

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

Jeff Taylor<sup>1</sup>, Linda M. V. Martel<sup>1</sup>, Kevin M. Cannon<sup>2</sup>,  
Elizabeth B. Rampe<sup>3</sup>, David F. Blake<sup>1,4</sup>, Philippe Sarrazin<sup>5</sup>

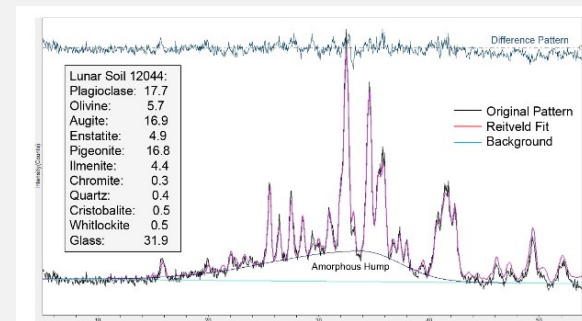
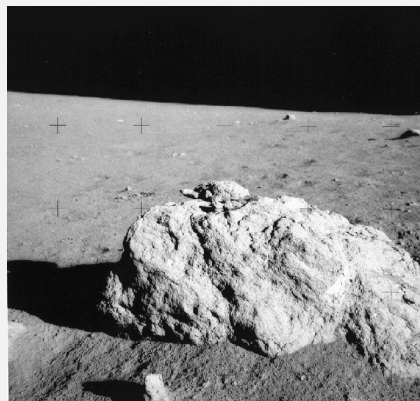
<sup>1</sup>University of Hawai'i

<sup>2</sup>Colorado School of Mines

<sup>3</sup>NASA Johnson Space Center

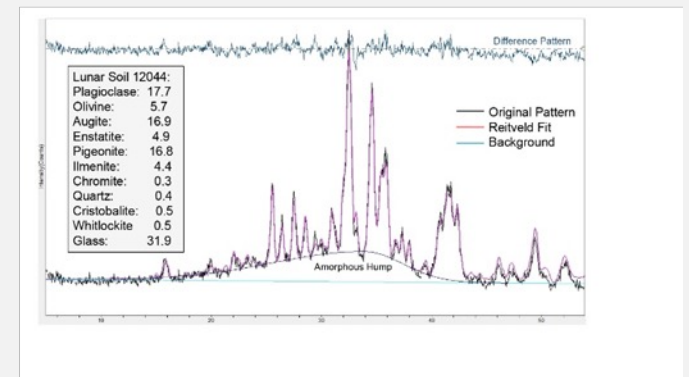
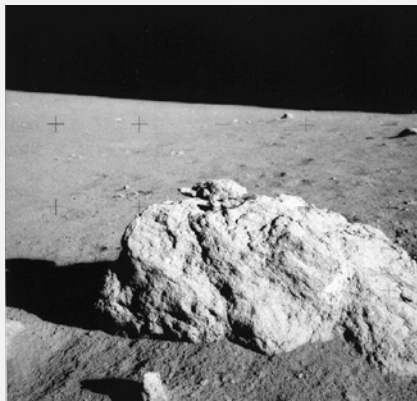
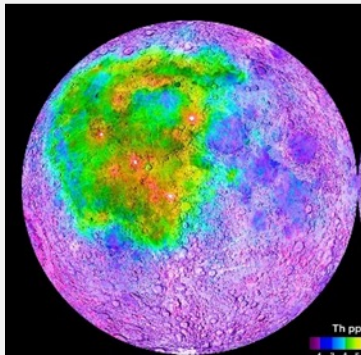
<sup>4</sup>NASA Ames Research Center

