Prospecting for Lunar Resources Using Remote Sensing and *In Situ* Analysis

Jeff Taylor[1], Linda M. V. Martel[1], Kevin M. Cannon[2], Elizabeth B. Rampe[3], David F. Blake[1,4], Philippe Sarrazin[5]

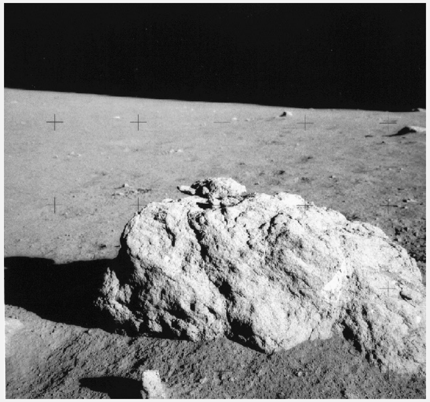
[1]University of Hawai‘i

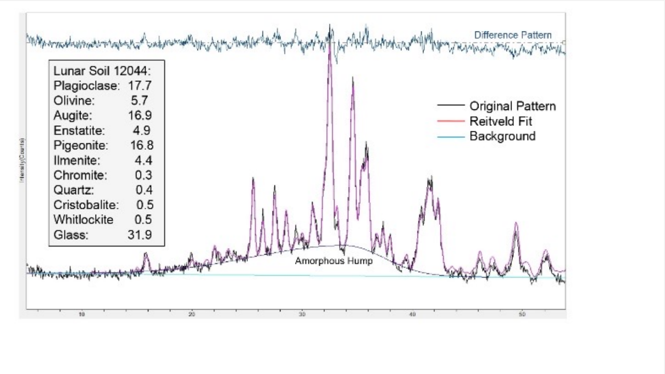
[2]Colorado School of Mines

[3]NASA Johnson Space Center

[4]NASA Ames Research Center

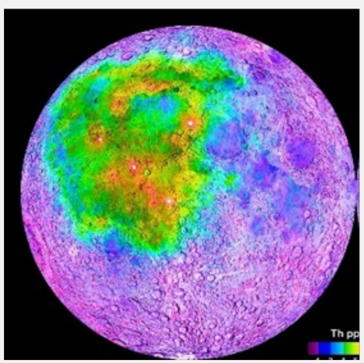
[5]eXaminArt LLC

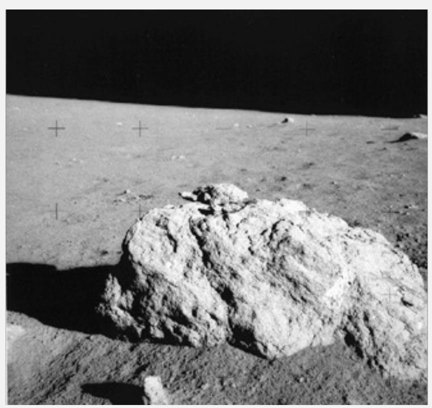


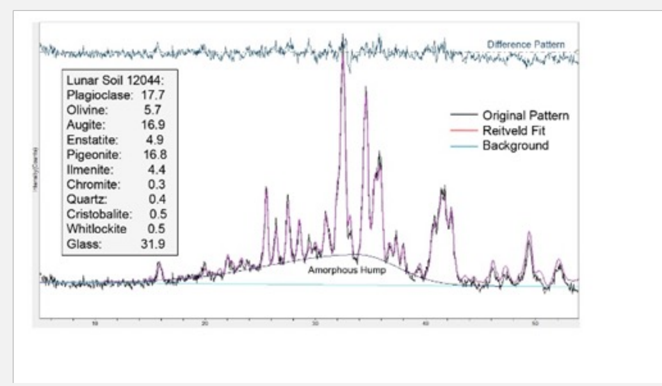


Outline

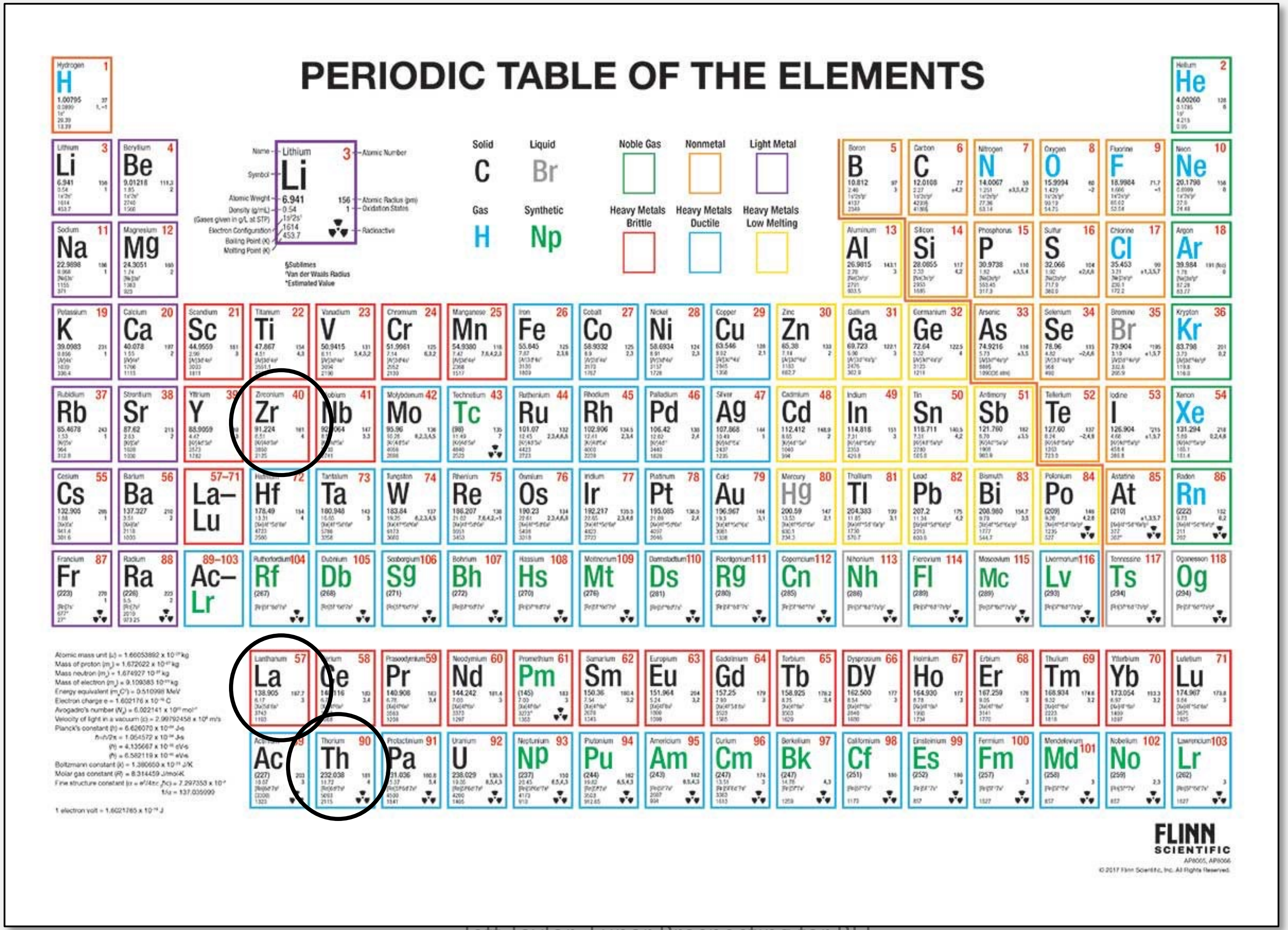
- Focus on Rare Earth Elements (REE) as an example
- Th and REE global distribution
- Tools for *in situ* analysis



