Workshop: Cutting Edge Technology for Understanding the Earth (& the Moon)

The Next Steps for Robotic Exploration of the Moon

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Outline

Apollo 17: 7 Dec 1972

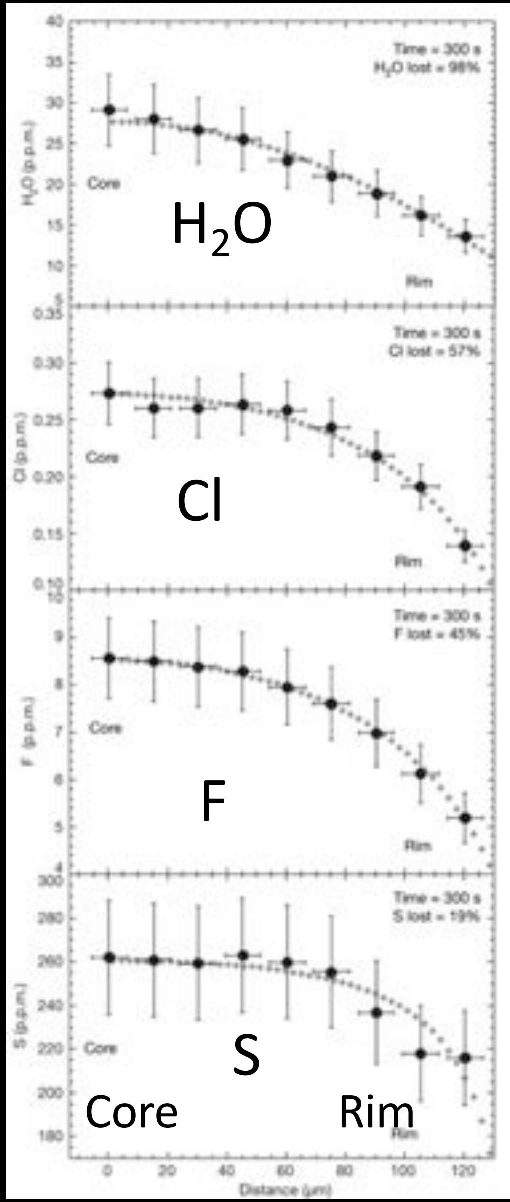
Robotic Exploration in addition to Humans

- Sample Return
- Resources
- Geophysics

Artemis 1: 21 Nov 2022

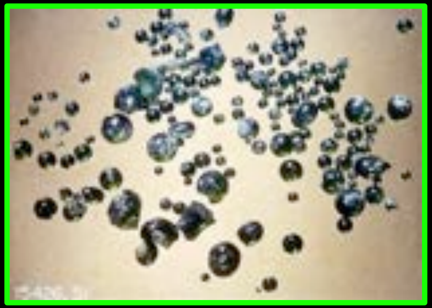
Samples: The Gift that Keeps on Giving

- After Apollo was concluded, Moon considered to be "dry".
- Volcanic glasses collected by Apollo 15 (1971) and Apollo 17 (1972) were shown in 2008 to contain water and other volatiles once analytical technology had been developed to make these analyses.



Saal et al. (2008) *Nature* **454**, 192-195

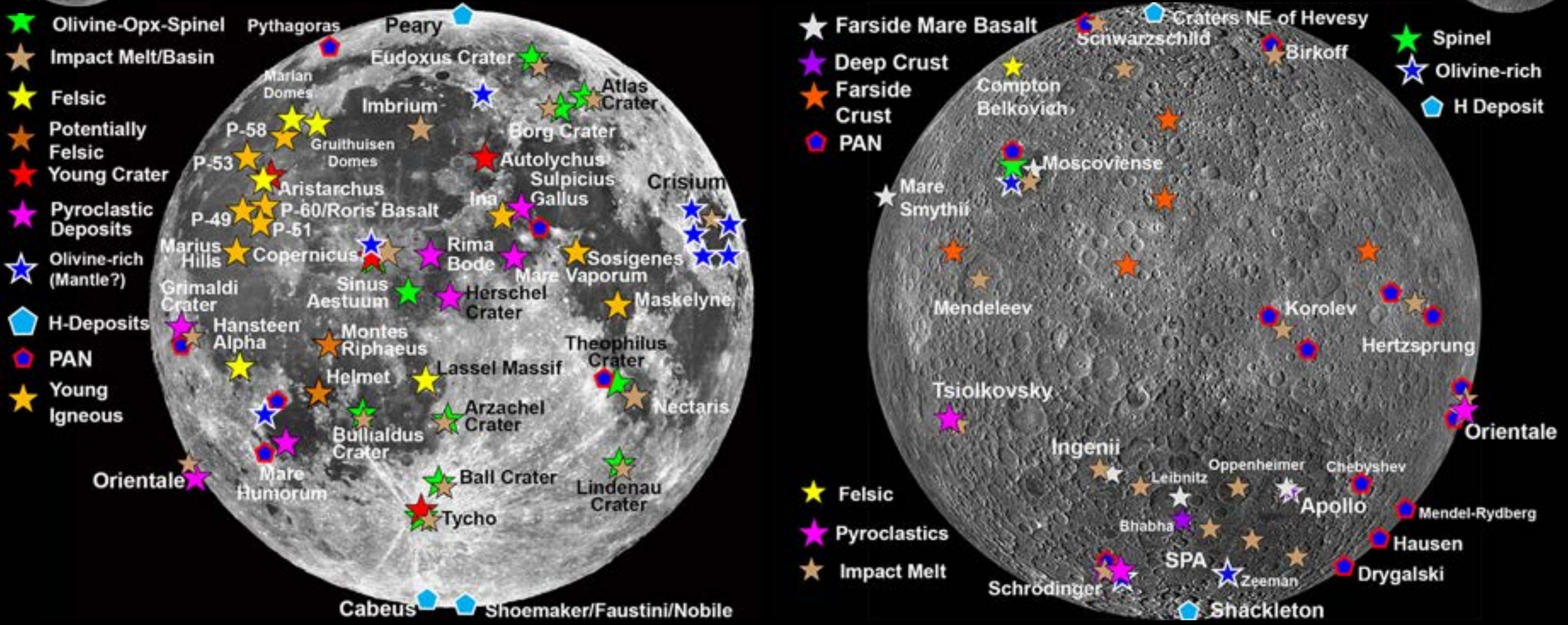
~30 µg/g H_2O



Sample Return

Sample return is considered essential in many lunar science and exploration documents produced by the lunar community and the National Academies of Science, Engineering, & Medicine.

Potential Sample Return Sites



Targets: Olivine, Opx, Spinel lithologies; Crater impact melts; Felsic lithologies; Young igneous; Far-side mare basalts; Pyroclastic deposits; Hydrogen/ice deposits; Deep crust/mantle; Farside crust; Pure anorthosite.

