Assessing the Resource Potential of the Moon: The Case for a Decadal-Scale Robotic Lunar Exploration Program

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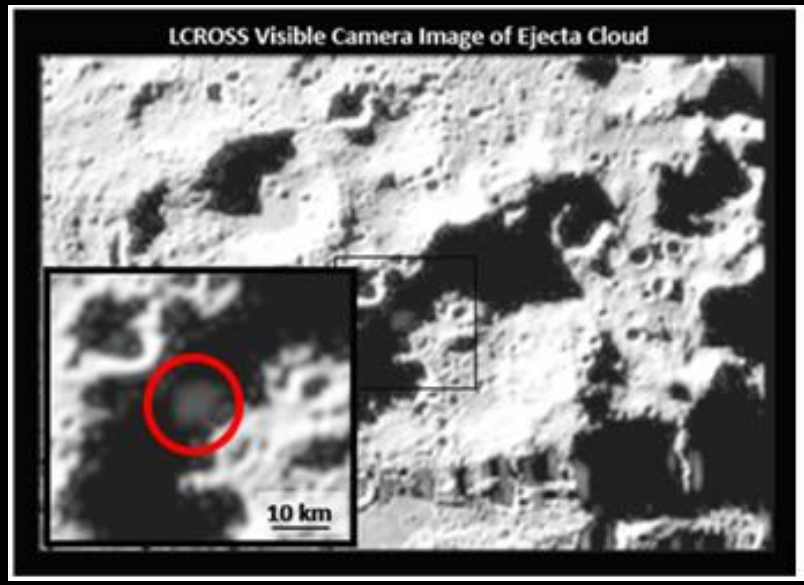
Annual LEAG Workshop Sep 14-16, 2010

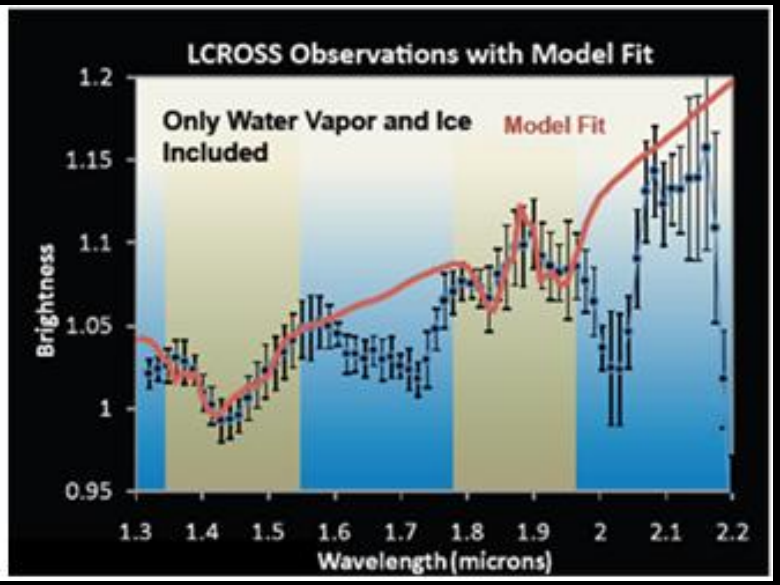
Space Resource Roundtable
and
Planetary and Terrestrial Mining Science Symposium

Someday We Will Settle the Moon

“Everything has changed but our way of thinking” – Neil A Einstein

A Game Changer: Water and other Volatiles Confirmed on the Moon





- The lunar cold traps are:
  - Potentially the coldest locations in the solar system
  - Potentially the most stable reservoirs for long-term volatile storage in the solar system

The Resource Potential of the Moon

Q1: Can lunar resources make space operations and exploration – within and beyond cis-lunar space – more affordable?

Q2. Can lunar resources help to solve problems for the Earth?

