

Knowledge needed: Resource Assessment

G. Jeffrey Taylor

Hawai`i Institute of Geophysics and
Planetology

University of Hawai`i at Manoa

Knowledge needed: Resource Assessment

- Preliminary considerations
- Where to search
- Commodities
- Example 1: Non-metals
- Example 2: Volatile elements in pyroclastic deposits
- Recommendations

Lunar Resources and Our Future in Space

- The new NASA focus may lead to human habitation of the Solar System
- We will need indigenous resources to live on the Moon and Mars and to explore elsewhere
- “Near-Earth resources cannot only foster the growth of human activities in space, but are essential to any long-term space activities.” McKay et al. ((1992) *Space Resources*.
- “The extended lunar presence on the Moon will enable astronauts to...harness the Moon’s abundant resources...”
President George W. Bush
- At this meeting, we begin prospecting in earnest

Sustained Human Presence: Driven by Resource Exploration and Utilization

- Sustained human presence (on the Moon or Mars) absolutely requires use of *in situ* resources
- Use them in the short term to support sustainable presence on the Moon
- Show how to extract *in situ* resources so we can do the same on Mars—this is an essential step in human missions to Mars and in eventual human habitation of Mars
- In the long term, find and extract increasingly exotic resources to support the growing lunar industrial base and population

Science and Resources

- Resource exploration *is* science
- Fundamental science plays crucial role in prospecting for resources and in their extraction
 - Lunar geologic setting—guides exploration strategy
 - Local and regional chemical compositions and mineral abundances
 - Concentration mechanisms—implies understanding how mechanisms operate (e.g., volatile transfer, igneous fractionation)
 - Modification of deposits

Where to Search for Lunar Resources

- Polar regions: potential volatile deposits (Paul Lucey will talk about this)
- The rest of the Moon (I'll concentrate on this)
- In both cases, we need to:
 - Characterize the resources (phases, concentrations, locations, physical properties)
 - Assay the resources by detailed investigations (almost certainly by *in situ* measurements, field work, and high-quality *in situ* measurements or sample returns)
 - Conduct extraction experiments (laboratory experiments, lunar missions)

Lunar Geologic Occurrence of Some Important Commodities

Type of Occurrence	Main Commodities	Where on Moon
Mafic igneous rocks	Fe, Cr, Ti, (Pt, Pd)	Central peaks of craters; crater rim deposits; maria
Evolved igneous rocks	K, P, Th, U, Zr, rare earth elements	Procellarum KREEP terrane (western nearside)
Explosive volcanic deposits	Fe, Zn, Cd, Hg, Pb, Cu, F, Cl	Pyroclastic deposits; near-vent deposits in maria
Meteoritic debris	Ni, Pt, Pd, Ir, Au	Regolith, regolith breccias, highland impact breccias, segregations in impact melt sheets
Regolith	Solar wind gases; microscopic metallic iron	Regolith
Volatile deposits	H ₂ O, H, OH; other compounds (comet species, Hg)	Polar regions, particularly in permanently-shadowed craters

