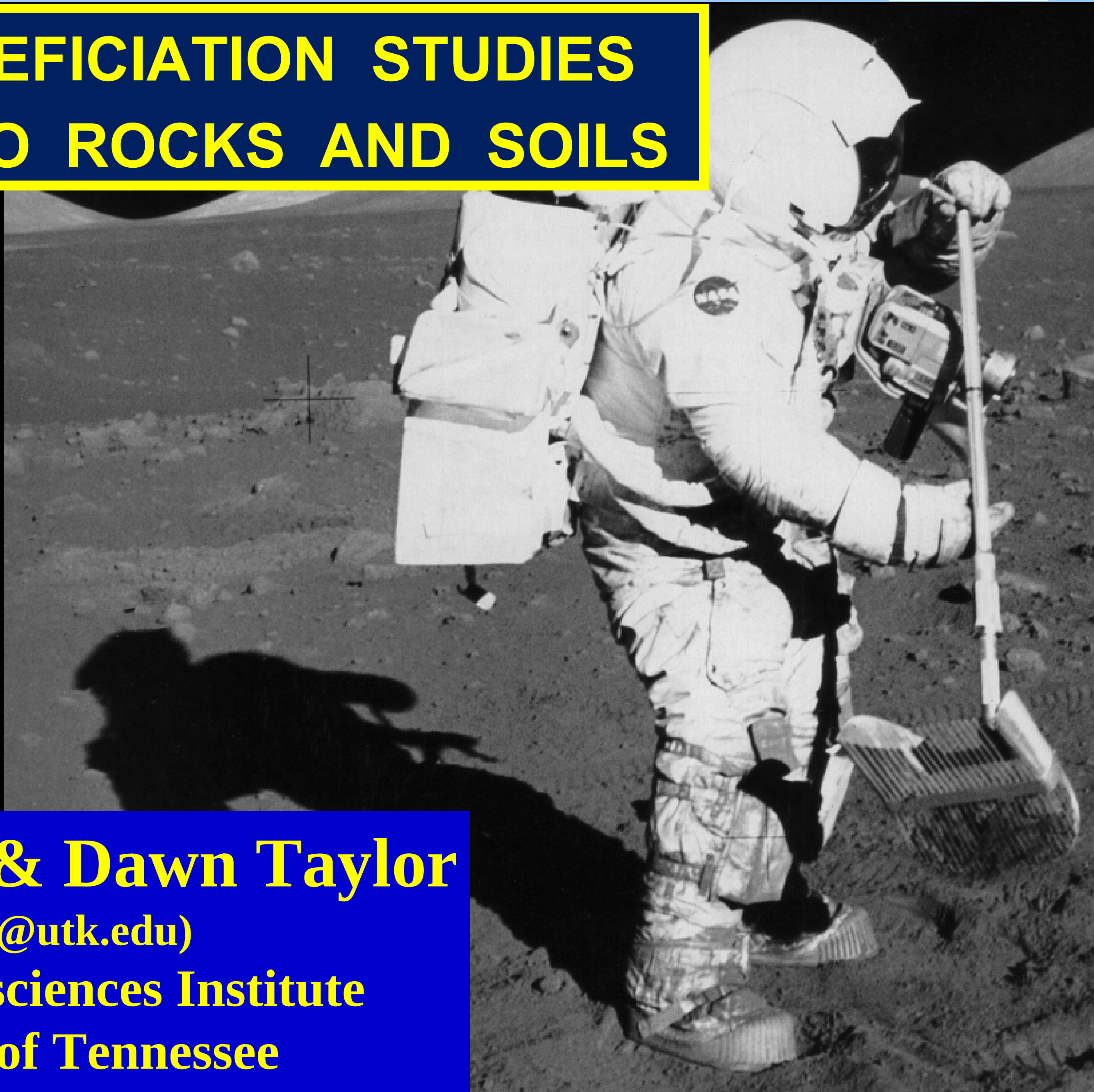
MINERAL BENEFICIATION STUDIES USING APOLLO ROCKS AND SOILS



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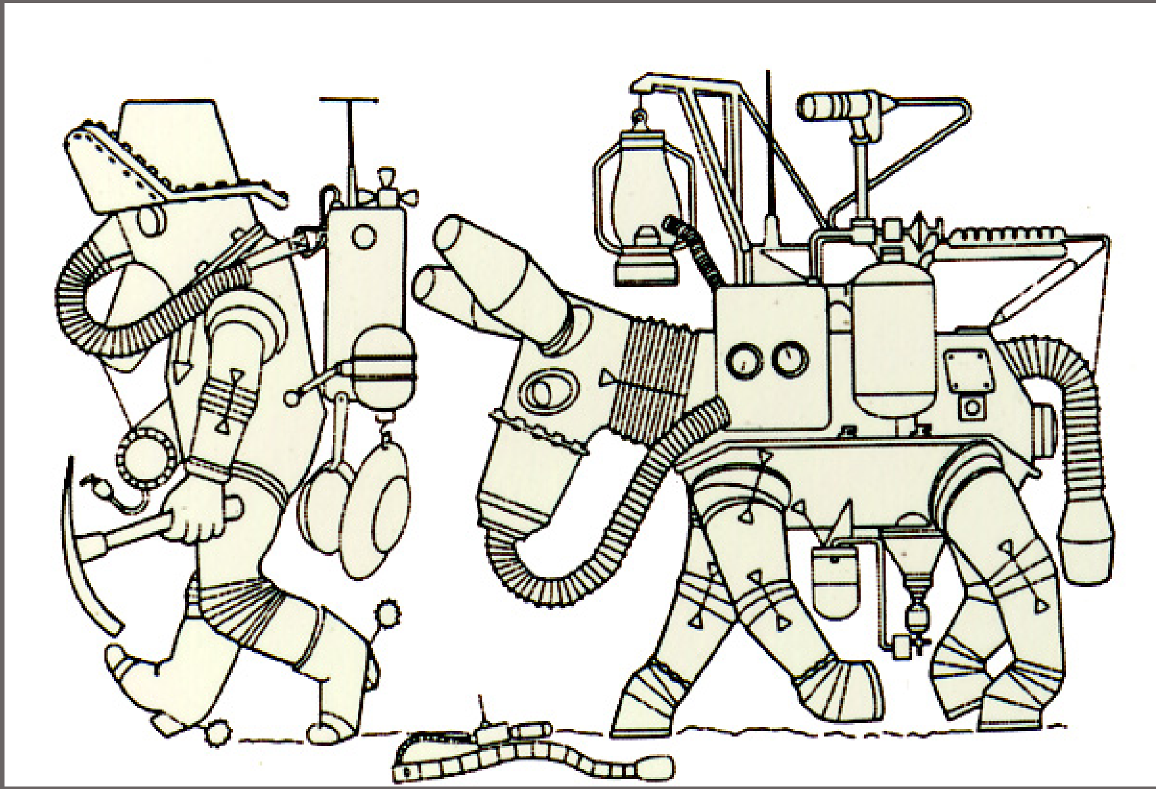
ISRU of the Moon



LUNAR SCIENCE IS THE ENTIRE BASIS FOR OUR KNOWLEDGE OF LUNAR RESOURCES;

Science is the Ingredient that makes

Resource Utilization of the Moon Possible

PROCESS FACTORS TO BE CONSIDERED FOR AN ISRU PROCESS

- **Simplicity of the overall Process**
  - Batch vs. Continuous Modes
- **Resupply Mass**
  - for reagent Makeup + Attrition of system
- **Plant Mass and energy Requirements**
  - (Include Feedstock Processing)
  - Sensitivity to Production Rate
  - comparison: Series of Small Self-Contained Modular vs Constructing a Single Large Plant.
  - Effect of solar and Nuclear-Electric Power sources.
- **Evaluation of Feedstock**
  - Rocks vs. soils; Maria vs. Highlands
  - Beneficiated and Unbeneficiated Feedstock
  - sensitivity of Process Mass and Power to Feedstock

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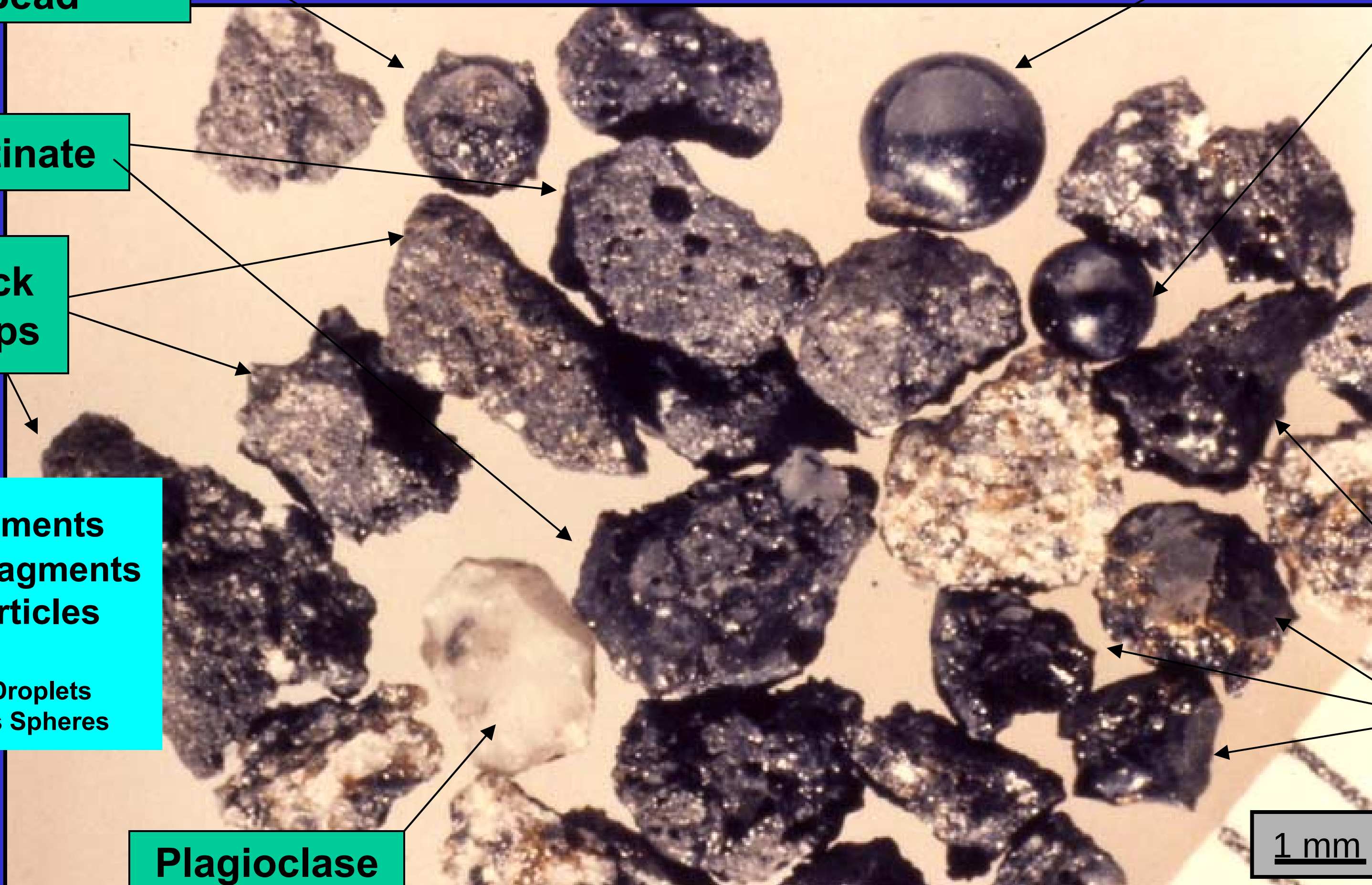
Lunar Mare Soil



- Rock Fragments
- Mineral Fragments
- Glassy Particles
  - Agglutinates
  - Impact-Glass Droplets
  - Volcanic Glass Spheres