Contents

Architecture and Concept of Operations

Space Resource Roundtable
and
Planetary and Terrestrial Mining Science Symposium

ISRU Cycle (Space Mining)

Remote Survey

Resource Prospecting and Definition

Extraction Mining

Beneficiation

Processing

Waste

Product

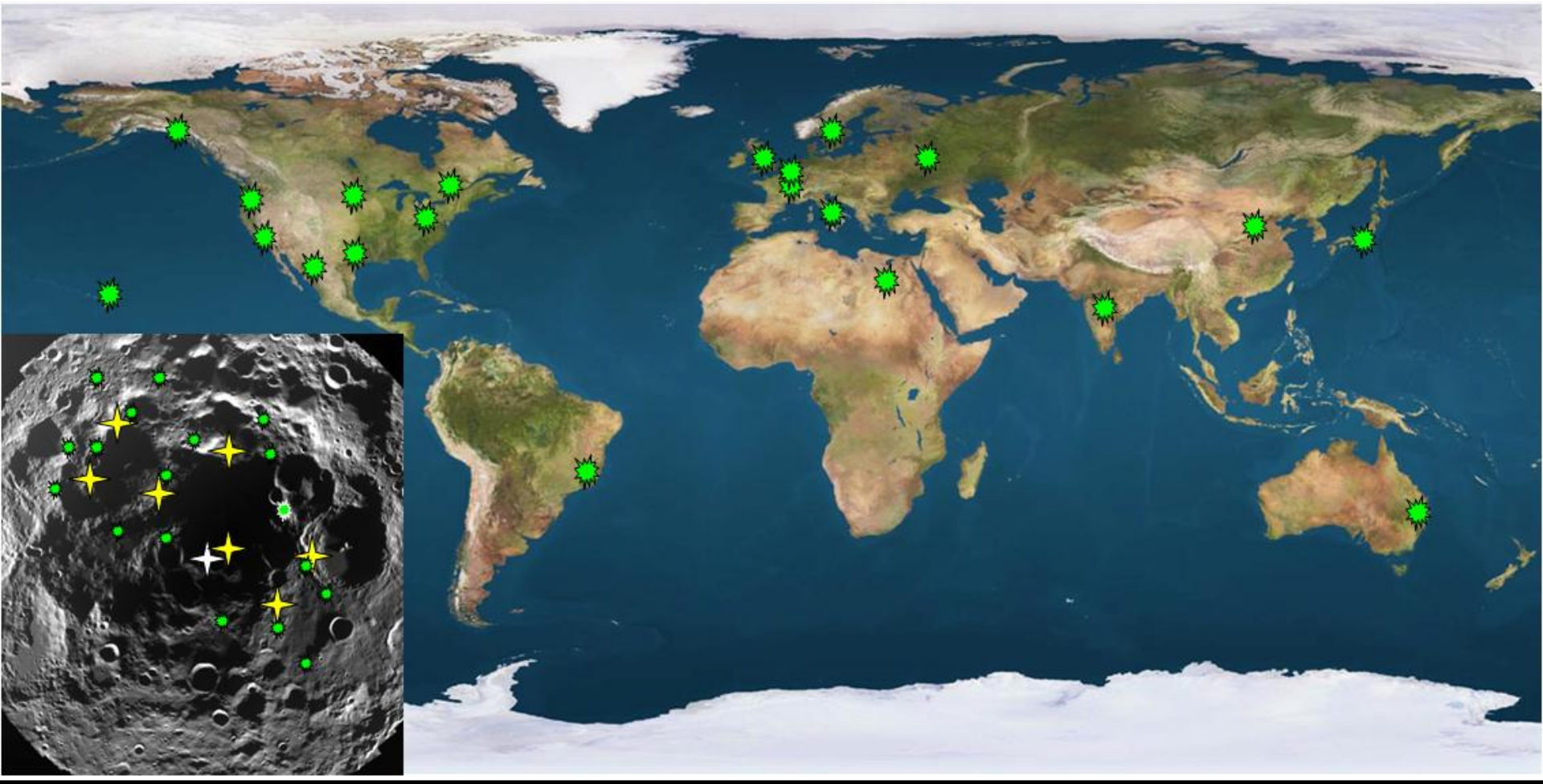
Thermal Wadis and Compact Rovers

A New Kind of Exploration Program

Proposed Decadal Exploration/ Resource Prospecting Program

- Develop extensive resource maps
  - Tens of standard class rovers providing prospecting functions
    - With potentially unique combinations of instruments (spectrometers, core drilling, ground penetrating radar, etc)
- Operated by students and other members of the public
  - Under the guidance/direction of PIs that are trained in lunar science
  - Operating from and involving universities, high schools and informal science centers
  - Additionally investigating broader issues such as the eventual settlement of the Moon