<sup>5</sup>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

# PERIODIC TABLE OF THE ELEMENTS

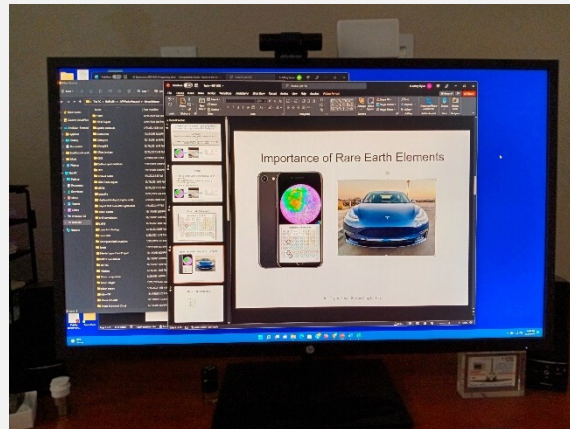
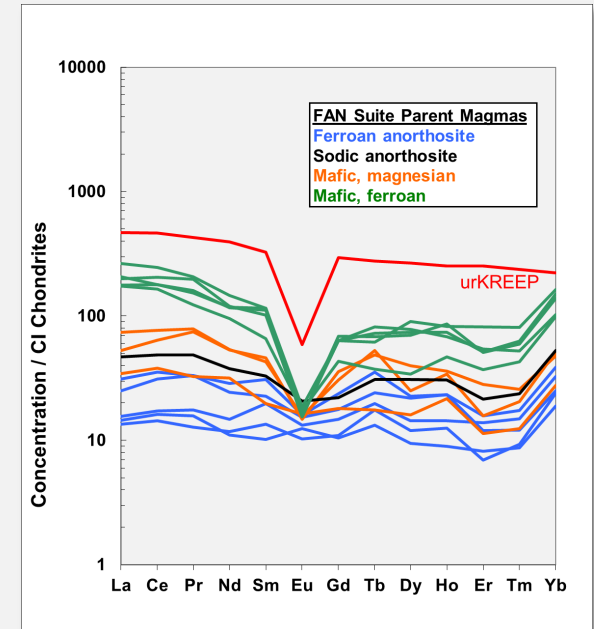
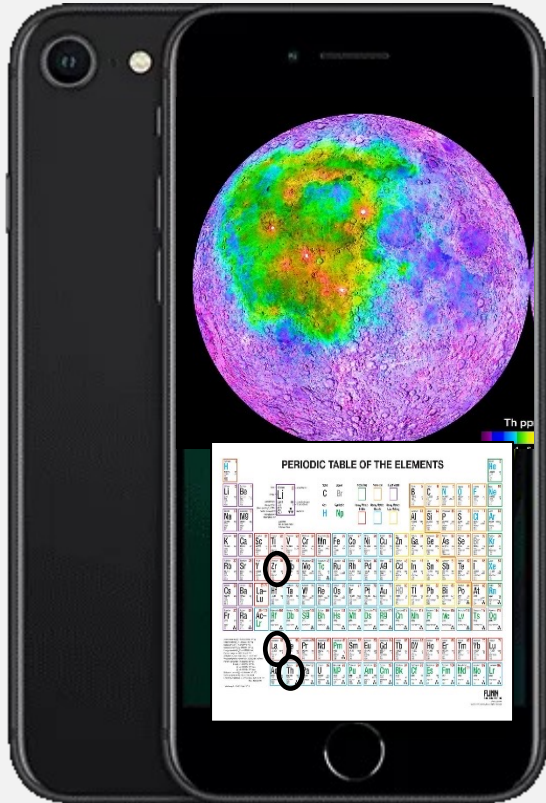
<b>H</b> 1 1.00794 1.008 20.18 12.81																	<b>He</b> 2 4.00260 4.0026 4.0026															
<b>Li</b> 3 6.941 0.534 0.01218 119.2 15.83 16.68 16.94 632.7	<b>Be</b> 4 9.01218 119.2 1.85 1.57 2.90 3.56																	<b>Ne</b> 10 20.1797 20.1798 20.1797														
<b>Na</b> 11 22.98976 22.9898 0.968 0.968 115.5 371	<b>Mg</b> 12 24.30509 24.305 1.74 1.74 118.3 365																	<b>Ar</b> 18 39.948 39.948 1.78 1.78 188.2 361.7														
<b>K</b> 19 39.0983 39.0983 0.8618 0.8618 132.9 369.6	<b>Ca</b> 20 40.078 40.078 1.55 1.55 137.3 369.6	<b>Sc</b> 21 44.9559 44.9559 2.98 2.98 146.3 369.6	<b>Ti</b> 22 47.867 47.867 4.54 4.54 134.4 369.6	<b>V</b> 23 50.9415 50.9415 6.09 6.09 133.5 369.6	<b>Cr</b> 24 51.9961 51.9961 7.19 7.19 133.5 369.6	<b>Mn</b> 25 54.938 54.938 7.47 7.47 133.5 369.6	<b>Fe</b> 26 55.845 55.845 7.87 7.87 133.5 369.6	<b>Co</b> 27 58.9332 58.9332 8.90 8.90 133.5 369.6	<b>Ni</b> 28 58.6934 58.6934 8.90 8.90 133.5 369.6	<b>Cu</b> 29 63.546 63.546 8.96 8.96 133.5 369.6	<b>Zn</b> 30 65.38 65.38 7.14 7.14 133.5 369.6	<b>Ga</b> 31 69.723 69.723 5.91 5.91 133.5 369.6	<b>Ge</b> 32 72.64 72.64 5.32 5.32 133.5 369.6	<b>As</b> 33 74.9216 74.9216 5.78 5.78 133.5 369.6	<b>Se</b> 34 78.96 78.96 4.81 4.81 133.5 369.6	<b>Br</b> 35 79.904 79.904 3.12 3.12 133.5 369.6	<b>Kr</b> 36 83.796 83.796 3.71 3.71 133.5 369.6															
<b>Rb</b> 37 85.4678 85.4678 1.47 1.47 133.5 369.6	<b>Sr</b> 38 87.62 87.62 2.54 2.54 133.5 369.6	<b>Y</b> 39 88.9058 88.9058 4.47 4.47 133.5 369.6	<b>Zr</b> 40 91.224 91.224 6.01 6.01 133.5 369.6	<b>Nb</b> 41 92.9064 92.9064 6.48 6.48 133.5 369.6	<b>Mo</b> 42 95.94 95.94 10.22 10.22 133.5 369.6	<b>Tc</b> 43 98.9062 98.9062 11.49 11.49 133.5 369.6	<b>Ru</b> 44 101.07 101.07 12.41 12.41 133.5 369.6	<b>Rh</b> 45 102.9055 102.9055 12.41 12.41 133.5 369.6	<b>Pd</b> 46 106.42 106.42 12.02 12.02 133.5 369.6	<b>Ag</b> 47 107.8682 107.8682 11.35 11.35 133.5 369.6	<b>Cd</b> 48 112.411 112.411 11.32 11.32 133.5 369.6	<b>In</b> 49 114.818 114.818 7.31 7.31 133.5 369.6	<b>Sn</b> 50 118.710 118.710 7.28 7.28 133.5 369.6	<b>Sb</b> 51 121.760 121.760 6.69 6.69 133.5 369.6	<b>Te</b> 52 127.60 127.60 6.24 6.24 133.5 369.6	<b>I</b> 53 126.905 126.905 4.93 4.93 133.5 369.6	<b>Xe</b> 54 131.29 131.29 5.5 5.5 133.5 369.6															
<b>Cs</b> 55 132.905 132.905 3.51 3.51 133.5 369.6	<b>Ba</b> 56 137.327 137.327 3.62 3.62 133.5 369.6	<b>La</b> 57-71 138.905 138.905 9.32 9.32 133.5 369.6	<b>Hf</b> 72 178.49 178.49 13.31 13.31 133.5 369.6	<b>Ta</b> 73 180.947 180.947 12.61 12.61 133.5 369.6	<b>W</b> 74 183.84 183.84 19.30 19.30 133.5 369.6	<b>Re</b> 75 186.207 186.207 21.02 21.02 133.5 369.6	<b>Os</b> 76 190.23 190.23 22.41 22.41 133.5 369.6	<b>Ir</b> 77 192.22 192.22 22.56 22.56 133.5 369.6	<b>Pt</b> 78 195.084 195.084 21.45 21.45 133.5 369.6	<b>Au</b> 79 196.967 196.967 19.30 19.30 133.5 369.6	<b>Hg</b> 80 200.59 200.59 13.55 13.55 133.5 369.6	<b>Tl</b> 81 204.384 204.384 11.53 11.53 133.5 369.6	<b>Pb</b> 82 207.2 207.2 11.34 11.34 133.5 369.6	<b>Bi</b> 83 208.98 208.98 9.80 9.80 133.5 369.6	<b>Po</b> 84 209 209 9.19 9.19 133.5 369.6	<b>At</b> 85 210 210 9.4 9.4 133.5 369.6	<b>Rn</b> 86 222 222 9.73 9.73 133.5 369.6															
<b>Fr</b> 87 223 223 2.01 2.01 133.5 369.6	<b>Ra</b> 88 226 226 1.4 1.4 133.5 369.6	<b>Ac</b> 89-103 227 227 10.2 10.2 133.5 369.6	<b>Rf</b> 104 261 261 13.2 13.2 133.5 369.6	<b>Db</b> 105 262 262 13.7 13.7 133.5 369.6	<b>Sg</b> 106 266 266 14.1 14.1 133.5 369.6	<b>Bh</b> 107 268 268 14.4 14.4 133.5 369.6	<b>Hs</b> 108 277 277 14.1 14.1 133.5 369.6	<b>Mt</b> 109 268 268 14.1 14.1 133.5 369.6	<b>Ds</b> 110 271 271 14.1 14.1 133.5 369.6	<b>Rg</b> 111 272 272 14.1 14.1 133.5 369.6	<b>Cn</b> 112 285 285 14.1 14.1 133.5 369.6	<b>Nh</b> 113 284 284 14.1 14.1 133.5 369.6	<b>Fl</b> 114 289 289 14.1 14.1 133.5 369.6	<b>Mc</b> 115 288 288 14.1 14.1 133.5 369.6	<b>Lv</b> 116 293 293 14.1 14.1 133.5 369.6	<b>Ts</b> 117 294 294 14.1 14.1 133.5 369.6	<b>Og</b> 118 294 294 14.1 14.1 133.5 369.6															
																		<b>La</b> 57 138.905 138.905 9.32 9.32 133.5 369.6	<b>Ce</b> 58 140.12 140.12 9.58 9.58 133.5 369.6	<b>Pr</b> 59 140.907 140.907 9.51 9.51 133.5 369.6	<b>Nd</b> 60 144.242 144.242 9.84 9.84 133.5 369.6	<b>Pm</b> 61 144.913 144.913 9.73 9.73 133.5 369.6	<b>Sm</b> 62 150.36 150.36 10.29 10.29 133.5 369.6	<b>Eu</b> 63 151.964 151.964 10.36 10.36 133.5 369.6	<b>Gd</b> 64 157.25 157.25 10.75 10.75 133.5 369.6	<b>Tb</b> 65 158.925 158.925 10.49 10.49 133.5 369.6	<b>Dy</b> 66 162.50 162.50 10.81 10.81 133.5 369.6	<b>Ho</b> 67 164.930 164.930 10.79 10.79 133.5 369.6	<b>Er</b> 68 167.259 167.259 10.84 10.84 133.5 369.6	<b>Tm</b> 69 168.934 168.934 10.49 10.49 133.5 369.6	<b>Yb</b> 70 173.054 173.054 10.49 10.49 133.5 369.6	<b>Lu</b> 71 174.967 174.967 9.84 9.84 133.5 369.6
<b>Ac</b> 89 227 227 10.2 10.2 133.5 369.6	<b>Th</b> 90 232.0377 232.0377 11.7 11.7 133.5 369.6	<b>Pa</b> 91 231.036888 231.036888 15.2 15.2 133.5 369.6	<b>U</b> 92 238.02891 238.02891 19.1 19.1 133.5 369.6	<b>Np</b> 93 237.048173 237.048173 20.45 20.45 133.5 369.6	<b>Pu</b> 94 244.06422 244.06422 19.84 19.84 133.5 369.6	<b>Am</b> 95 243.061361 243.061361 19.84 19.84 133.5 369.6	<b>Cm</b> 96 247.071377 247.071377 19.84 19.84 133.5 369.6	<b>Bk</b> 97 247.071377 247.071377 19.84 19.84 133.5 369.6	<b>Cf</b> 98 251.083288 251.083288 19.84 19.84 133.5 369.6	<b>Es</b> 99 252.083288 252.083288 19.84 19.84 133.5 369.6	<b>Fm</b> 100 257.103288 257.103288 19.84 19.84 133.5 369.6	<b>Md</b> 101 258.103288 258.103288 19.84 19.84 133.5 369.6	<b>No</b> 102 259.103288 259.103288 19.84 19.84 133.5 369.6	<b>Lr</b> 103 262.103288 262.103288 19.84 19.84 133.5 369.6																		