Regolith: broken up rock material; '**Soil**': <1 cm portion of the Regolith

Dust: < 20 μm portion of the Soil

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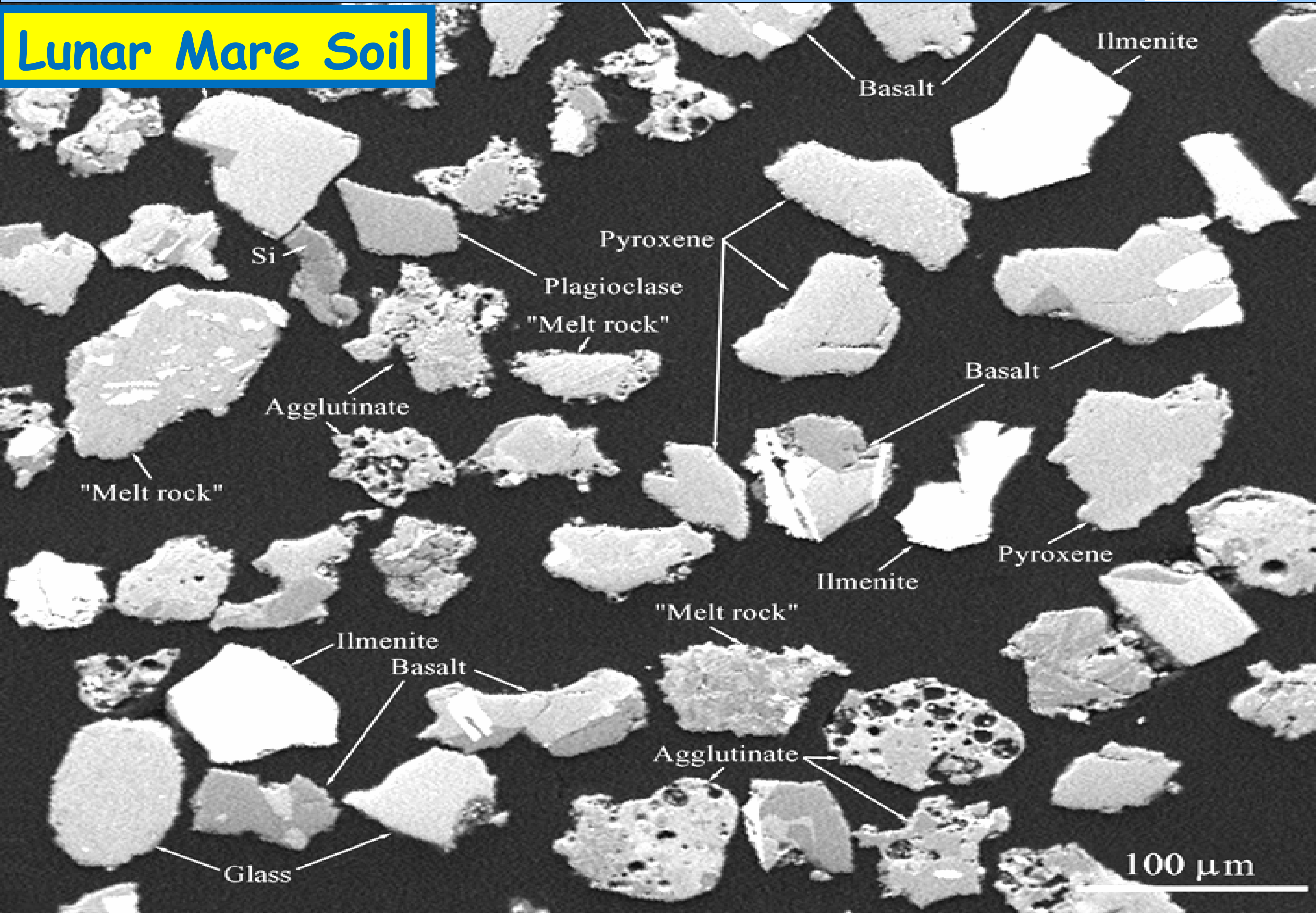
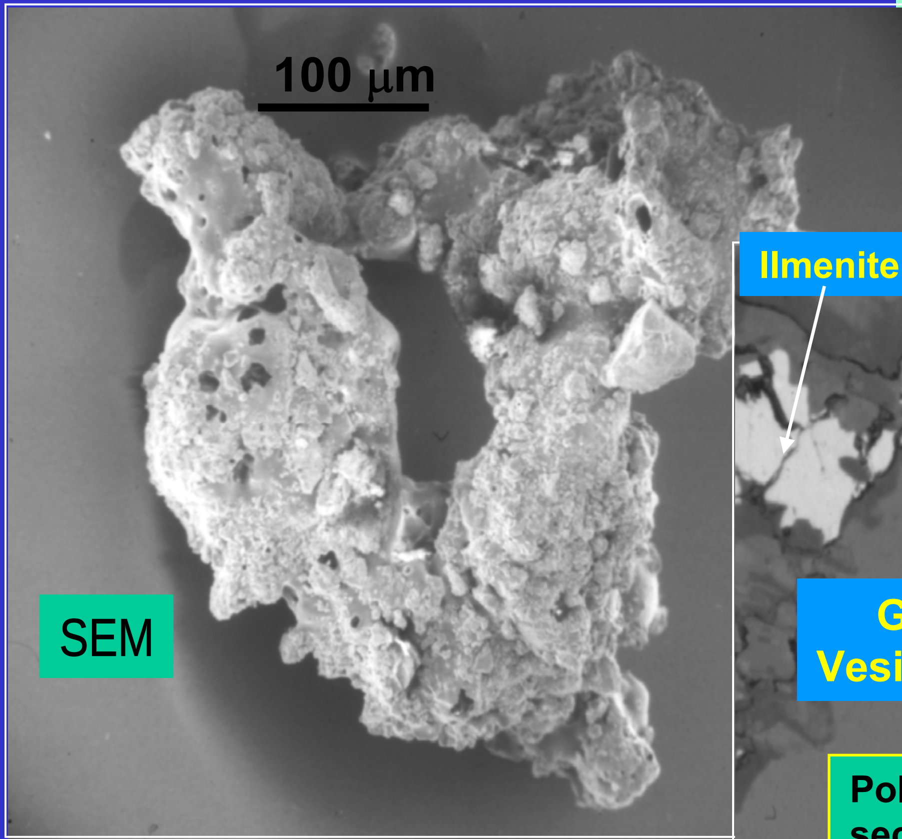
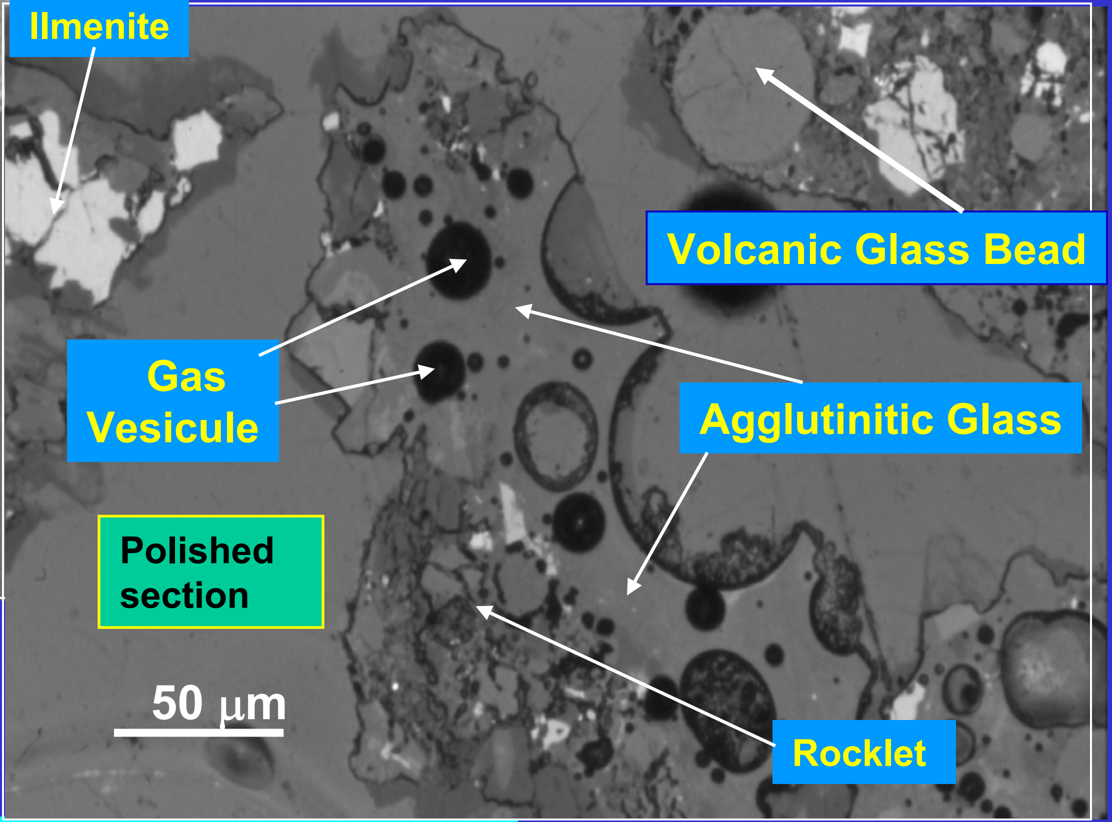
Lunar Mare Soil



Agglutinates





Pieces of minerals, rocklets, and glass welded together by shock-melt glass

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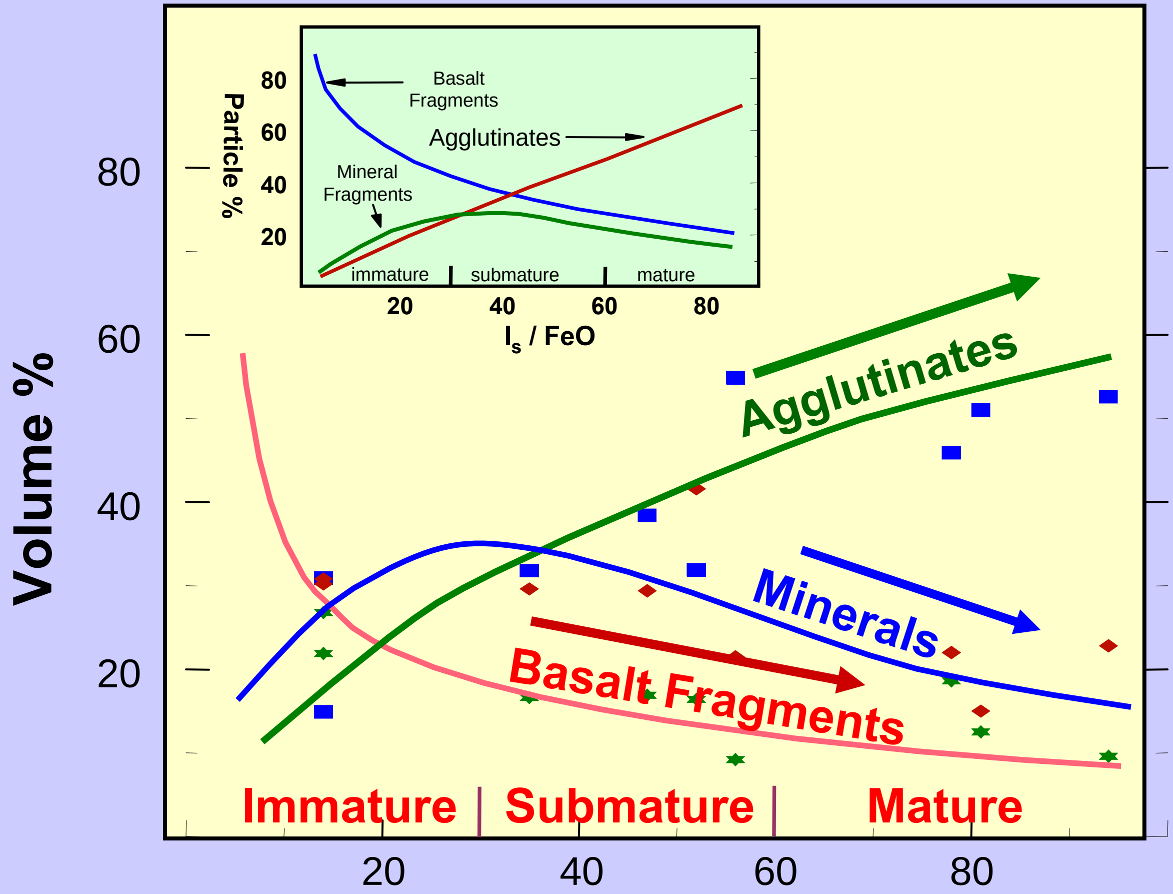
Soil Maturation of a Mare Soil



Taylor & McKay (1992)

I_s / FeO = MATURITY →

EXPOSURE AGE →

Immature Soil is Better for Mineral Beneficiation Than Mature Soil!

