



Lunar Resources: What are we looking for and where do we find them?

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Presentation Scope

Efficient use of lunar in-situ resources will help lower the cost of exploration – if needed infrastructure is minimal

- **What are key lunar resources?**
 - **Focus on those with near-term utility to manned Exploration**
- **More detailed look at oxygen and water**
 - **Possible distribution, manifestation**
- **Mapping at relevant spatial scales**
- **Conclusions**



Lunar Resource Overview

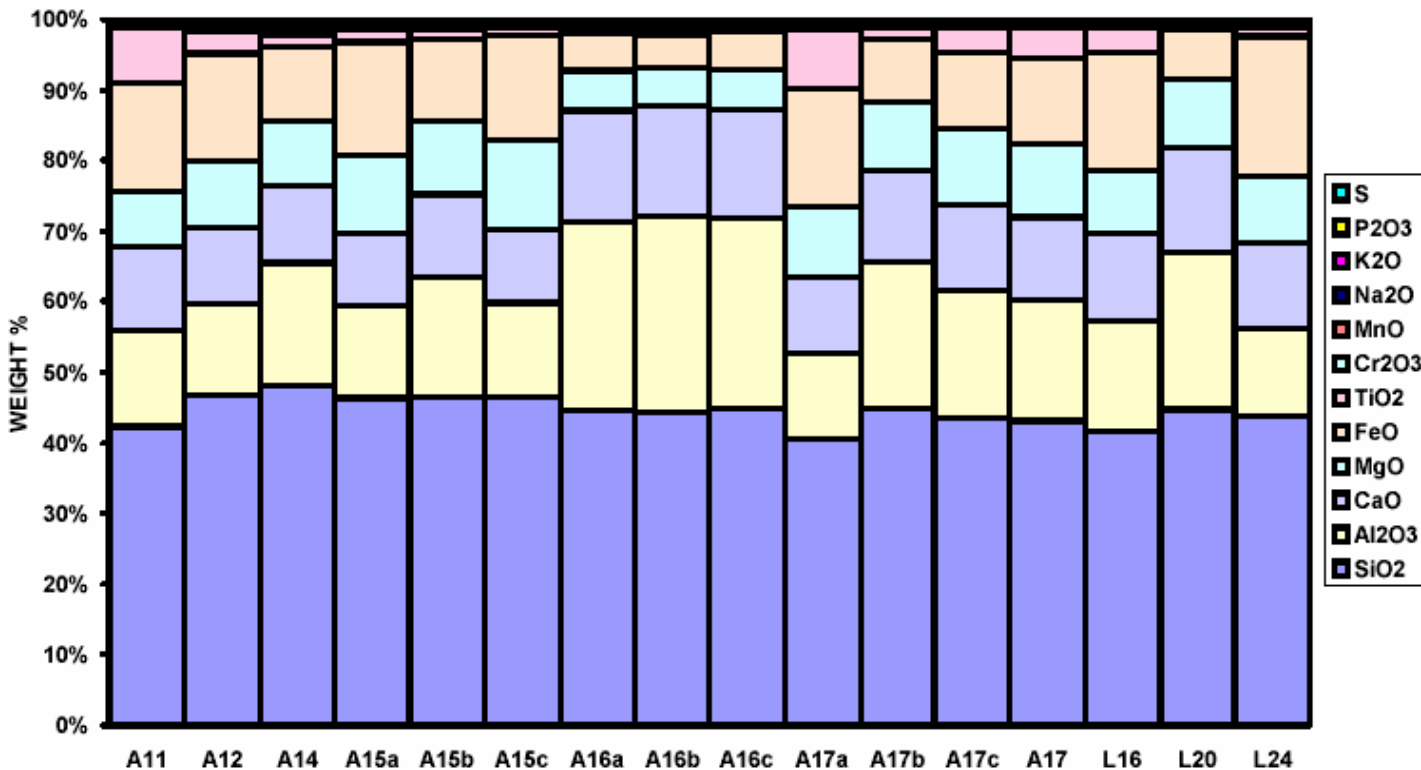
Resource	Use	Abundance
Water	Life support, propellant, stored power	1-2 wt% in polar shadows?
Oxygen	Life support, propulsion	Widespread mineral oxides, 40-45 wt%
Volatiles (CO, CH ₄ ...)	Propellants	Polar ???
³ He	Fusion power source	Few-ppb from solar wind
Metals	Lunar manufacturing	Fe, Ti oxides: 0-15 metal wt%
Silicon	Solar cells	SiO ₂ widespread, Si ~25 wt%
Bulk Regolith	Radiation shielding	Ubiquitous
Ceramic Precursors	Lunar manufacturing	Varied, few-30 wt%