Proposed Decadal Exploration/ Resource Prospecting Program



Proposed Decadal Exploration/ Resource Prospecting Program

- Outcomes
  - Larger numbers of students drawn into and graduated with degrees in the STEM (Science, Technology, Engineering and Mathematics) disciplines
  - Using resource maps and the results of technology demonstrators, combined with economics and business studies, we will develop an understanding of the resource potential of the Moon

Some Thoughts on Lunar Resources and Applications

Space Resource Roundtable
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Potential Lunar Ore Resources

Solar Wind Implanted Volatiles

H, He, C,
N, Ne,
Ar, Kr, Xe

Incompatible Trace Elements

All alkali elements (except Na),
alkaline-earth elements (except Ca),
the Rare Earth Elements (REE), B,
Zr, Nb, Sn, Hf, Ta, U, Th

Major and Minor Components

O, Si, Al,
Fe, Mg,
Ca, Na, Ti,
P, Sc, V,
Cr, Mn,
Ga, Sr

Vapor-Mobilized Elements

S, the halogens,
Cu, Zn, As, Se,
Ag, Cd, In, Te,
Hg, Tl, Pb, Bi

Siderophile Elements

Fe, Co, Ni,
Ge, Mo,
Ru, Rh,
Pd, Sb, W,
Re, Os, ir,
Pt , Au

Haskin, LA, RO Colson, DT Vaniman and SL Gillett, "A Geochemical Assessment of Possible Lunar Ore Formation", *Resources of Near Earth Space*, 1993.
Available online at: http://www.nss.org/settlement/spaceresources/resources2.html

Incompatible Trace Elements

GAO

Accountability • Integrity • Reliability

Objective 1: China's Market Dominance May Affect Future U.S. Availability of Rare Earth Materials

- Some government and rare earth industry officials believe that China plans on greater vertical integration of the rare earth materials market in the future, which would increase China's total market power and dominance.
- While China is currently exporting rare earth oxides and metals, some rare earth industry officials believe that in the future China will only export finished rare earth material products with higher value.

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GAO Report: Rare Earth Minerals in the Defense Supply Chain, August 14, 2010.
Available online at: *www.**gao**.gov/new.items/d10617r.pdf*