Atomic mass unit (u) = 1.66053892 x 10<sup>-27</sup> kg  
 Mass of proton (m<sub>p</sub>) = 1.67262 x 10<sup>-27</sup> kg  
 Mass of neutron (m<sub>n</sub>) = 1.67493 x 10<sup>-27</sup> kg  
 Mass of electron (m<sub>e</sub>) = 9.10938 x 10<sup>-31</sup> kg  
 Energy equivalent (E<sub>0</sub>) = 0.5109989 MeV  
 Electron charge (e) = 1.602176 x 10<sup>-19</sup> C  
 Rydberg's number (R<sub>∞</sub>) = 1.097373 x 10<sup>7</sup> m<sup>-1</sup>  
 Velocity of light in a vacuum (c) = 2.99792458 x 10<sup>8</sup> m/s  
 Planck's constant (h) = 6.626070 x 10<sup>-34</sup> J·s  
 Boltzmann's constant (k) = 1.380658 x 10<sup>-23</sup> J/K  
 Molar gas constant (R) = 8.314472 J/mol·K  
 Fine structure constant (α) = 7.2973525 x 10<sup>-3</sup>  
 1 electron volt = 1.6021765 x 10<sup>-19</sup> J

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# Importance of Rare Earth Elements



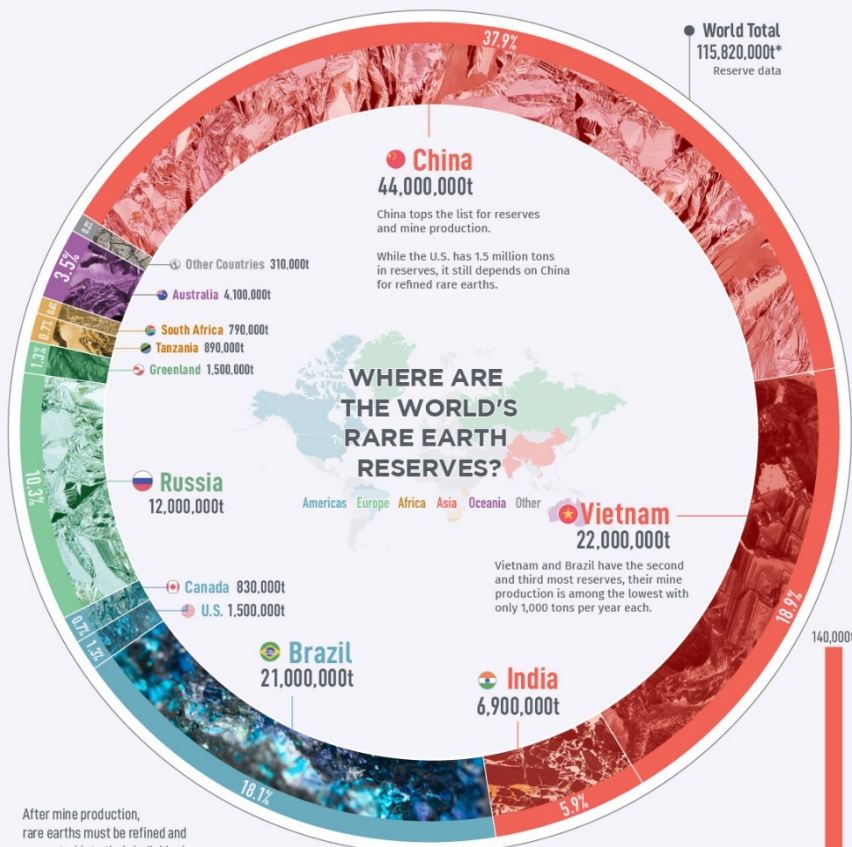


# WHERE IN THE WORLD ARE ALL THE RARE EARTHS?

Rare earth elements (REEs) are a group of 17 elements whose importance is critical in high technology. Their use has exploded as electronics and renewable technologies increasingly have become part of everyone's daily lives.

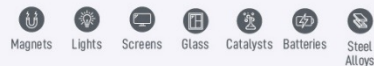
Rare earths are abundant in the Earth's crust but mineable concentrations are less common, making reserves potential very valuable and strategic.

\*The USGS tracked the world's reserves in tons (imperial).



After mine production, rare earths must be refined and separated into their individual metals for their particular uses.

#### Uses:



#### Mine Production 2020



Source: USGS Mineral Commodity Summaries, Rare Earths

**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.



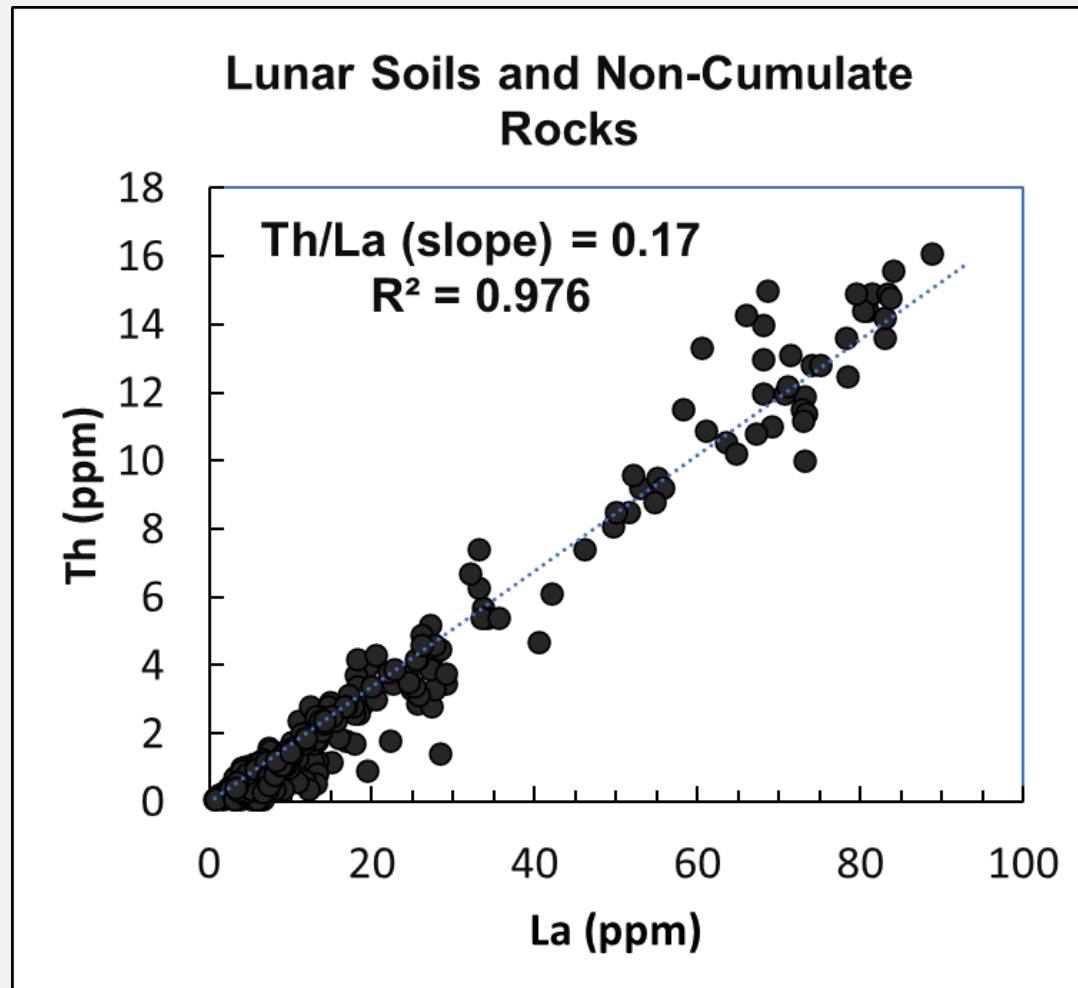
## Optimistic Note:

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

Tech transfer to Earth mining??