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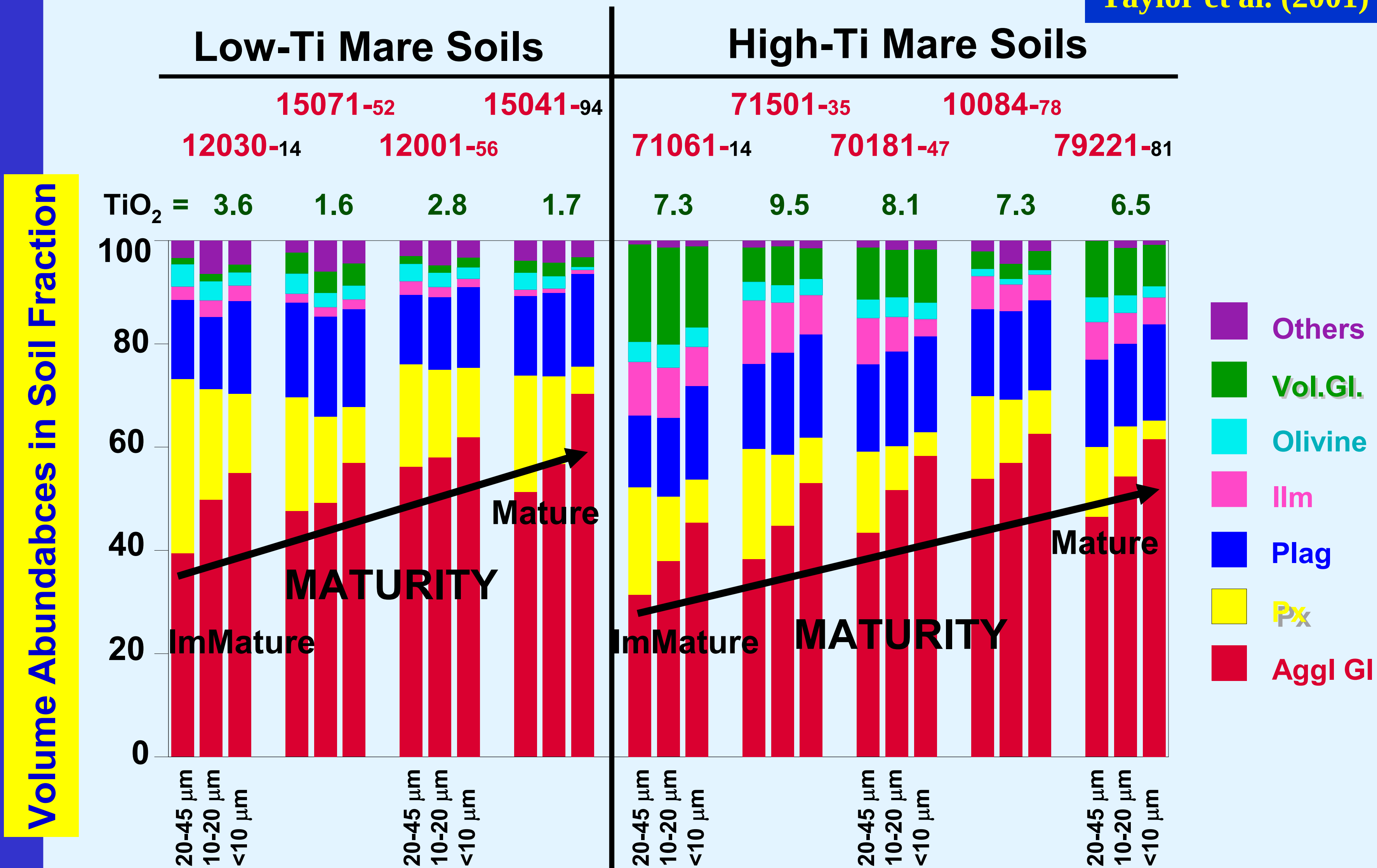
Taylor et al. (2001)



Glass abundances Increase as Grain-Size Decreases

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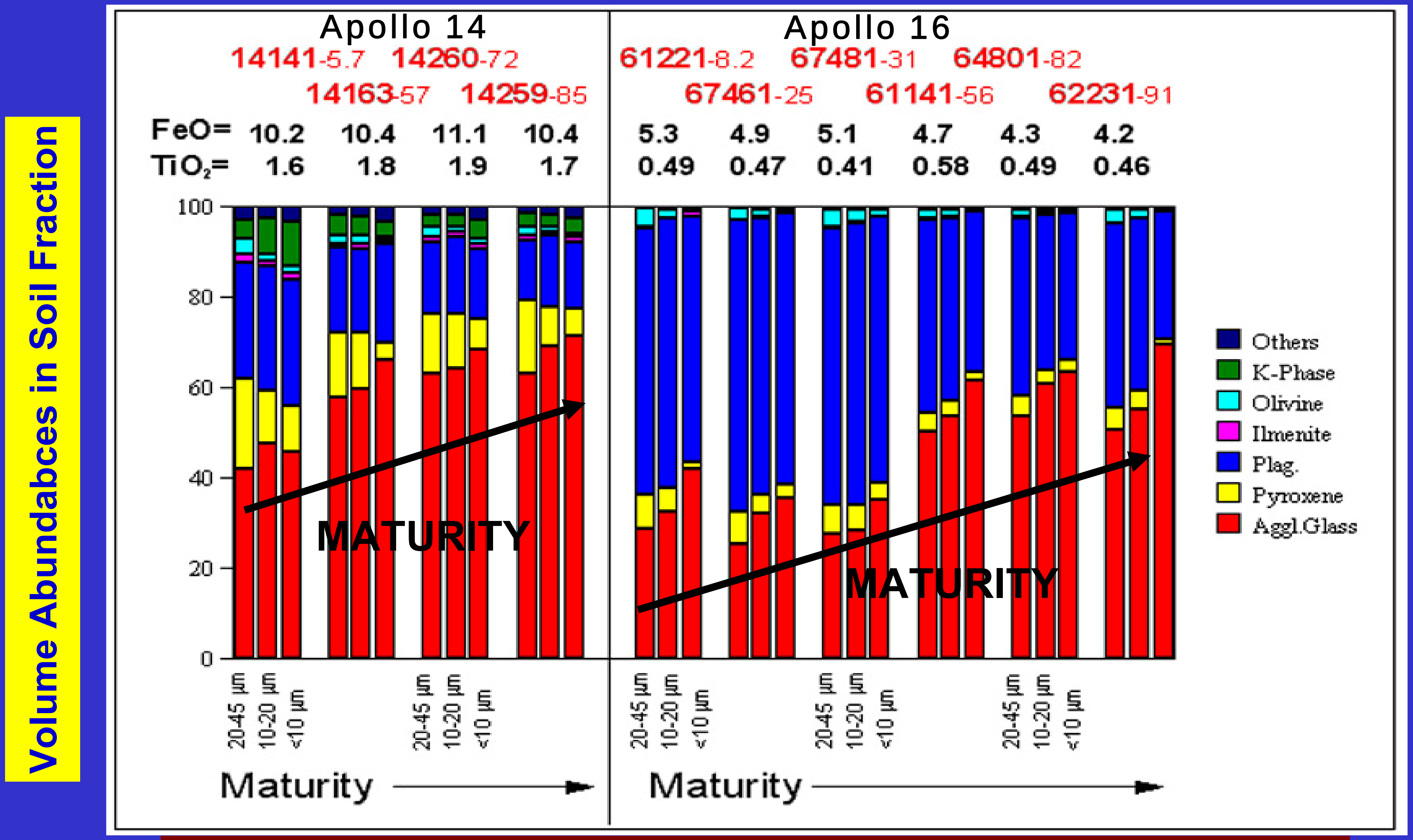
Lunar Highland Soils

Taylor et al. (2010)



Glass abundances Increase as Grain-Size Decreases

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Production of LLOX by LLH Reduction of Ilmenite

recycle

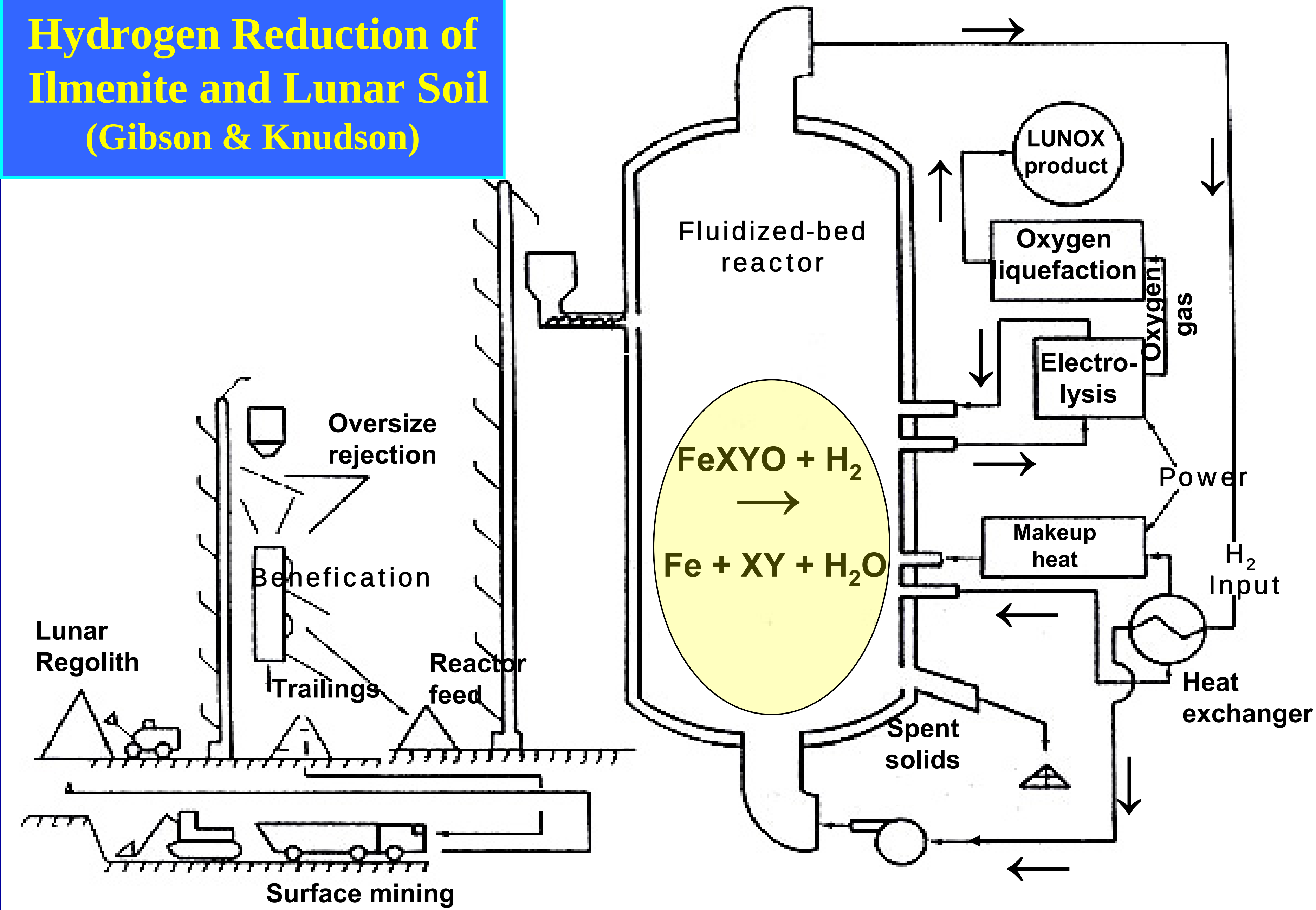
$$FeTiO_3 + H_2 \underset{\Delta}{\rightleftharpoons} Fe + TiO_2 + H_2O \xrightarrow{\text{electrolysis}} H_2 + \tfrac{1}{2} O_2$$

Ilmenite feed | **Solid Product** | **Oxygen Product**

H_2 most easily breaks the bonds between the Fe and the O!

$$Fe\,XYO + H_2 \xrightarrow[\Delta]{} Fe + XY + H_2O$$

Hydrogen Reduction of Ilmenite and Lunar Soil
(Gibson & Knudson)



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Magnetic Beneficiation: Apollo Rocks and Soils

Magnetic Susceptibilities of Sized Soils and Crushed/Sized Rocks

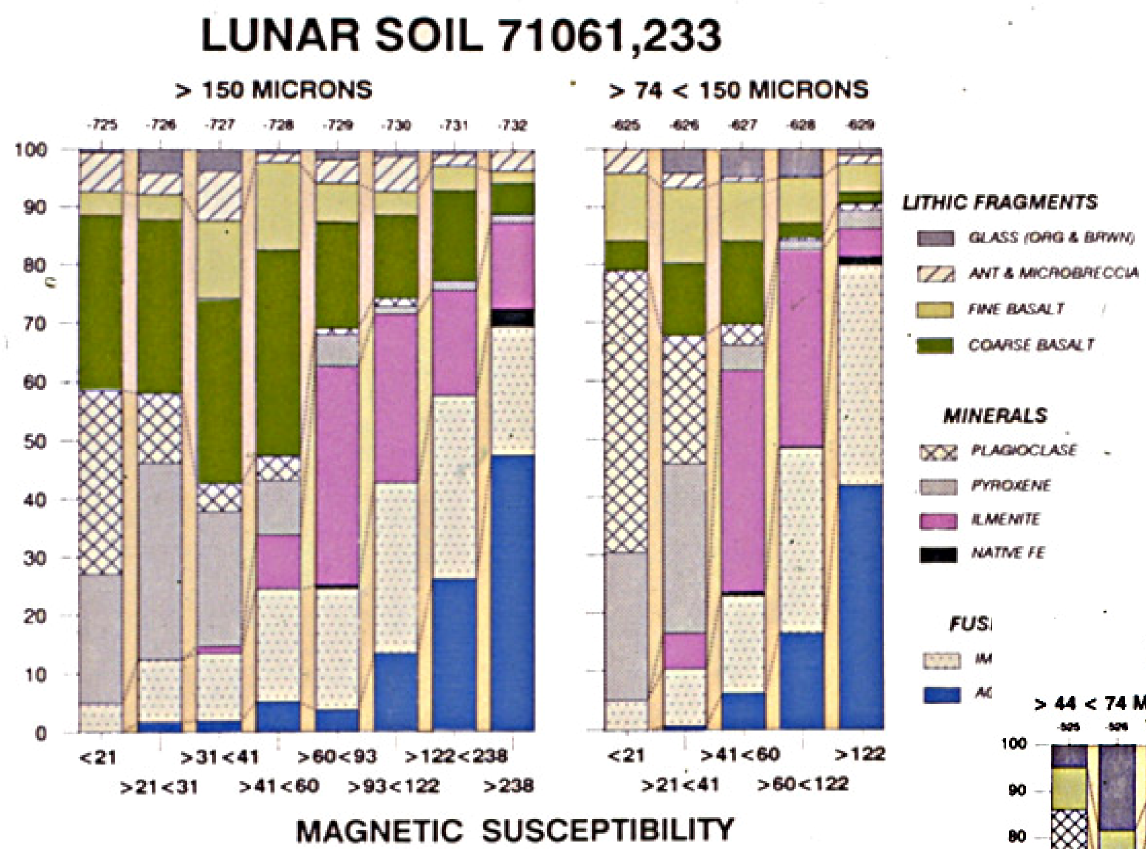
Calibrated Frantz Magnetic Separator + Magnetic Susceptibility Standards

