Evolution of the Lunar Regolith

David S. McKay

Chief Scientist for Astrobiology

Astromaterials Research and Exploration Science (ARES) Directorate

NASA Johnson Space Center

Major Processes

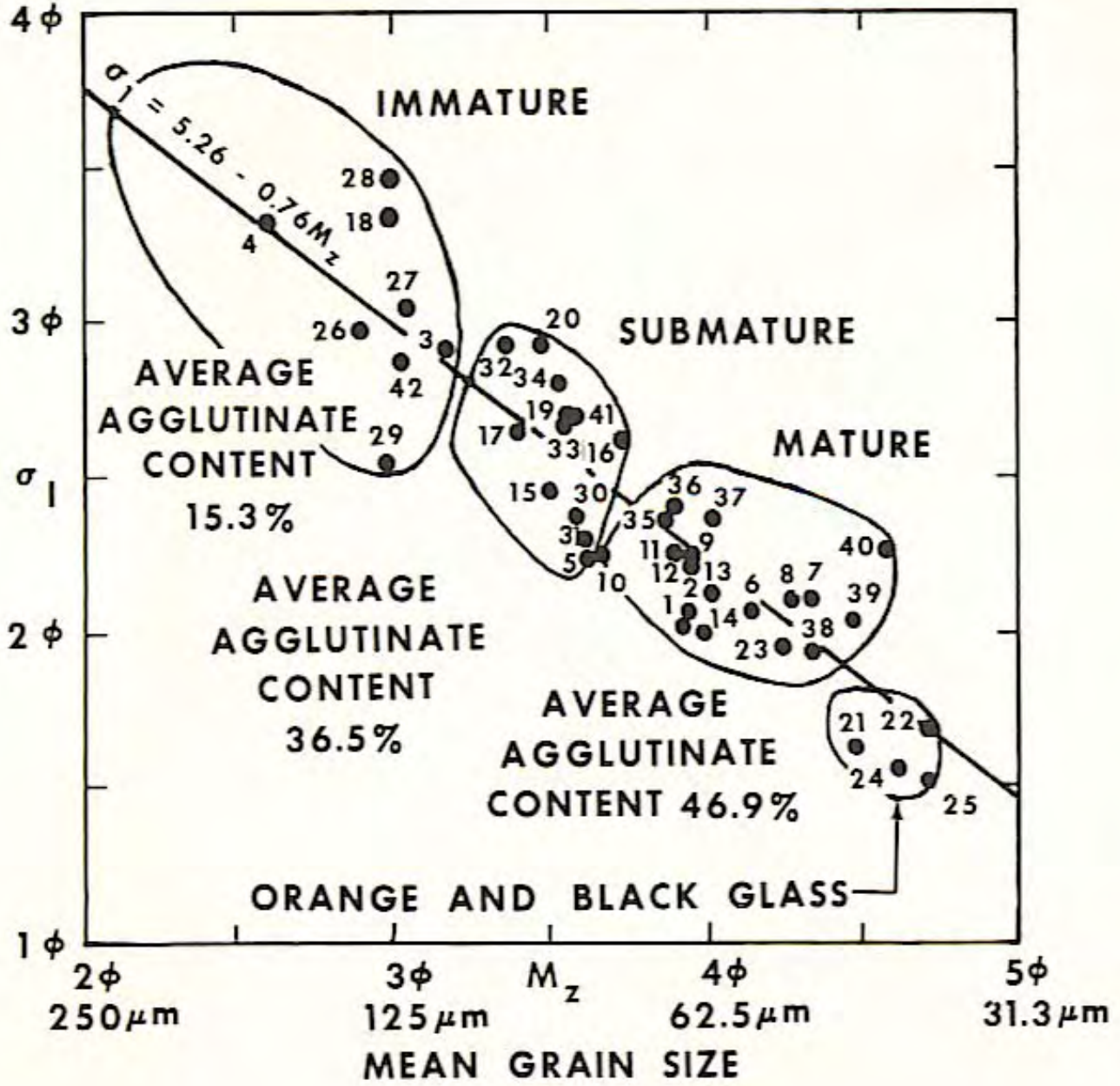
- **Impact communition**
- **Impact melting**
- **Formation of agglutinates**
- **Solar wind sputtering**
- **Impact vaporization**
- **Impact vapor condensation**
- **Shock welding of grains**
- **Thermal welding of grains**

Concept of soil maturity

- Maturity of lunar soil is the collection of properties which have changed over time as the soil has been exposed at or near the surface
- Immature soils have had little exposure
- Mature soils have have significant exposure
- The most mature lunar soils have had around 100my exposure time

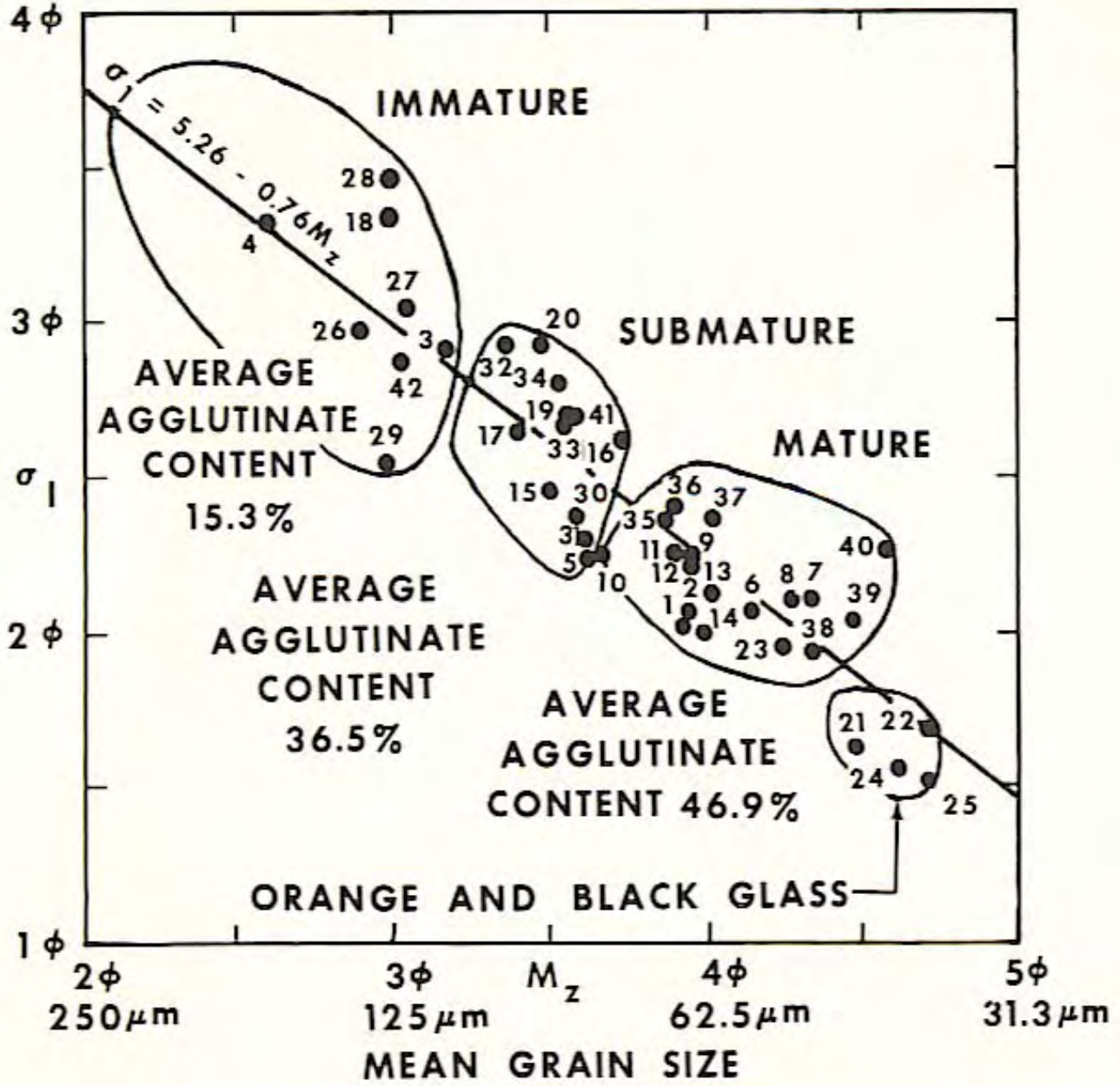
What happens as lunar soils mature?