Oxygen: Sources & Variability

- In water or mineral oxides
- Small variability in Apollo samples

Lunar Mare Oxides: Lateral Composition



Is there a need to map the distribution with higher precision?

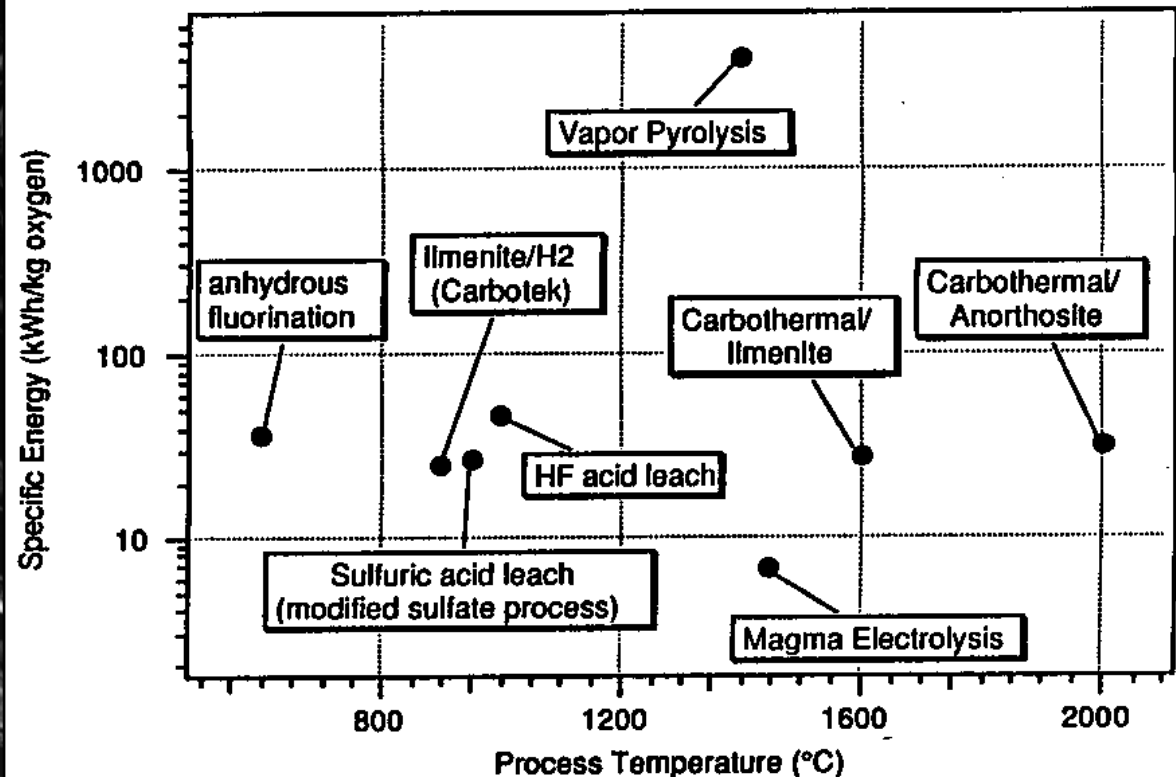


Oxygen Extraction Techniques

There are multiple techniques that have been developed for oxygen extraction from mineral oxides

