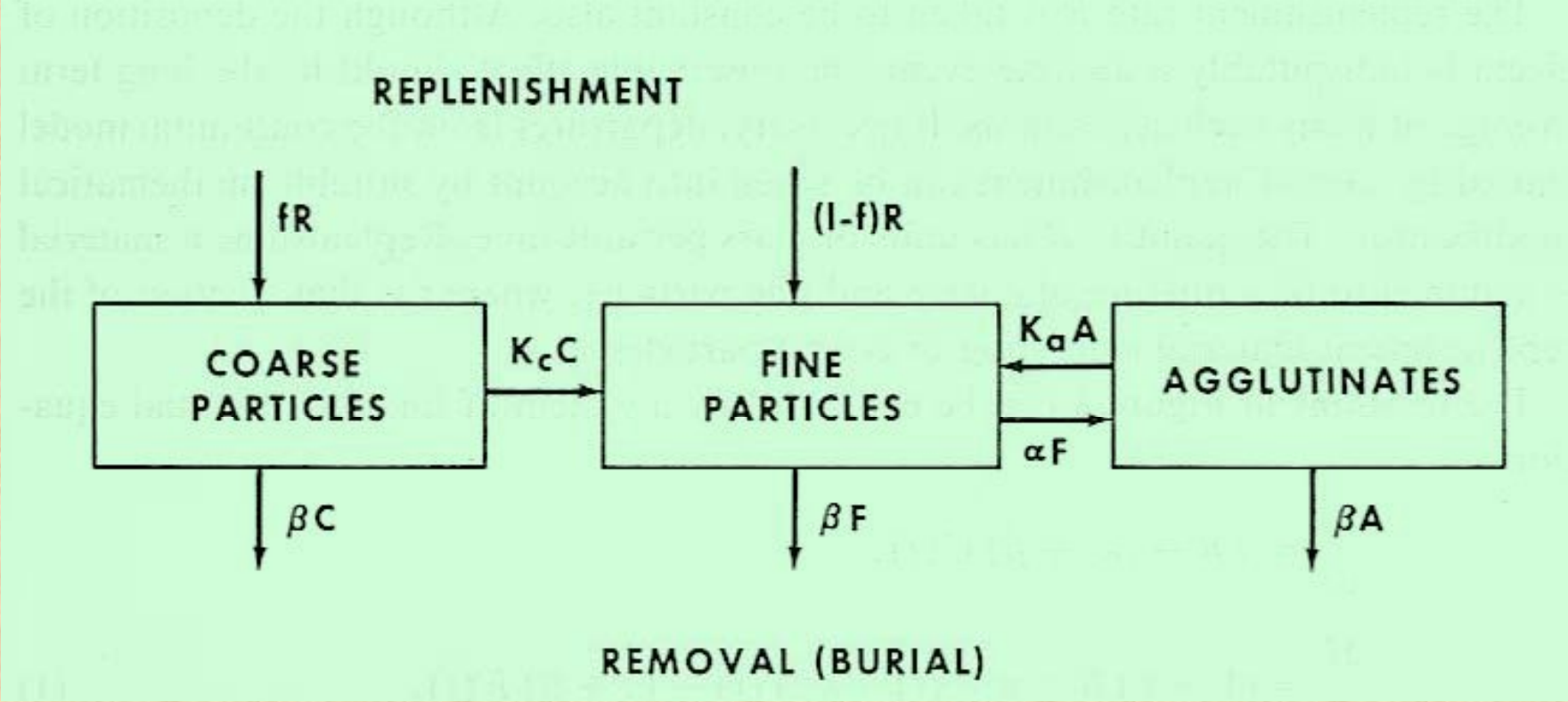


The evolution of lunar soils can be modeled:

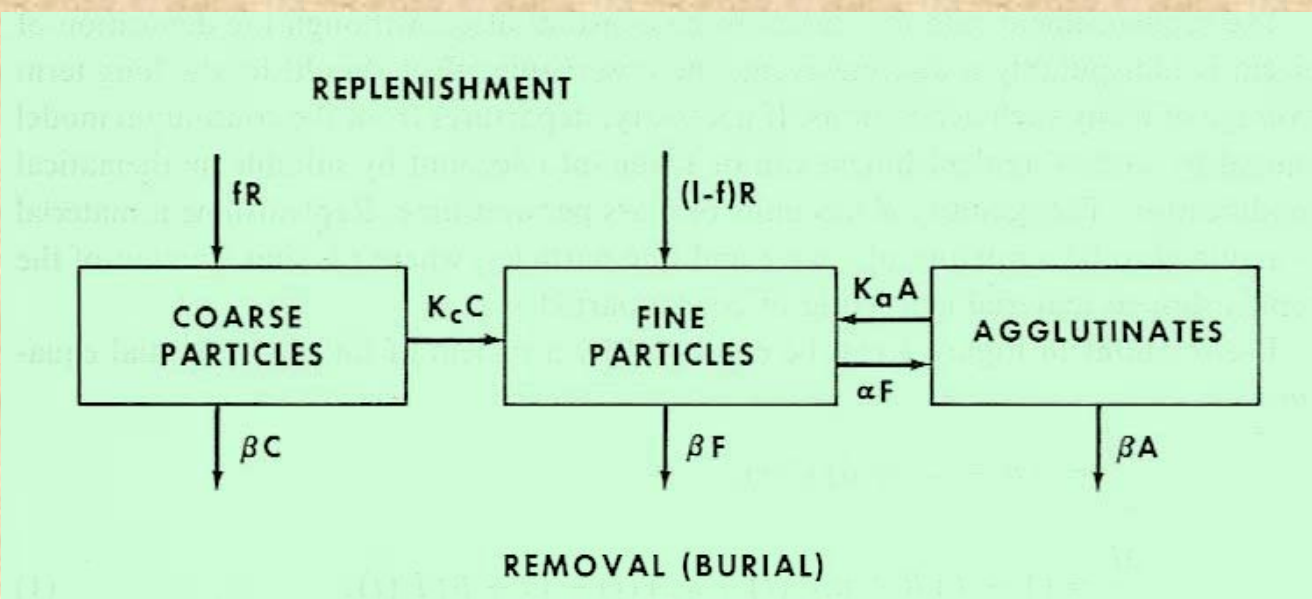


The evolution of lunar soils can be modeled:

The model can be described by equations



The evolution of lunar soils can be modeled:



$$\frac{dC}{dt} = fR - (\kappa_c + \beta)\, C(t),$$

$$\frac{dF}{dt} = (1 - f)\, R + \kappa_c C(t) + \kappa_a A(t) - (\alpha + \beta)\, F(t),$$