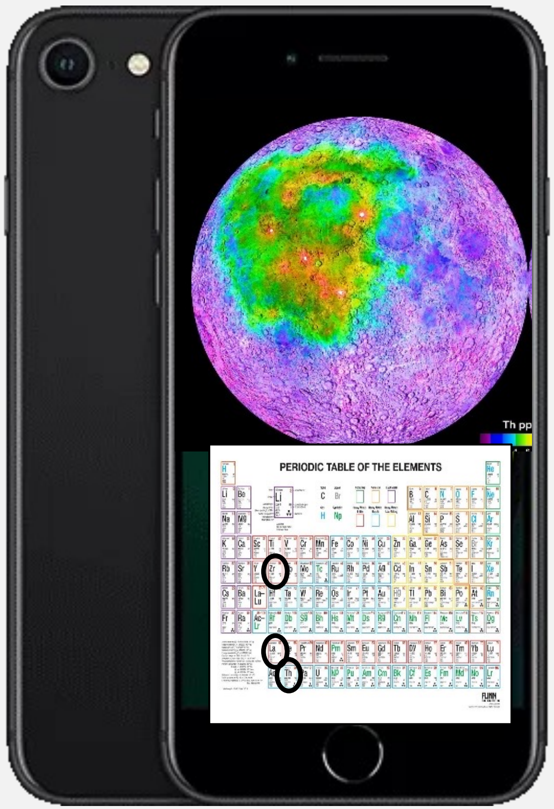


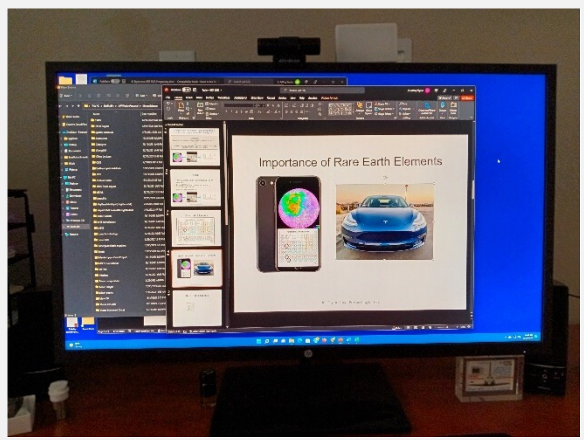


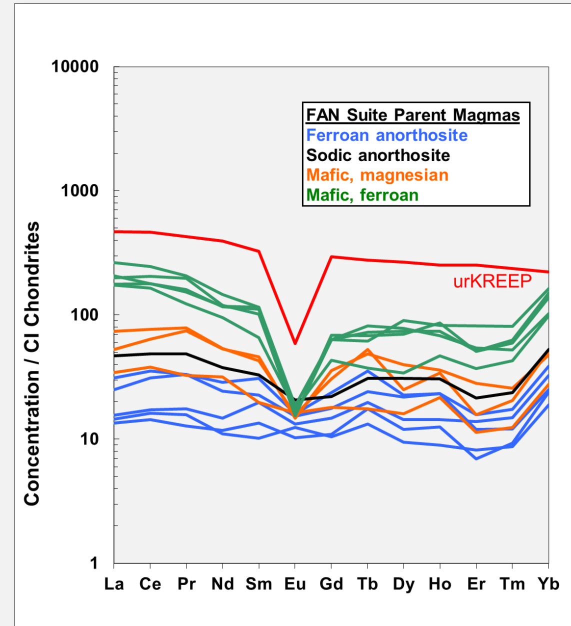
Rare Earth Elements

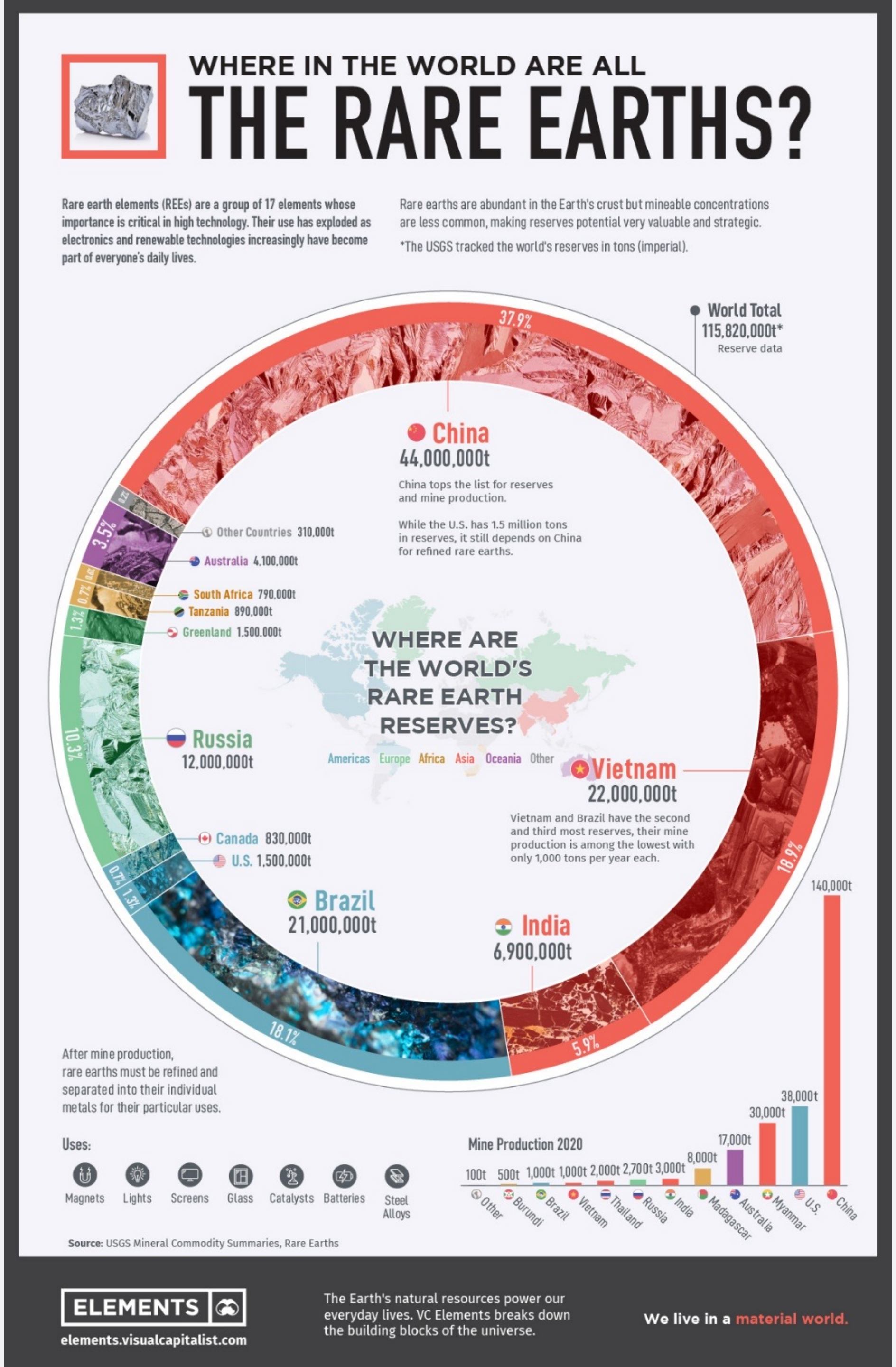


Importance of Rare Earth Elements









World total reserves: 115,820,000 Tons

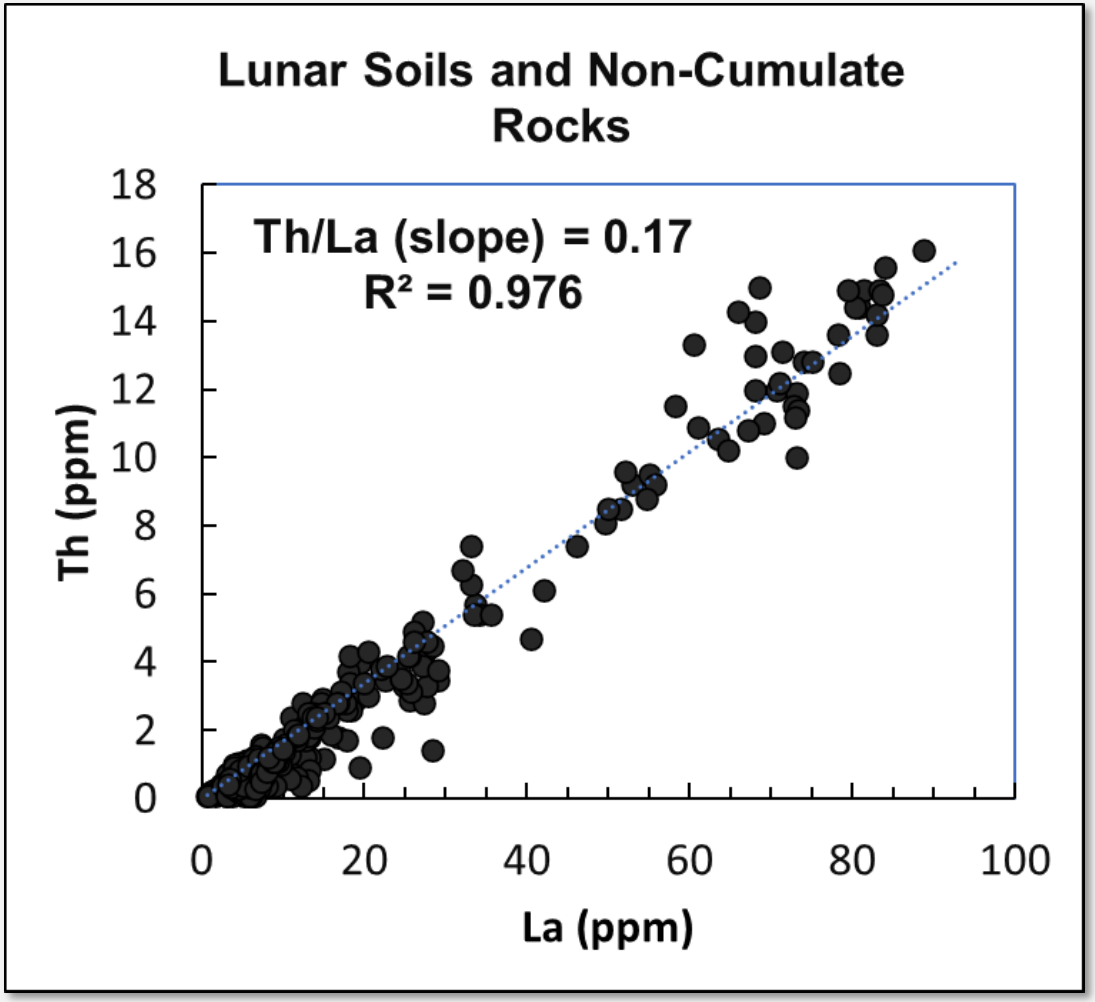