Most involve either gas-phase reduction and/or electrolytic separation at high temperatures – Electrolytic separation of water for oxygen is also favorable (if water is abundant)

The Majority of Lunar Oxygen Producing Schemes Require Between 20-50 kWh per kg of Oxygen Collected



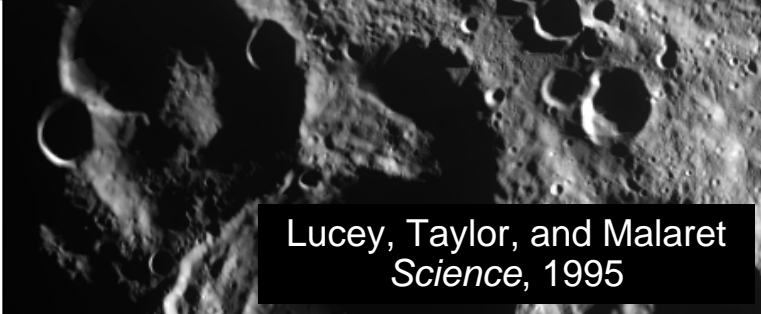
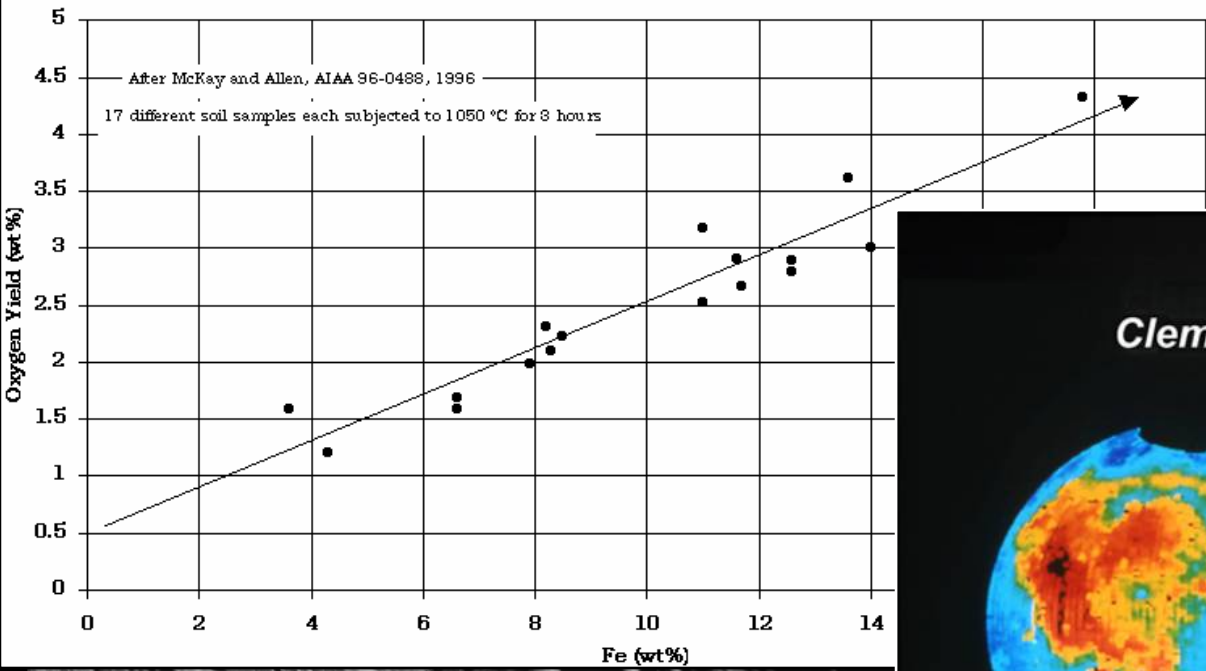
After L. W. Mason, p. 1139, in SPACE 92, ASCE (1992)