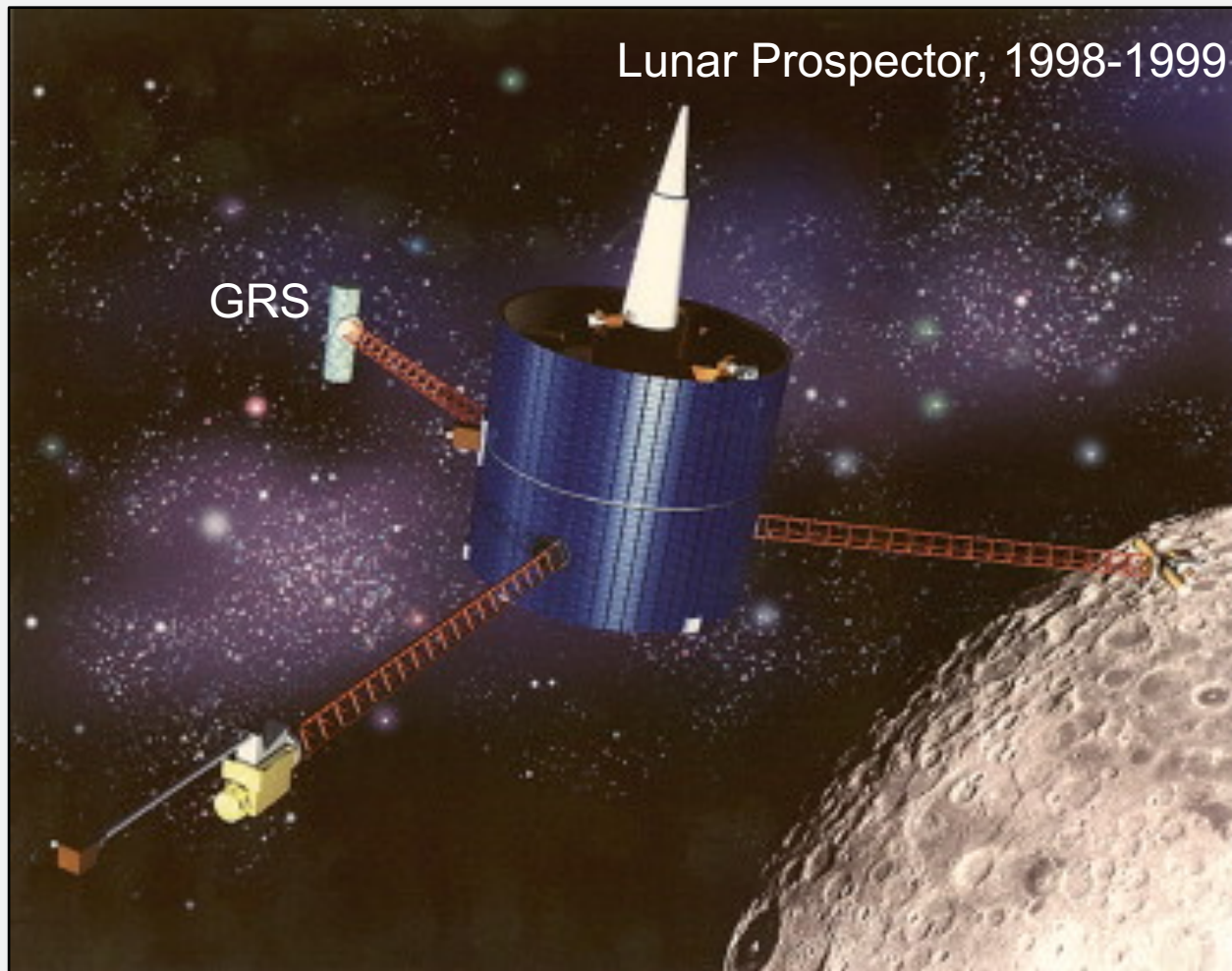


# Th correlates with REE



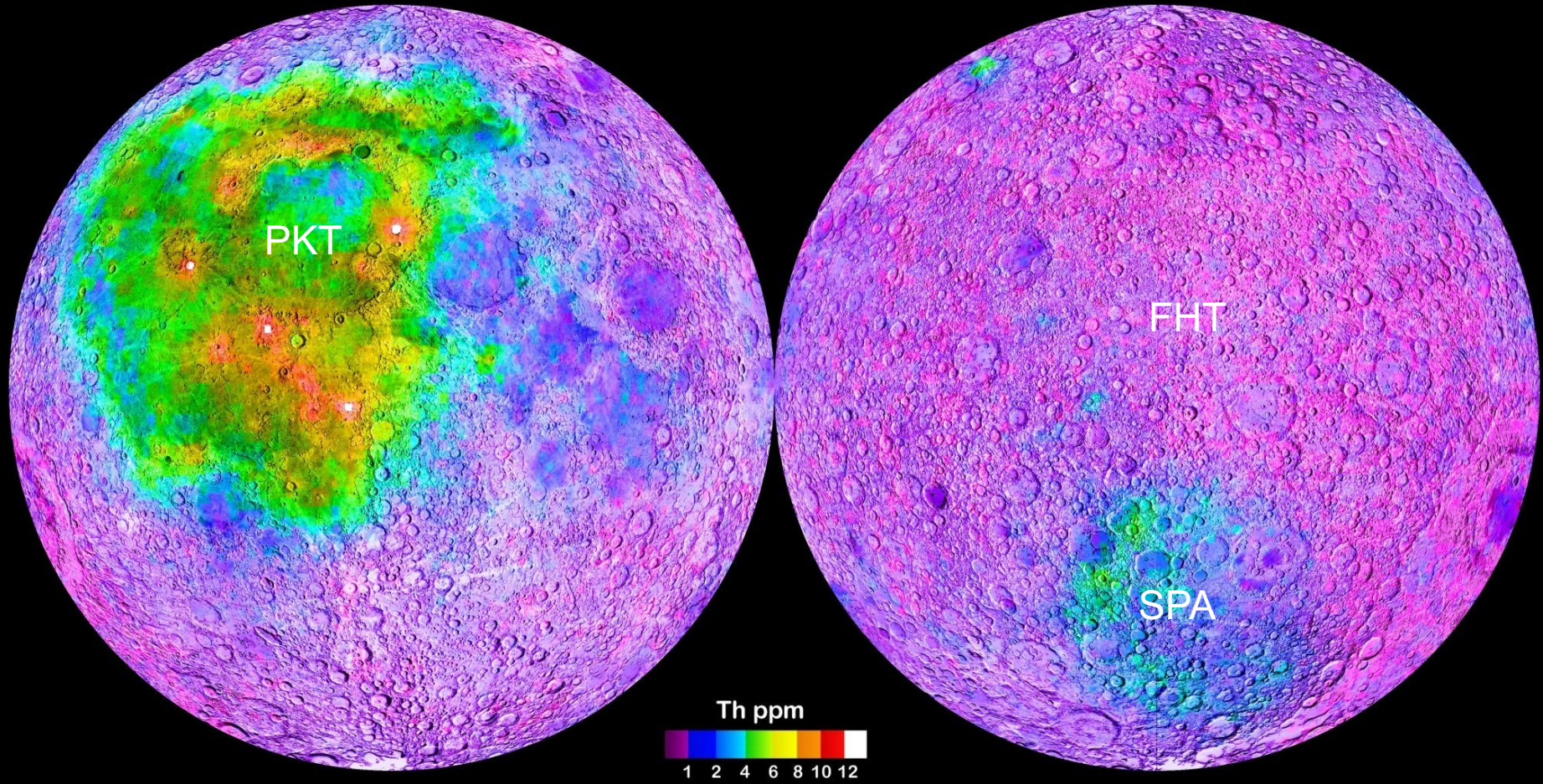


# Lunar Prospector Measured Global Abundance of Thorium





# Global Distribution of Thorium from Orbital Gamma-Ray