Collected Susceptibility Modes as Splits

Particle Abundances:

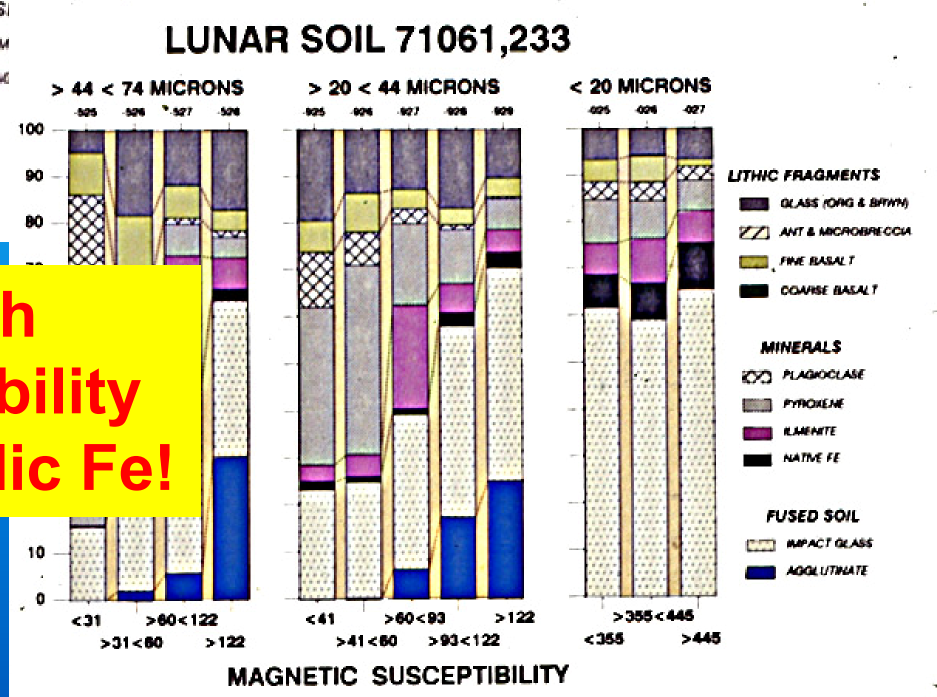
- Polished Grain Mount in Epoxy
- EMP X-ray Digital Imaging

Details in Oder and Taylor (1990)



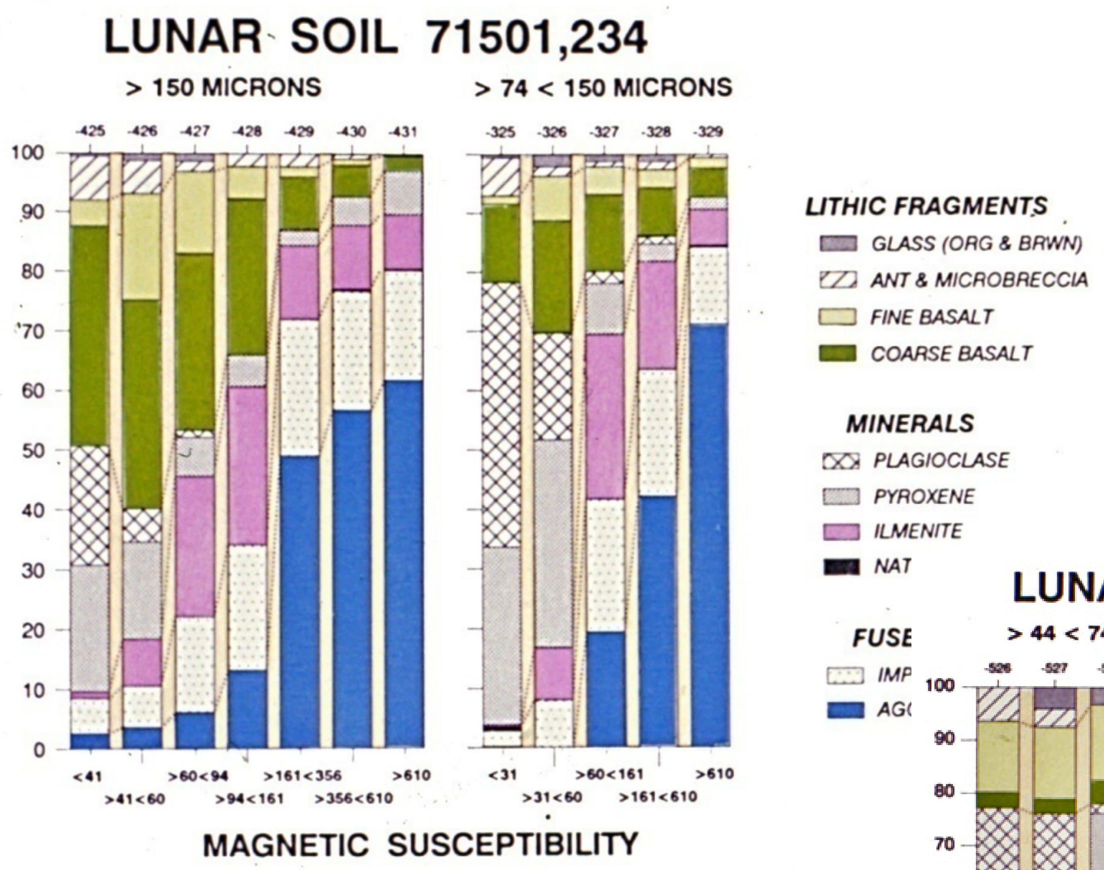
Hi-Ti Apollo 17 IMMATURE Soil (Is/FeO = 14)

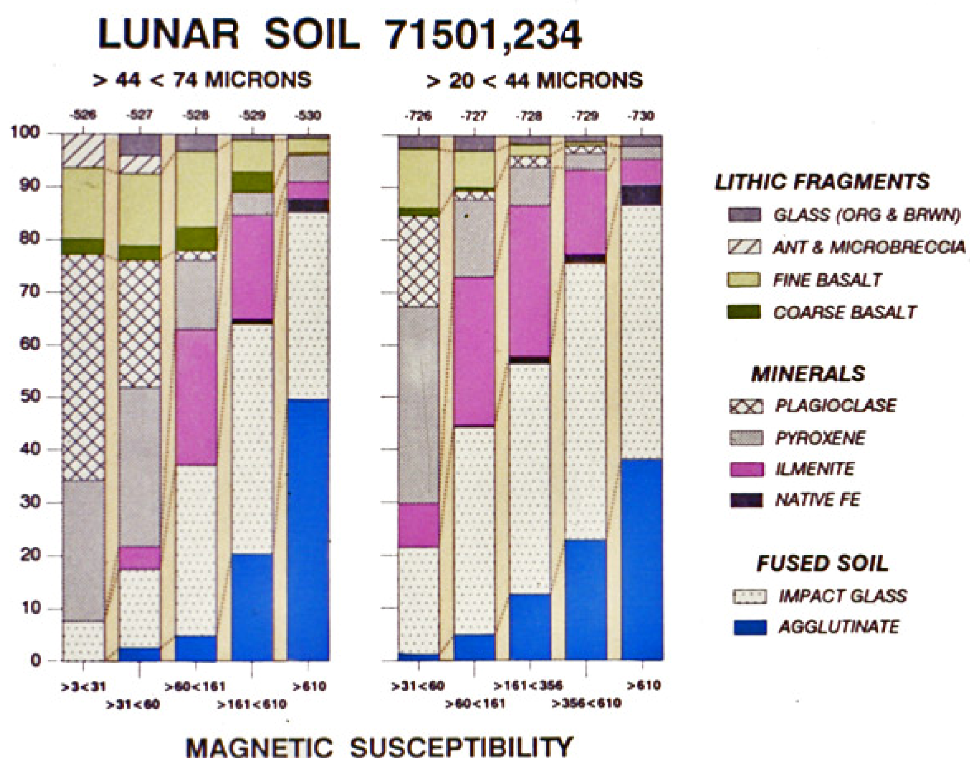
Taylor & Oder (1990)



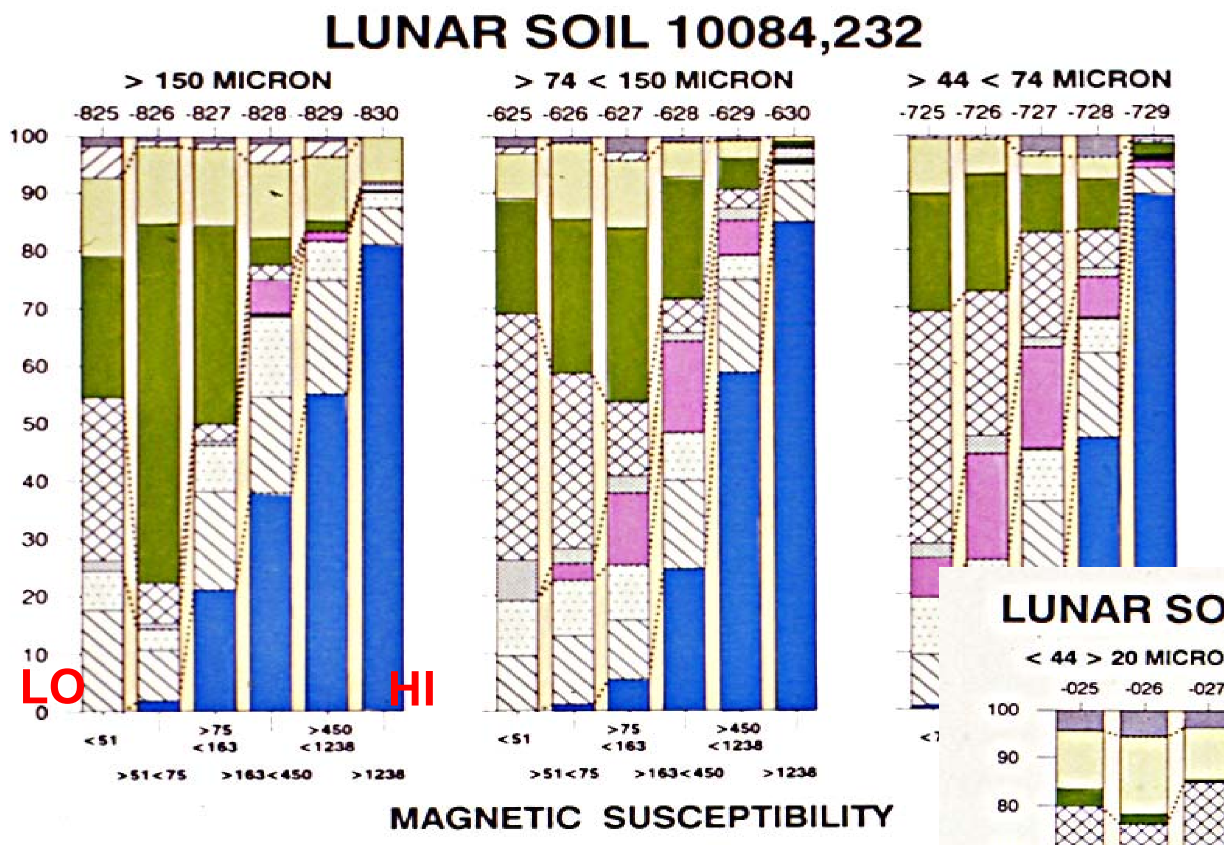
Impact Glass Increases with Increasing Magnetic Susceptibility As a result of Nanophase Metallic Fe!