$$\frac{dA}{dt} = \alpha F(t) - (\kappa_a + \beta)\, A(t).$$

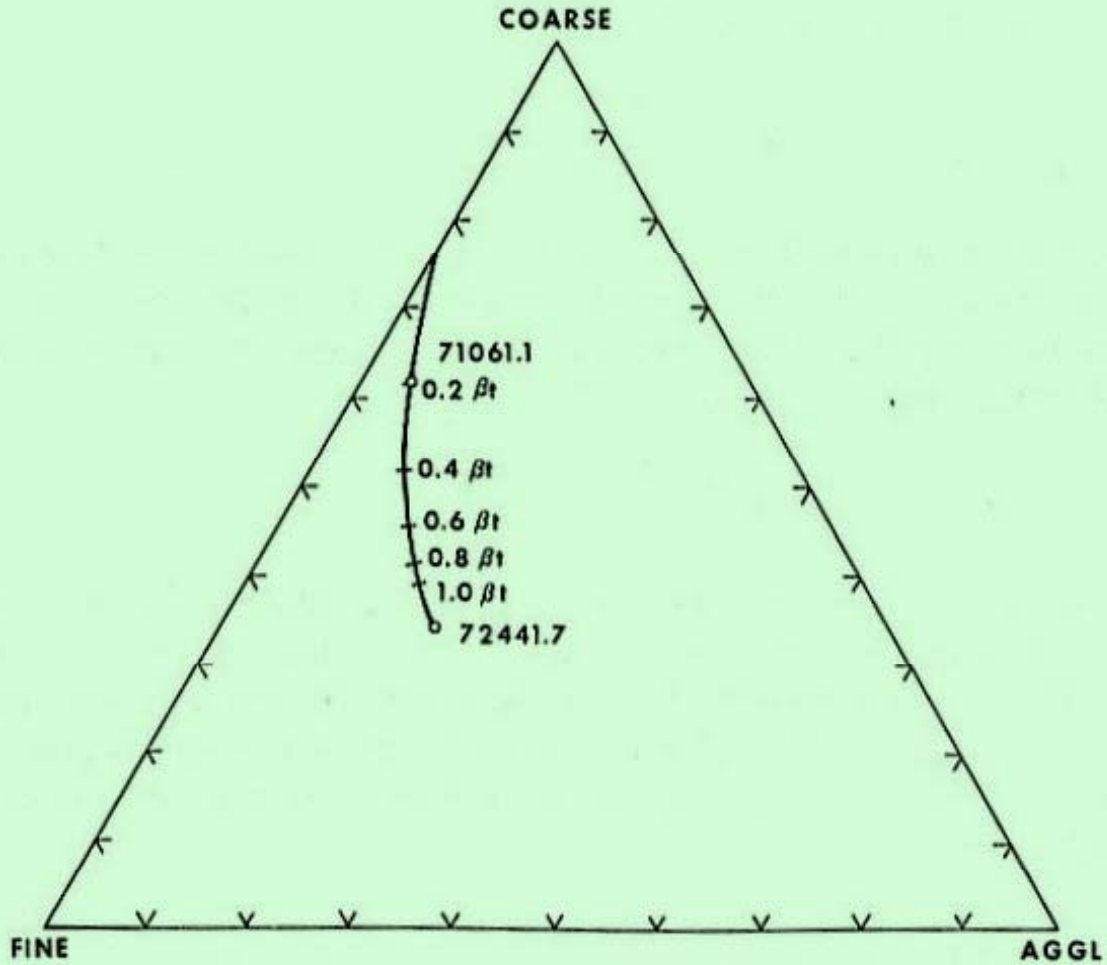