Incompatible Trace Elements

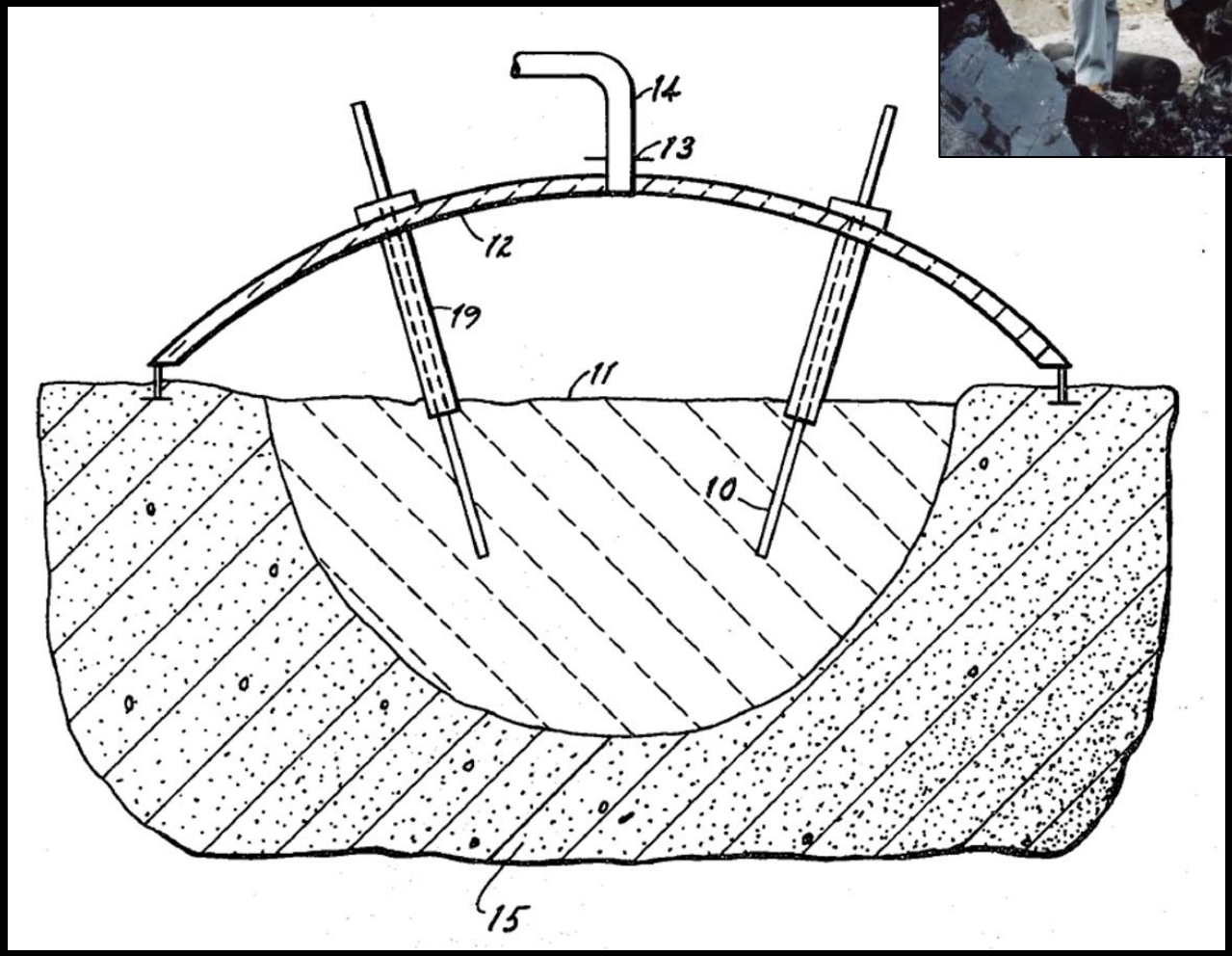
Apollo 11 Data for Five Rare Earth Elements

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

- KREEP materials can be further concentrated using fractional crystalization and separated/purified using solvent extraction

Q: Where are the highest concentrations of KREEP on the lunar surface?