Dirty Business

Mining REE:
1. Strip mining
2. Leach out REE using toxic chemicals.
3. Usually ignore environmental consequences.

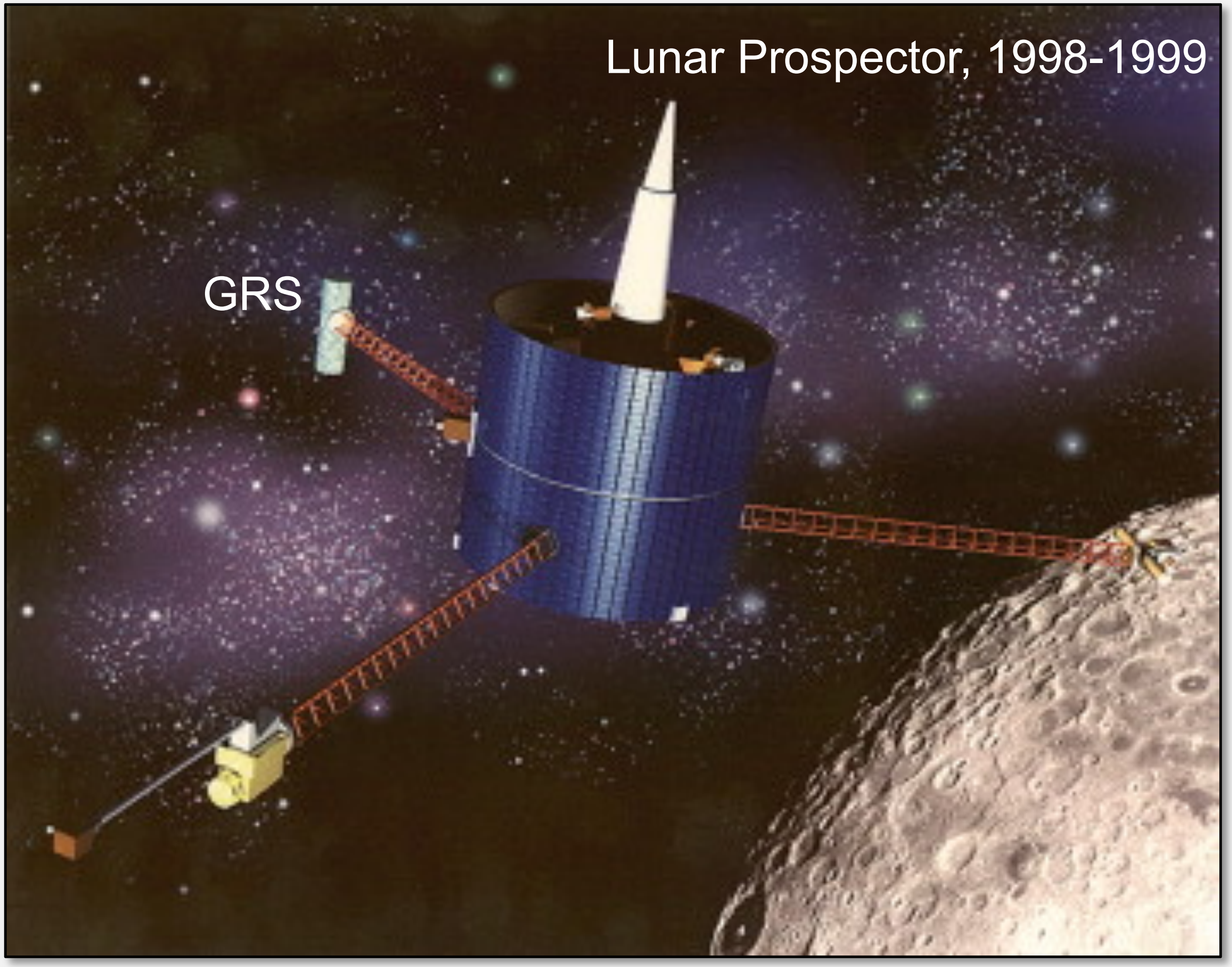
Optimistic Note:
Mining REE on the Moon could not involve water, so other extraction techniques would need to be developed.

Tech transfer to Earth mining??