- **The mean grain size decreases**


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
28
18
4
27
26
3
42
29
20
32
34
19
41
17
33
16
15
30
3
5
36
37
35
11
9
40
12
13
10
2
6
8
7
39
1
14
38
23
21
22
24
25
2φ
250μm
3φ
125μm
Mz
4φ
62.5μm
5φ
31.3μm
MEAN GRAIN SIZE

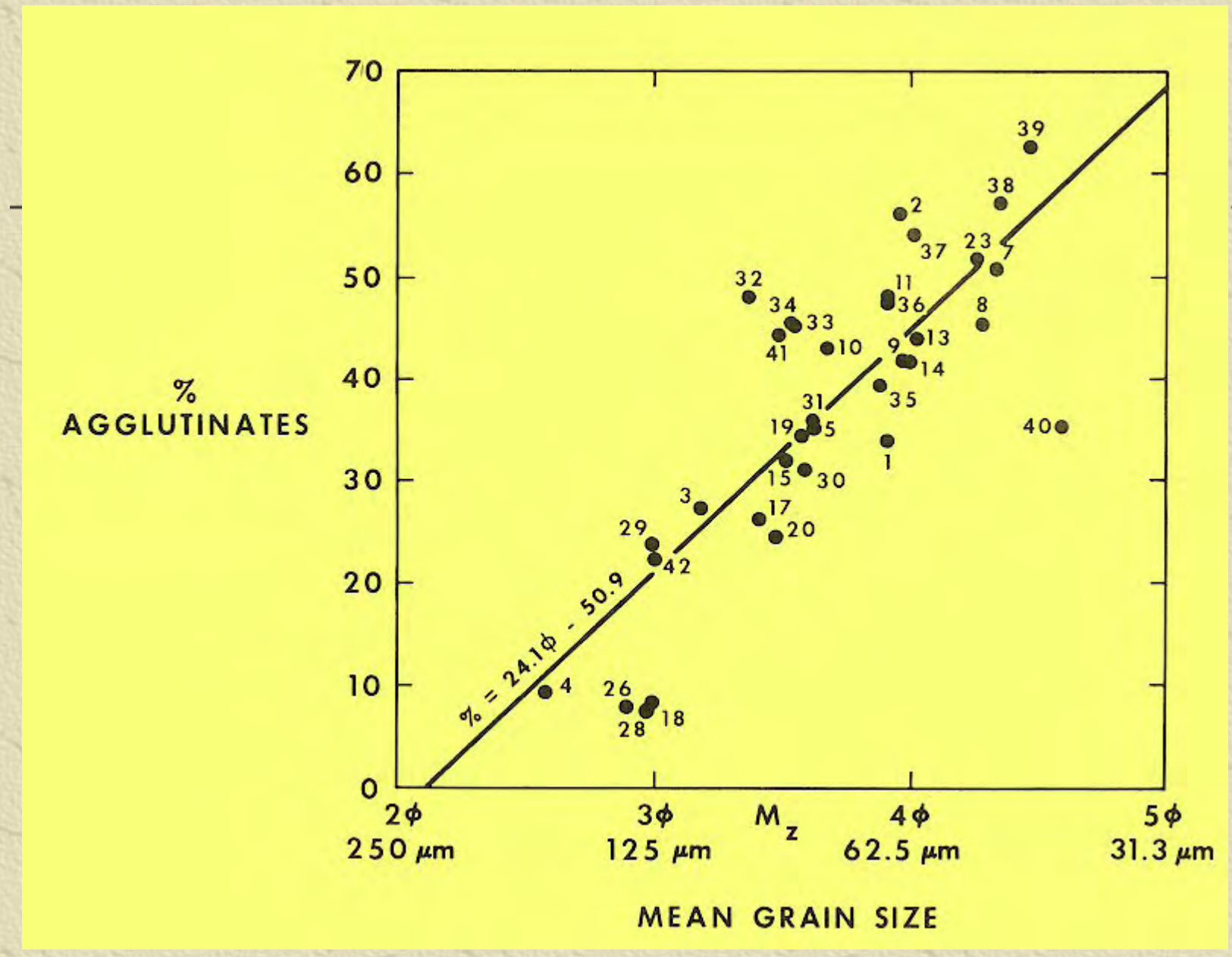
What happens as lunar soils mature?

- The mean grain size decreases and the agglutinate abundance increases
- **The standard deviation decreases**


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
28
18
4
27
26
3
42
29
20
32
34
19
41
17
33
16
15
30
3
5
36
37
35
11
9
40
12
13
10
2
6
8
7
39
1
14
38
23
21
22
24
25
2φ
250μm
3φ
125μm
Mz
4φ
62.5μm
5φ
31.3μm
MEAN GRAIN SIZE

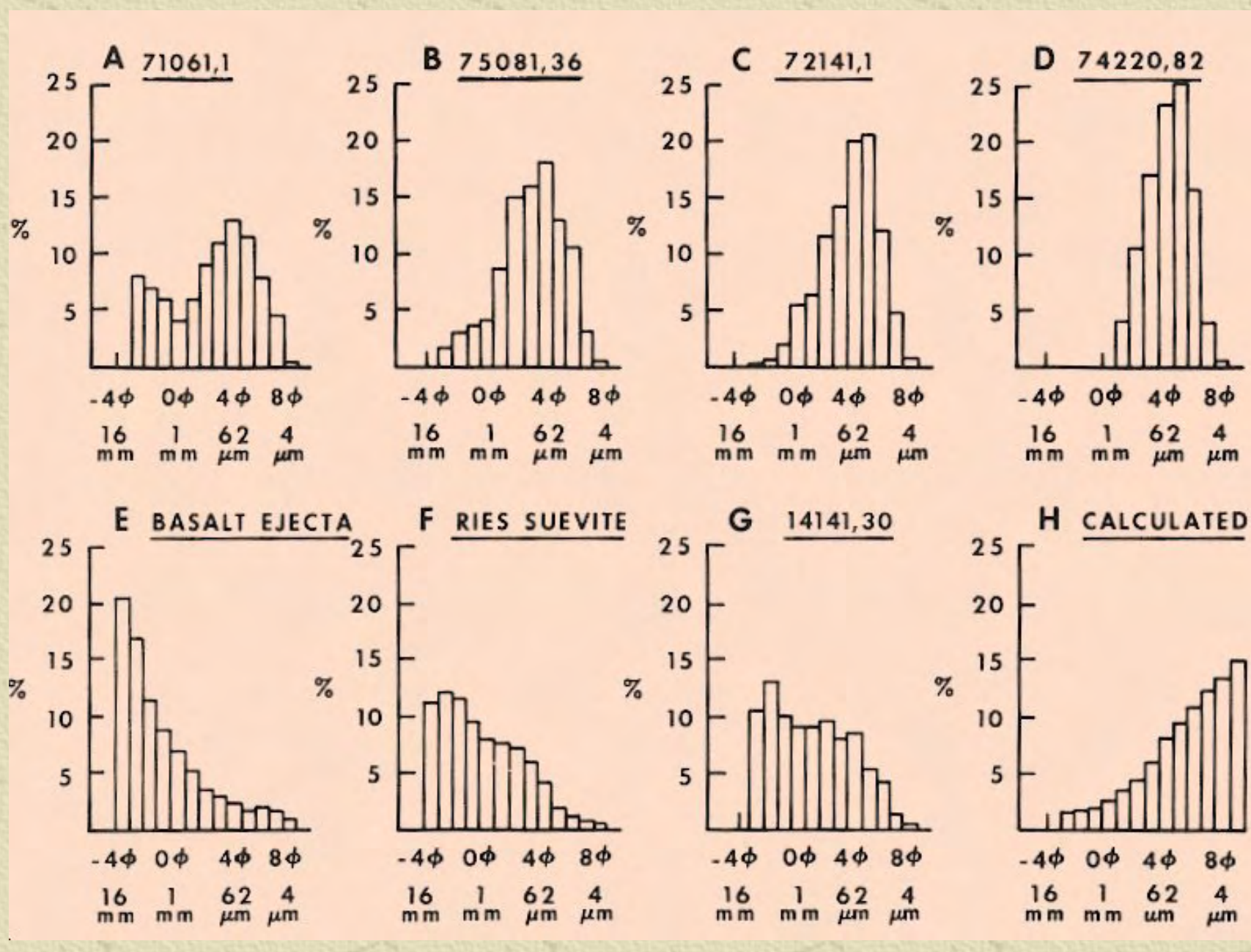
What happens as lunar soils mature?