Optimizing Oxygen Yields

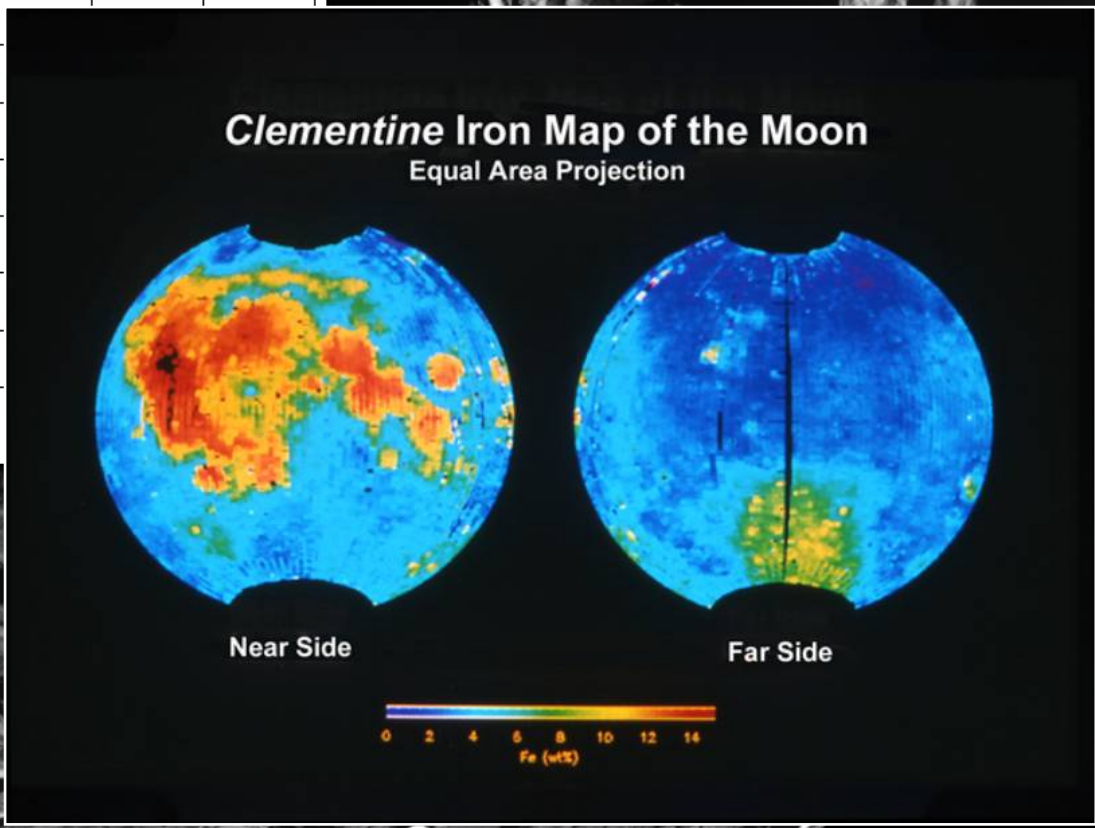
Oxygen production correlates with Fe content...

The Yield of Oxygen From Lunar Soils In Contact With High Temperature Hydrogen is Strongly Dependent on the Initial Iron Content



Lucey, Taylor, and Malaret Science, 1995

From McKay & Allen, 1996



...so improved mapping would be beneficial



Lunar Water and Volatiles

What volatile abundances did Apollo find?