Spectroscopy

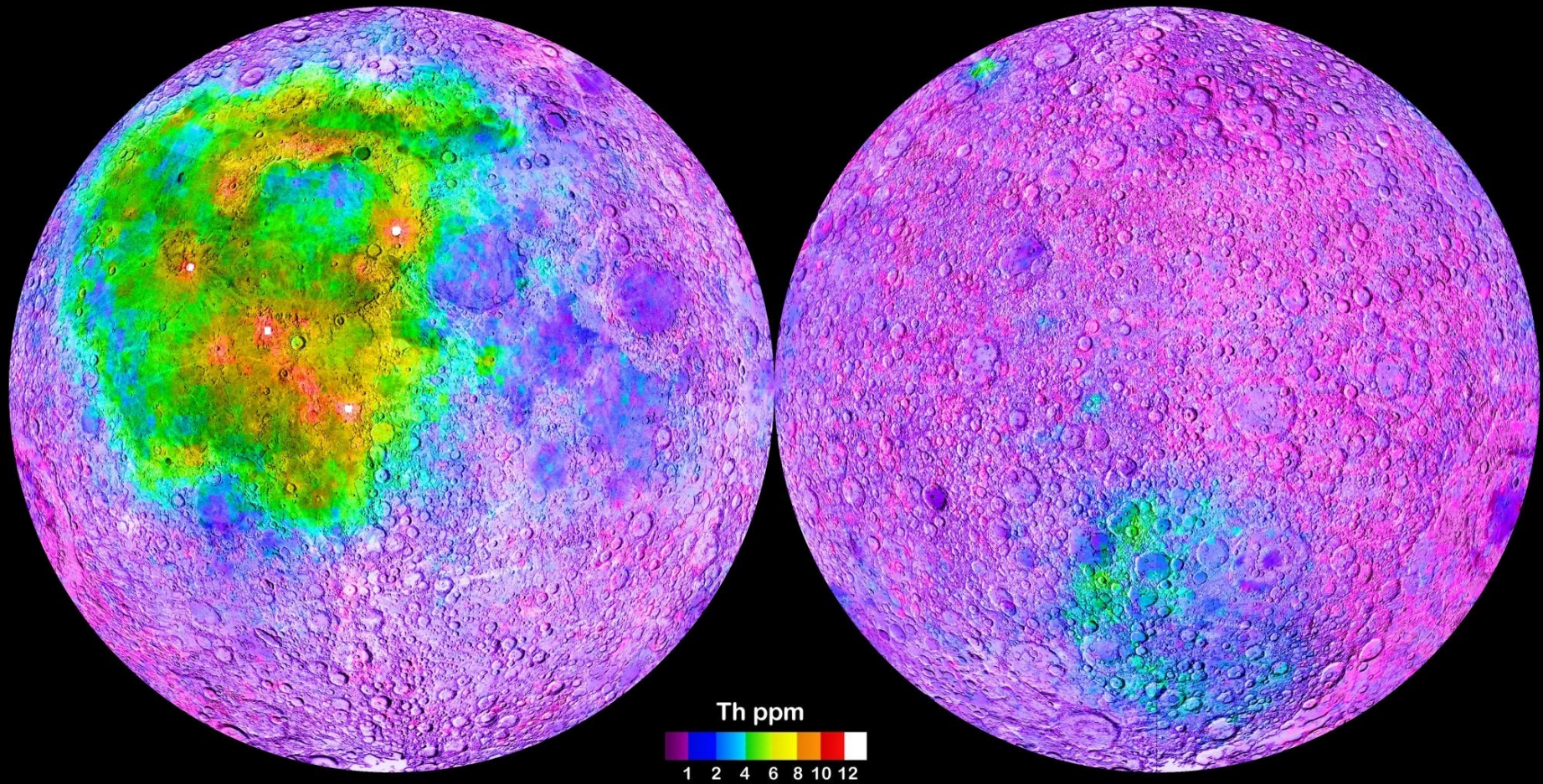


**PKT** = Procellarum KREEP Terrane   **FHT** = Feldspathic Highlands Terrane   **SPAT** = South Pole Aitken Terrane



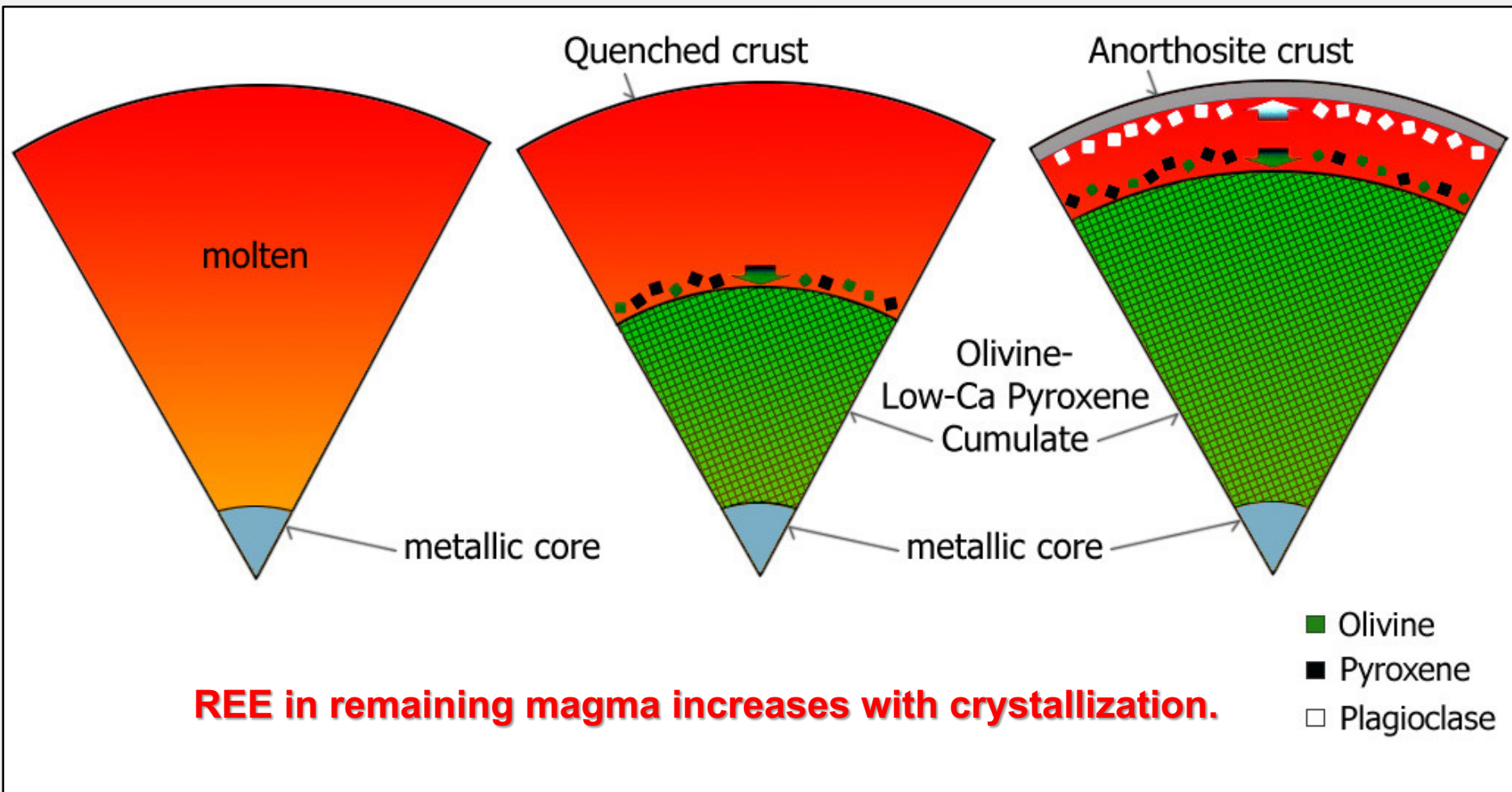
## Fun Facts:

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

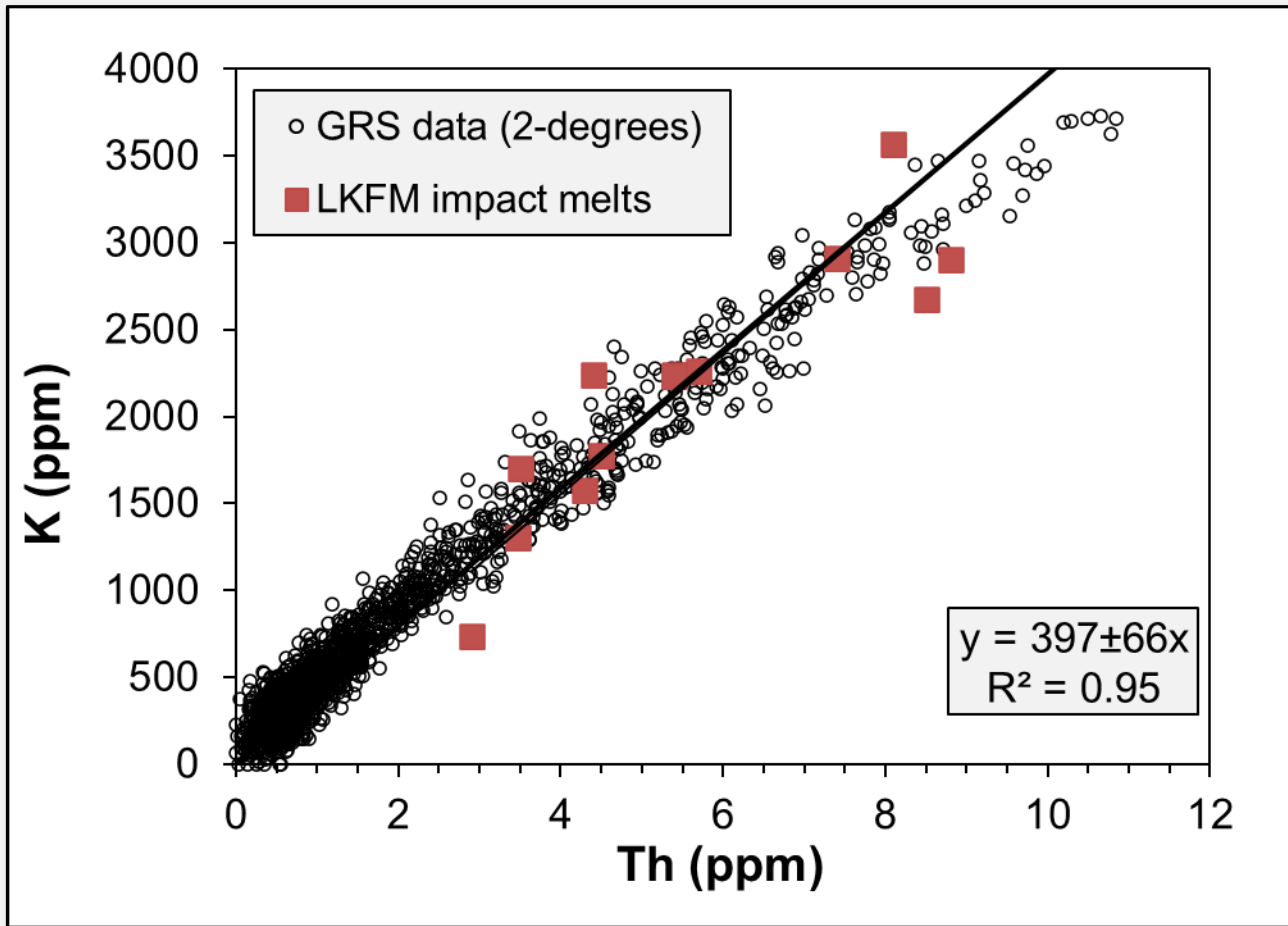




# PKT is the Product of Fractional Crystallization of the Lunar Magma Ocean



# Important Bulk Planet Information

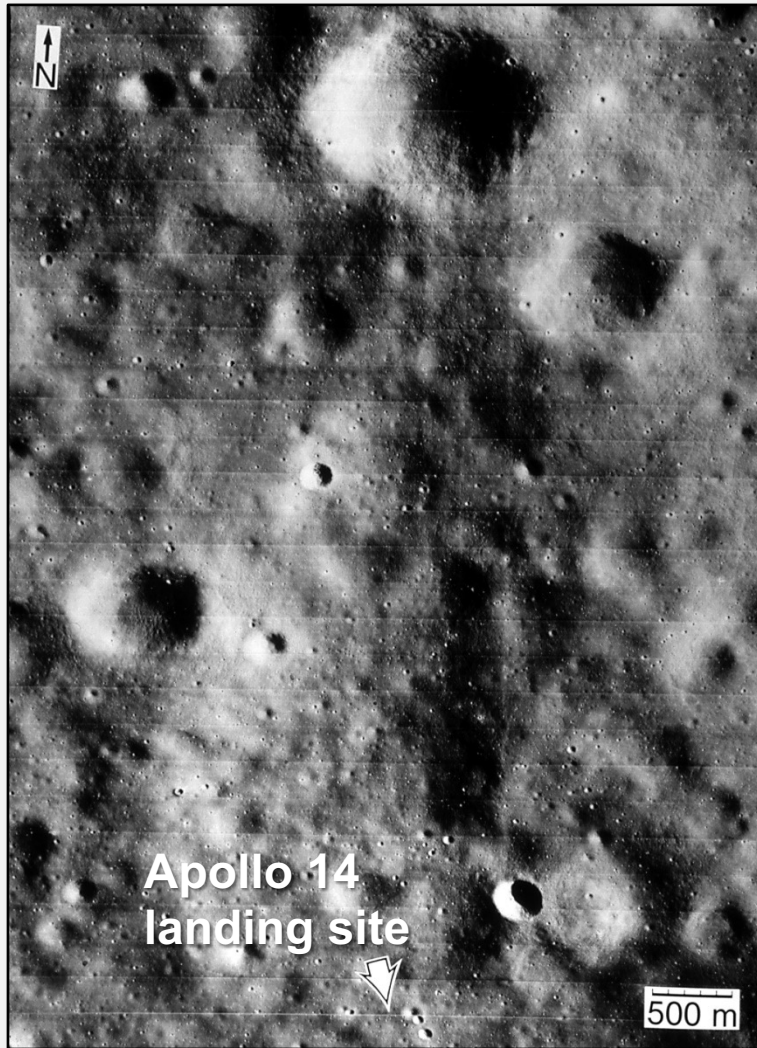


The low concentrations of K and other alkali metals in the Moon implies that REE are not associated with **alkaline magmatism** as on Earth.