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

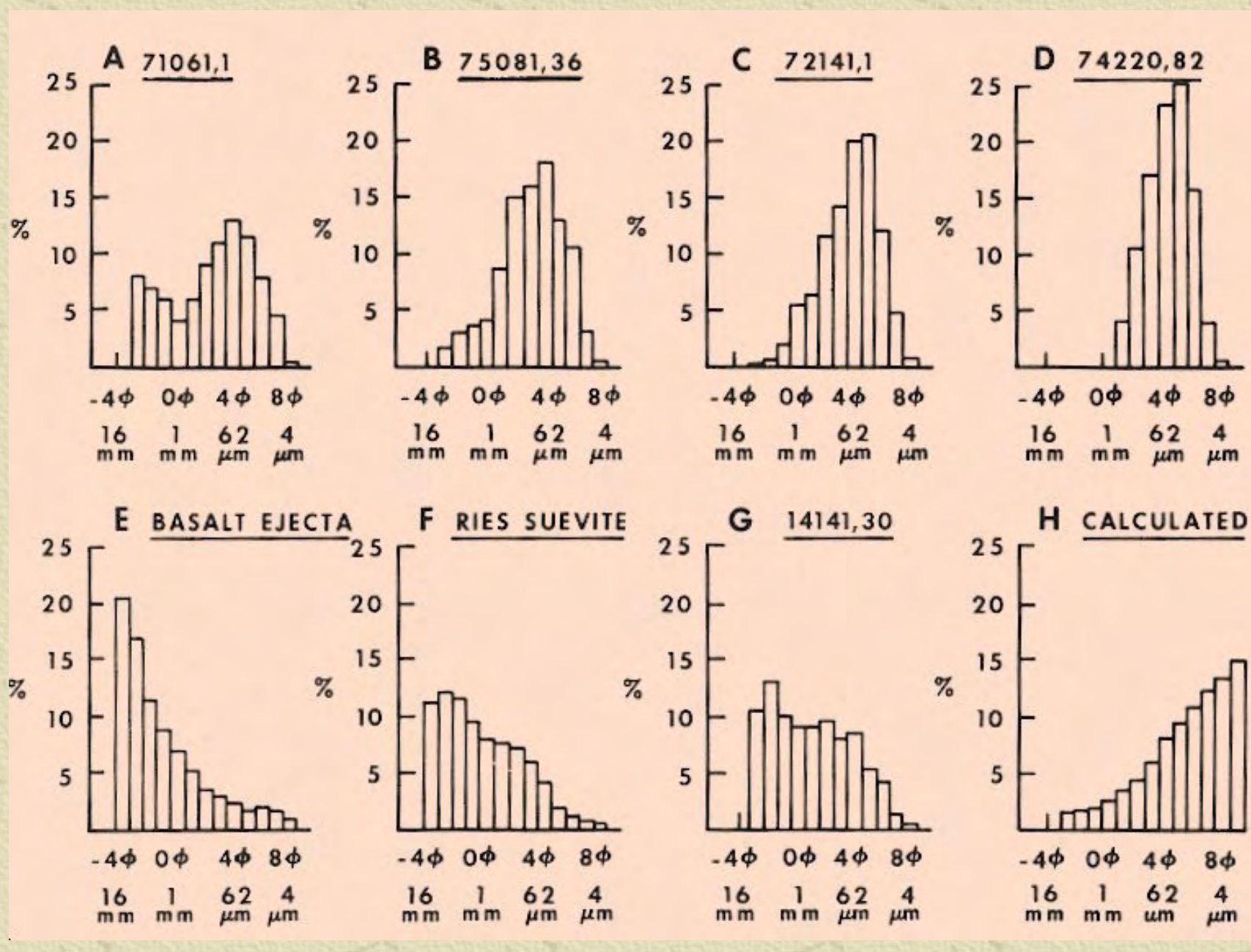

70
60
50
40
30
20
10
0
% AGGLUTINATES
% = 24.1φ - 50.9
2φ
250 μm
3φ
125 μm
Mz
4φ
62.5 μm
5φ
31.3 μm
MEAN GRAIN SIZE
39
38
2
37
23
7
32
11
34
36
8
33
41
10
9
13
14
31
35
19
5
40
1
15
30
3
17
29
20
42
4
26
28
18