- Values consistent with solar wind input

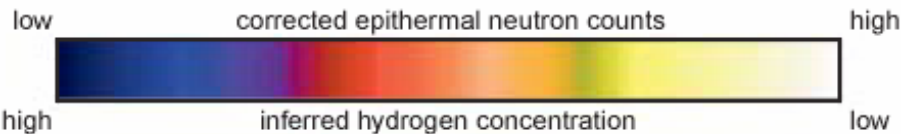
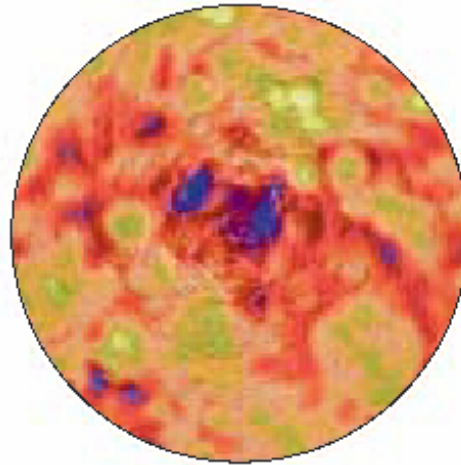
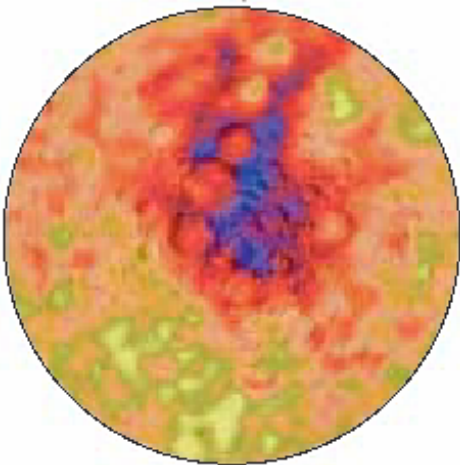
Table 1
Volatile Elements in Apollo 11 Regolith
(Lunar Sourcebook)

Element	Wt. ppm*
H	60
C	154
N	78
He	46
S	1240

*Average values

north pole

south pole



Lunar Prospector neutron spectrometer found polar hydrogen

Values consistent with 1-2 wt % water in permanently shadowed regions; thermodynamically stable in cold regions (<100K)



Water: Input and Loss Mechanisms

What are relative time and spatial scales?

Sources

- Cometary and meteoritic input – 100cm deposition in 10^9 yrs?? (Arnold, 1979) – *episodic source*
- Implanted solar wind H reacting with regolith oxygen during micro impacts – subsequent stochastic migration to polar cold traps – 10cm in 10^9 yrs? (Vondrak and Crider, 2000) – *constant source*