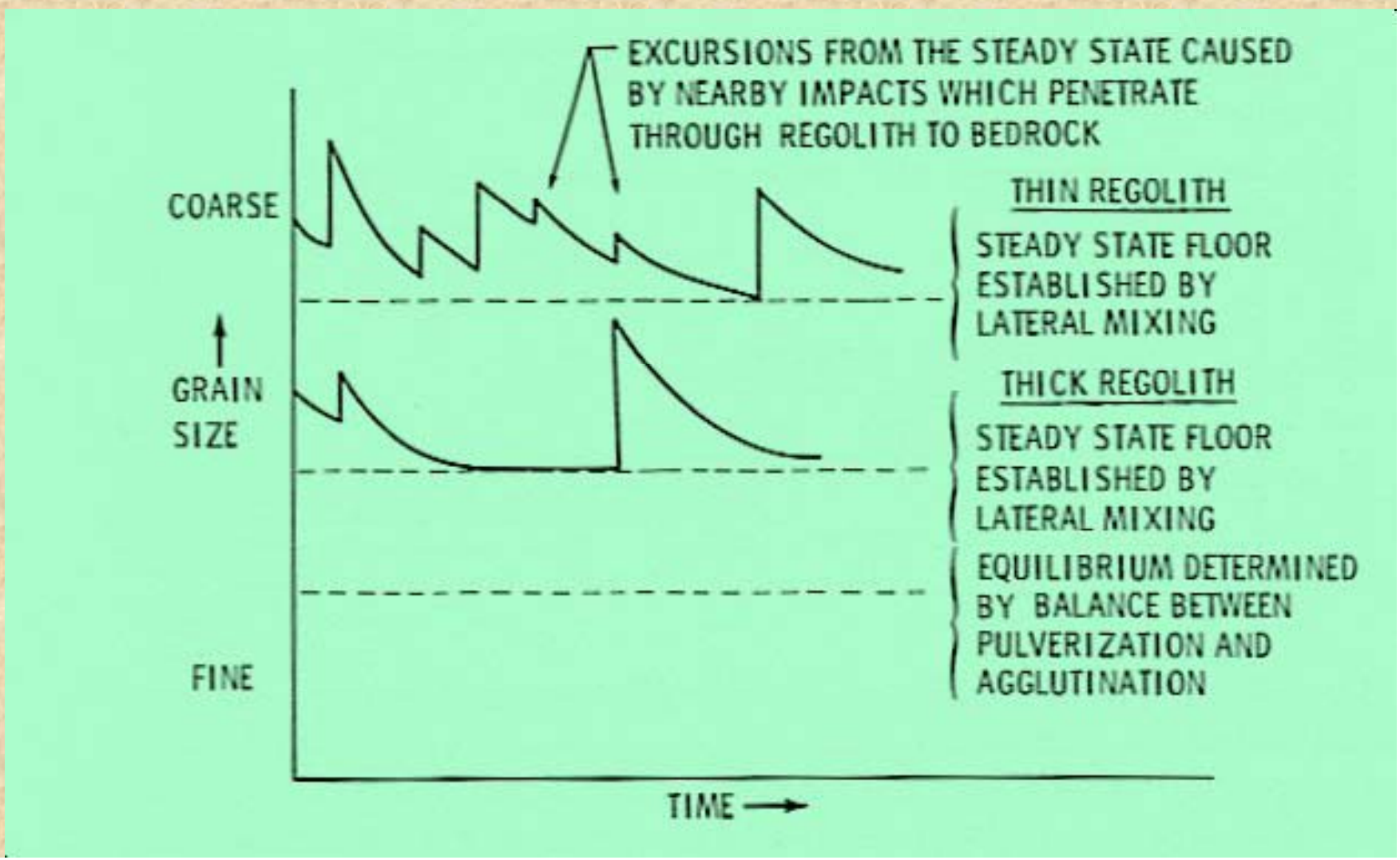
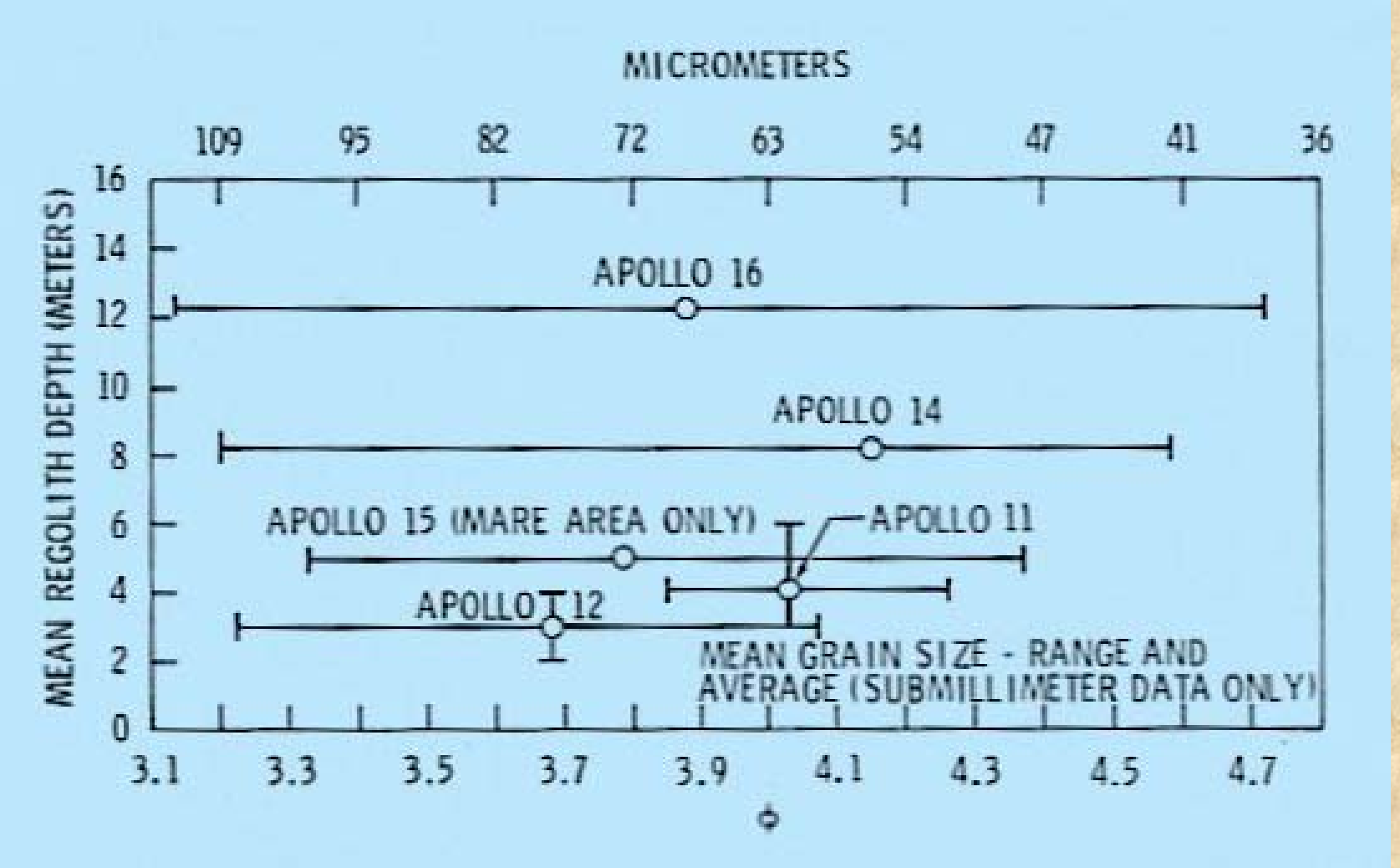