Hi-Ti Apollo 17 SUBMATURE Soil (Is/FeO = 35)



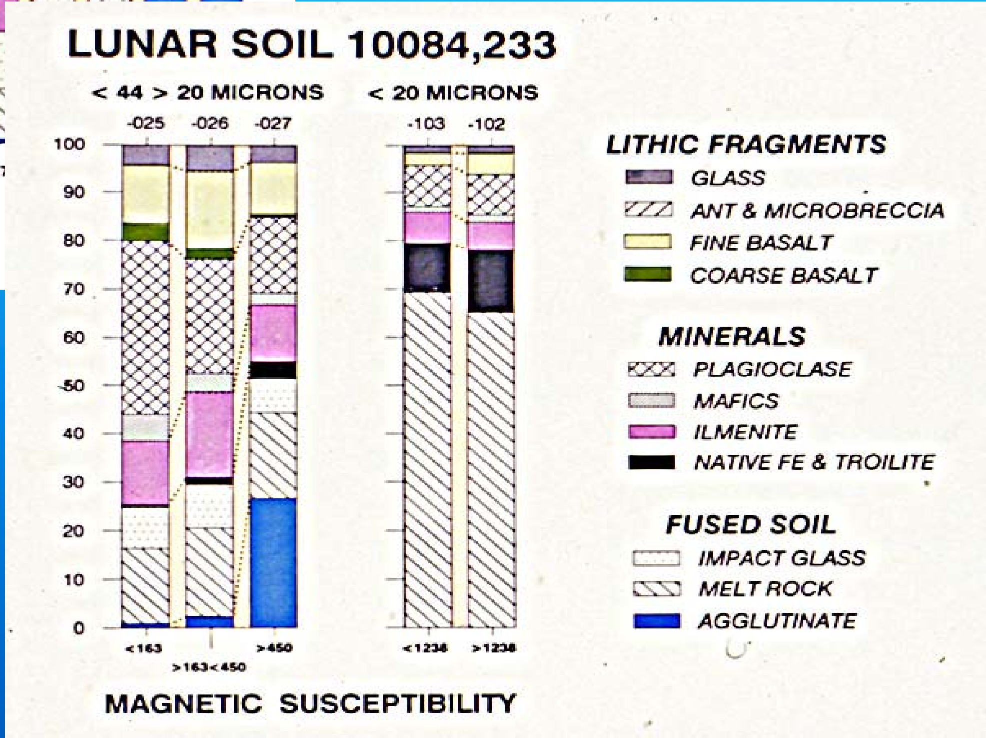


Taylor & Oder (1990)



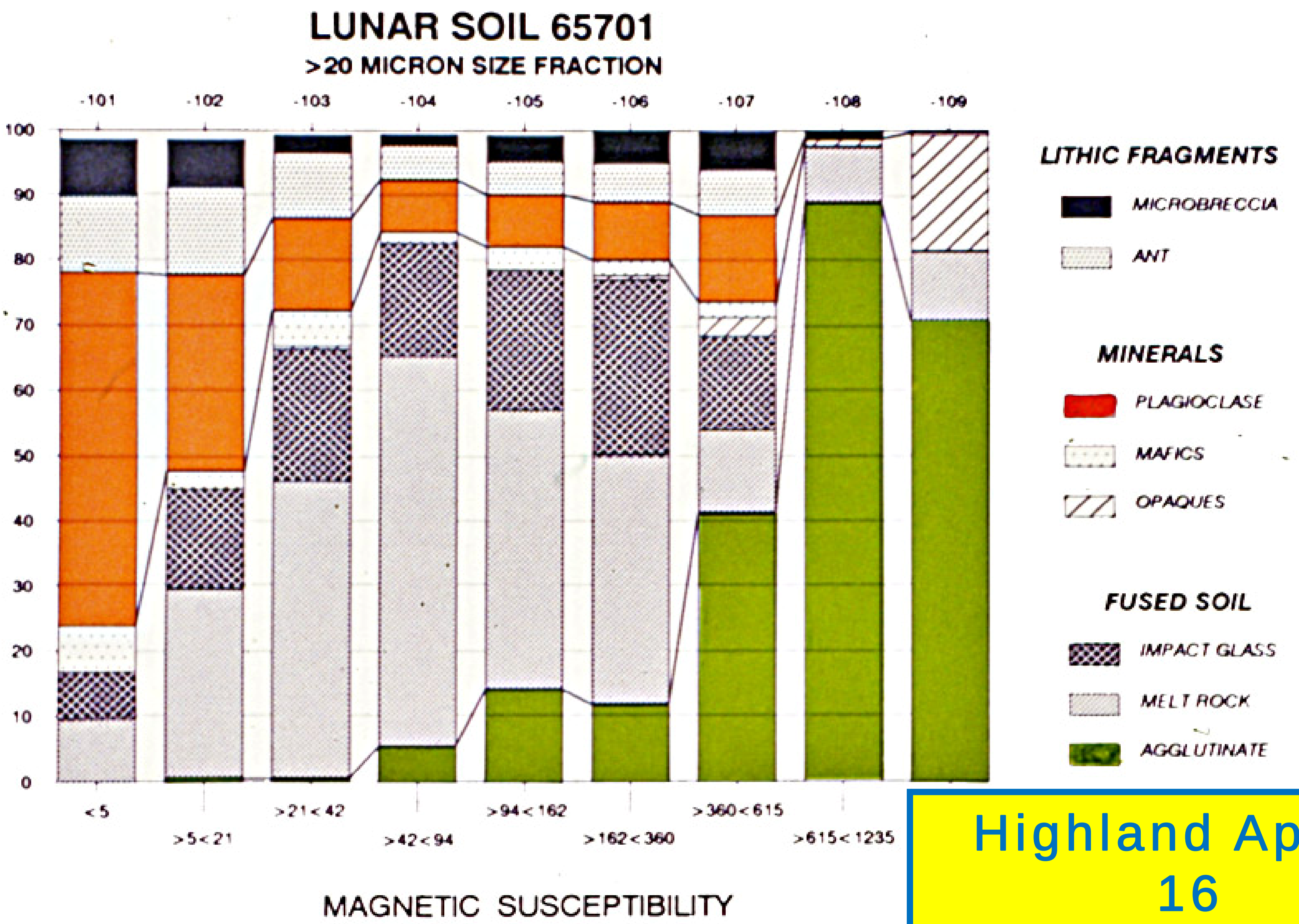
Hi-Ti Apollo 11 MATURE Soil (Is/FeO = 76)

Taylor & Oder (1990)



<20 µm size fraction:
Most grains have
Hi Mag. Susc.

= Hi Is/FeO (lots of np-Fe)



Taylor & Oder (1990)

Highland Apollo 16

MATURE Soil

(Is/FeO = 106)

Some Conclusions from Mare Soil study

Ilmenite Concentrates in Intermediate Magnetic Susceptibilities of 60-160 m cc/gm; this is in distinct contrast to terrestrial ilmenite;

Ilmenite Abundance Decreases as Maturity Increases.

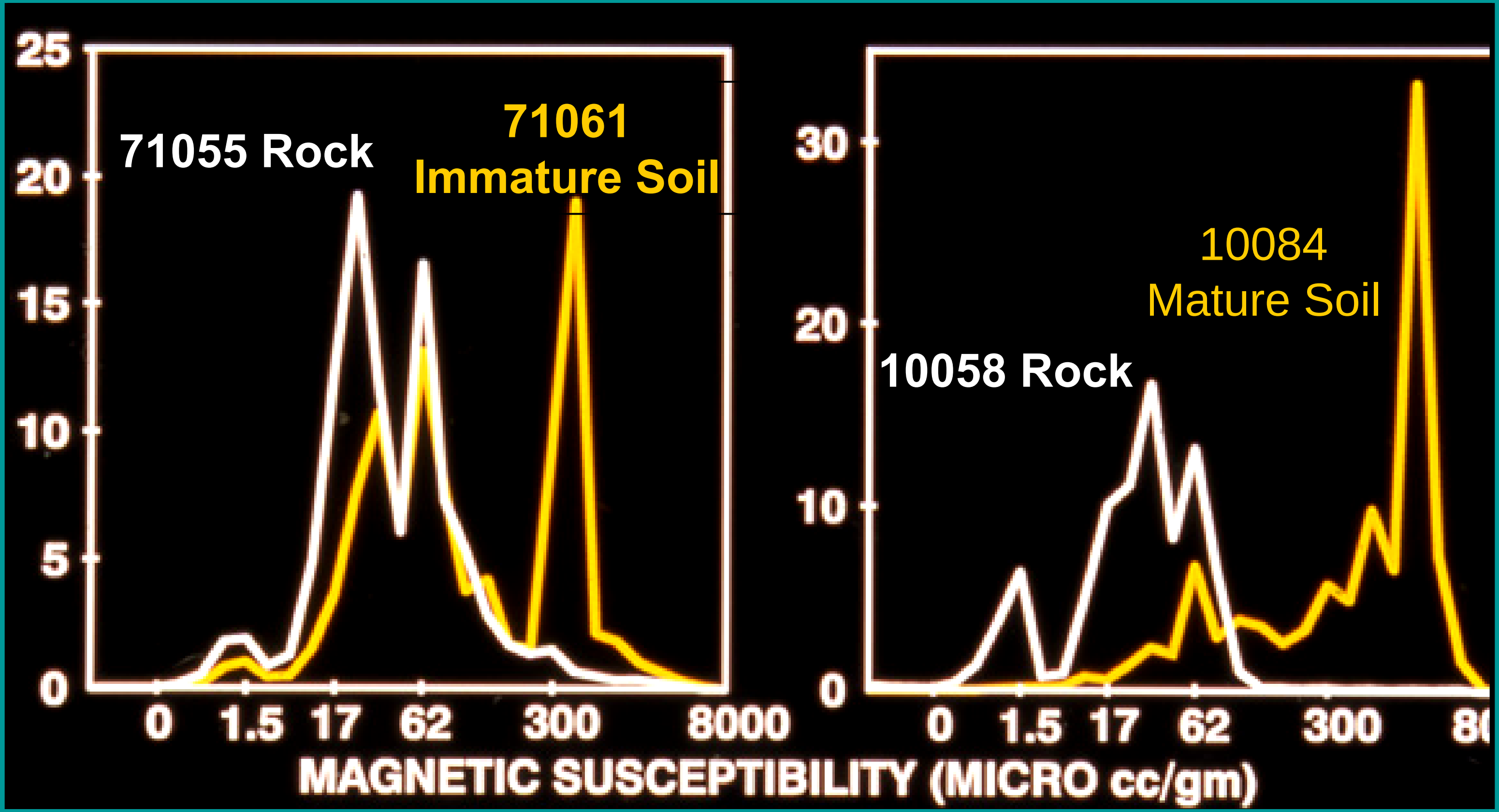
Best Soil for Ilmenite Recovery = Immature Hi-Ti Mare Soil.

Major Portion of Ilmenite is in Coarse-Grained Basalts Fragments In the >74 micron Fractions; Grinding of the >74 micron Soil is Necessary to Liberate these Ilmenites

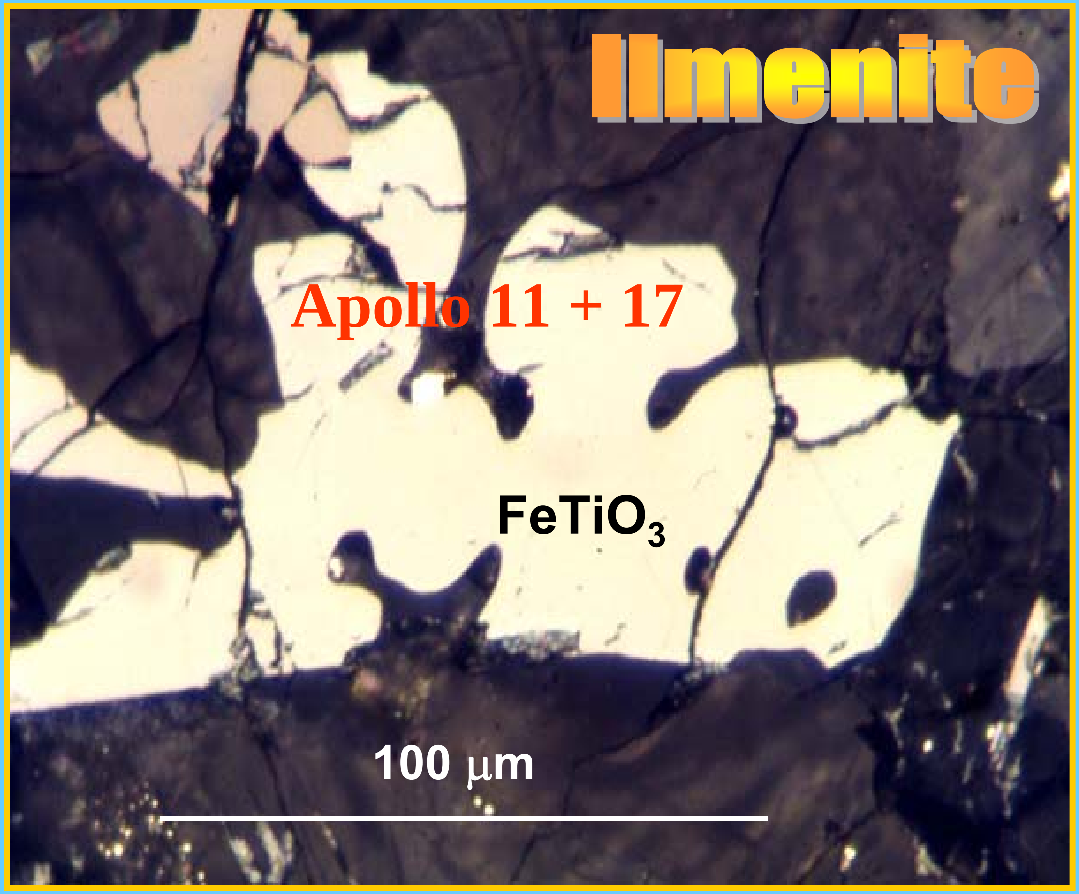
Although ~50% of the Ilmenite in a Hi-Ti Soil can be Recovered by Magnetic Separation, it may be difficult to “high-grade”;

Estimated that about 0.1 lb. of Ilmenite of an Immature Hi-Ti Mare soil Can be Recovered per Pound of Soil.