For reference: K/Th in bulk Earth is 3000



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

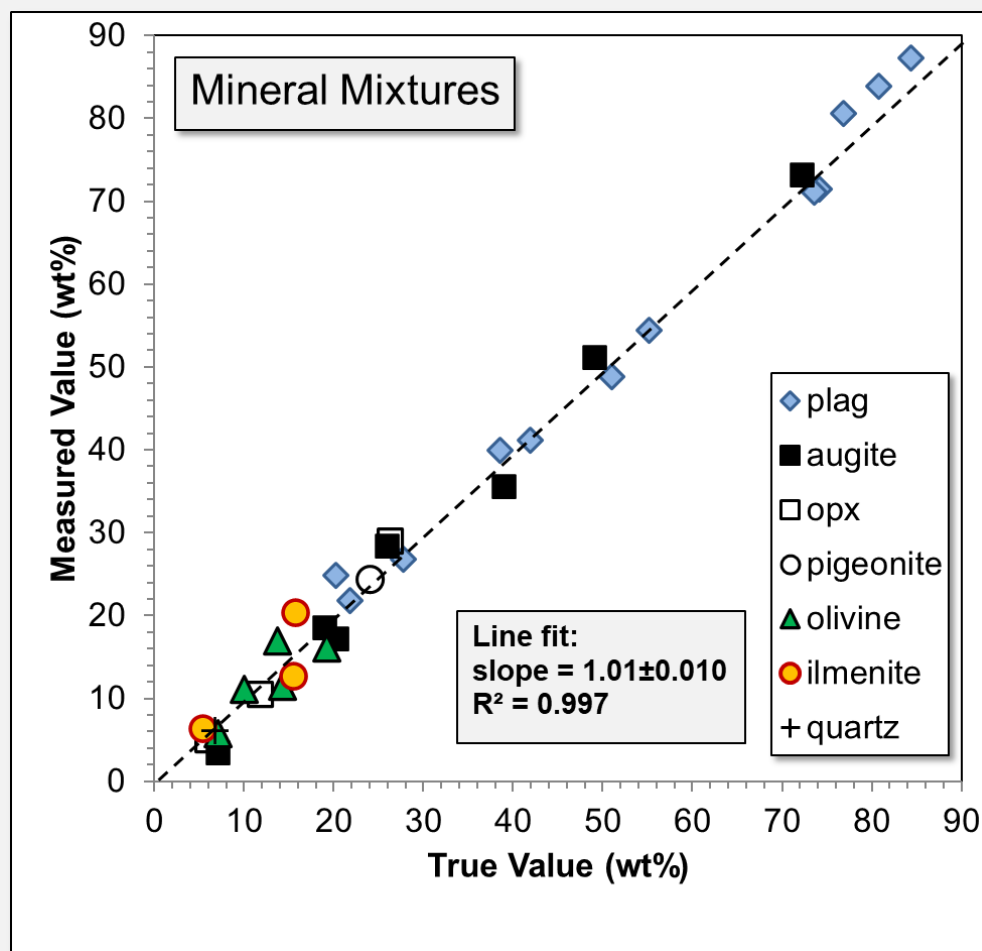
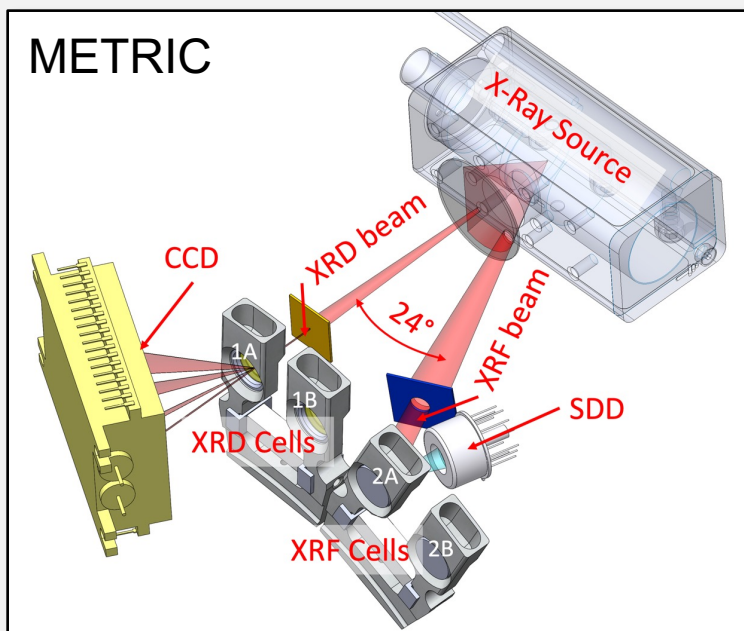


## Need:

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

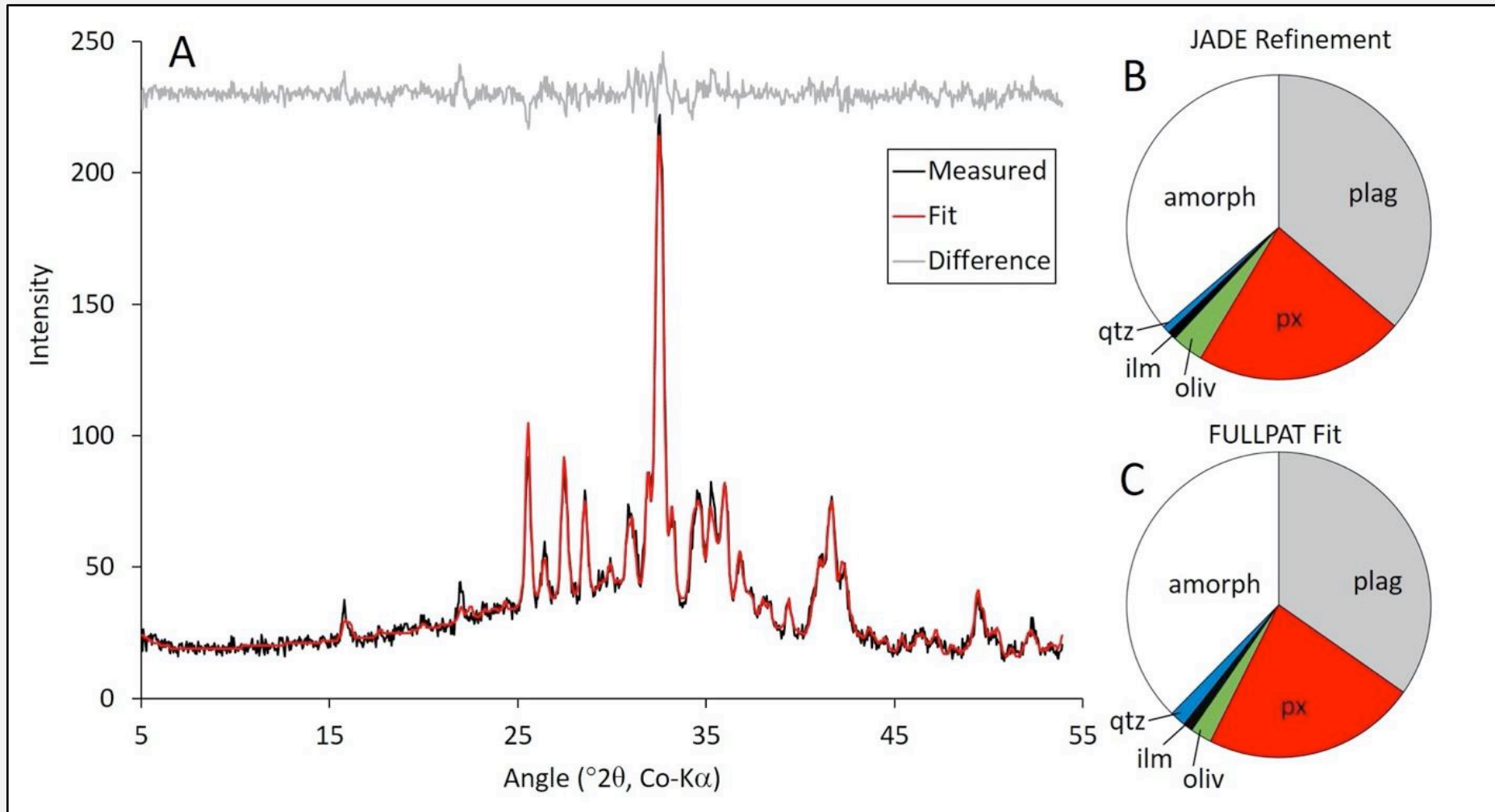
Portion of Lunar Orbiter photograph III-133-H2 of the region north of the Apollo 14 landing site.