Fig. 2. A soil can be plotted as a point on a ternary diagram with coarse particle, fine particle, and agglutinate end members. In a given system, a fresh ejecta soil matures along a calculable trajectory from the *CF* side to a steady state soil near the center of the diagram. An immature soil and a mature soil from the Apollo 17 site are plotted for illustration. The cross marks on the trajectory represent the positions of an evolving soil in this system at five equally spaced time intervals.

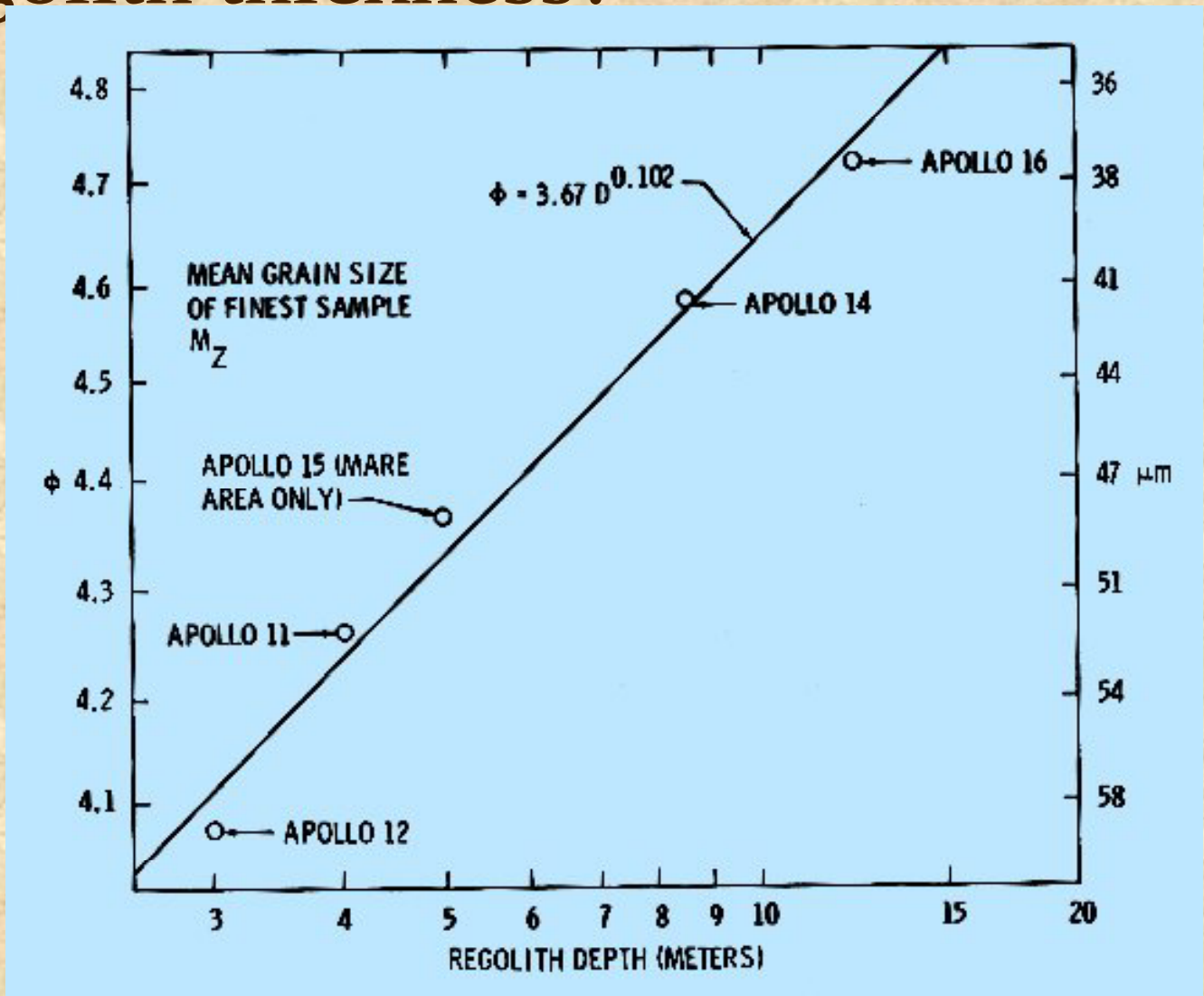
How does regolith evolution relate to regolith thickness?



How does regolith evolution relate to regolith thickness?



How does regolith evolution relate to regolith thickness?



Conclusions

- The lunar regolith has evolved in a complex but predictable way
- Soil maturity is a key concept that must be considered an independent parameter in planning lunar operations
- For some lunar surface operations, maturity is more important than chemistry or mineralogy
- Simulants must consider maturity-related properties
- Simply grinding rock will not produce an adequate simulant
- Determination of grain size distribution must a key element of future exploration