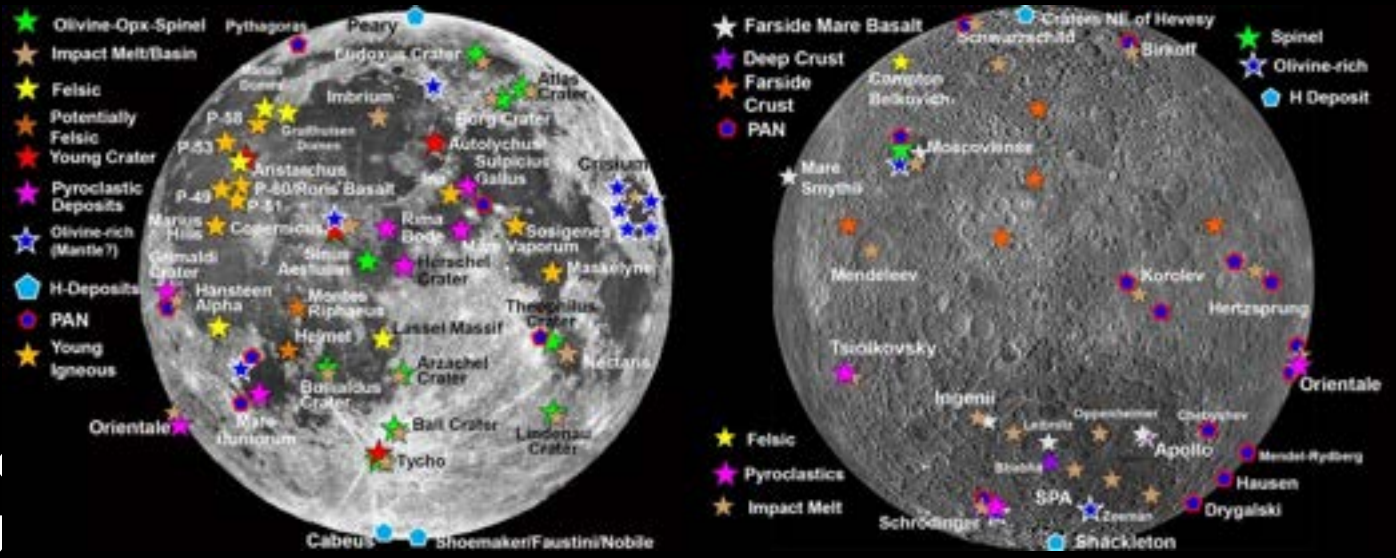
Reconnaissance sample return from areas away from Artemis landings to guide future human exploration

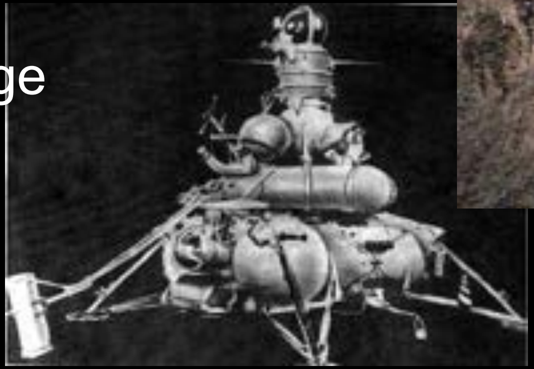
Sample Return

Sample Return Technology Development: Science Requirements

<u>Gather the sample</u>:

- Precision landing necessary? How precise? static lander sufficient?
- Is bulk regolith sufficient?
- Will hand samples be necessary?
- Will the sampling need to be done with a fet rover or the lander & how far will it need to g
- How will samples be transferred to the return vehicle?
- Will the samples require special storage conditions (e.g., cryogenic)?
- Are surface samples sufficient or will drilling/coring be needed?





Sample Return

- Reconnaissance Sample Return:
  - One sample will NOT answer ALL questions, but it's a start! Hence "reconnaissance" SR
  - Initially locations and science/exploration questions that can be assessed with samples returned by a simple static lander
  - Evolving to more targeted samples requiring fetch rover and/or precision landing
  - Highlight locations for human exploration

- Mobility over several kilometers:
  - Mapping lunar swirls
  - Understanding pyroclastic deposit extent and composition
  - Local/regional subsurface regolith stratigraphy
  - **Resource prospecting**

Lunar Resources

The Moon has three broad categories of potential resources that enable humans to live of the land

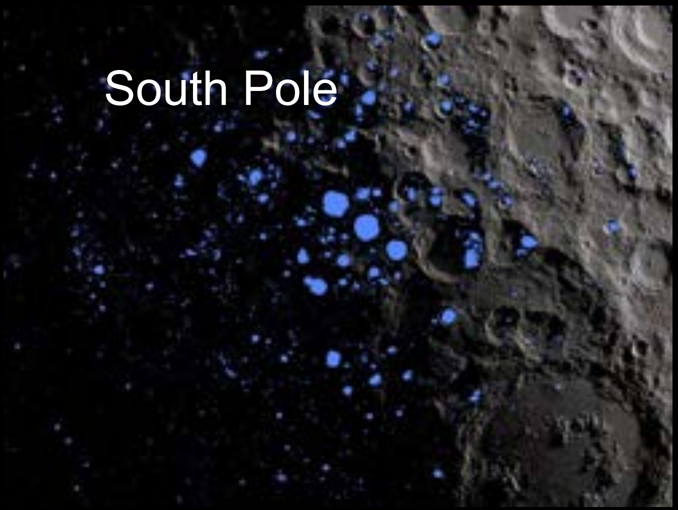
Polar volatile deposits – in and around polar permanently shadowed craters

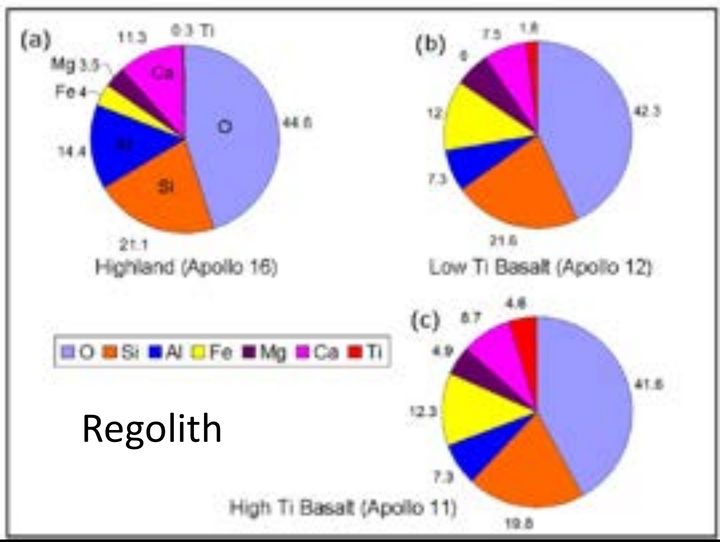
Regolith:

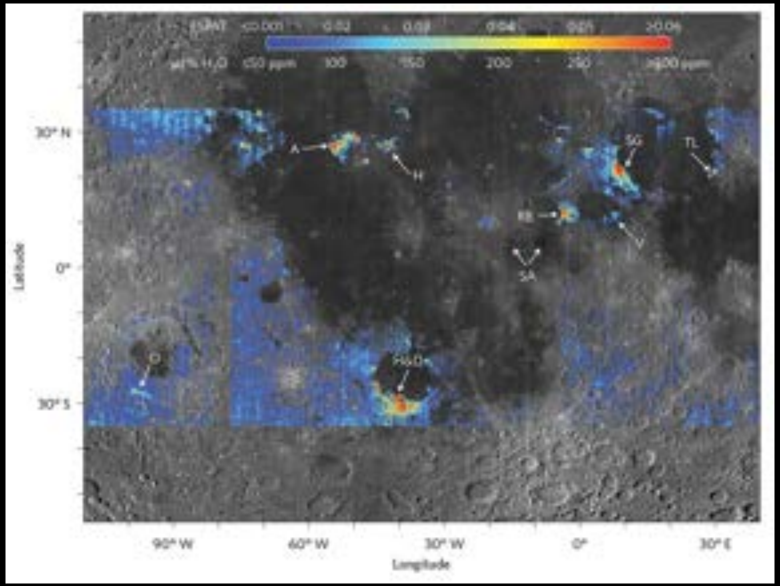
- Building materials (e.g. 3D printing),
- Metals,
- Oxygen
- Solar wind volatiles (H, He C, N, etc.)
- Platinum group metals
- Rare earth elements
- Th, U