Losses

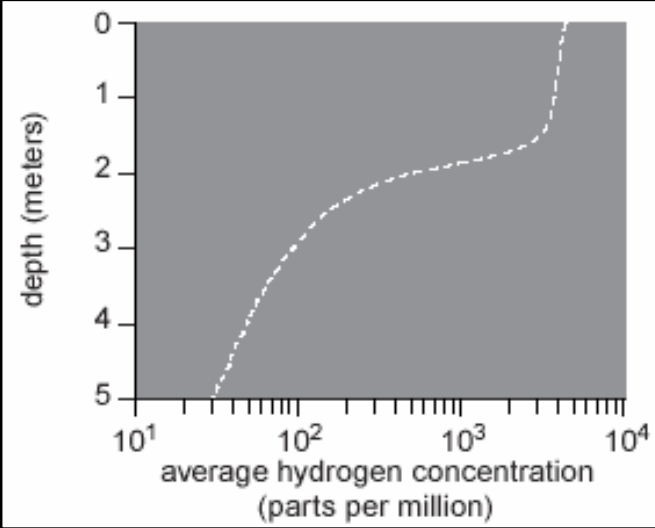
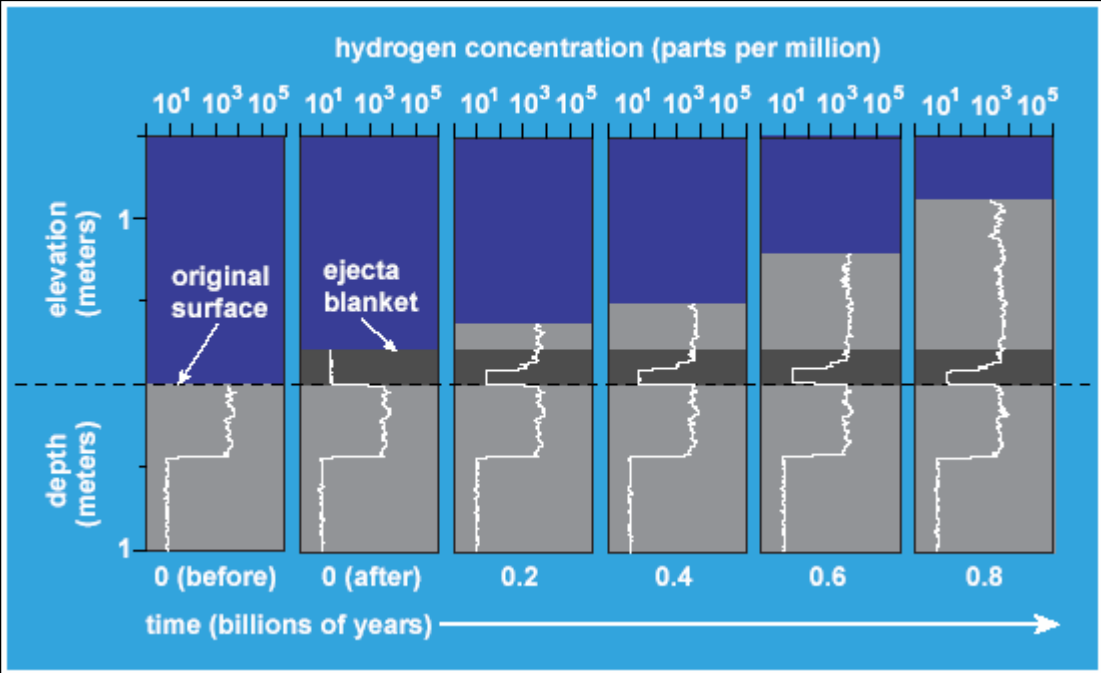
- UV Photodissociation (solar, earth, interstellar) – few hour time scale, but only on immediate surface
- GCR erosion – 10^6 - 10^7 yr time scale, down to 50cm
- Impact erosion – how much loss?

...And gardening mixes this in top few meters



Distribution of Water

What do we expect on a theoretical basis?



From Vondrak and Crider

*But the cometary input is not known –
Bottom line: we need to explore to find out!*



Prospecting for Water



LRO – 2008

- Neutron Spectrometer – few km footprint, ~m depth
- Global thermal mapping at 300m res.
- Mini-SAR (Radar)
- Ly alpha detection of dissociation

RLEP Lander #1 – 2011(?)

- In-situ validation at lunar south pole (nominal)
- Mobile platform (rover or hopper) to access perm shadowed regions