# Mineralogy



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

# Apollo Soil (<150 $\mu\text{m}$ ) 14149



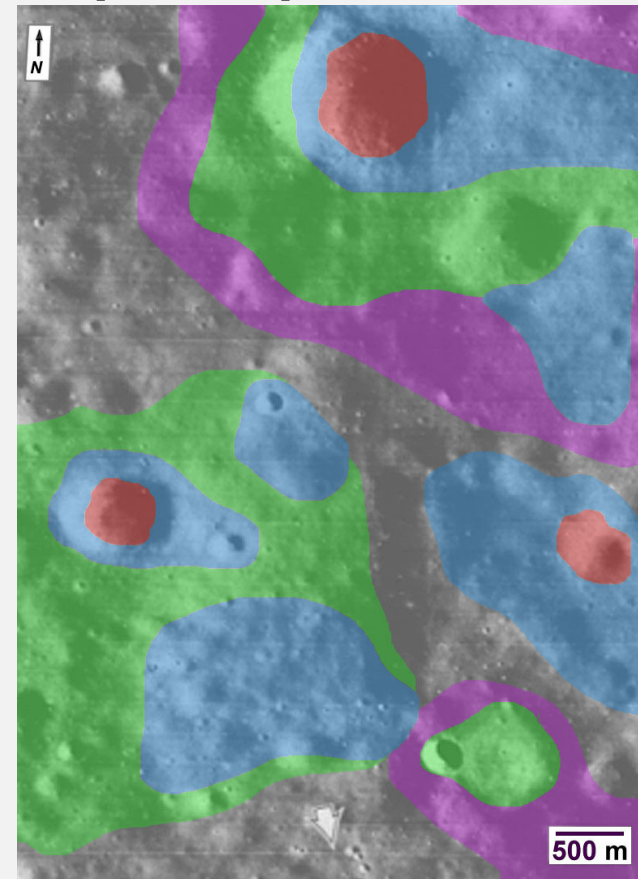
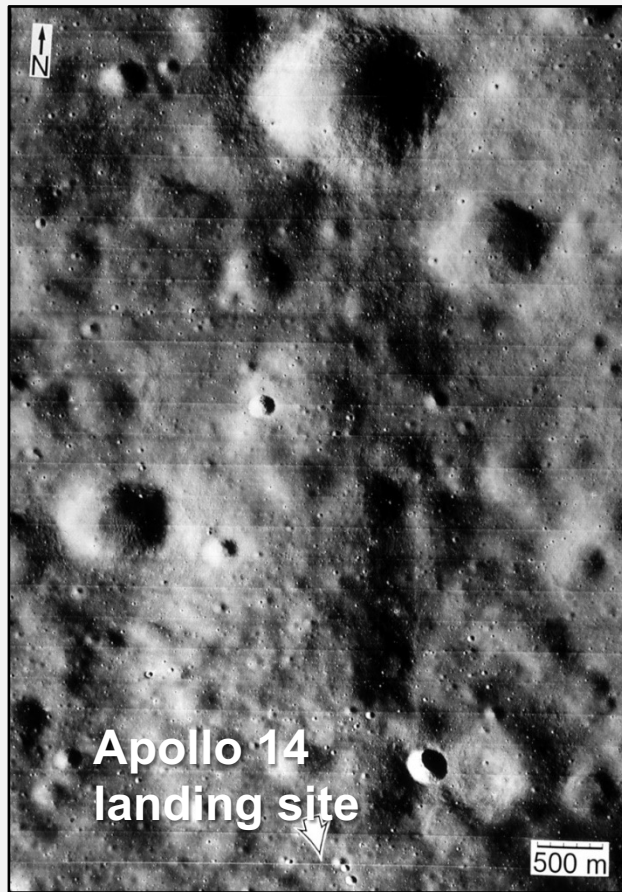
# X-Ray Fluorescence (XRF)

- 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

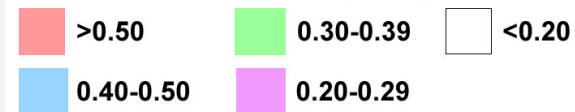
FHT



# X-Ray Fluorescence (XRF) Example



zirconium (wt%)



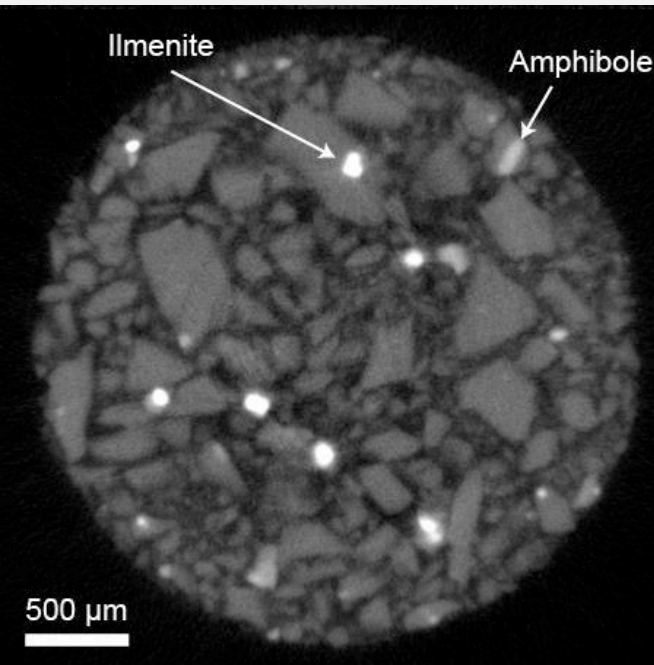
Rover(s) equipped with XRF device as in METRIC instrument payload traverses an area, stopping to determine Zr concentration at numerous (100s) of spots, allowing us to map the Zr distribution.

# X-Ray micro-CT (XCT)

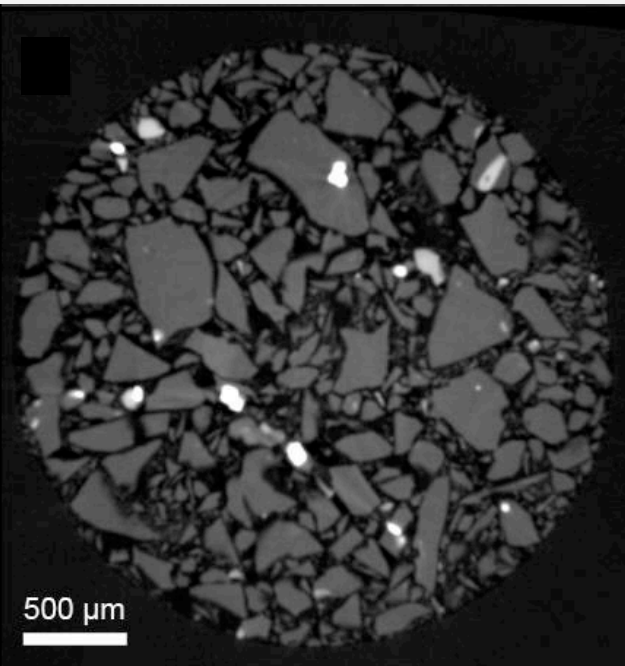
- New instrument in prototype stage
- Non-destructive high-resolution three-dimensional imaging technique. Characterizes:
  - Internal features of multiphase materials
  - Phase variability and grain size distribution of porous granular materials
- Provides physical linkage to:
  - Mineralogy determined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

# X-Ray micro-CT: Analog Example

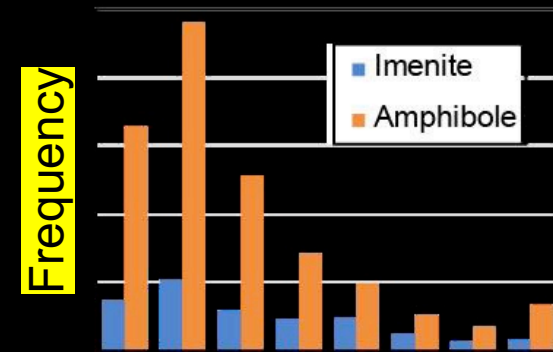
## Crushed Terrestrial Dacite Lava



METRIC XCT Prototype



Zeiss Versa 620 lab instrument



Romy Hanna, University of Texas

Grain size distribution  
from XCT data

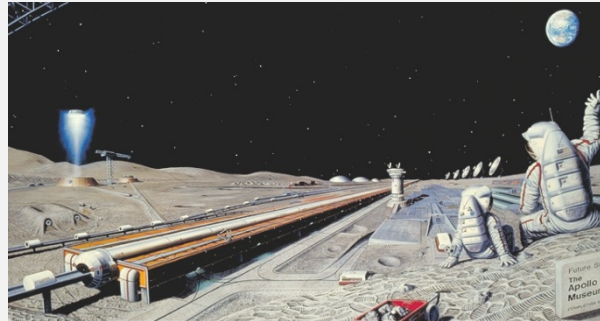
# Prospecting for REE

- 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).



# Exploration

## Settlement



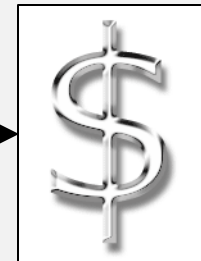
## Science



## Resources



## Commerce



**Exploring and using resources deepens our understanding of basic science.**

Jeff Taylor: Lunar Prospecting for REE