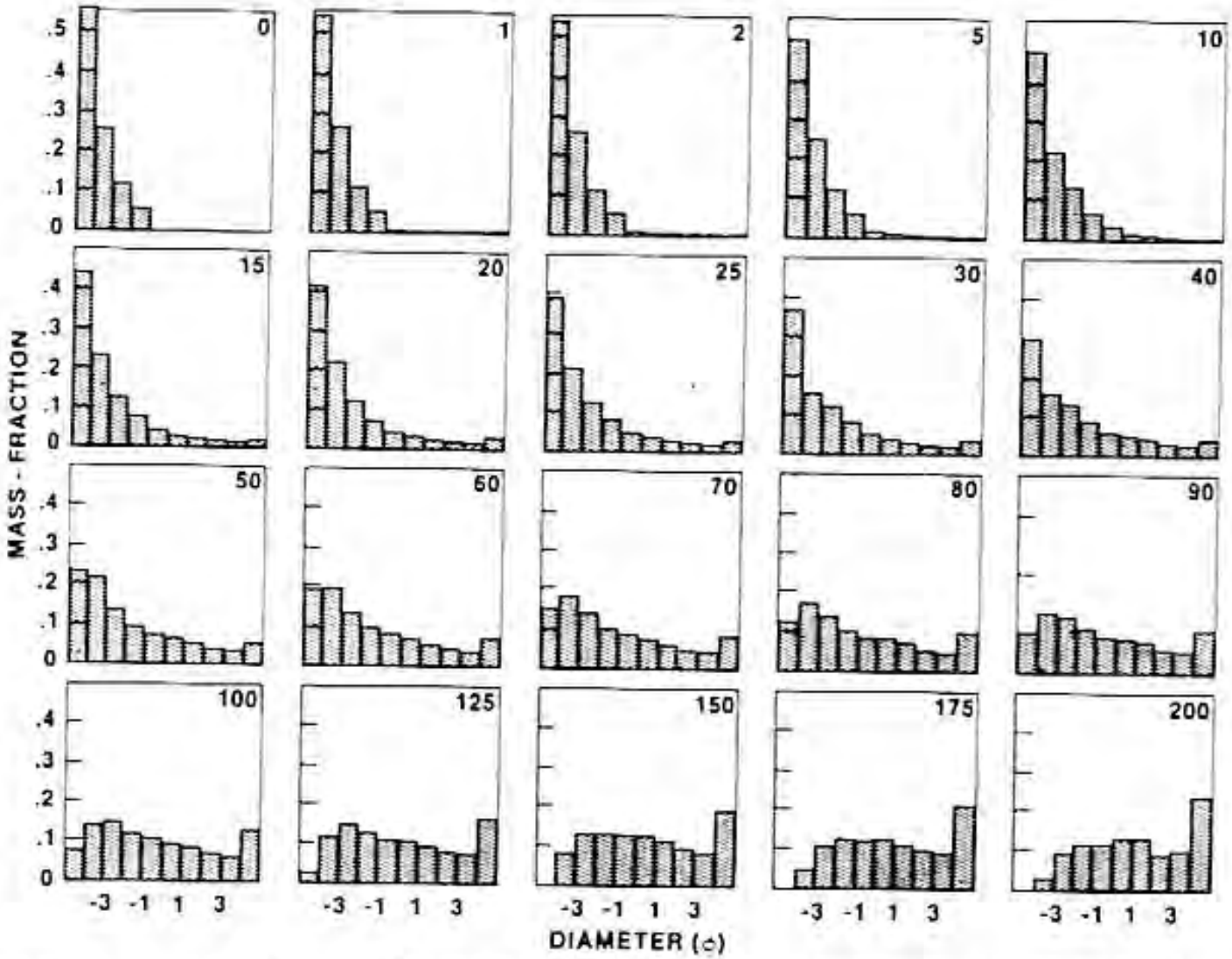
What happens as lunar soils mature?

- 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

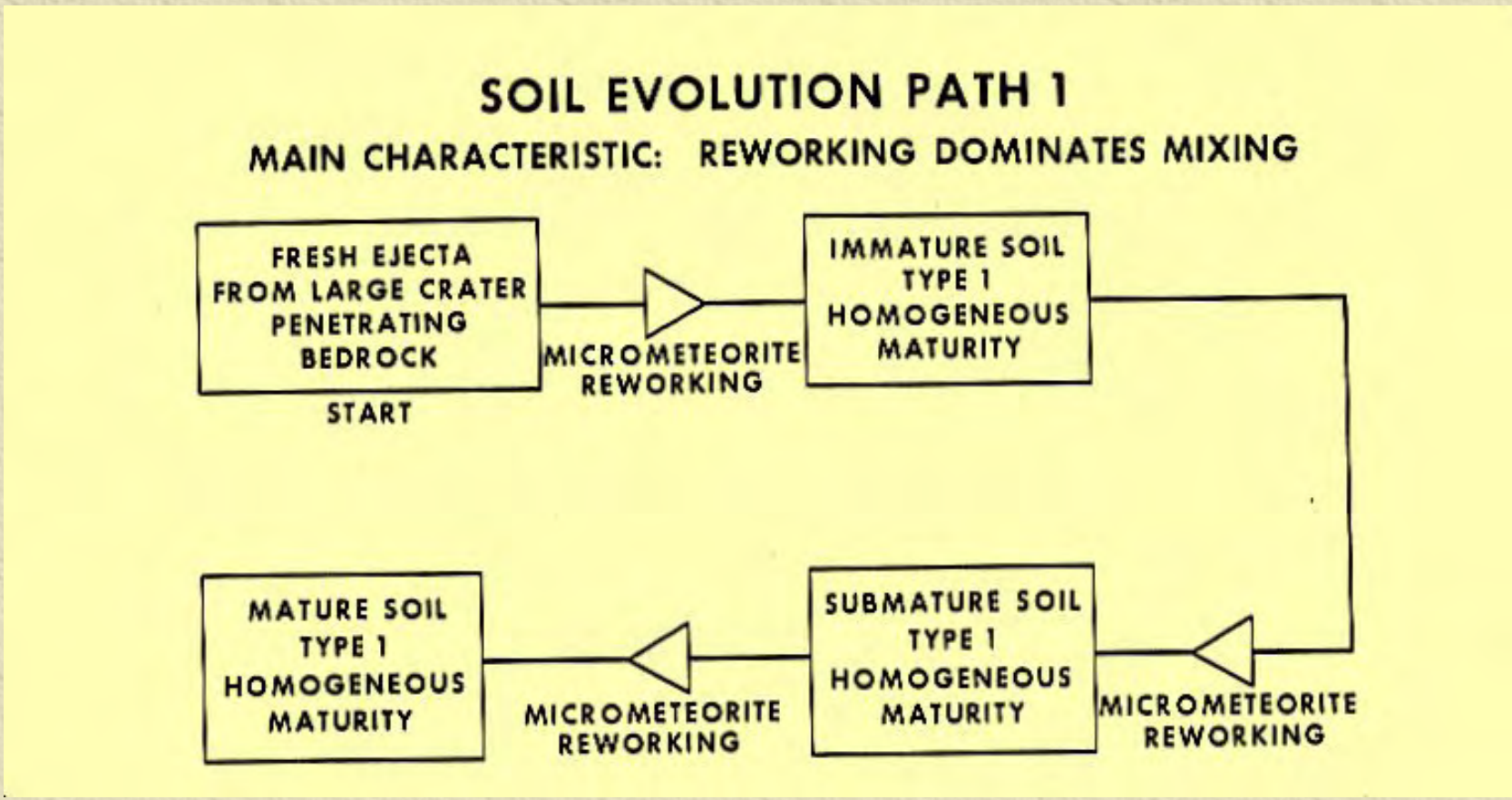
How do lunar size distributions compare to experimental data?