Pyroclastic Deposits

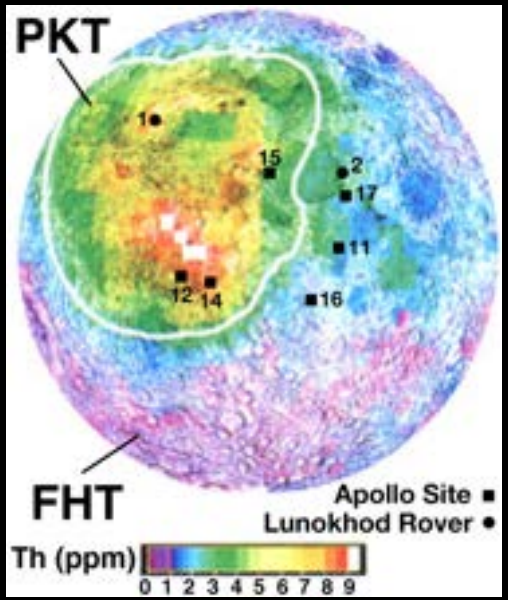
- Volatiles
- Metals







Milliken & Li (2017) *Nat. Geosci.* **10**, 561-565.



Jolliff et al. (2000) *JGR.* **105**, 4197-4216.

Importance of Lunar Resources

(Potentially) Enable:

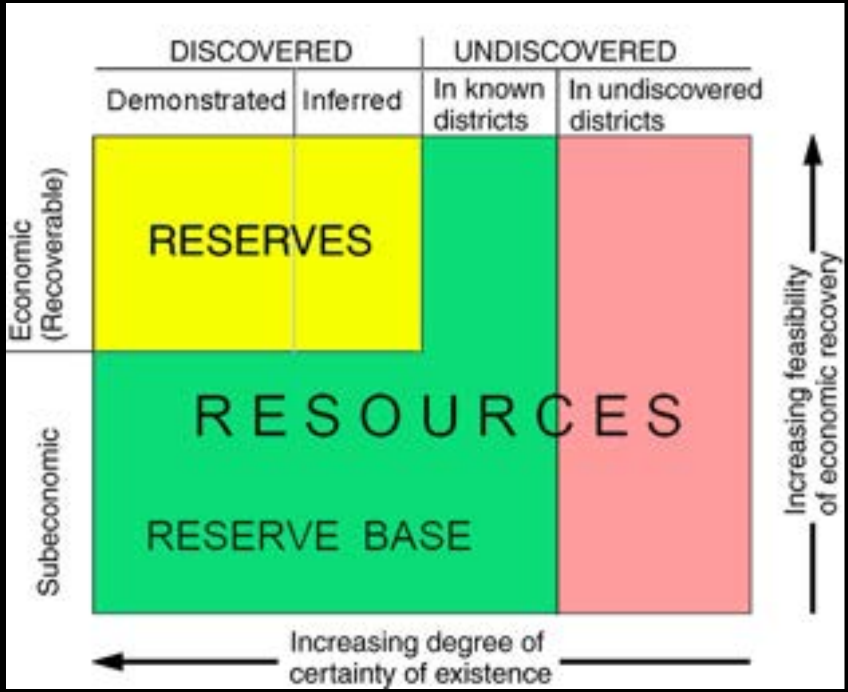
- Sustainable human exploration (facilitate a permanent human presence)
- Commercial involvement in lunar exploration
- International cooperation/collaboration

The term “resource” has been used many times when ”reserve” is intended.

Resource: a concentration of naturally occurring solid, liquid, or gaseous materials in or on the crust in such form that economic extraction of a commodity is regarded as feasible.

Reserve: That portion of an identified resource from which a usable mineral or energy commodity can be economically and legally extracted at the time of determination

United States Geological Survey (1980) Principles of a Resource/Reserve classification for minerals, Geol. Survey Circ. 831. https://pubs.er.usgs.gov/publication/cir831

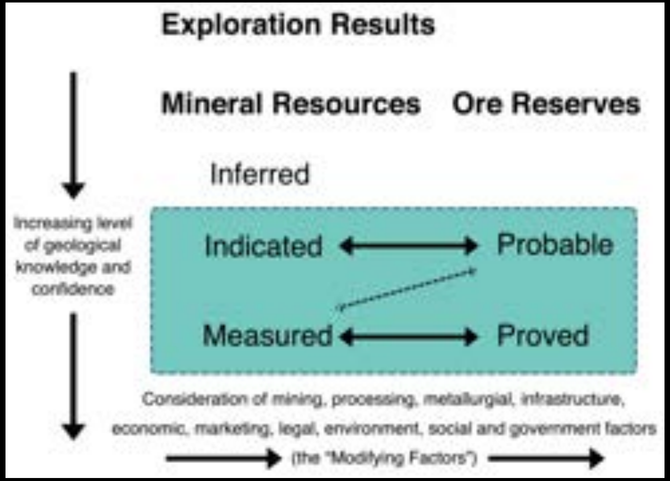


Issues with Lunar Resources

Road-blocks in the ISRU value chain:

Reserves ⟷ Demand/Market(s) (Customers)

Ground-truth Data & Demand/ Market(s) need to be obtained/ established to understand if lunar resources are reserves.



Cannon & Britt (2020) *Icarus* **347**, 113778

- Kleinhenz et al. (2020) Lunar Water ISRU Measurement Study (LWIMS) NASA/TM-20205008626
- Kleinhenz (2022) ISRU Potential Water Mine Site Preliminary Evaluation for NASA Artemis Campaign. https://isruinfo.com/public/index.php?page=srr_22
- Espejel (2022) From Resource to Reserve → LORS (Lunar Ore Reserve Standards), Luxembourg Space Resources Week https://www.youtube.com/watch?v=4keSUCvS3Kc [33 minutes in]

International Lunar Resource Prospecting Campaign

- PSR Resource Potential (large craters)
- Brown et al. (2022) *Icarus* **377**, Article 114874
    - Used 10 orbital datasets to rank surface and subsurface ice retention potential
    - Ranks PSRs – targets for surface evaluation
    - Neutron data very coarse, but have Mini-RF data
    - **Top 10 PSRs = >6,000 km^2 of real estate!**

DATASET	Pixel Scale (m/px)
Diviner annual maximum bolometric temperature	240
Diviner average bolometric winter temperature	240
Diviner ice depth stability paleo/today	240
LAMP FUV off-band/on-band ratio & Lyman-α albedo	240
LOLA active normal reflectance	500
M^3 near-IR ice detection	280
Mini-RF monostatic CPR	150 & 30
LEND wt% WEH abundance	~10,000
LPNS wt% WEH abundance	15,000 to 45,000
LROC NAC PSR imaging	10 to 40

Lunar PSR volatile rankings for PSRs with total scores ≥9.