Fractional Crystallization



- Partial melting enriches ITEs
- Volatiles are off-gassed

Vapor Mobilized Elements

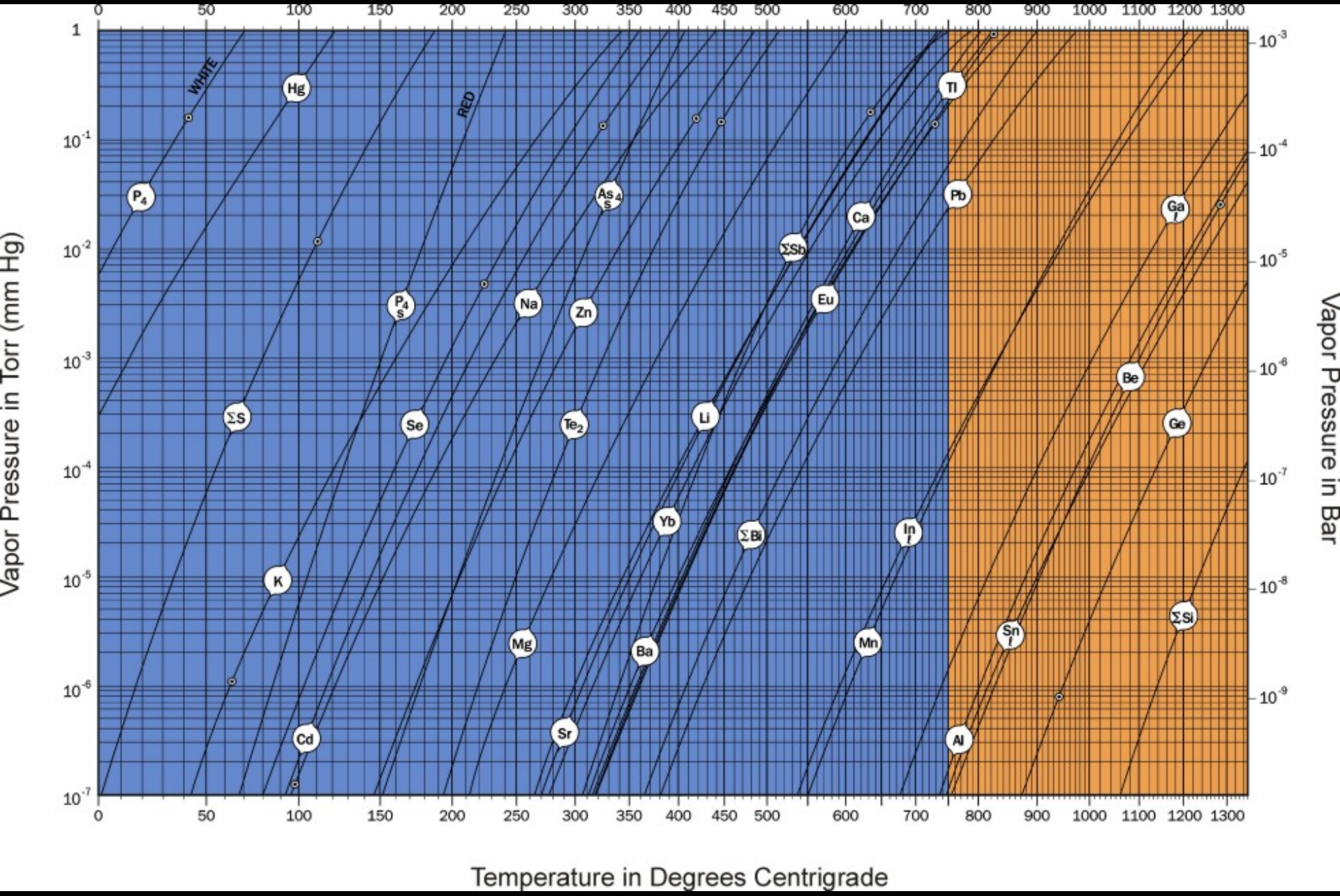
Apollo 11 Data for Five VMEs

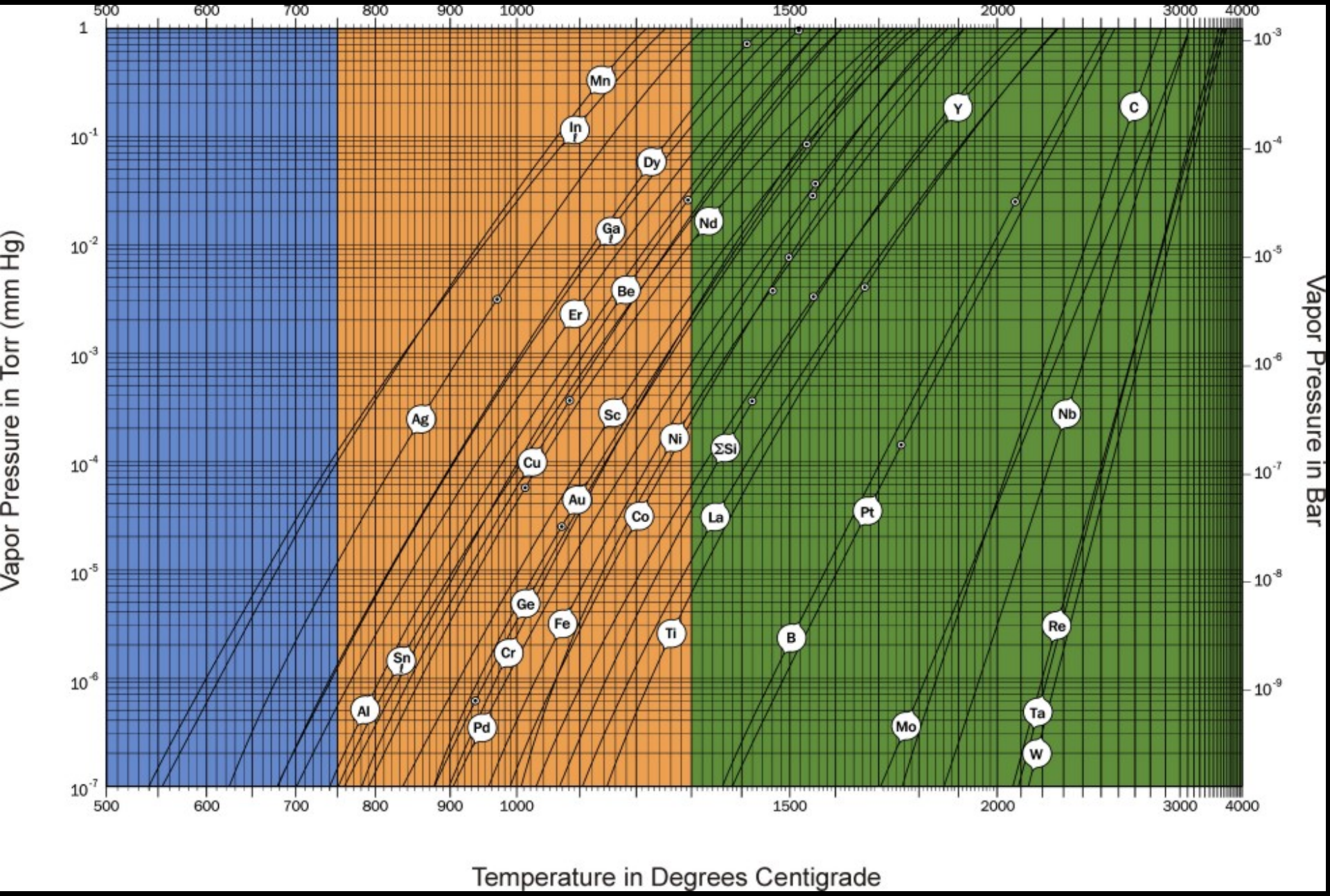
		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Ag	ppb	1.5	18	9	75
Cd	ppb	10	100	50	150
In	ppb	3	5	<10	25
Te	ppb	16	72	---	1
Se	ppm	0.7	1.6	0.8	0.05

Q: Will VMEs be found in higher concentrations in polar regions, within or in the vicinity of cold traps?

Conclusions

- Discussed an architecture for participatory lunar robotic exploration that:
  - Supports national educational objectives (STEM education)
  - Provides the information that defines the resource potential of the Moon
- Discussed the possibility that lunar resources might help to solve problems on the Earth
  - National Security technologies
  - Sustainable energy systems
- Raised the hypothesis that other VMEs – including those of interest for sustainable energy systems (e.g., Te, In, etc) -- will be found in the coldest locations on the Moon


Vapor Pressure in Torr (mm Hg)
Vapor Pressure in Bar
Temperature in Degrees Centrigrade
WHITE
RED
Hg
P4
ΣS
K
Cd
P4 s
Se
Na
Zn
Te2
Mg
Sr
As4 s
Ba
Yb
Li
ΣBi
ΣSb
Eu
Ca
Mn
Tl
Pb
In l
Al
Sn l
Ga l
Be
Ge
ΣSi


Vapor Pressure in Torr (mm Hg)
Vapor Pressure in Bar
Temperature in Degrees Centigrade
500
600
700
800
900
1000
1500
2000
3000
4000
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Mn
In
Dy
Ga
Nd
Be
Er
Ag
Sc
Ni
ΣSi
Cu
Au
Co
La
Ge
Fe
Ti
Cr
Sn
Al
Pd
Y
C
Nb
Pt
B
Re
Mo
Ta
W