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

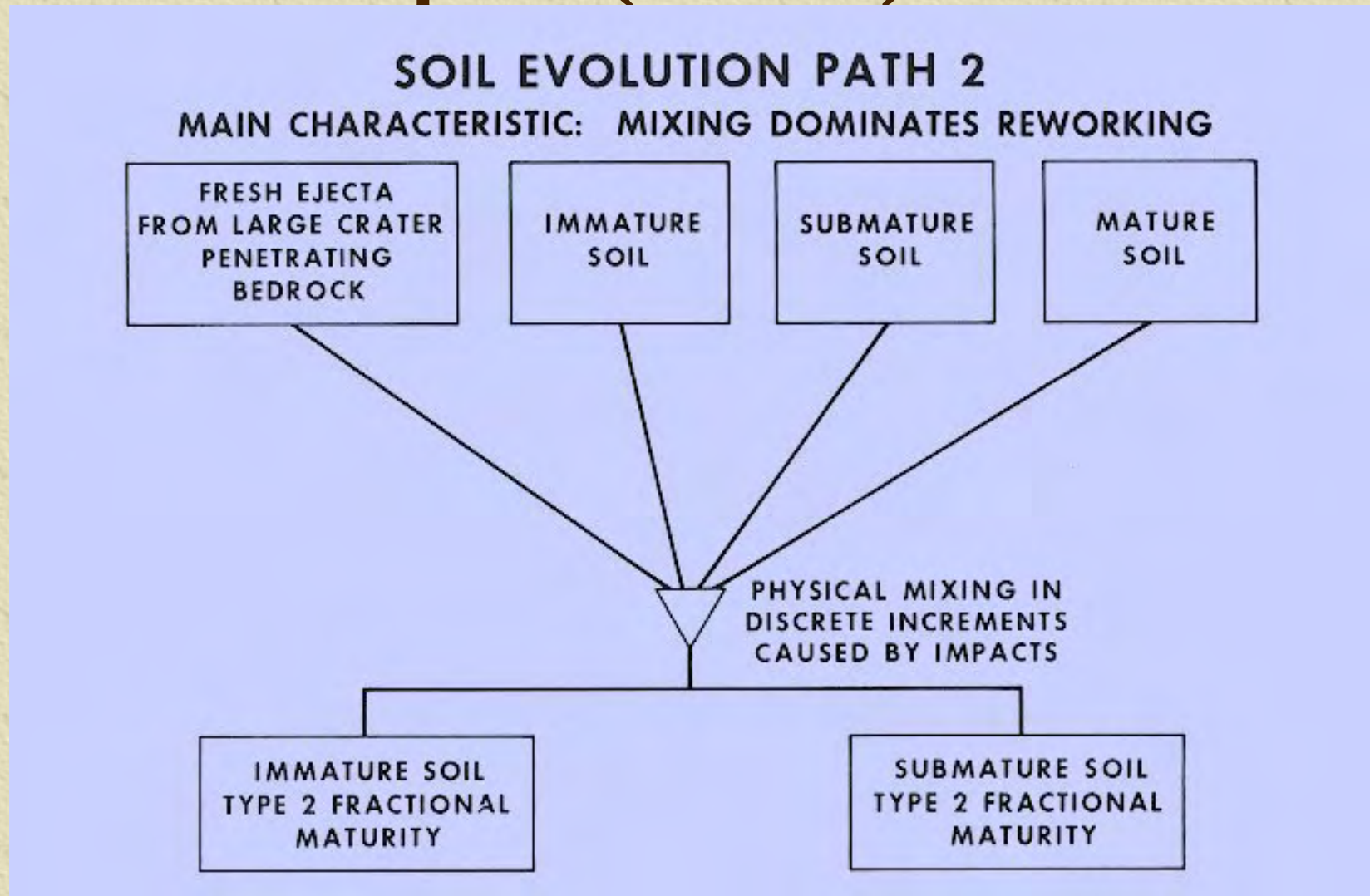


Differential grain-size distribution after select number of shots (shot number in upper right-hand corner). Note that ire population of >16–32 mm fragments, initially constituting 56% by weight, is ultimately destroyed and the grain-size ution changes from positively to negatively skewed.

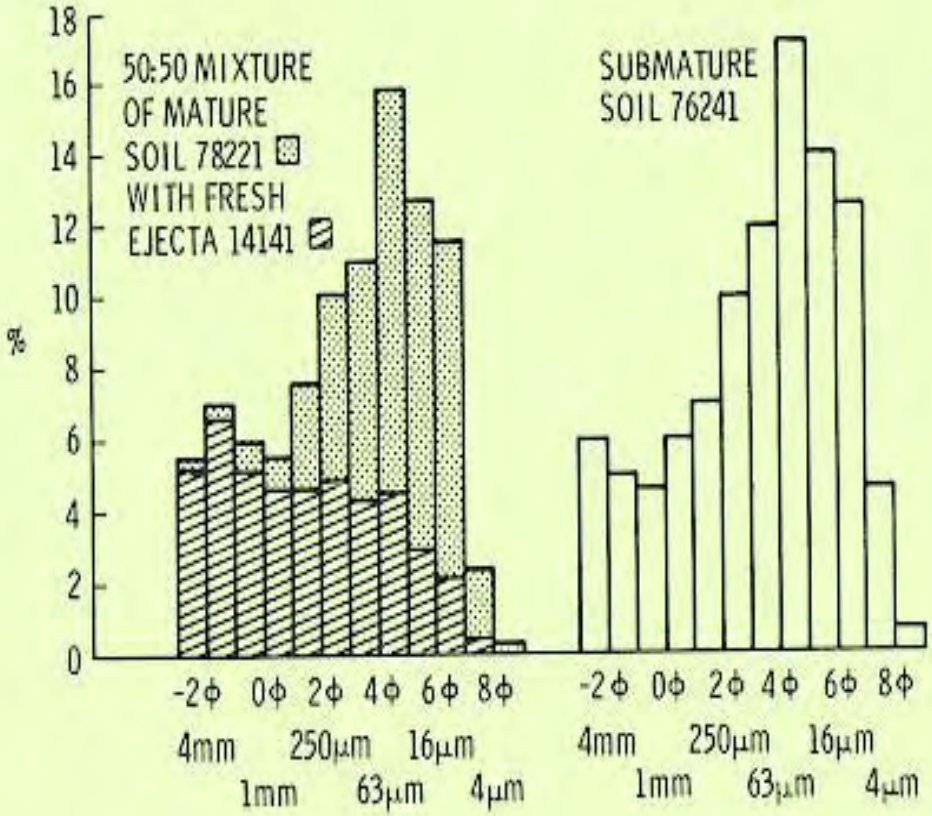
Soils follow an evolution path as they become more mature (Path 1)



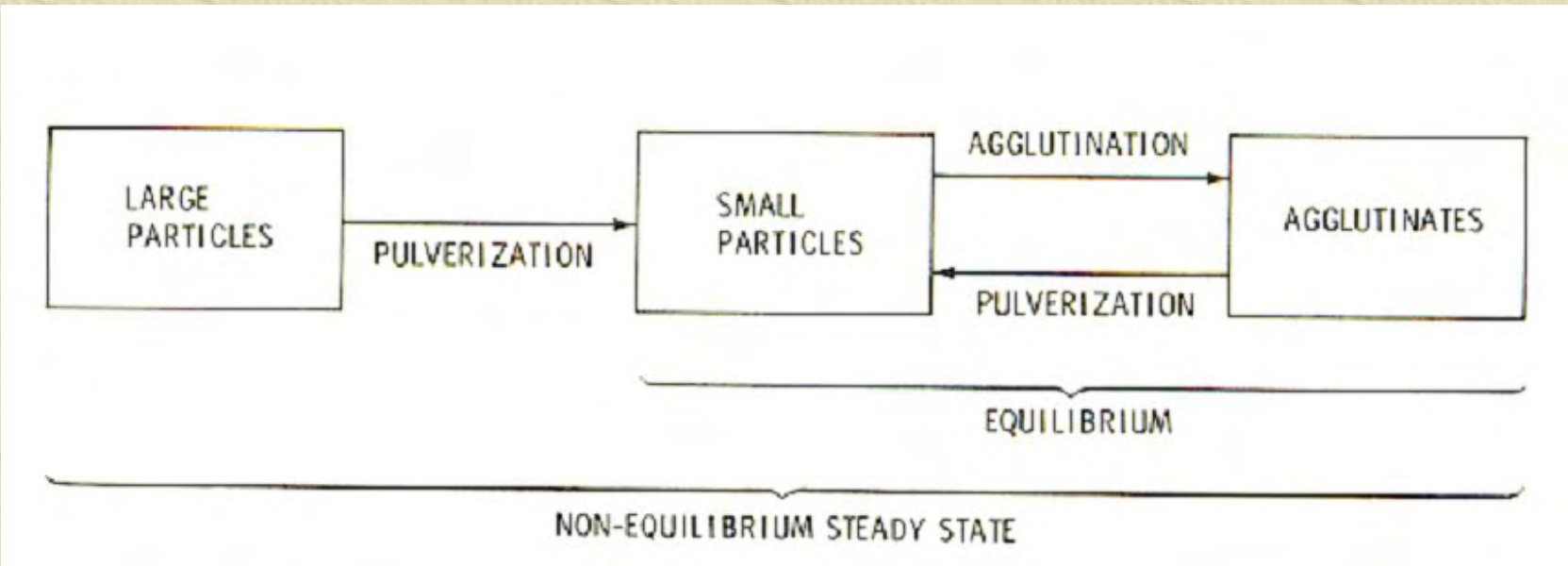
Soils may also follow a different evolution path (Path 2)