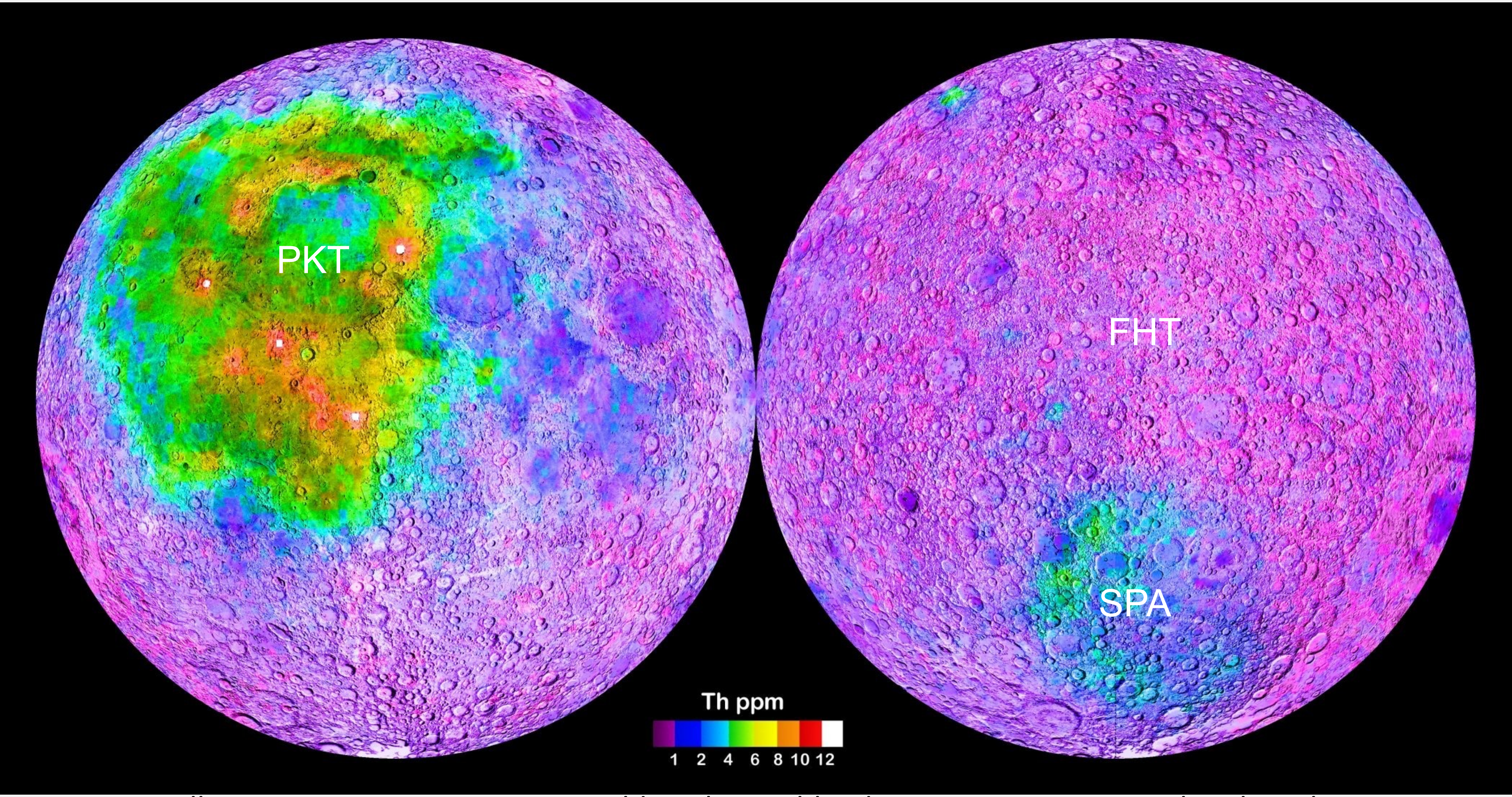
Th correlates with REE



Lunar Prospector Measured Global Abundance of Thorium



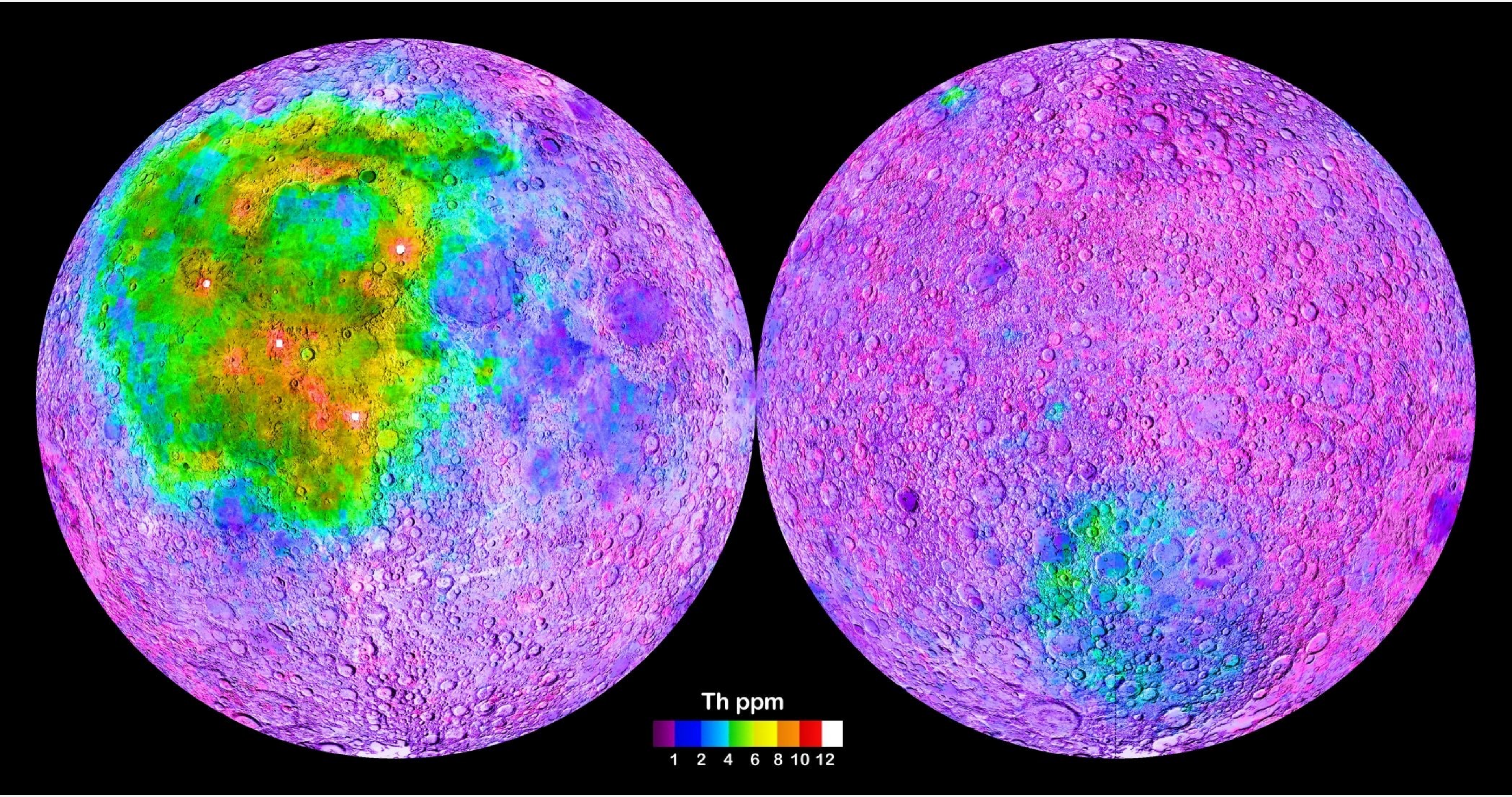
Global Distribution of Thorium from Orbital Gamma-Ray Spectroscopy