MAGNETOGRAMS



Taylor & Oder (1990)


Ilmenite
Apollo 11 + 17
$FeTiO_3$
100 μm

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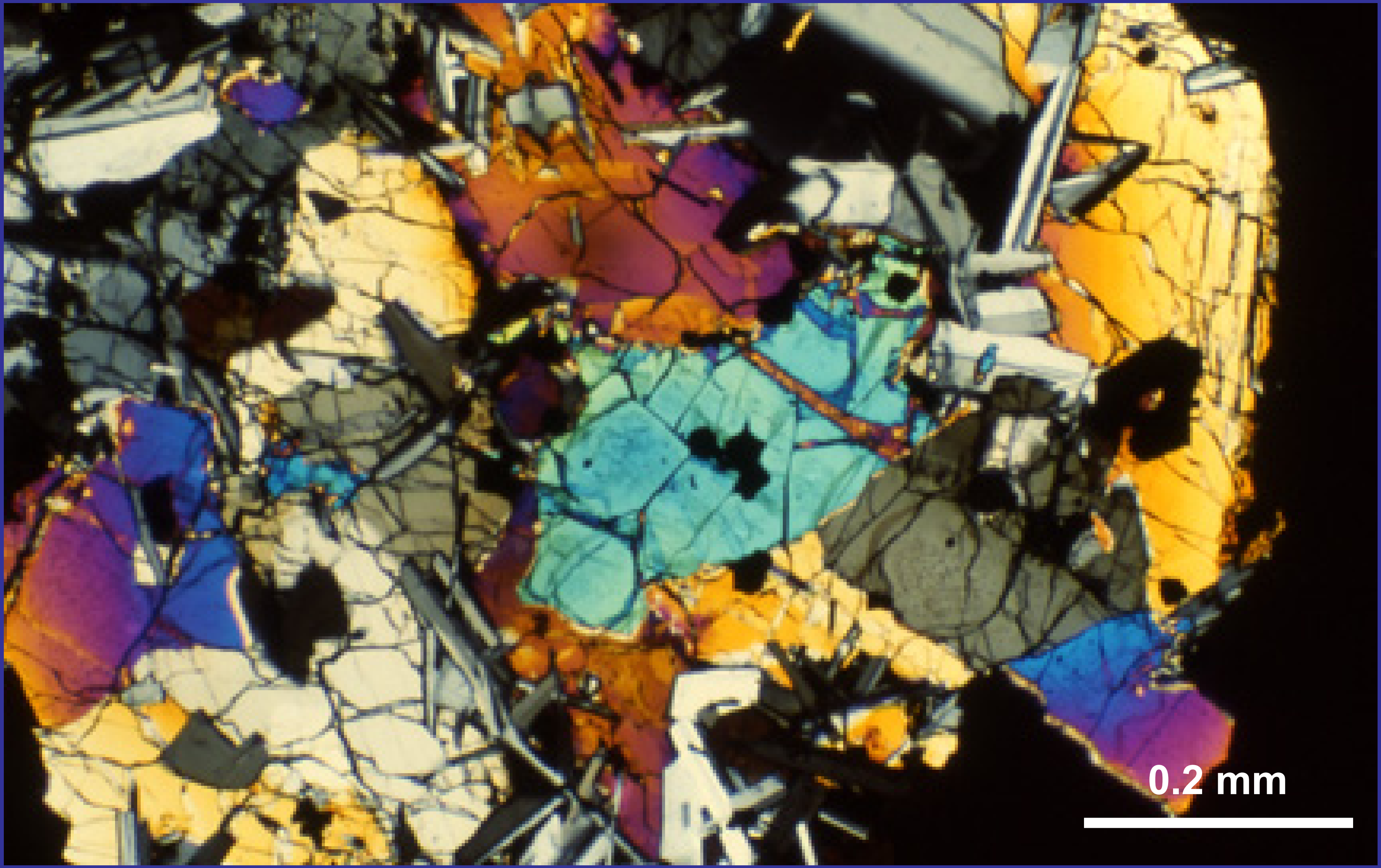
Apollo 15 Mare Basalt



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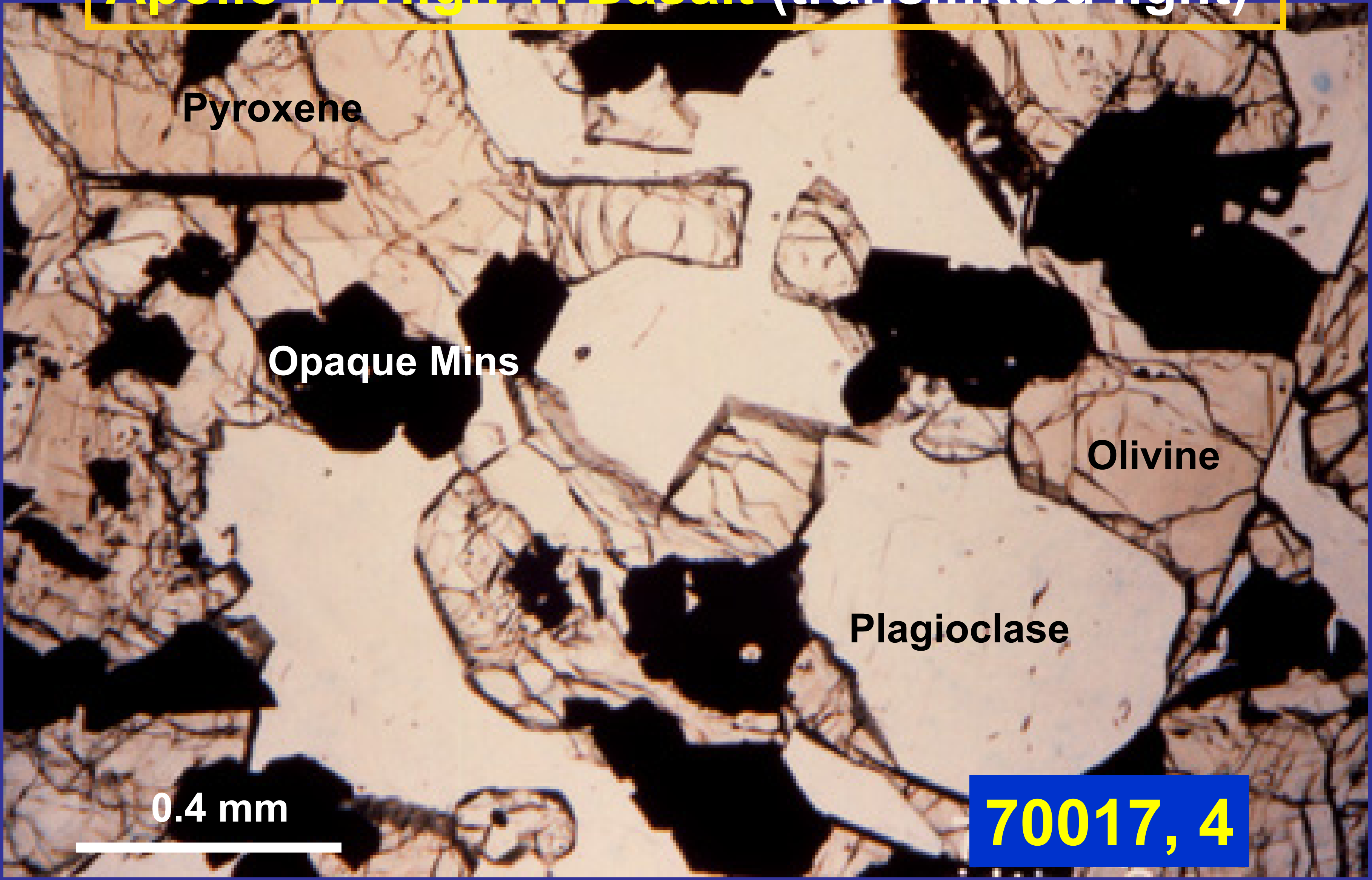
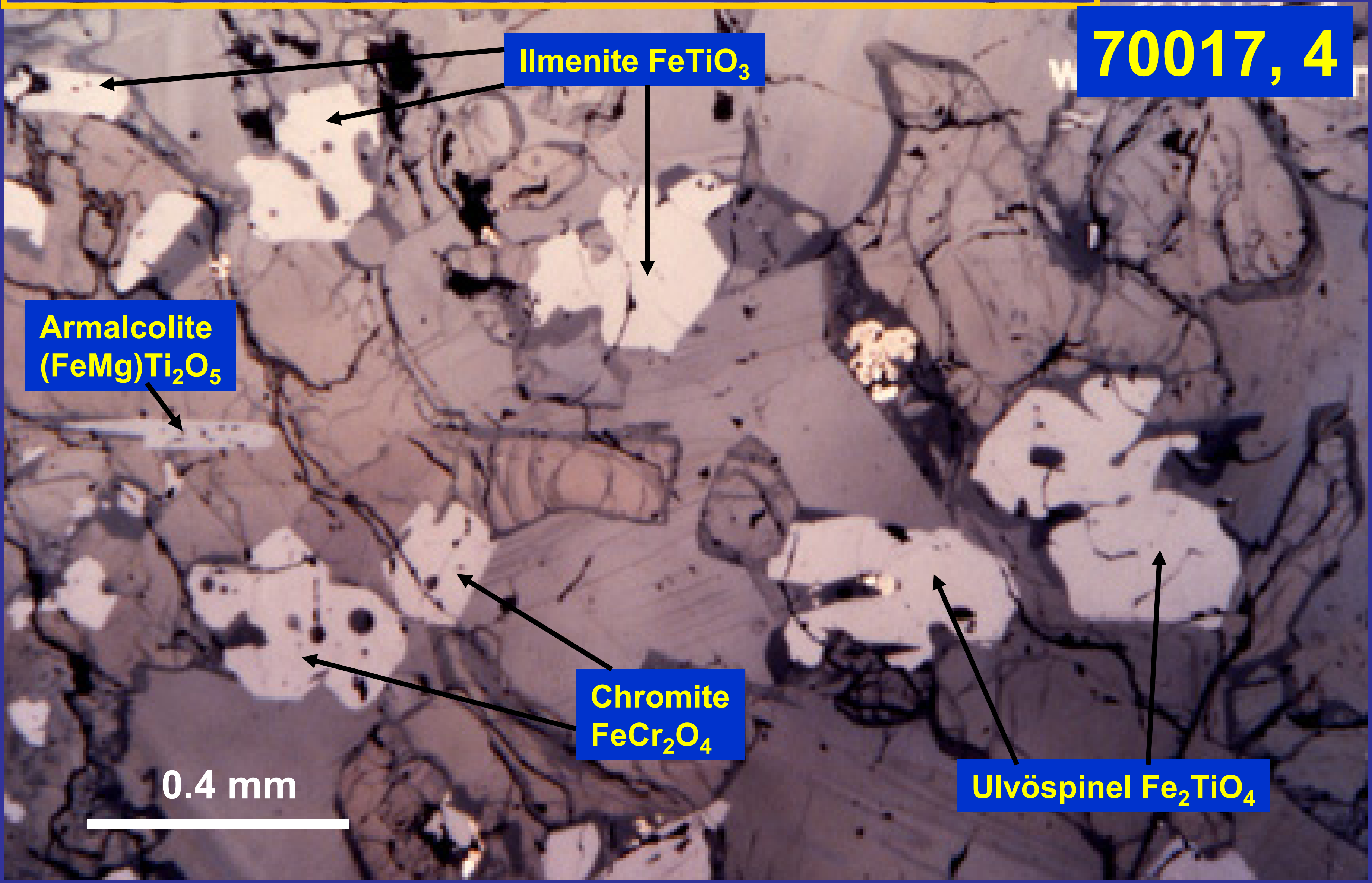
Apollo 17 High-Ti Basalt (transmitted light)