Rank	PSR Name	Surface Score	Subsurface Score	Total Score
1	Faustini (FA-1)	8	6	14
2	Cabeus (CA-1)	7	6	13
3	Haworth (HA-1)	8	5	13
4	Shoemaker (SHO-1)	7	5	12
5	Sverdrup (SV-1)	8	4	12
6	de Gerlache (DG-1)	6	5	11
7	Amundsen (AM-1)	6	4	10
8	Rohzhd. U (ROU-1)	5	5	10
9	Shackleton (SH-1)	5	5	10
10	Cabeus (CA-2)	5	5	10
11	Nobile (NO-2)	6	4	10
12	Sverdrup (SV-3)	6	4	10
13	Shoemaker (SHO-3)	4	5	9
14	Slater (SL-1)	5	4	9
15	Rohzhd. U (ROU-2)	5	4	9
16	Shackleton (SH-3)	5	4	9
17	Shackleton (SH-4)	5	4	9
18	Haworth (HA-3)	5	4	9
19	Scott (SC-2)	5	4	9
20	Slater (SL-4)	5	4	9
21	Cabeus B (CAB-1)	6	3	9

Benefits of an International Lunar Resource Prospecting Camp…

An International Lunar Resource Prospecting Campaign would comply with the Outer Space Treaty

Outer Space Treat…

Exploration and … , promote, and encourage …

O…

… other celestial bodies, is not subject … …n of sovereignty, by means of use or … …er means.

…reaty – Article I, Paragraph 1

…ration and use of outer space, including the Moon and other …stial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.

Data Needed from an International Lunar Resource Prospecting Campaign

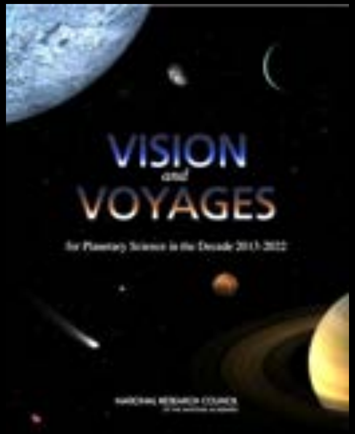
Robotic surface exploration with mobility is essential

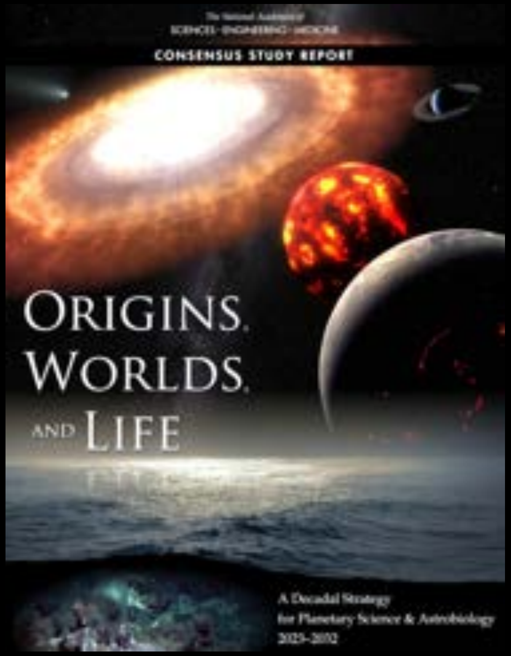
Table 1: Datasets for lunar volatile resource evaluation

Dataset	Specific Data	Use	Measurement
Composition	Concentration of the resource Concentration & composition of impurities	Evaluate potential investment needed for refining the product	Required Fidelity?
Form	Cement in pore space; Layers; Irregular blocks; Loose ice grains with regolith	Develop efficient extraction techniques	
Distribution	Horizontal Vertical	Variability needs to be documented to understand the volume of the resource	
Geotechnical	Torque and power required for any drills to penetrate the deposit; Energy required to move loose regolith; Hardness of the deposit;	Understand the effort required to mine the deposit and investment needed in developing extraction capabilities.	
Near-surface Regolith Stratigraphy	Buried and surface rock populations Ice block/layer distribtuion	Will impact the extractibility of the regolith resource	
Accesibility	Traverse paths;	Ease of accessibility has an impact on cost of developing robotic miners.	

(Re)Establishing the Lunar Geophysical Network (LGN)

LGN has been a top lunar mission as rated by Vision & Voyages 2013-2022, and Origins, Worlds, and Life 2023-2032 – the last two NASA Planetary Decadal Surveys.



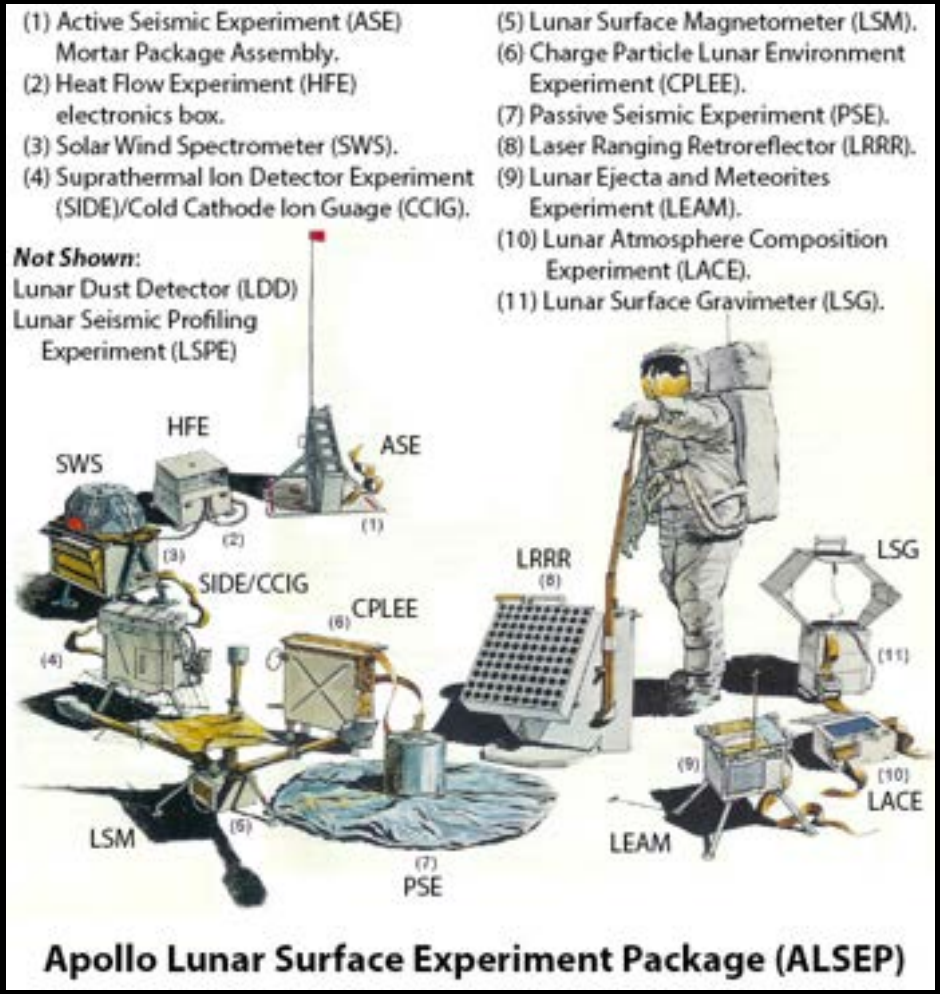


Science Objectives:

- *Determine the internal structure and size of the crust, mantle, and core to constrain the composition, mineralogy, and lithologic variability of the Moon.*
- *Determine the distribution and origin of lunar seismic activity in order to better understand the origin of moonquakes and provide insights into the current dynamics of the lunar interior and the interplay with external phenomena such as tidal interactions with Earth.*
- *Determine the global heat-flow budget for the Moon in order to more precisely constrain the distribution of heat-producing elements in the crust and mantle, the origin and nature of the Moon's asymmetry, its thermal evolution, and the extent it was initially melted.*