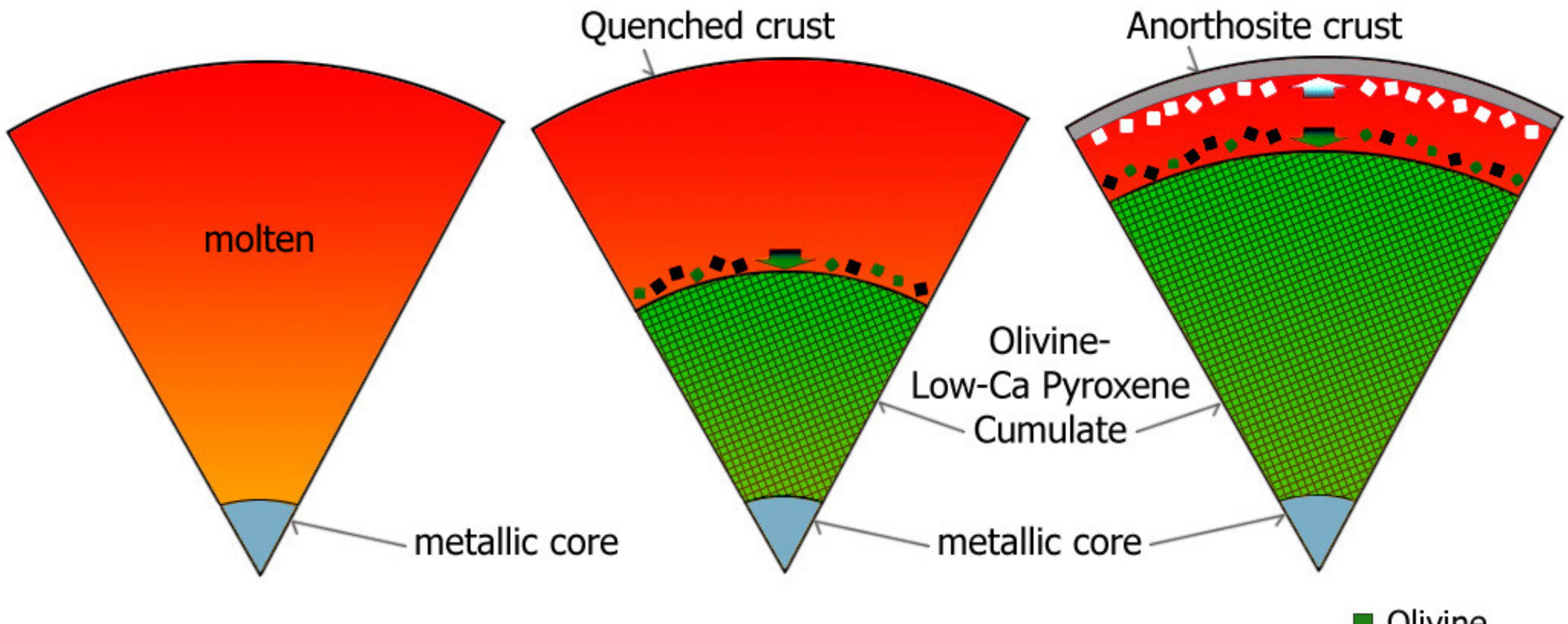
PKT = Procellarum KREEP Terrane **FHT** = Feldspathic Highlands Terrane **SPAT** = South Pole Aitken Terrane

Fun Facts:

- 40% of Moon's total Th is in crust in the PKT
- 9% is in the mantle below the PKT

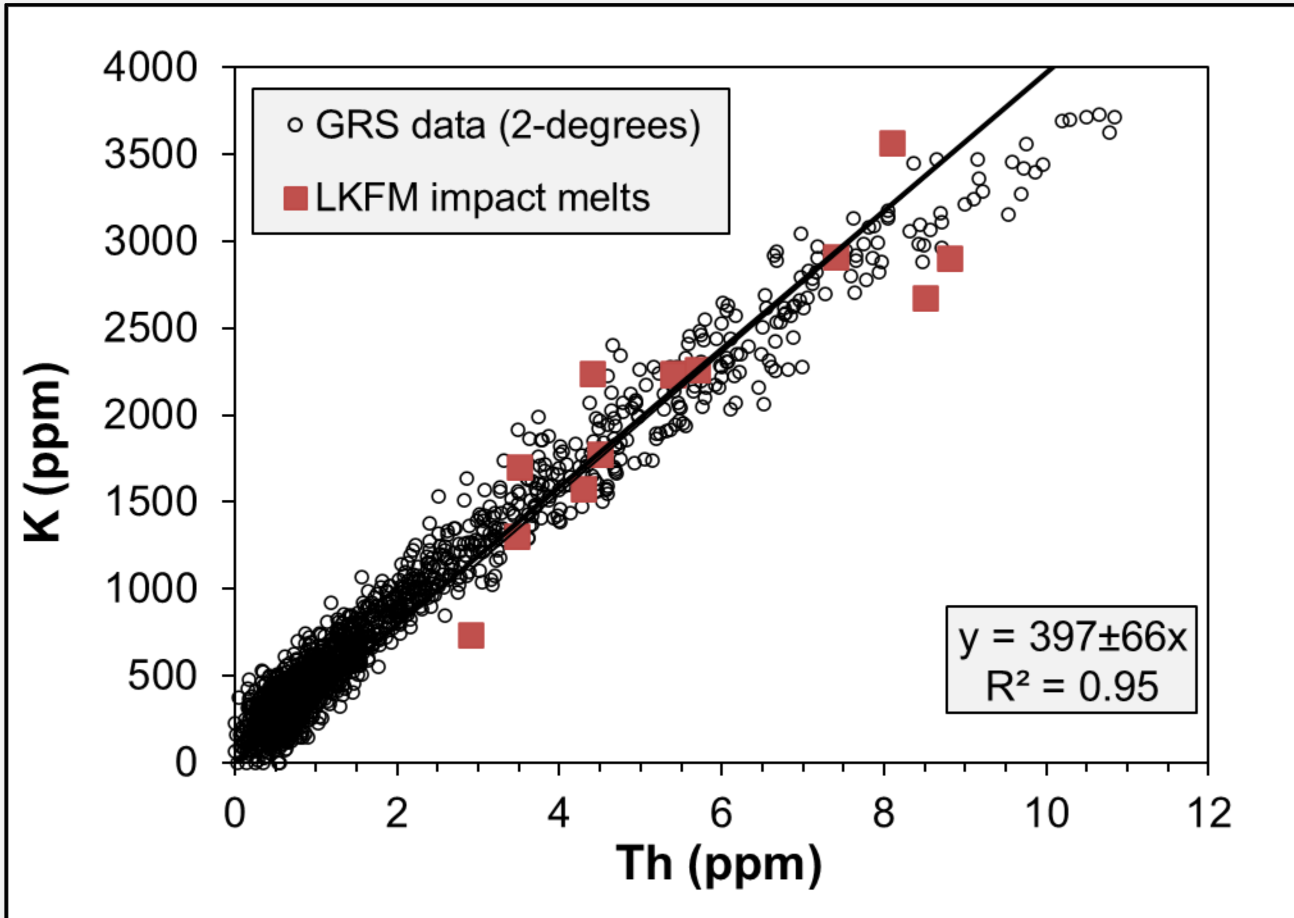


PKT is the Product of Fractional Crystallization of the Lunar Magma Ocean



REE in remaining magma increases with crystallization.

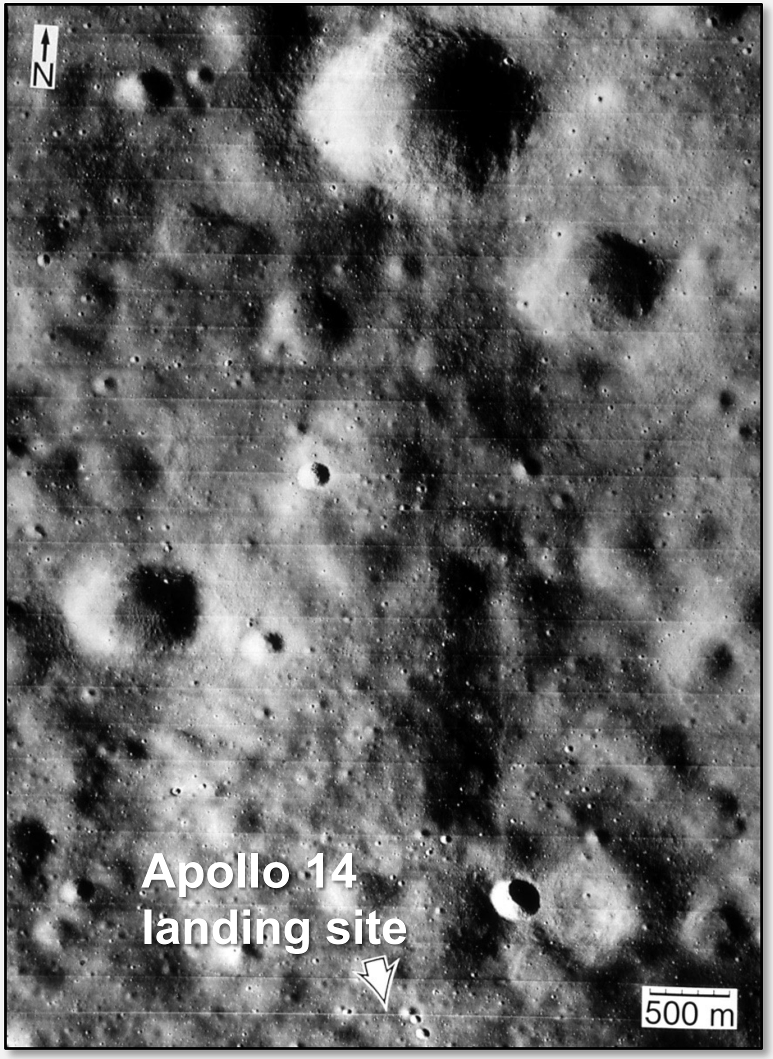
Important Bulk Planet Information



The low concentrations of K and other alkali metals in the Moon implies that REE are not associated with **alkaline magmatism** as on Earth.