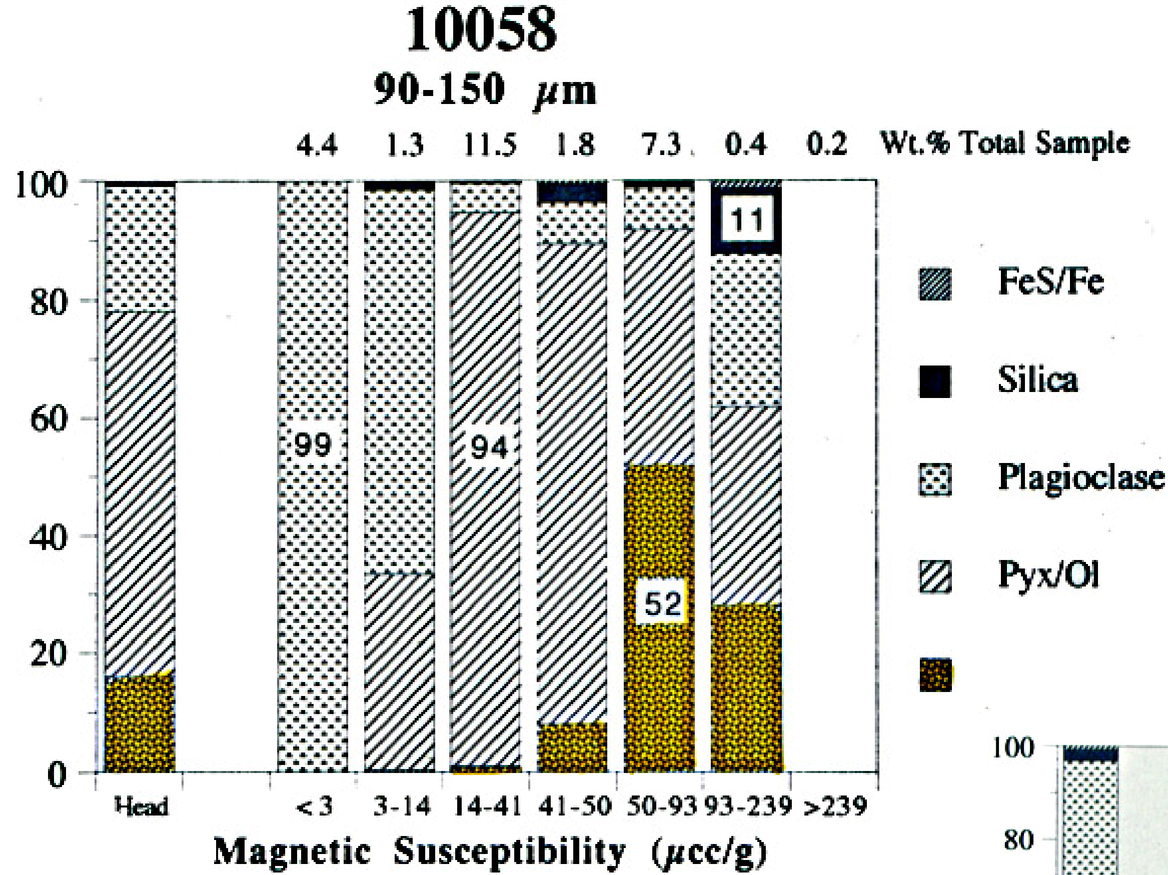


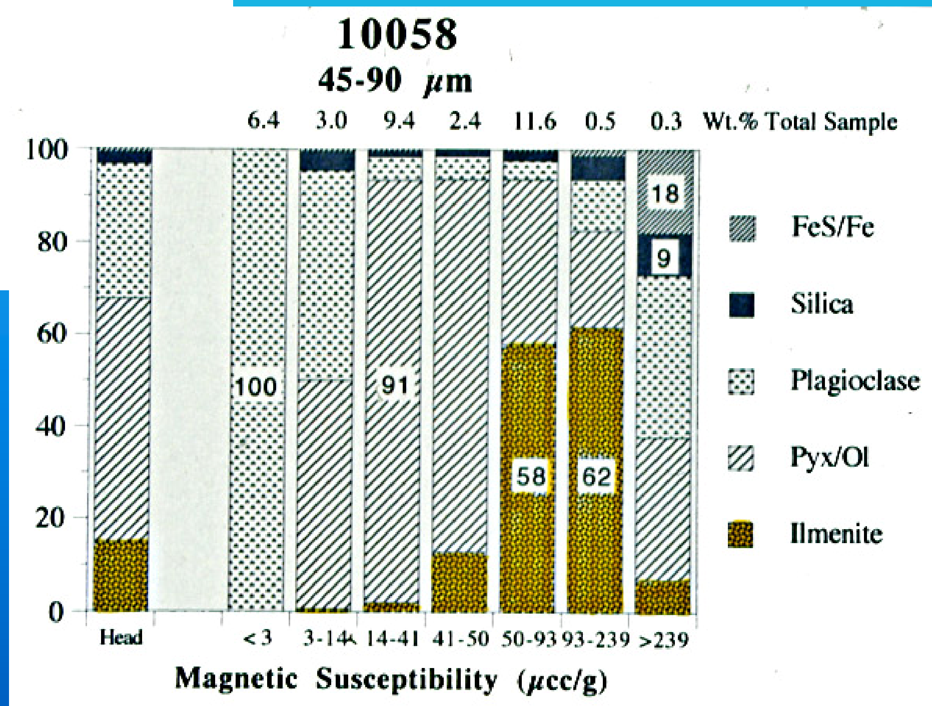
Apollo 17 High-Ti Basalt (reflected light)



Apollo 11 Rock
Medium-Grained
Hi-Ti Mare Basalt

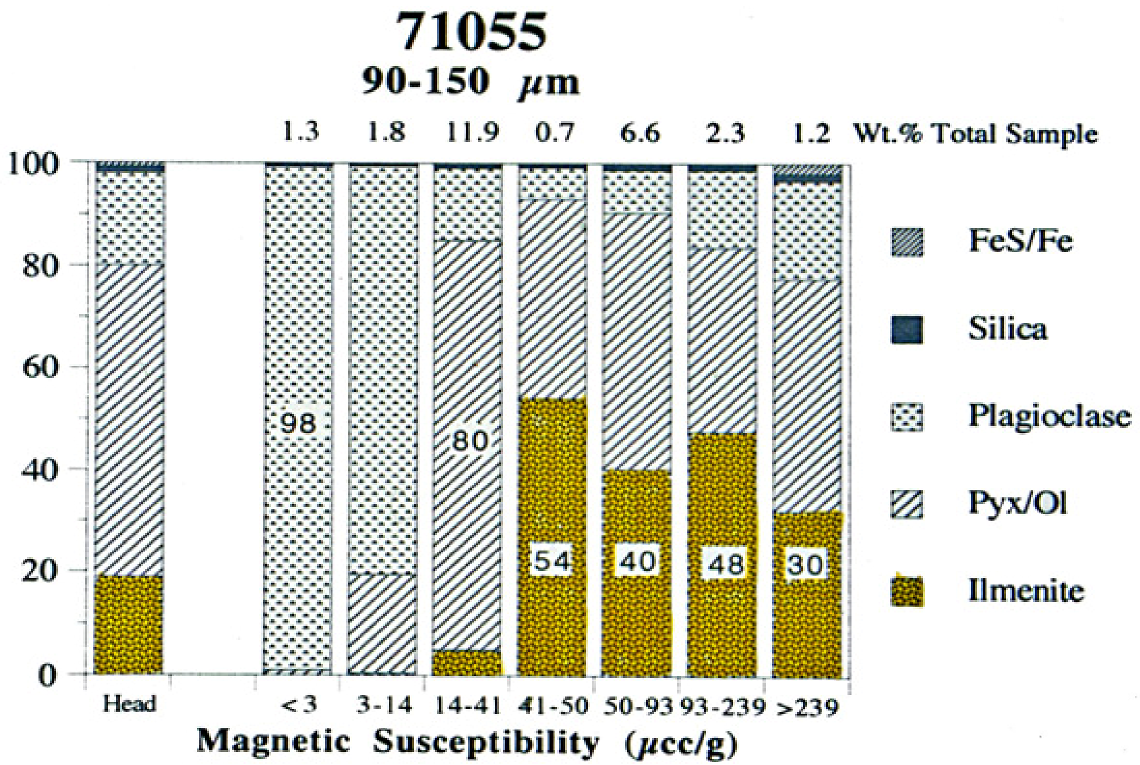
CRUSHED

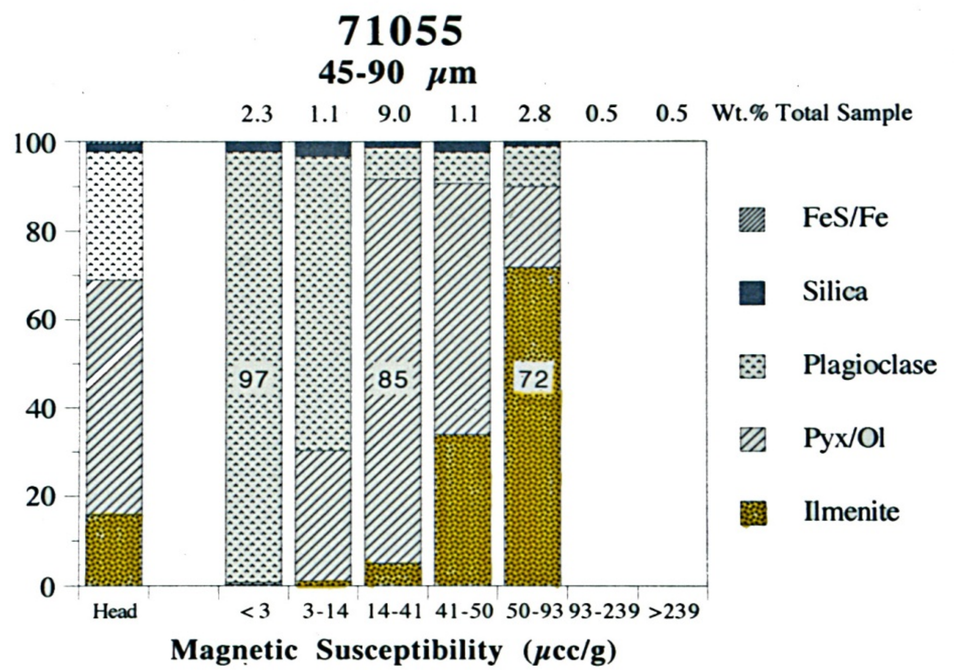




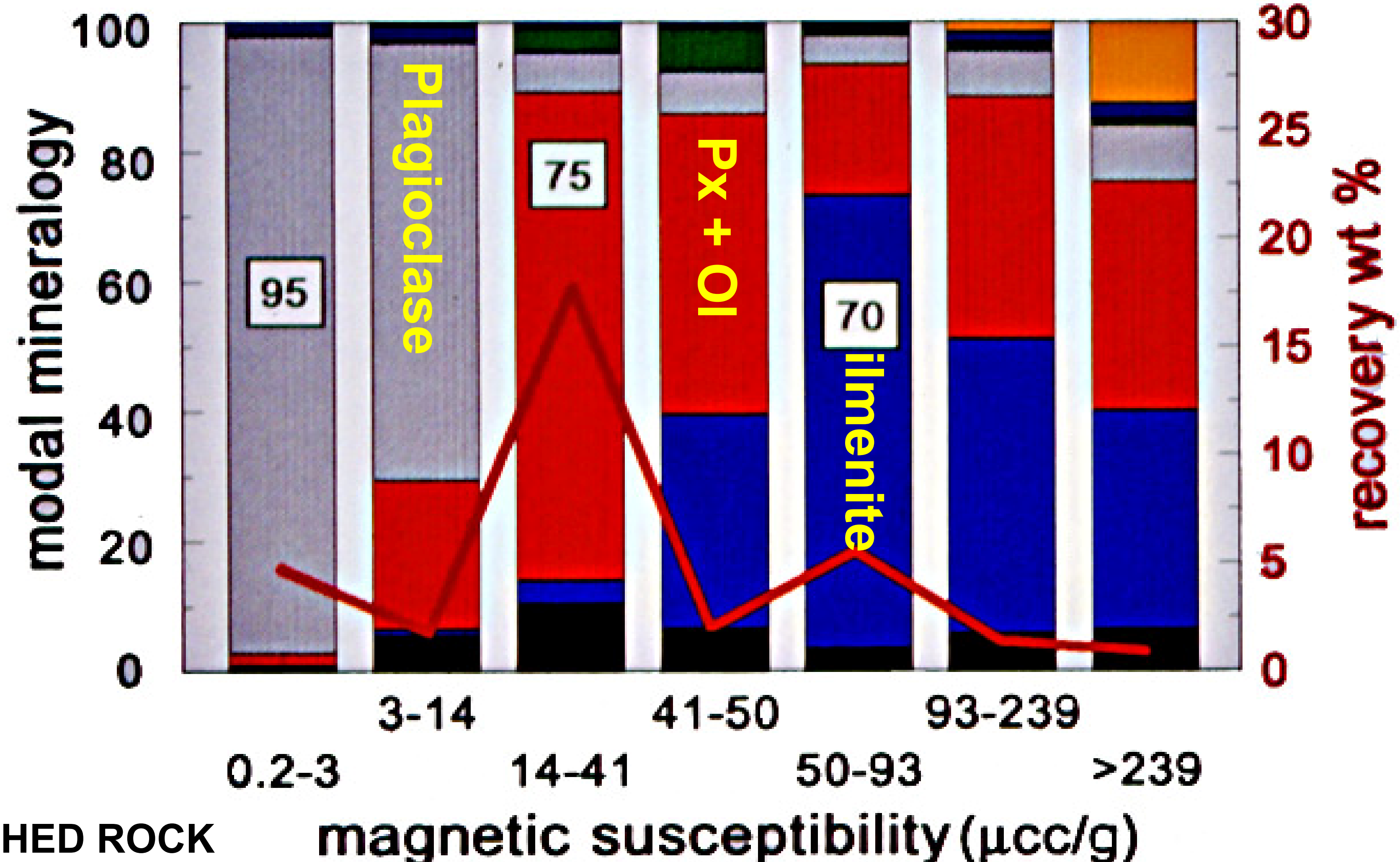
Apollo 17 Rock Fine-Grained Hi-Ti Mare Basalt