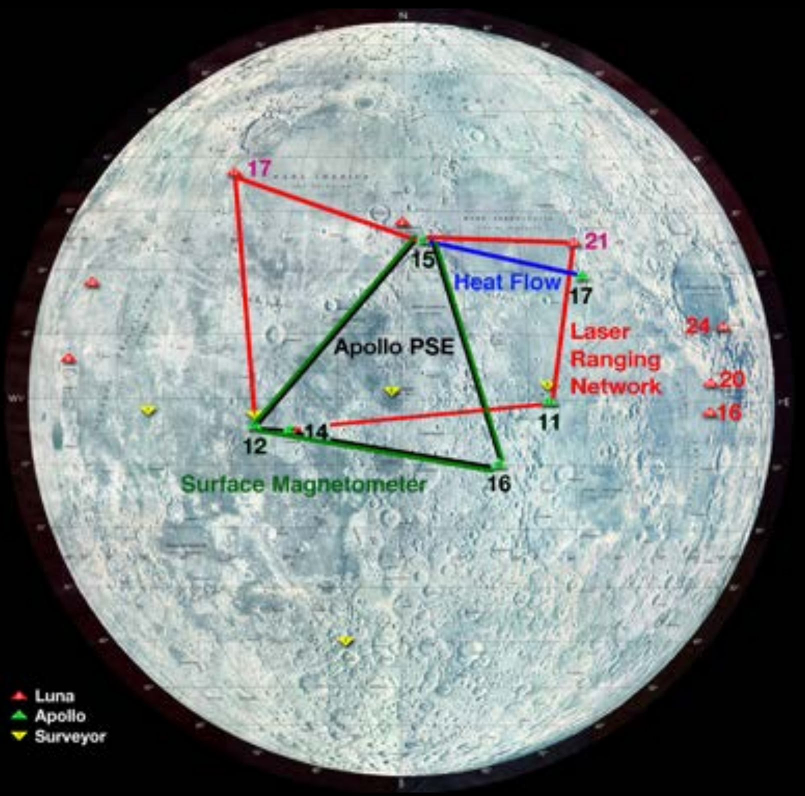
The mission shall address all three objectives.

Apollo Knowledge



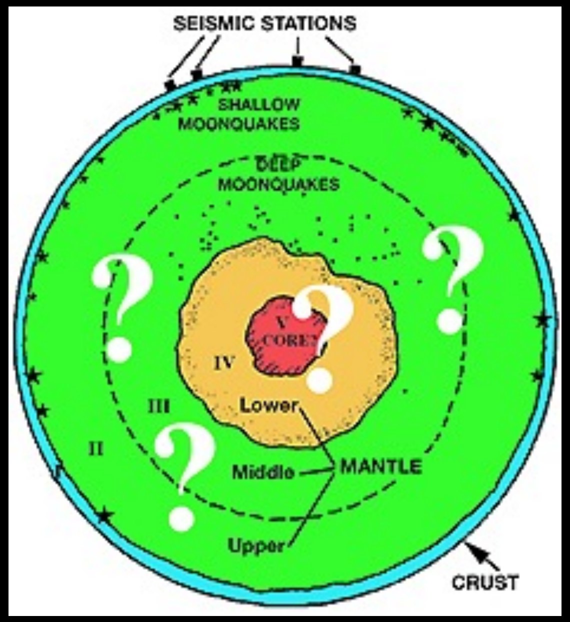
Apollo Lunar Surface Experiment Package (ALSEP)

Acronym	Apollo Mission
ASE	14, 16
CCIG	12, 14, 15
HFE	15, 17
LACE	17
LDD	12, 14, 15
LEAM	17
LRRR	11, 14, 15
LSG	17
LSM	12, 14, 15, 16
LSP	17
PSE	12, 14, 15, 16
SIDE	12, 14, 15
SWS	12, 15



Apollo Knowledge

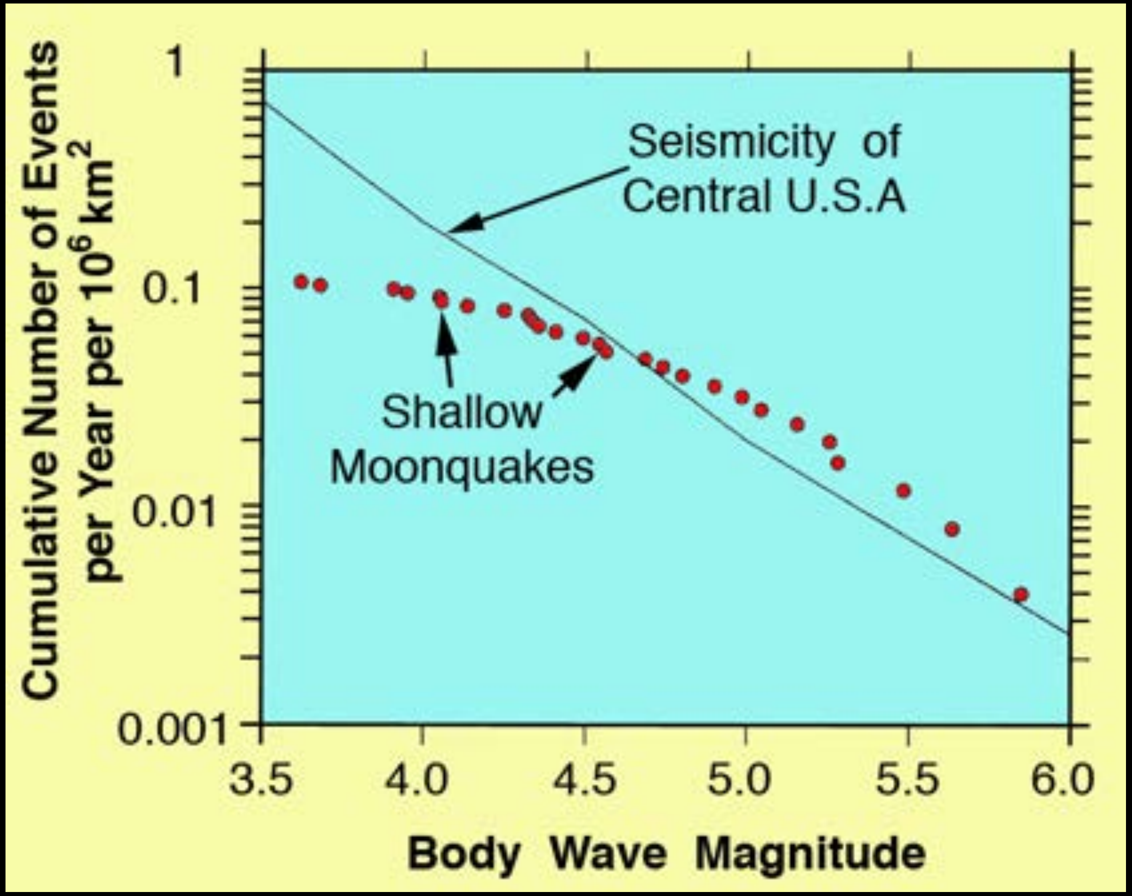
4 types of events induce seismicity on the Moon.