Mixed, path 2 soils may have unusual properties

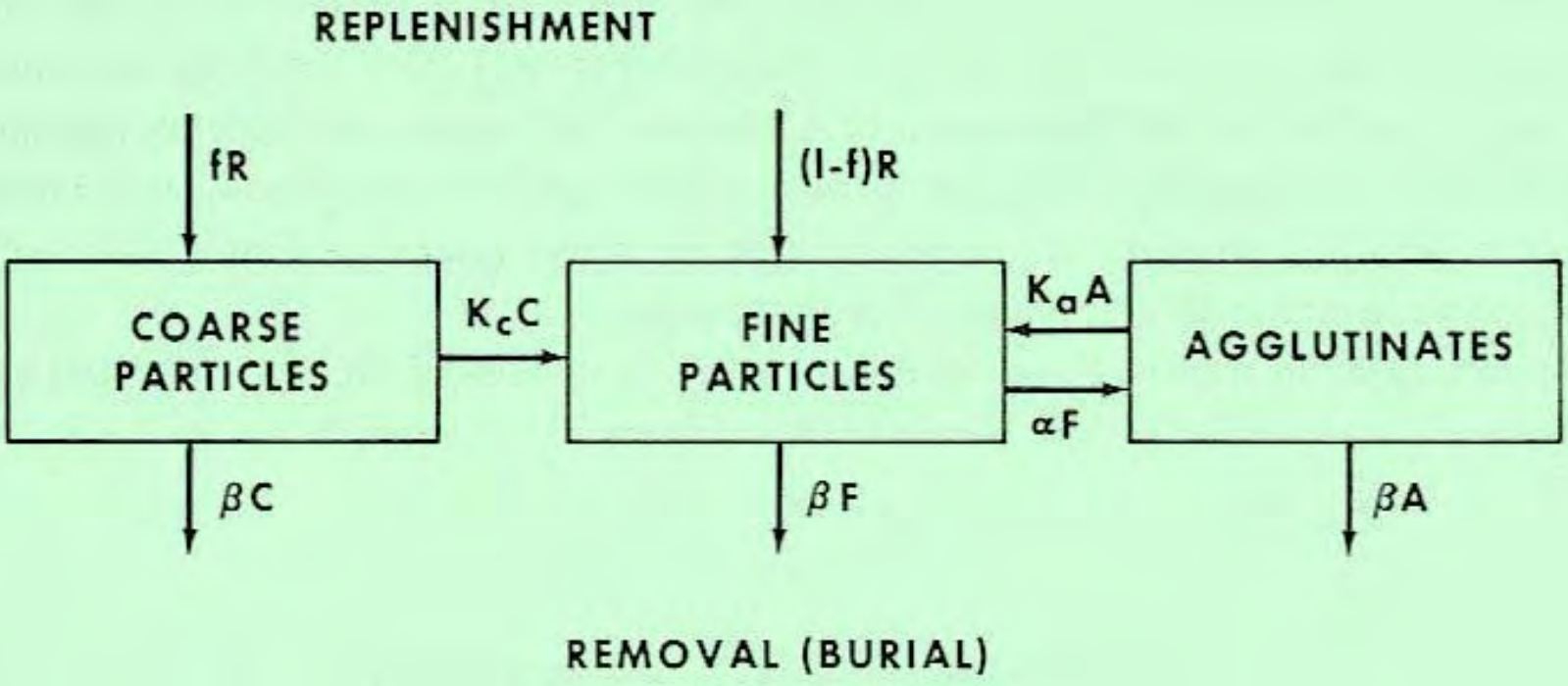


The evolution of lunar soils can be modeled:

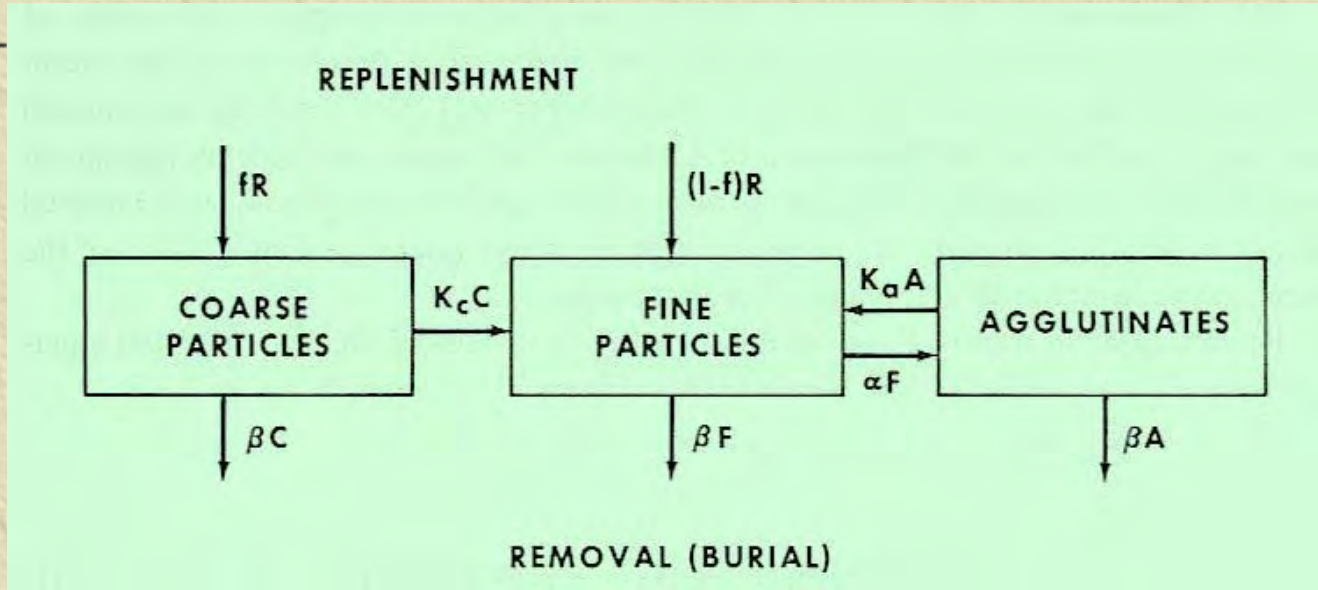


The evolution of lunar soils can be modeled:

The model can be described by equations



The evolution of lunar soils can be modeled:



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

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

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

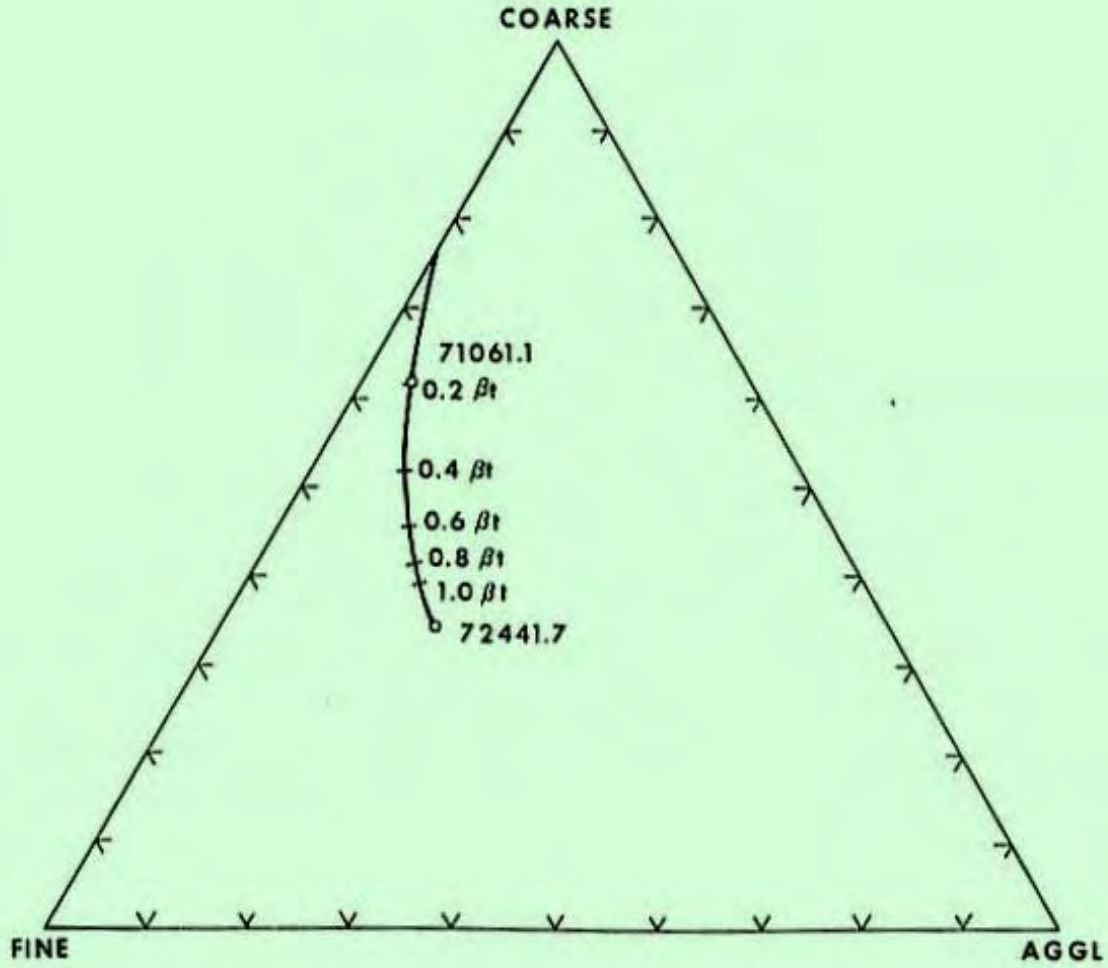
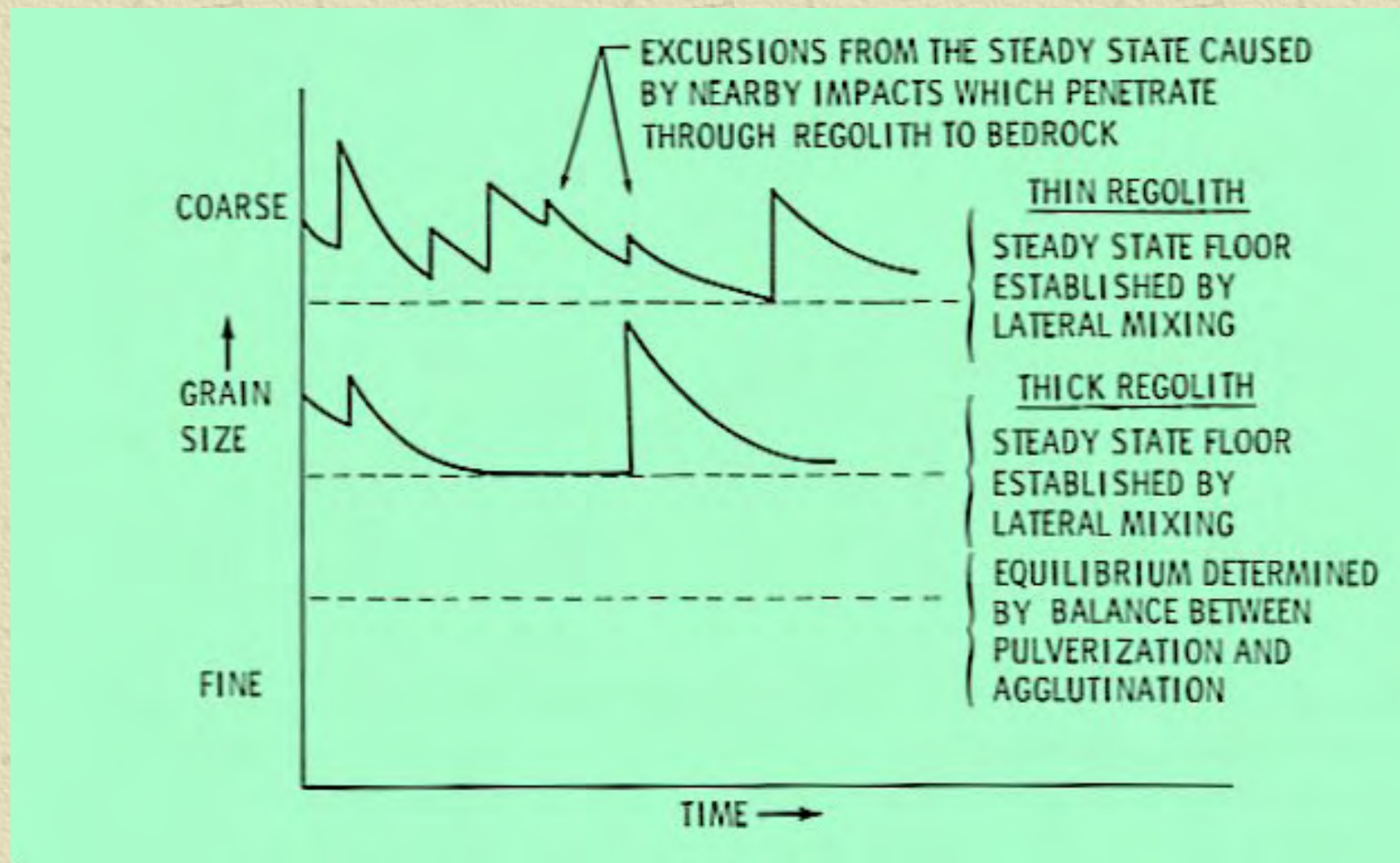
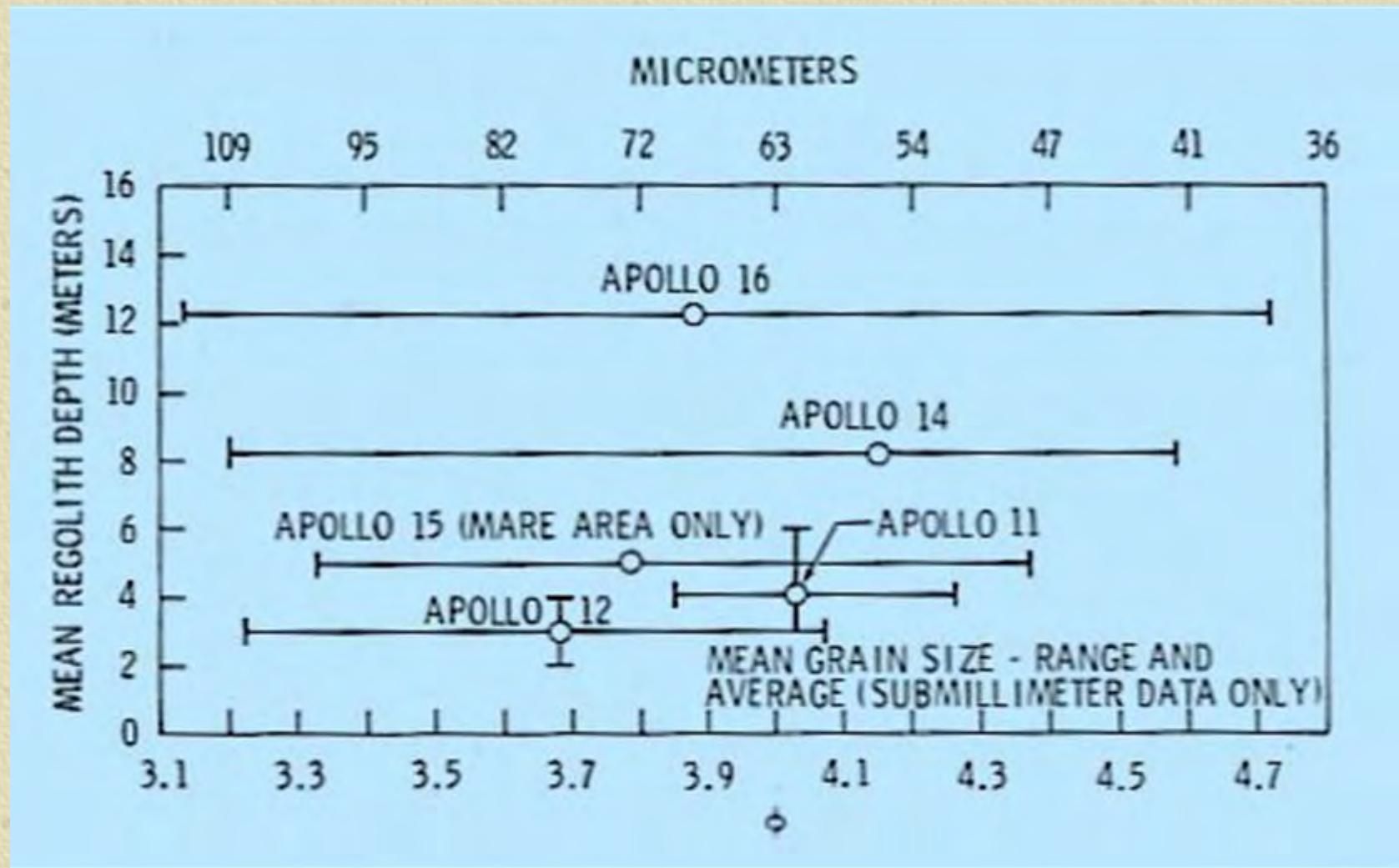