No Search Required for Some Elements

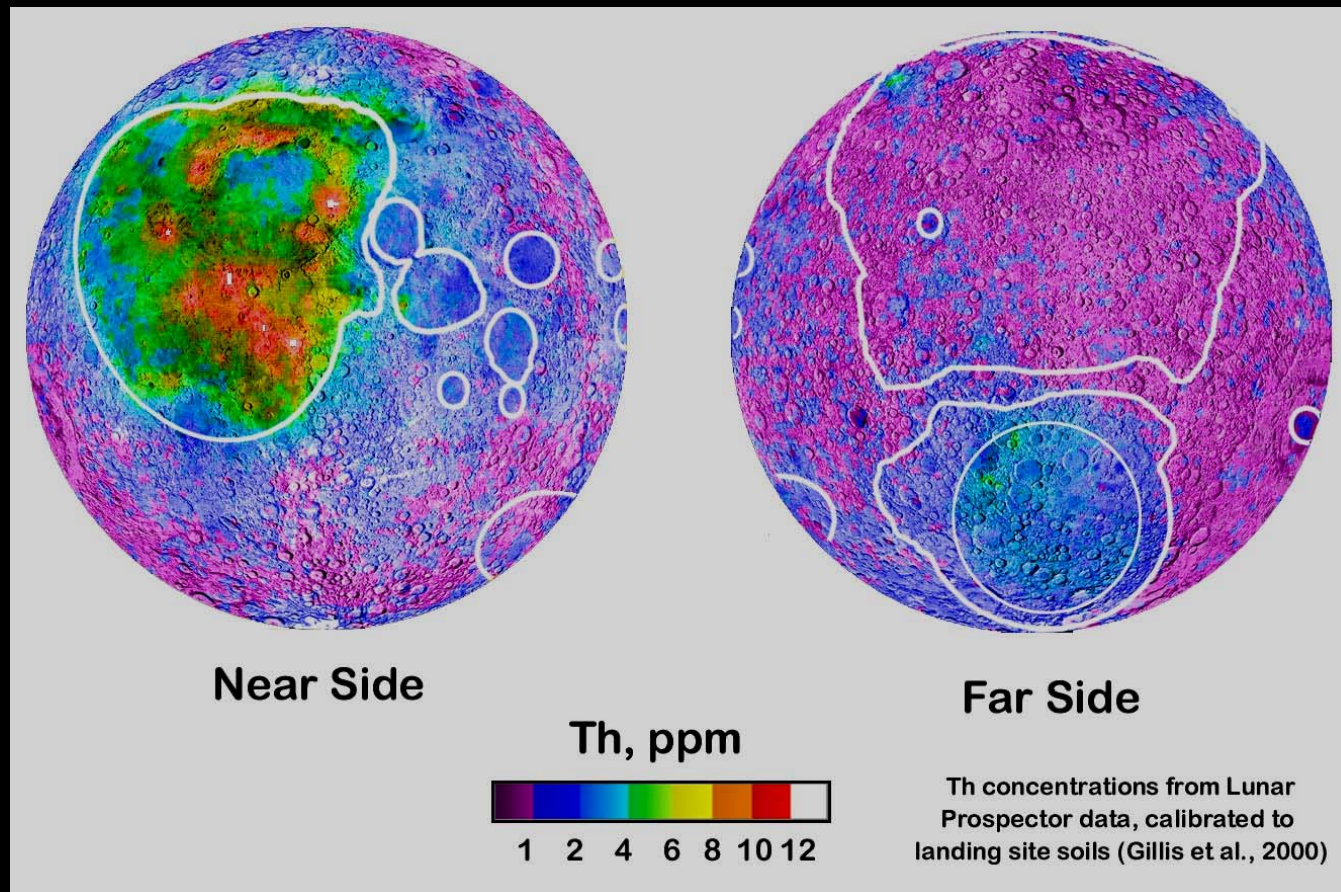
- Some useful elements are abundant in the lunar regolith so searching for high concentrations may not be necessary:
 - Fe and Ti in mare regolith (especially regolith developed on high-Ti mare basalt)
 - Al and Ca in highlands regolith
 - Si everywhere
 - Oxygen everywhere, but easier to extract from some materials (ilmenite, pyroclastic glass) than others
- For these, the most important thing we can do is to perform end-to-end extraction experiments on the Moon
- Are other data needed?

Example of a Search Strategy (1): Non-Metals

- KREEP terrain
- Enriched in:
 - Zr (for making high-temperature furnaces as an oxide, strengthening iron alloys)
 - P (fertilizer, some metallurgical applications)
 - Li (alloying agent in Al, CO₂ absorber as hydroxide, heat transfer medium as liquid metal)
 - K (fertilizer)
- Can search for any one of these, or for rare earth elements, Th, or U, as all are correlated

Prospecting for Non-Metals: Step 1

- Identify areas rich in an element of interest or in a tracer element. In this case use Th as marker for K, REE, P, U, Zr, etc.

