Two Resource Targets with Scientific Return

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Targets

1. Volcanic pyroclastic deposits

2. Evolved igneous rocks
Regional Pyroclastic Deposits
Aristarchus Pyroclastic Deposit

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Two Resource Targets
Resource Potential

• High-FeO glass readily reduced by hydrogen to metallic iron and $\text{H}_2\text{O}$
• Loose material may be relatively easy to handle
• Fine grain size makes chemical reactions more rapid
• No beneficiation needed
Apollo 17 Orange Glass

- Only pyroclastic deposit studied in field
Orange Glass Characteristics

Mean grain size = 40 µm
Finer than typical lunar regolith
Clods in Pyroclastic Deposits

Orange Glass Clods

Green Glass Clods
Other Resources

Fe and H₂O by Reduction

Allen et al. (1994, 1996)

Surface of orange glass sphere contains metallic iron spheres

Aristarchus deposits are high in Fe, and glassy, hence efficient for O₂ production.
Enrichments in Volatile Elements in Pyroclastic glass deposits

- Surfaces of pyroclastic glasses enriched in Zn, Cd, Hg, Pb, Cu, F, Cl compared to other lunar materials
- Probably were in gas phase associated with eruption
- Implies volatile reservoirs inside Moon
- May be a resource

Surface coatings enriched in volatile elements; largest crystals are NaCl, mounds enriched in Zn, S, etc.
Concentrations of Volatiles??

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New Story: $\text{H}_2\text{O}$ in Volcanic Glass

Initial concentration estimated at 70-745 ppm.
N-MORB glasses: $\sim$750-2000 ppm

Saal et al. (2008)
Regolith: Complication and Opportunity

- Regolith produced on pyroclastic deposits for $> 3$ Gy
- Thus, surface gardened to average depth of $>3$ m
- Complicates observations of pristine pyroclastic deposit and disrupts potential volatile concentrations
- But, gives opportunities:
  - Study regolith production on initially very fine-grained surface
  - Craters bring subsurface materials to surface
Measurements/Experiments Needed-1

- Bulk chemical composition, including search for Cl, S, Zn, and other volatiles
- Search for concentrations of volatiles
- Physical properties of deposits
  - Grain size distribution
  - Shapes, size, and distribution of clods
  - Geotechnical properties (e.g., cohesion)
- Relative amounts of crystals and glass
Measurements/Experiments-2

• *In situ* H$_2$O extraction experiments
• Determine lateral and vertical variations in properties (e.g., layering, interlayered lava flows)
• Characterize volcanic system (e.g., vent locations, lava channels)
Evolved Lunar Rocks

The Lunar Magma Ocean

- Quenched crust
- Olivine-Low-Ca Pyroxene Cumulate
- Anorthosite crust

- molten
- metallic core
- metallic core

Legend:
- Olivine
- Pyroxene
- Plagioclase

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Two Resource Targets
Resource Potential
Example: 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
The Asymmetric Moon

FeO wt.%

Th ppm

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KREEP Basalts
Felsites ("Granites")
Parent Magma Compositions

- Moon total inventory: 2 x chondrites
- Enrichments of a few 100 times that are common
- Extreme case is 10,000 x chondrites
Prospecting for Non-Metals

One Approach

- Rover autonomously traverses the region of interest
- On board sensor measures concentration of selected elements and minerals
- Measurements made every 10-100 meters
- Data transmitted to central station or satellite
- Allows us to contour distribution of the element(s)
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 are not magnetic
- They do differ in density:
  - Zircon: 4.7 g/cm$^3$
  - Apatite: 3.2 g/cm$^3$
  - K-feldspar: 2.6 g/cm$^3$
- They differ in solubility in aqueous solutions
- Techniques need to be developed to:
  - concentrate specific minerals (in vacuum)
  - extract elements of interest
Measurements/Experiments Needed

• Prospecting:
  – Orbital measurements of places with highest concentrations of rare elements
  – Detailed studies of concentrations and distributions of the elements and minerals that contain them
  – Requires long traverses, mapping, and determining vertical variations (crater ejecta, drilling)

• Extraction experiments (on Earth and Moon):
  – Mineral separation/concentration techniques