[Nakamura et al. (1982) *PLPSC* **13th**]

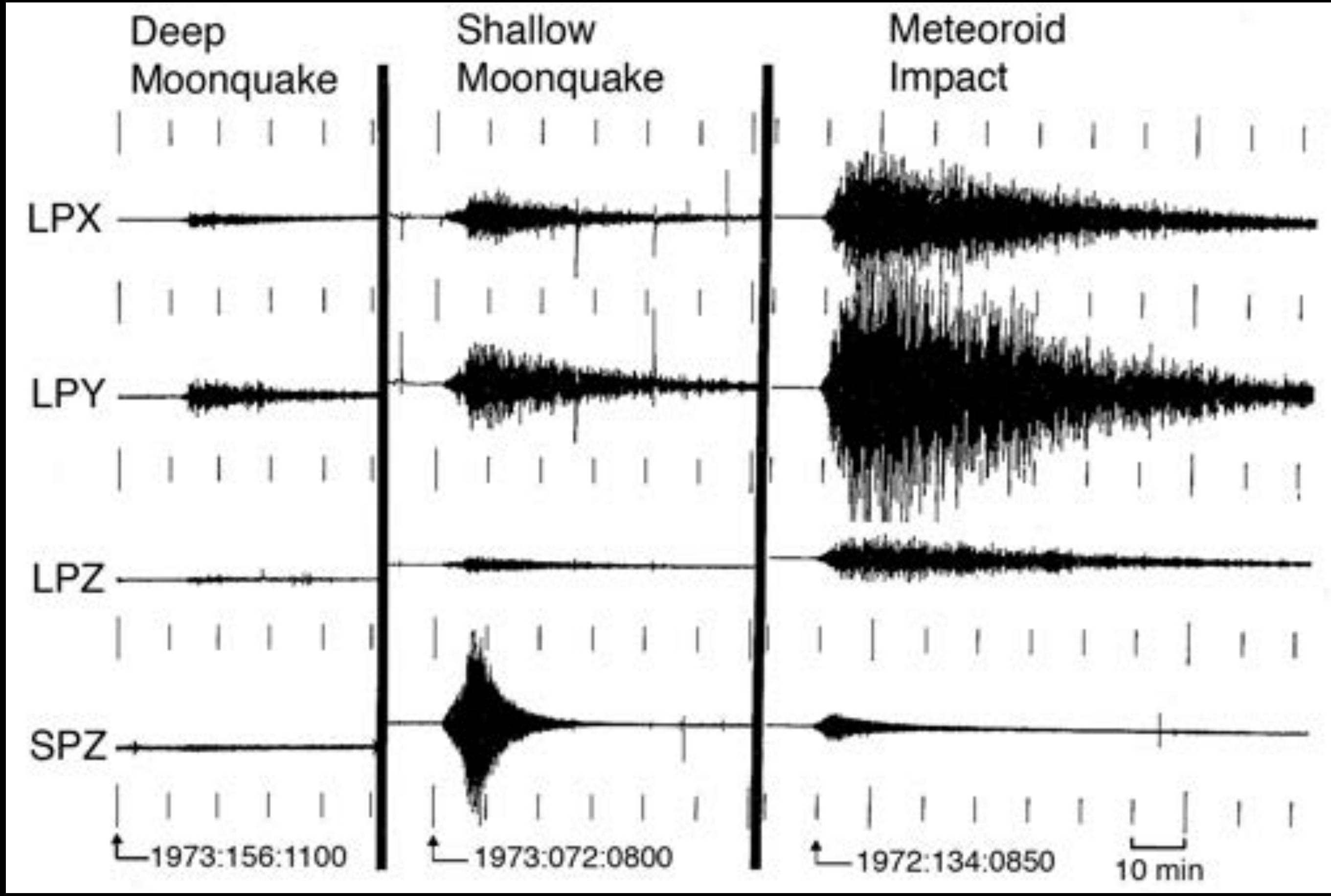
- **Deep Moonquakes** - 850-1,000 km. > 7,000 recorded. Originate from “nests” - 318 nests defined from Apollo seismic data to date. Small magnitude (< 3). Associated with tidal forces.
- **Thermal Moonquakes** - Associated with heating and expansion of the crust. Lowest magnitude of all Moonquakes.
- **Meteoroid Impacts** - > 1,700 events representing meteoroid masses between 0.1 and 100 kg were recorded 1969-1977. Smaller impacts were too numerous to count.
- **Shallow Moonquakes** - some > 5 magnitude. Exact locations unknown. Indirect evidence suggests focal depths of 50-200 km. May be associated with boundaries between dissimilar surface features. Exact origin unknown.

Apollo Knowledge



Oberst & Nakamura (1992) A Seismic Risk for the Lunar Base. 2nd Conference on Lunar Bases & Space Activities, 231-233