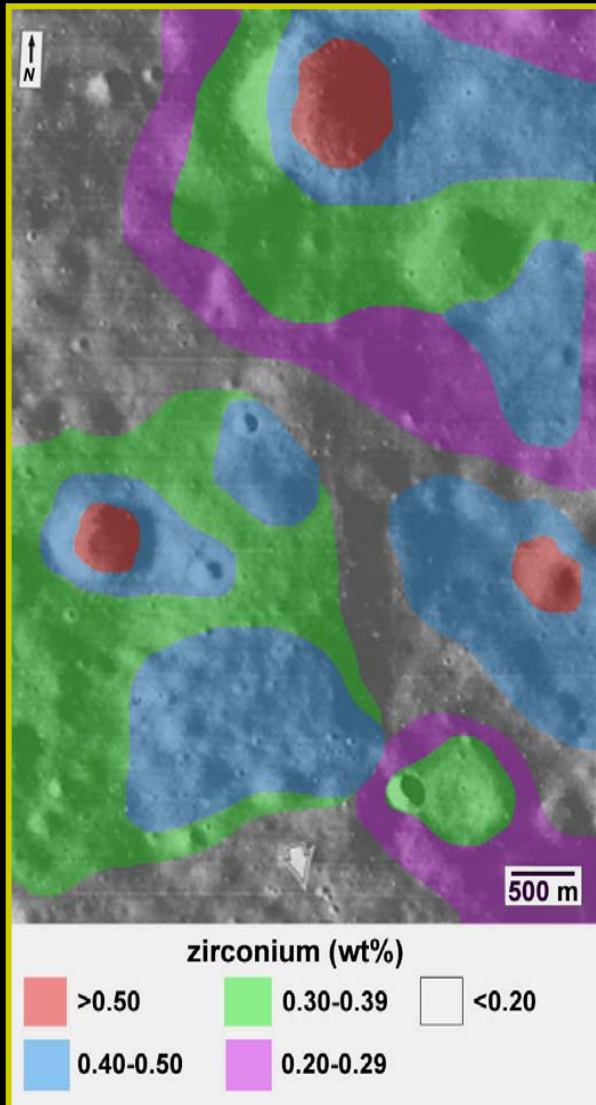


Prospecting for Non-Metals: Step 2

Make detailed studies of areas defined from global or regional data

One Approach

- Rover autonomously traverses the region of interest
- On board sensor measures concentration of selected element(s), e.g. Zr, or specific minerals, e.g., zircon, phosphates
- Measurements made every 10-100 meters
- Data transmitted to central station or satellite
- Allows us to contour distribution of the element(s)
- Needed: instruments to make the measurements rapidly; autonomous, long-lived rovers



Extracting Non-Metals from KREEP Regolith

- Zr, P, K, Li are found in minerals that are usually low in abundance, but in enriched deposits, might be abundant:

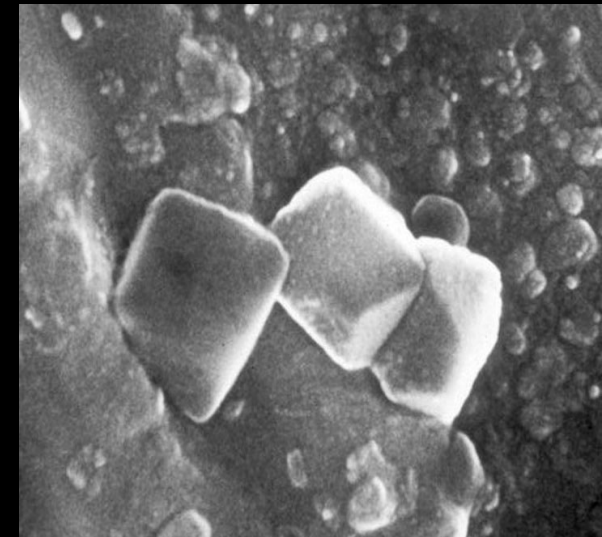
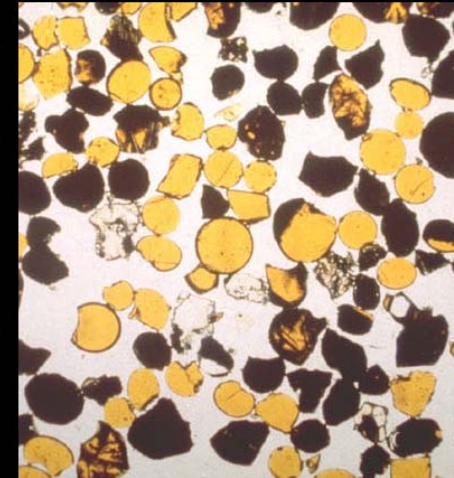
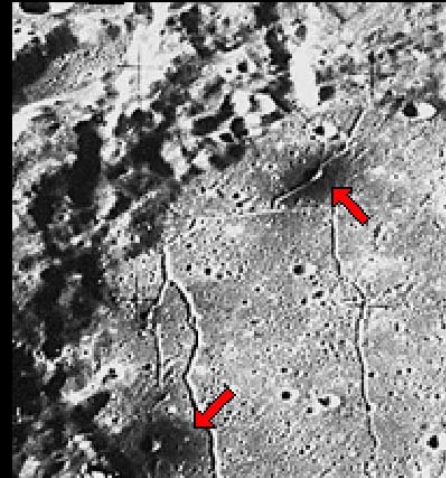
Element	Phase	Phase Abundance
Zr	Zircon, zirconolite	Up to 1%
P	Phosphates	Up to 10%
K, Li	K-feldspar, glassy mesostasis	Up to 15%

Extracting Non-Metals from KREEP Regolith

- Extraction is not simple:
 - regolith is fine grained
 - many mineral grains are incorporated into agglutinates
- Minerals of interest are not magnetic
- They do differ in density:
 - Zircon: 4.7 g/cm³
 - Apatite: 3.2 g/cm³
 - K-feldspar: 2.6 g/cm³
- They differ in solubility in aqueous solutions
- Techniques need to be developed to:
 - concentrate specific minerals (in vacuum)
 - extract elements of interest

Example of a Search Strategy (2): Volatile Elements from Pyroclastic Deposits

- Explosive volcanic deposits or near vents where more basalts erupted
- Enriched in:
 - Zn (useful for galvanizing metals, alloying)
 - Cl (water purification, cleaning compounds, used in the production of numerous products because of its high chemical reactivity)
- Might be concentrated in specific horizons or patches in volcanic deposits



Surface coatings on volcanic glass

Volatile elements from Volcanic Glass Deposits

- Need to search for concentrations of volatiles within a pyroclastic deposit
 - Field observations (teleoperators, humans)
 - *In situ* or lab analyses of drill samples or crater ejecta
- No studies of volatile extraction have been done, but elements might be extracted by:
 - Could be concentrated by abrasion
 - Differences in volatility might allow separation via heating
 - Differences in solubility or dissolution rates in solutions of different pH, T

Recommendations (2004-2015)

- Characterize at least one non-polar potential deposit (a region rich in Th; a pyroclastic deposit)
 - New orbital data? E.g., global high-resolution multispectral data base
 - *In situ* analyses or sample return
 - Exploration using rovers
- Develop new instruments capable of rapid analysis of elements present in the 10 to 1000 ppm range
- Conduct at least one end-to-end ISRU experiment on the Moon, such as extracting oxygen from pyroclastic deposits or high-Ti regolith