CRUSHED





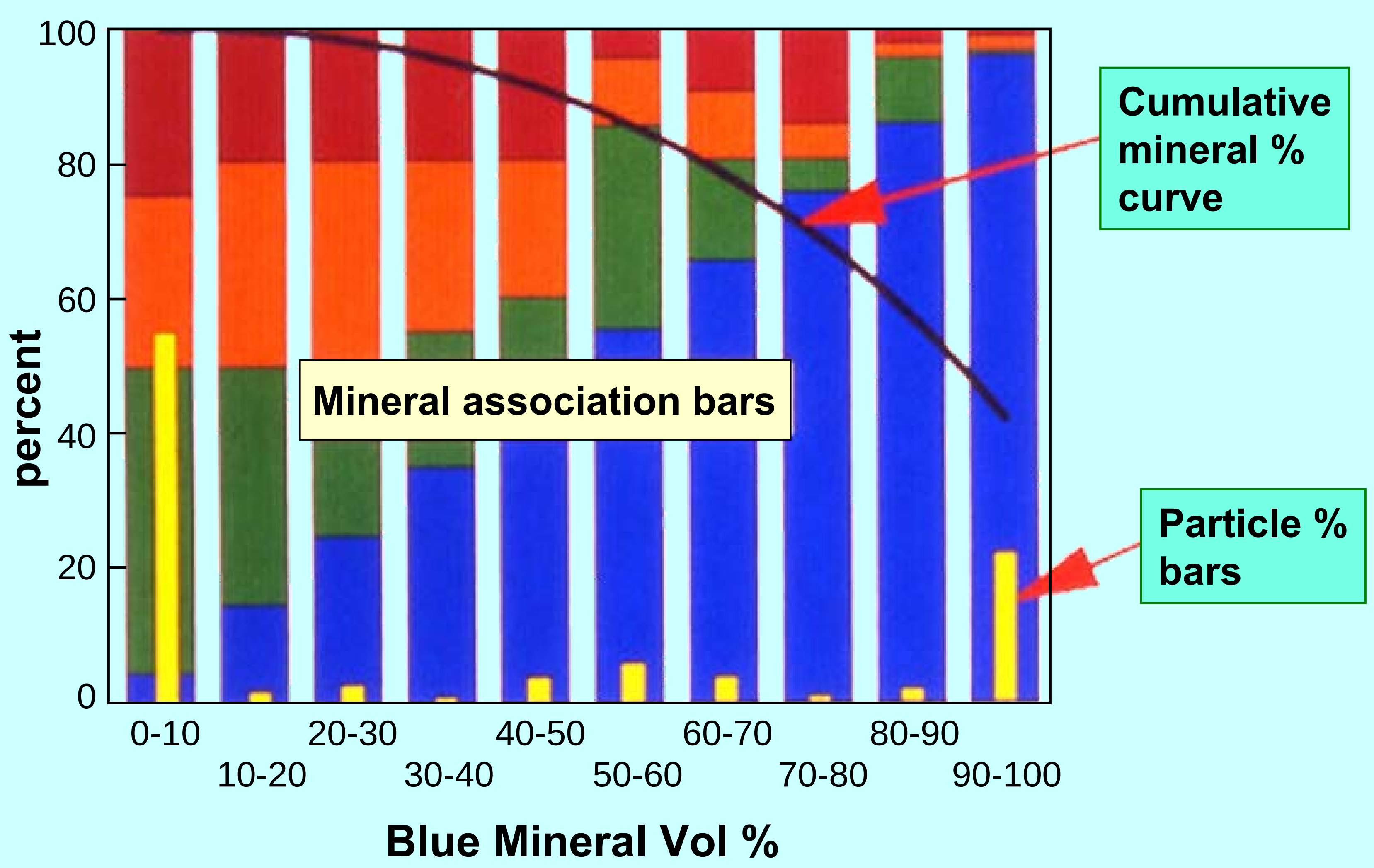
MINERALOGY AND MAGNETOGRAM OF THE 45-90 μm SIZE FRACTION OF 71055



CRUSHED ROCK

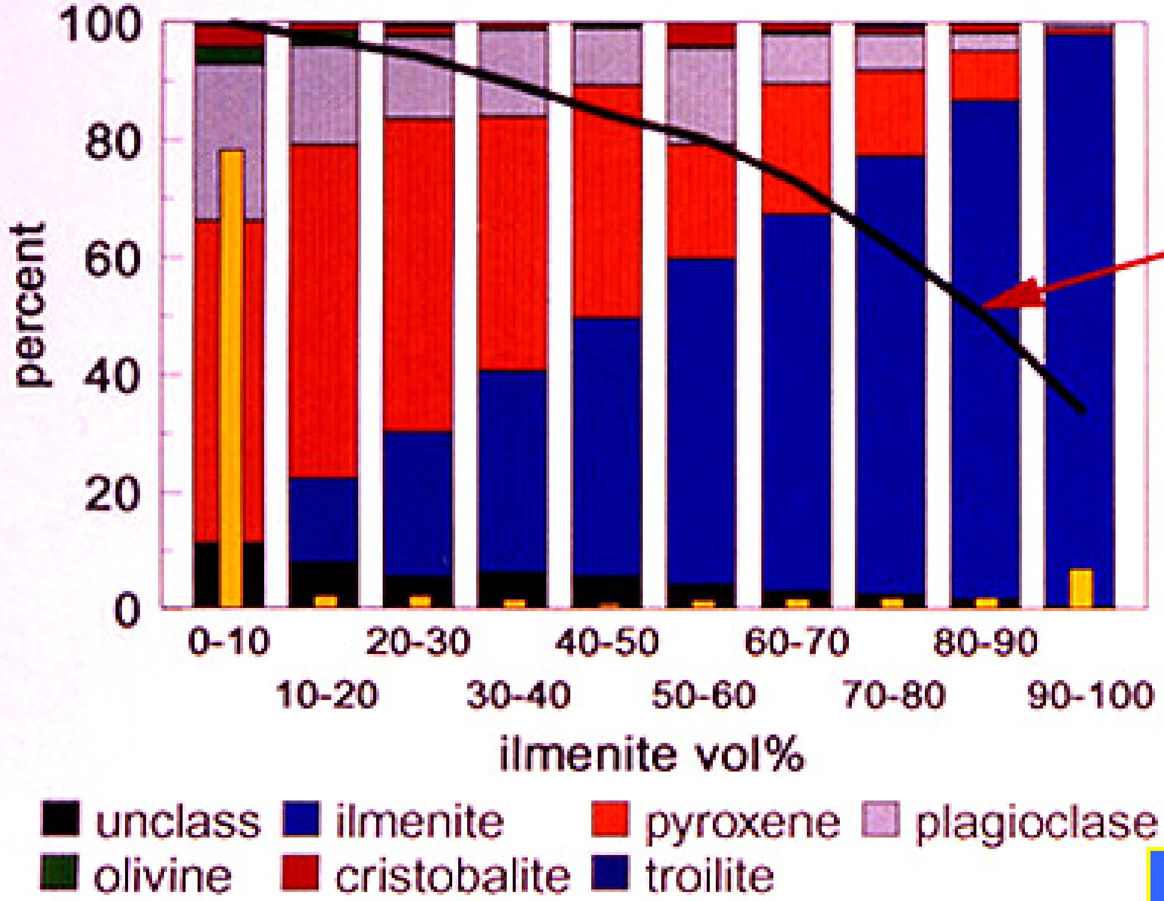
MINERAL LIBERATION

Composite Mineral Liberation Graph



Liberation Studies

Ilmenite Liberation for the 45 - 90 μm Size Fraction of Hi-Ti Basalt 71055



Only 50 vol % Ilmenite is Clean (80- 100% Liberated)

Chambers et al., 1994

Immature / Submature High-Ti Soil

PROS:

- **Soils are Already partially Beneficiated (= less handling than with rocks);**
- **Locations of High-Ti soils are Well Known, BUT not the abundances of Immature + Submature Soils;**
- **Small Equipment Masses and Low Energy Requirements**
- **Easy Haulage, Simple Sizing + Magnetic / Electrostatic Beneficiation**

CONS:

- **Lower Grade Feedstock than from Rocks;**
- **Lower Yields of Feedstock than from Rocks;**
- **Agglutinate / Impact Products complicate Beneficiation;**
- **Immature / Submature Soils not as Abundant as Mature;**
- **Immature / Submature Soil Locations Largely Unknown.**

Course-Grained High-Ti Basalts

PROS:

- **Higher Grade Feedstock than from Soils;**
- **Higher Yields of Feedstocks than from Soils;**
- **Lack of Weathering Products Simplifies Beneficiation**

CONS

- **Locations of Specific Rock Types Poorly Known (No Outcrops samples by Apollo Missions);**
- **Extensive Processing Required; Blasting, Grizzly, Crushing, Long Haulage;**
- **Large Equipment Masses (Crushing, Grizzly, Haulers) & Large Energy Requirements for Mining and Beneficiation.**

With Benefication of Lunar Soils by

1)Sizing

2)Magnetic separation

The Production of Ilmenite Feedstock is

Better for High-Ti Rocks (Taylor et al, 1992)

Than for High Ti Soils (Taylor and Order, 1990),

But by less than a Factor of Two

Conclusion

Most Feasible Production of Ilmenite-Rich Feedstock:

Magnetic / Electrostatic Beneficiation of the <150 >20 Micron Fraction of

Immature / submature High-Ti Soil

Questions for Resource Exploration of the Moon

- Lunar minerals of both mare soils and basalts were effectively concentrated by magnetic separation; Grades High; Yields Low!
- Where are ilmenite concentrations in the regolith the highest?
  Prime locations for oxygen production from ilmenite
  High concentrations of 3He, hydrogen
- Location of immature regolith specially suited for resource extraction?
  Less glass may mean easier extraction of oxygen from ilmenite.
- Crushed Rock Fragments are easier to magnetically separate than
  Soil Particles;
- Even though higher grade mineral feedstocks can be obtained by Magnetic Beneficiation of rocks, the increased cost of crushing and grinding may make soils the more feasible raw material.

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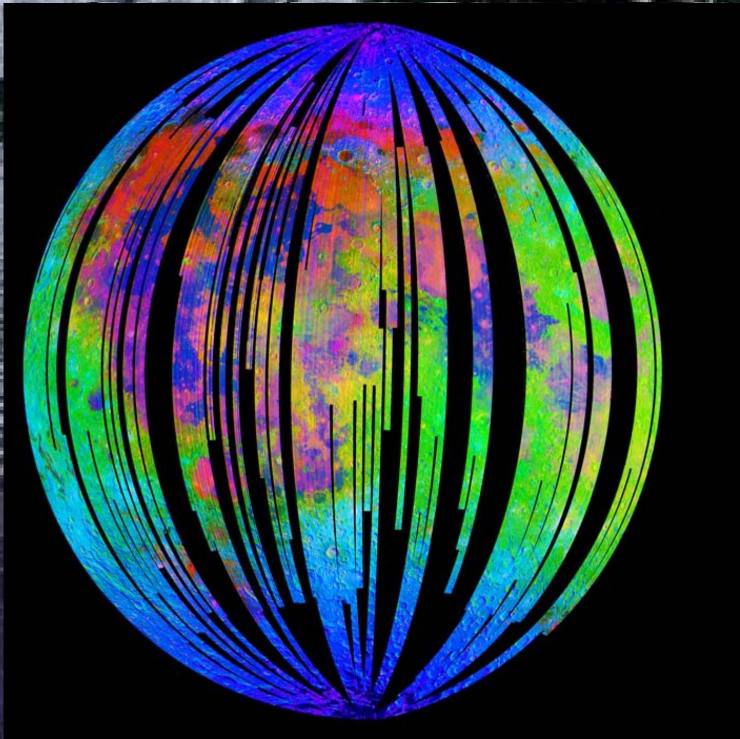
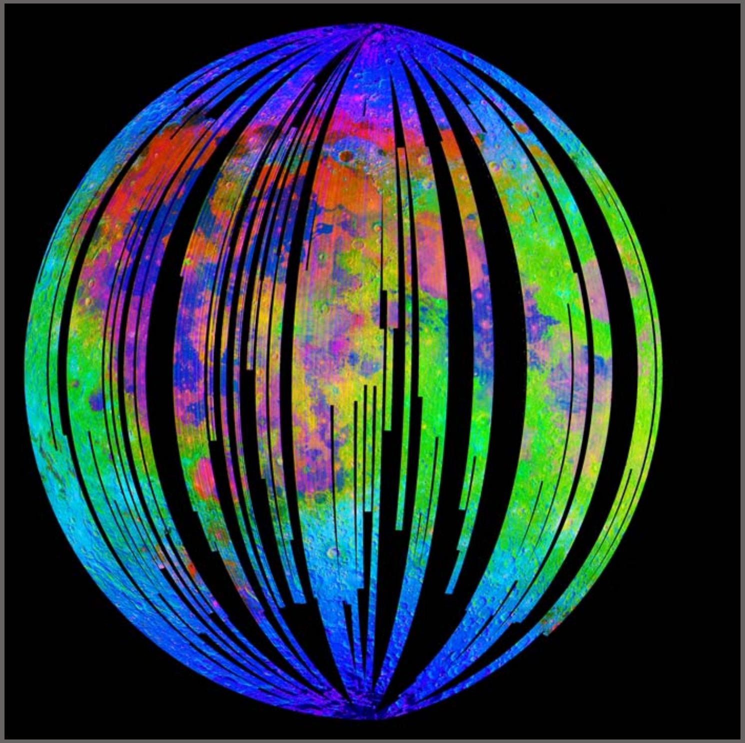


A "Watery" Lunar Surface



Three (3) Different Origins for water on the Moon

- Two (2) that are EXogenic (external)
- One (1) that is ENDogenic (internal)