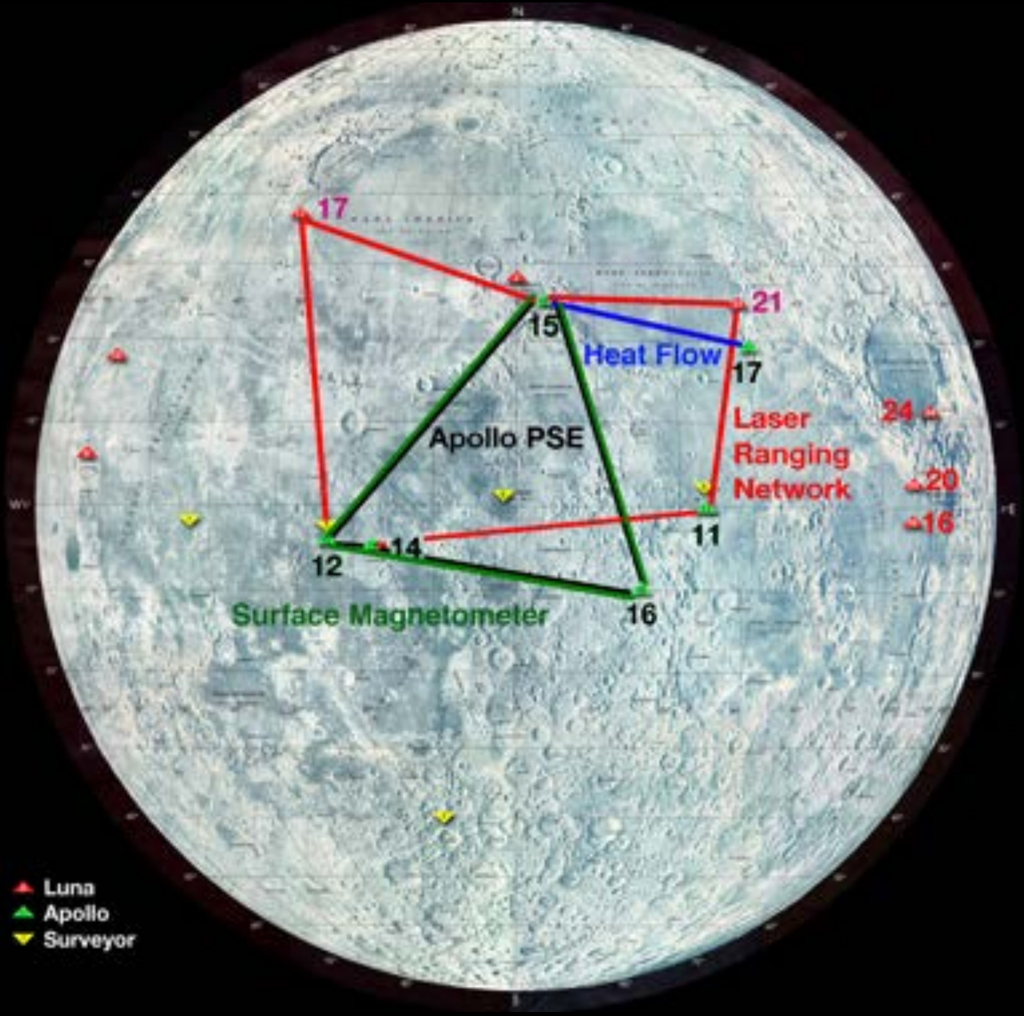
High Seismic Q

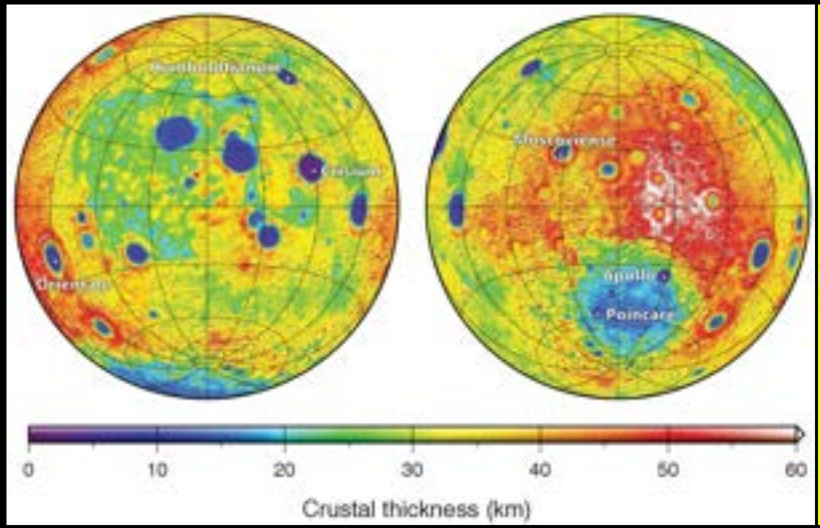


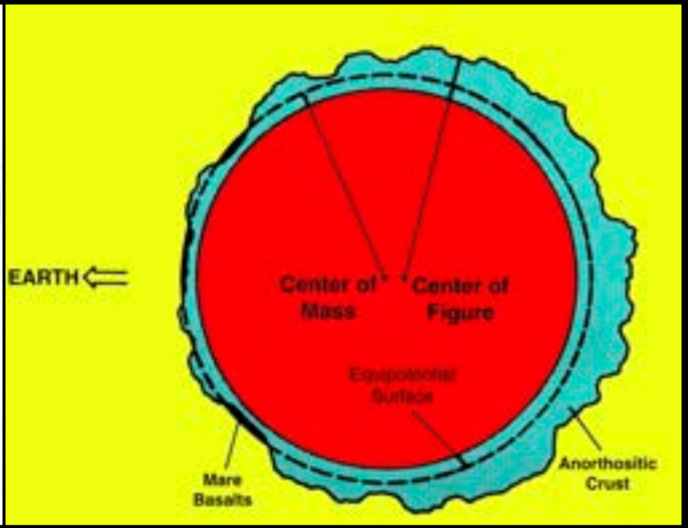
Why is Another Lunar Geophysical Network Needed?

- Network located on central nearside
- Far side has thicker crust – indirect evidence
- Offset center of mass & center of figure

e.g., Kaula et al. (1974) *PLSC* **5**, 3049-3058



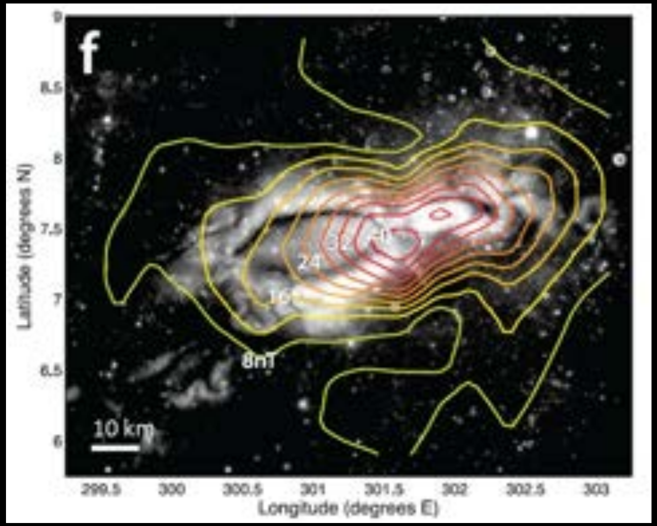


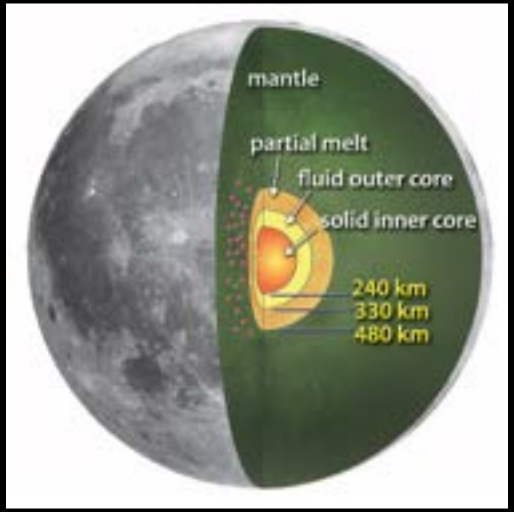


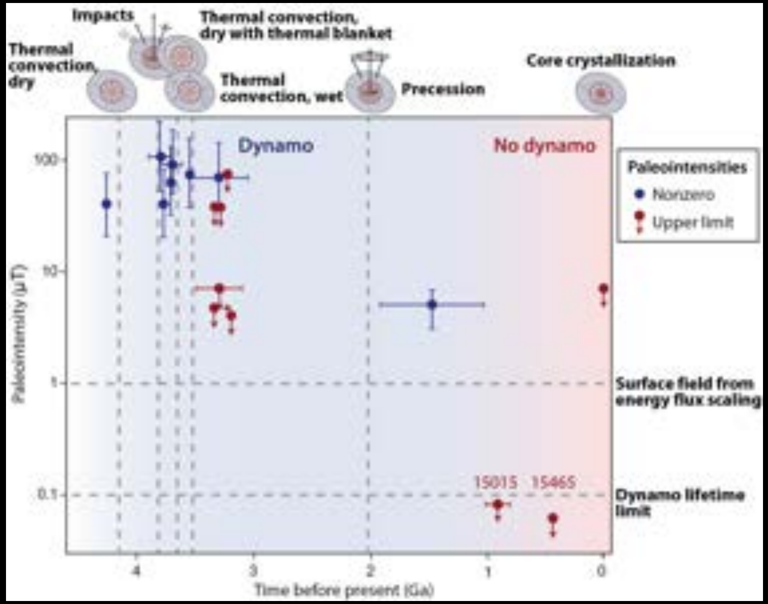
Wieczorek et al. (2013) *Science* **339**, 671-675

Why is Another Lunar Geophysical Network Needed?

- We don’t know the extent or duration of the now extinct lunar dynamo.
- We don’t know the exact origin of the Moon’s crustal magnetic anomalies/swirls.
- We don’t have unambiguous observations of a mid-mantle discontinuity (base of the LMO?), a partial melt layer above the outer core, or the nature of the inner core.
- We don’t know how surface hemispherical observations propagate into the interior.
- We don’t understand why/how all moonquakes occur.