Fig. 2. A soil can be plotted as a point on a ternary diagram with coarse particle, fine particle, and agglutinate end members. In a given system, a fresh ejecta soil matures along a calculable trajectory from the *CF* side to a steady state soil near the center of the diagram. An immature soil and a 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.

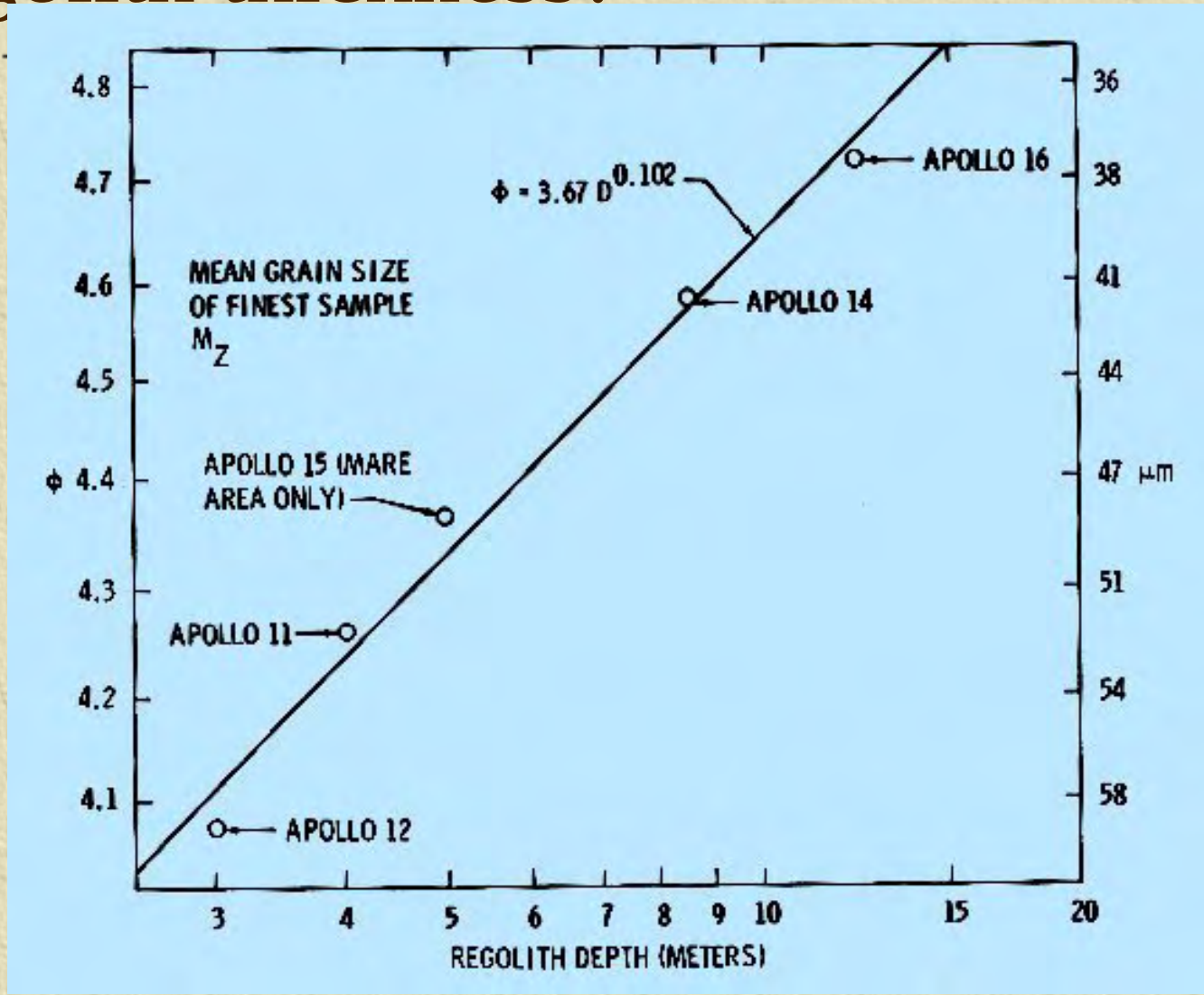
How does regolith evolution relate to regolith thickness?



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 it 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

A simulant workshop was held 14 years ago; the report is available at LPI