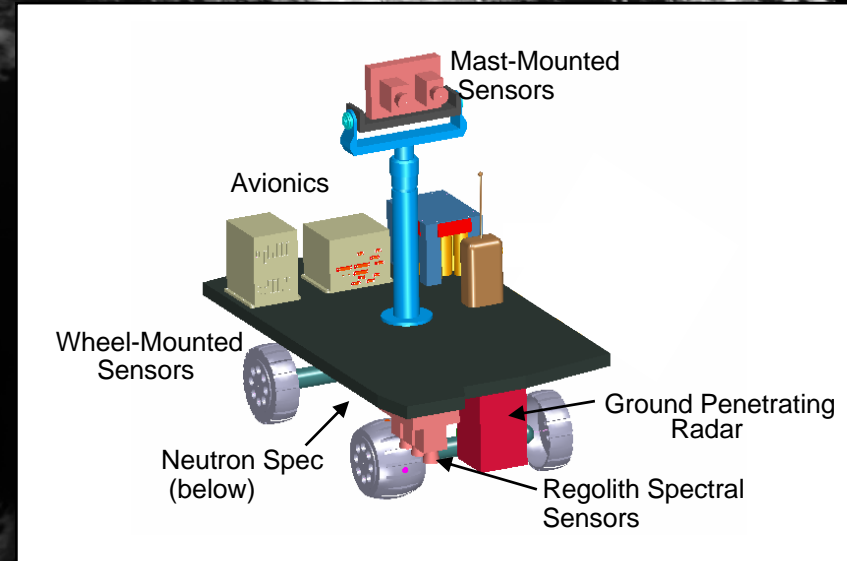
Surface expression of water may be very limited due to photodissociation and ejecta coverage – will likely need to **dig** to validate abundance



Prospecting at Base-Relevant Scales

Rover-based system capable of:

- Autonomous resource signature recognition and quantification
- Autonomous travel (hazard avoidance)
- Speed $>10\text{cm/s}$ (high sensitivity not needed)
- 3-D data collection
- Autonomy in mapping strategy

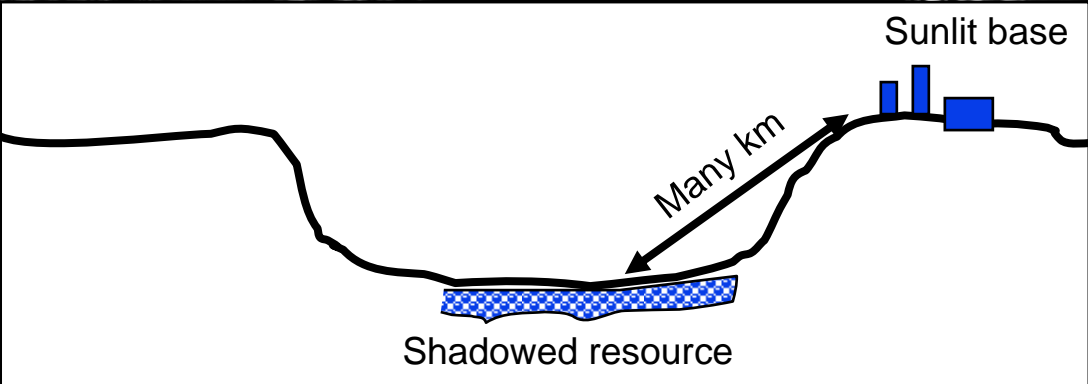


- *Wheel-mounted contact sensors (e.g., magnetometer, electrometer)*
- *Mast-mounted imagers for far-field context (multiband stereo imager)*
- *Platform-mounted imagers for near-field information (self-illuminated Vis/IR, Raman)*
- *Subsurface remote sensors (Neutron spectrometer, GPR, EM sounding)*
- *Subsurface drill (in-situ validation of composition, stratigraphy)*



Don't Overlook Infrastructure Costs!