For reference: K/Th in bulk Earth is 3000

Choose a place with high Th, land there, and explore using an array of instruments

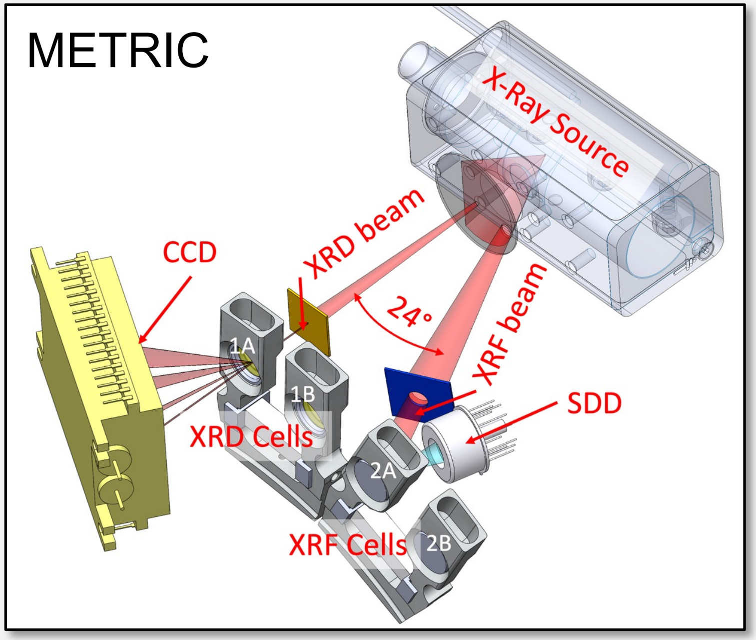


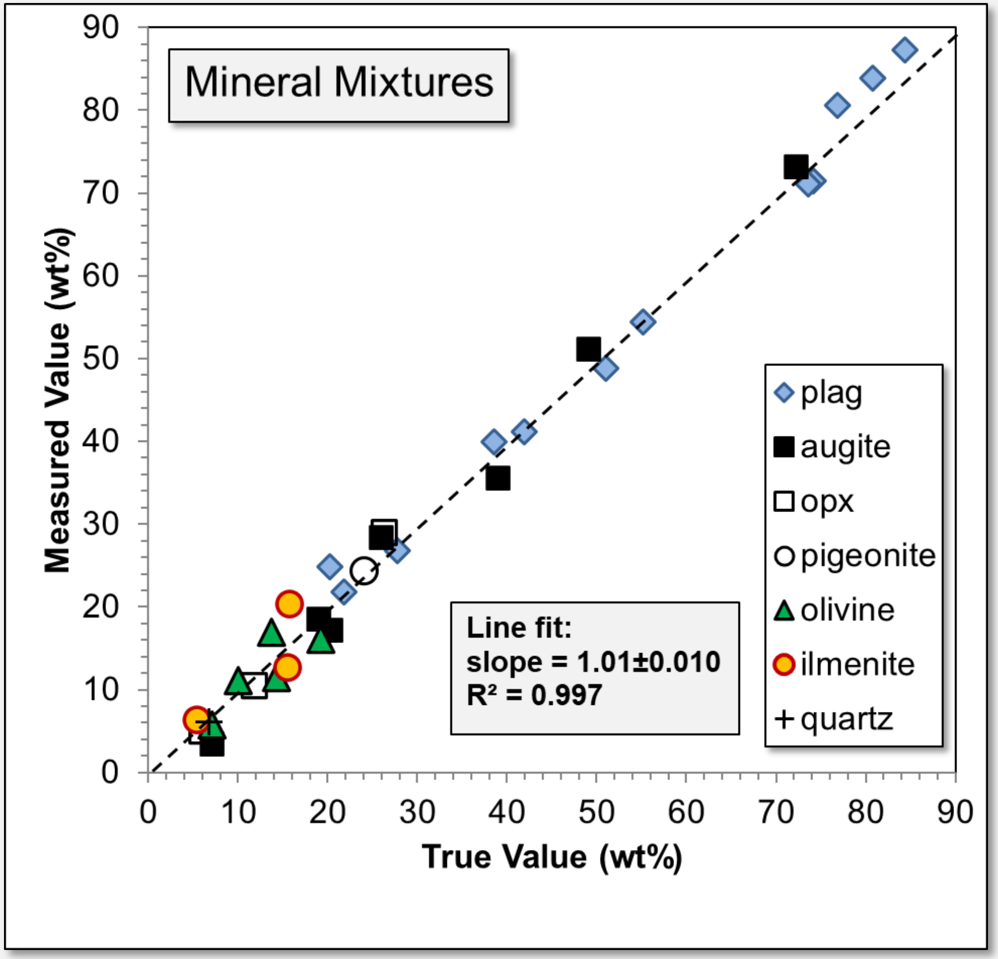
Need:

- Mineralogy (ID and abundance)
- Bulk chemical composition
  - Major elements
  - Trace elements
- Textural and physical properties of the regolith (and rocks)

Portion of Lunar Orbiter photograph III-133-H2 of the region north of the Apollo 14 landing site.

