Knowledge needed: Resource Assessment

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- 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

<table>
<thead>
<tr>
<th>Type of Occurrence</th>
<th>Main Commodities</th>
<th>Where on Moon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mafic igneous rocks</td>
<td>Fe, Cr, Ti, (Pt, Pd)</td>
<td>Central peaks of craters; crater rim deposits; maria</td>
</tr>
<tr>
<td>Evolved igneous rocks</td>
<td>K, P, Th, U, Zr, rare earth elements</td>
<td>Procellarum KREEP terrane (western nearside)</td>
</tr>
<tr>
<td>Explosive volcanic deposits</td>
<td>Fe, Zn, Cd, Hg, Pb, Cu, F, Cl</td>
<td>Pyroclastic deposits; near-vent deposits in maria</td>
</tr>
<tr>
<td>Meteoritic debris</td>
<td>Ni, Pt, Pd, Ir, Au</td>
<td>Regolith, regolith breccias, highland impact breccias, segregations in impact melt sheets</td>
</tr>
<tr>
<td>Regolith</td>
<td>Solar wind gases; microscopic metallic iron</td>
<td>Regolith</td>
</tr>
<tr>
<td>Volatile deposits</td>
<td>H₂O, H, OH; other compounds (comet species, Hg)</td>
<td>Polar regions, particularly in permanently-shadowed craters</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Element</th>
<th>Phase</th>
<th>Phase Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr</td>
<td>Zircon, zirconolite</td>
<td>Up to 1%</td>
</tr>
<tr>
<td>P</td>
<td>Phosphates</td>
<td>Up to 10%</td>
</tr>
<tr>
<td>K, Li</td>
<td>K-feldspar, glassy mesostasis</td>
<td>Up to 15%</td>
</tr>
</tbody>
</table>
Extracting Non-Metals from KREEP Regolith

- Extraction is not simple:
  - regolith is fine grained
  - many minerals 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 mare 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

• 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