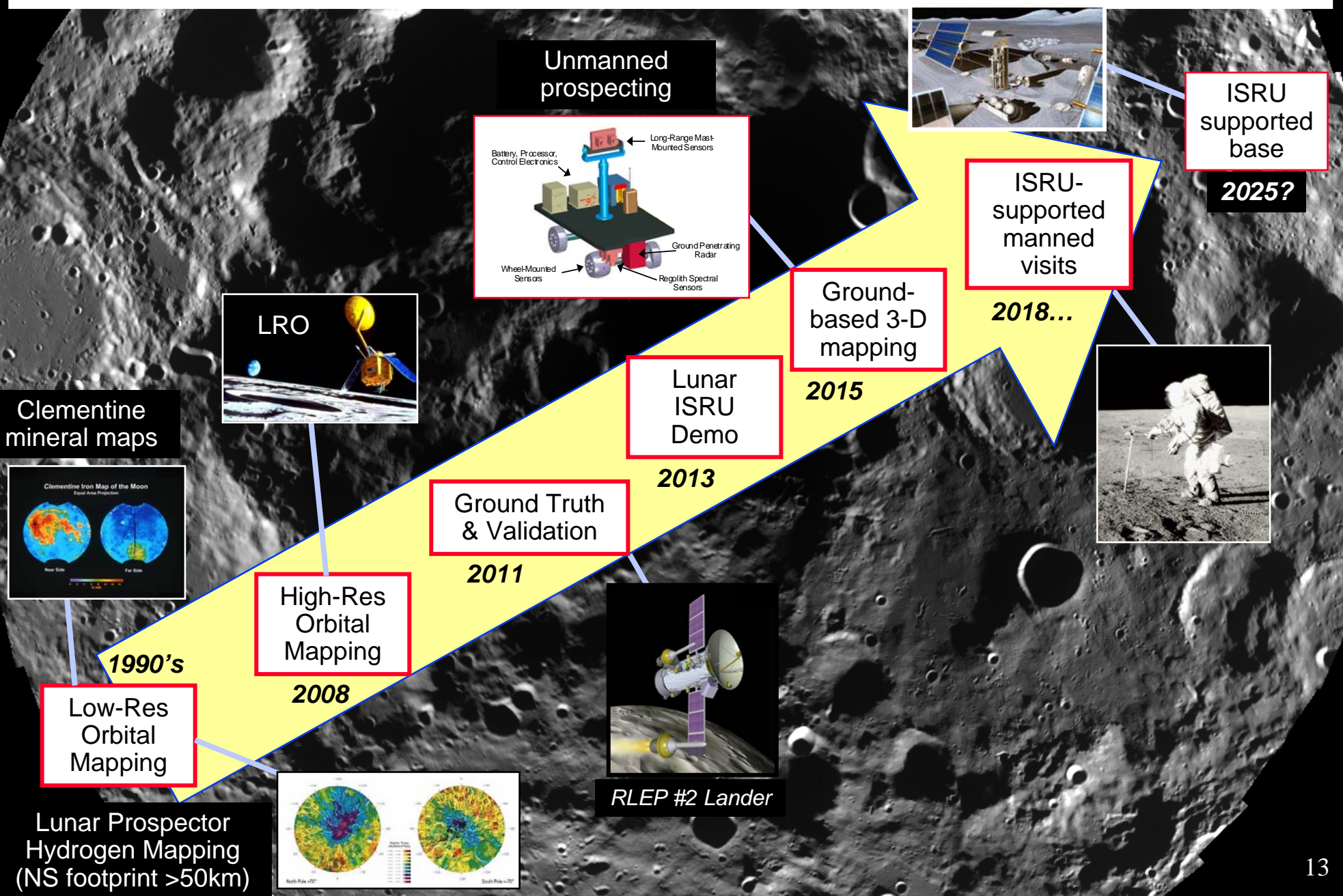
How to transport resource to location where it is of use?



This will require expensive infrastructure!



Lunar ISRU System Development Flow





Ground System Validation at Terrestrial Sites

- NASA and other groups have used Devon Island in N. Canada for the past decade for field testing
- We should take advantage of this if planning a field site in Alaska



Mars Society
experimental station



NASA Haughton-Mars Project
Base Camp



Conclusions

- Lunar resources can help offset exploration costs – but we must be aware of needed infrastructure burdens
- Near-term ISRU will likely concentrate on consumables such as **water** and **oxygen**
- Efficient ISRU system development requires a phase of ground-based mapping
- Terrestrial field testing at relevant sites will help lower implementation risk
- Same strategy is applicable to Martian resource exploration