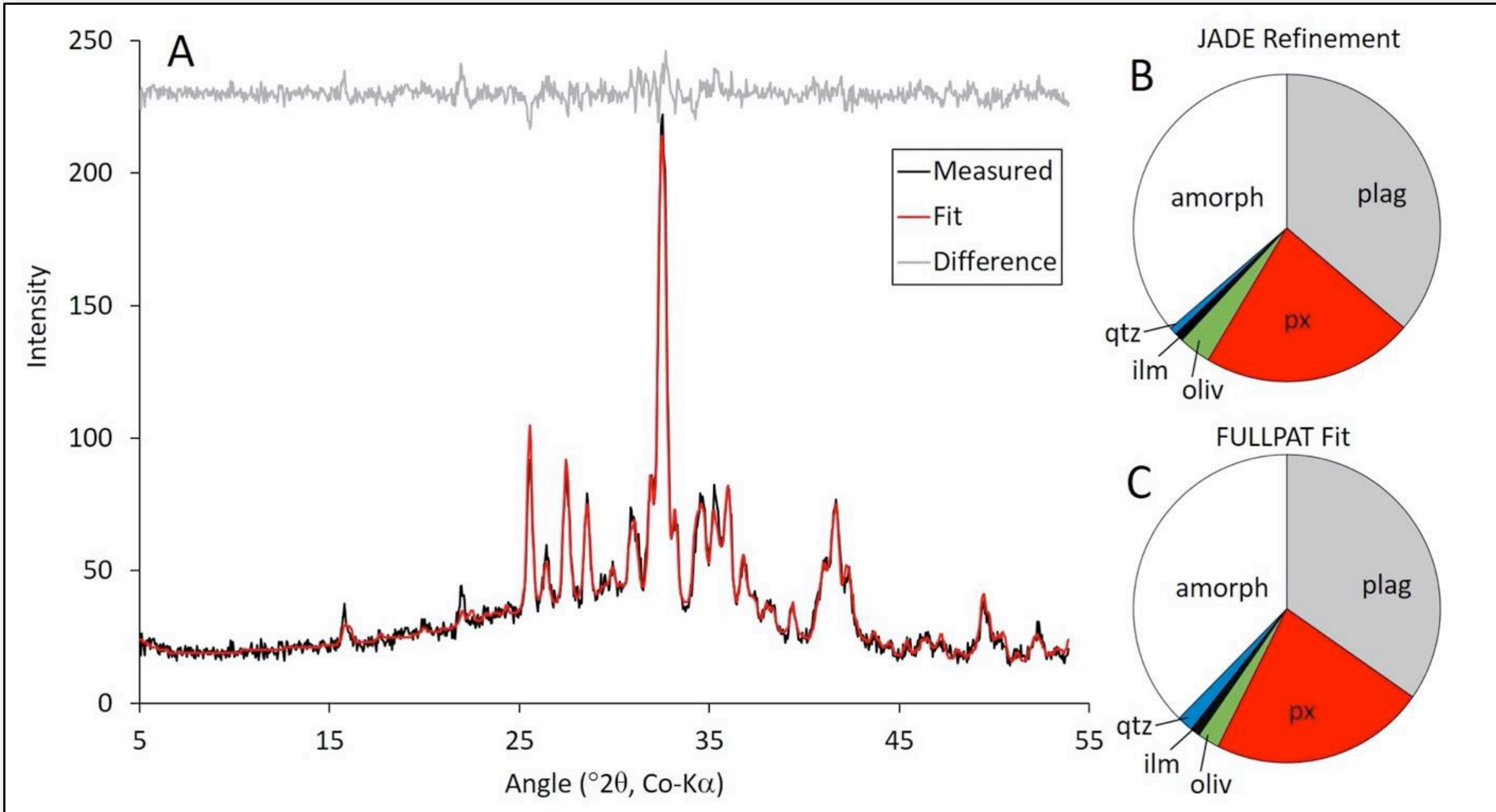
Mineralogy





Terrestrial spin off modeled after CheMin instrument on Curiosity rover on Mars.

Apollo Soil (<150 μm) 14149

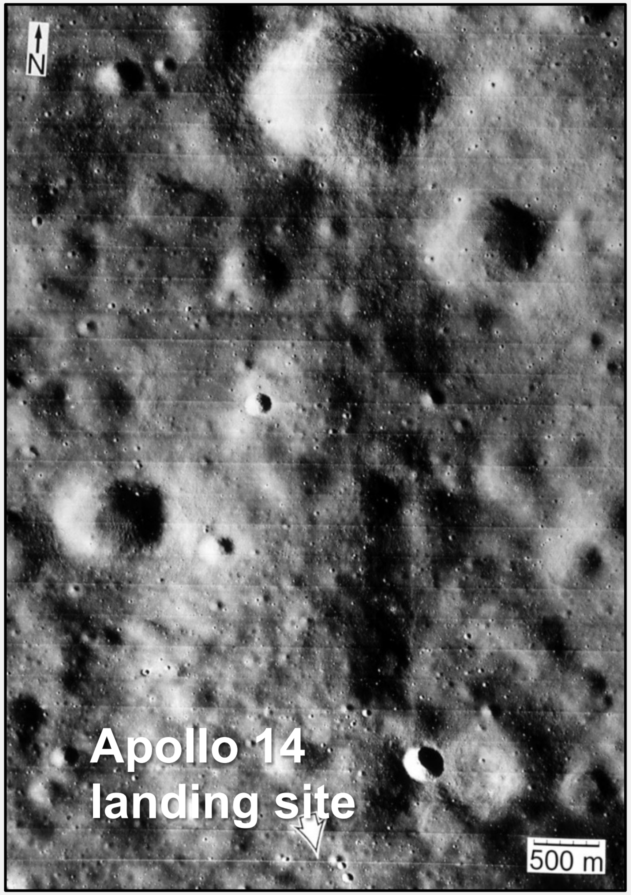


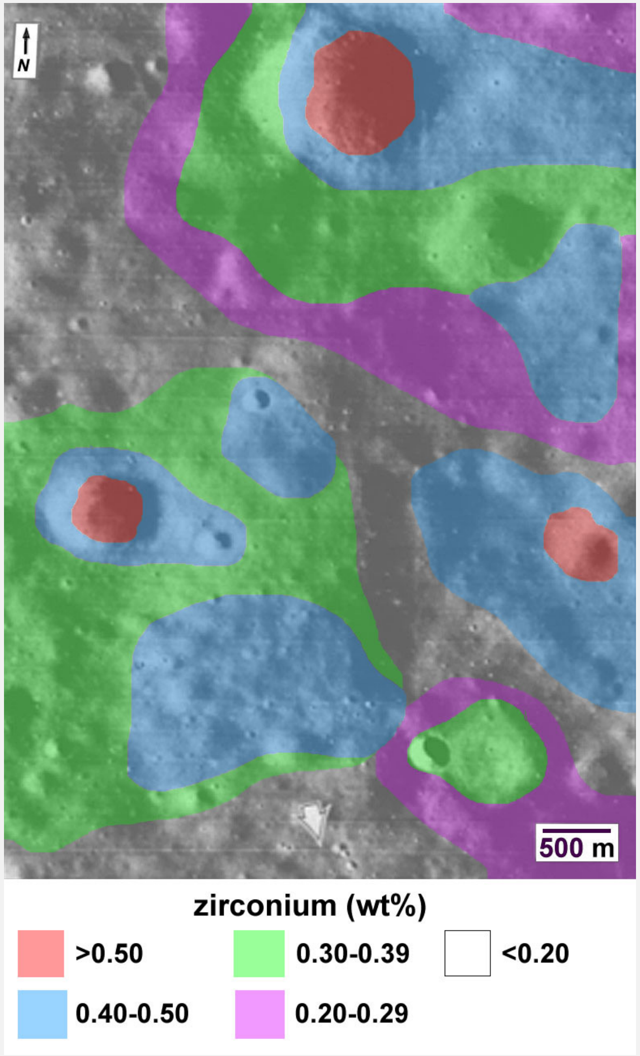
X-Ray Fluorescence (XRF)

- New instrument in prototype stage
- Modeling and previous experience indicates it will be possible to determine concentrations of these elements (at least):
  - Major and minor elements
    - Probably: Na, Mg
    - Certainly: Al, Si, P, K, Ca, Ti, Cr, Mn, Fe
  - Trace elements
    - Probably: Eu, Gd, Dy, Er, Th
    - Certainly: Zr, La, Ce, Nd, Sm, Yb, Lu

FHT

X-Ray Fluorescence (XRF) Example



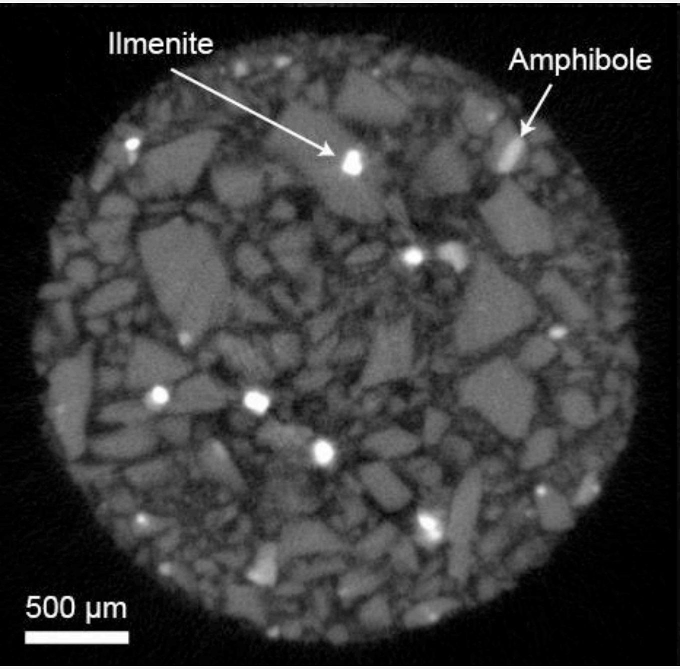


Rover(s) equipped with XRF device as in METRIC instrument payload traverses an area, stopping to determine Zr concentration at numerous (100s) of spots, allowing us to map the Zr distribution.

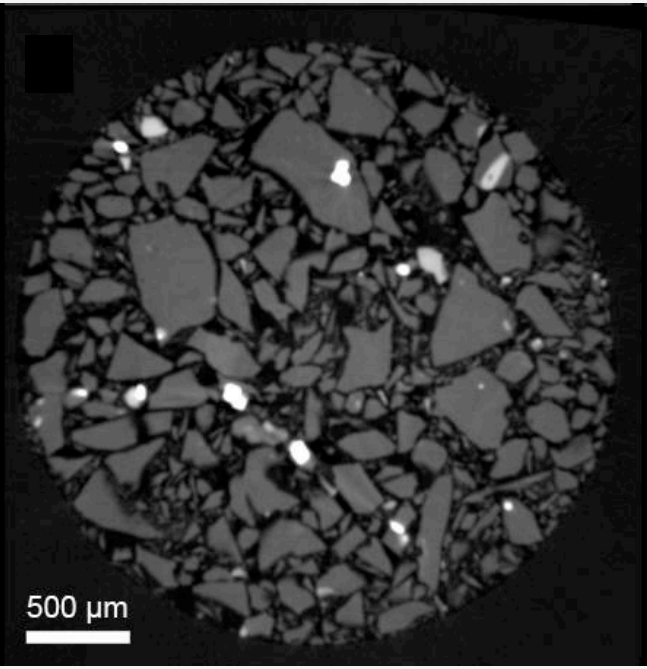
X-Ray micro-CT (XCT)

- New instrument in prototype stage
- Non-destructive high-resolution three-dimensional imaging technique. Characterizes:
  - Internal features of multiphase materials
  - Phase variability and grain size distribution of porous granular materials
- Provides physical linkage to:
  - Mineralogy determined by XRD
  - Information about rock fragments
  - Insight into geotechnical properties

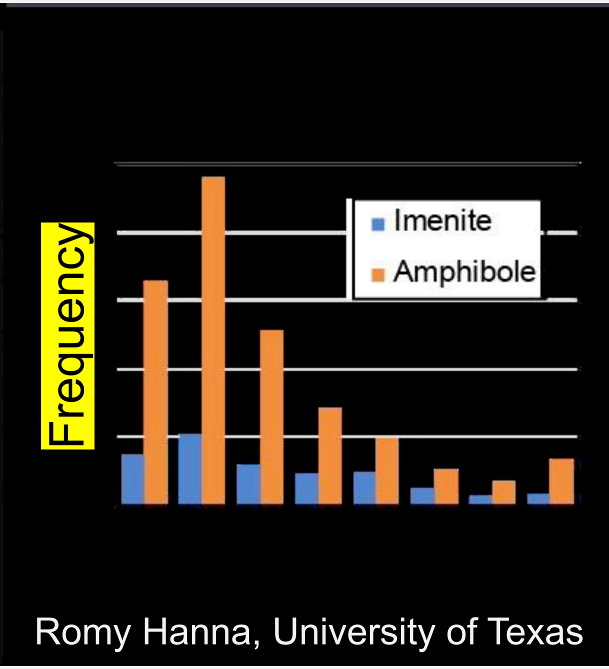
X-Ray micro-CT: Analog Example Crushed Terrestrial Dacite Lava



METRIC XCT Prototype



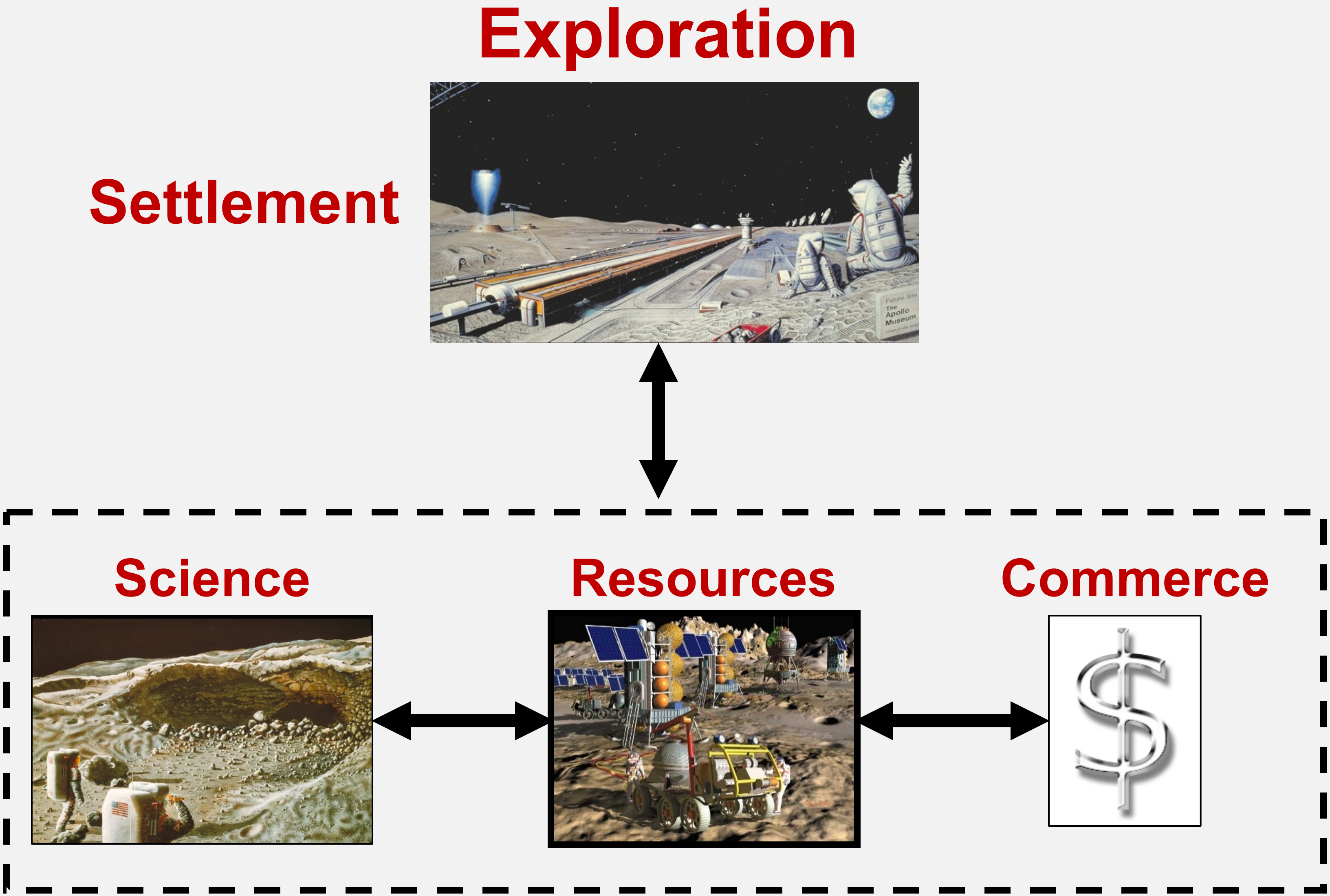
Zeiss Versa 620 lab instrument



Grain size distribution from XCT data

Prospecting for REE

- Get a lot of data for the Moon (mineralogy, chemical composition, physical properties…)
- Data needs to be at a wide range of scales: global from orbit (100 to 1 km resolution) to robotic (maybe human) surveys at promising locations (meters to submeter resolution)
- Do extensive research on the origins of potential ore deposits to understand petrologic and geochemical processes on the Moon (leads to advances in fundamental science aided by resource exploration).



Exploring and using resources deepens our understanding of basic science.