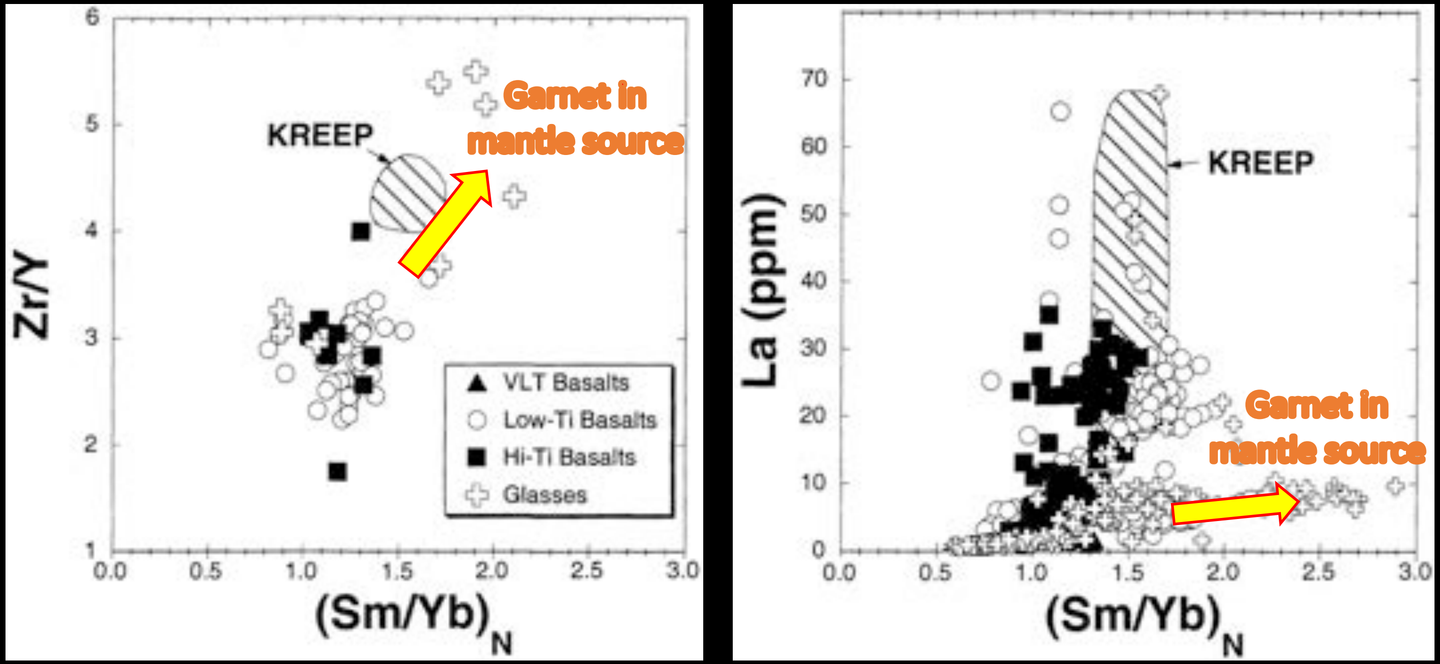






Why is Another Lunar Geophysical Network Needed?

Garnet in the lunar interior

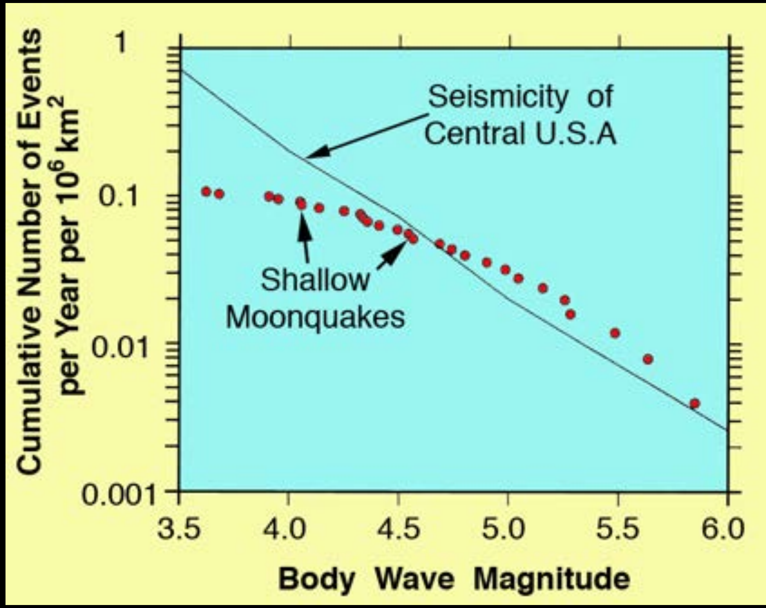


Neal (2001) *JGR* **106**, 27,865-27,885

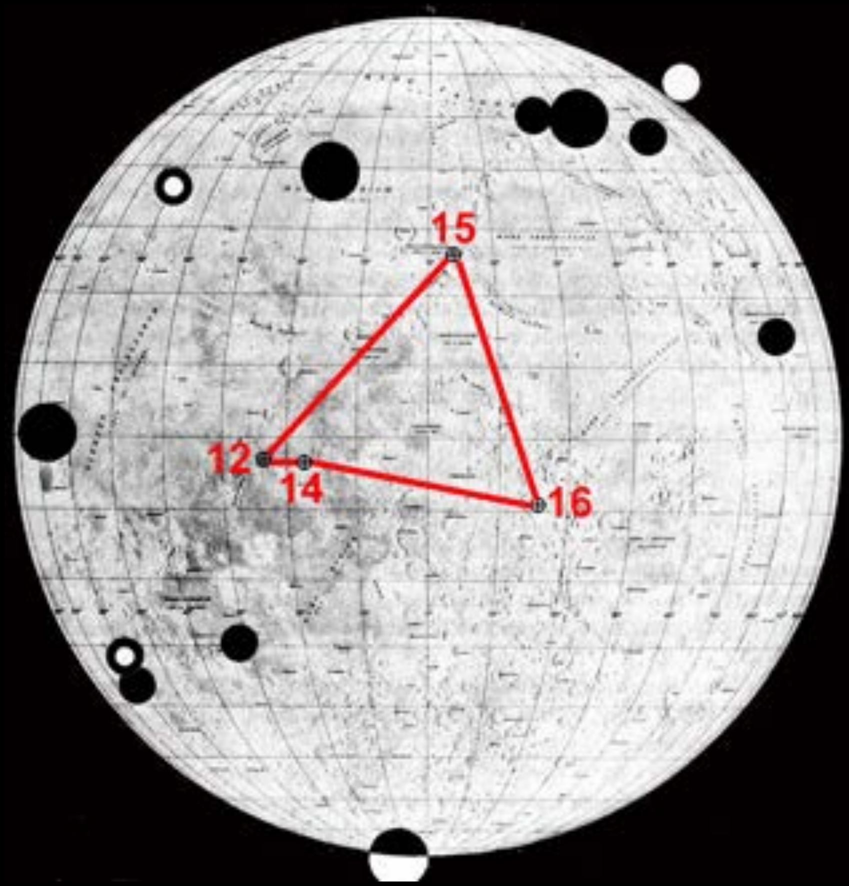
- Some studies suggest a velocity jump in the middle mantle (~500 km) that represents an increased proportion of Mg-rich olivine.
  Nakamura et al. (1974) **GRL 1**, 137-140; Nakamura (1983) JGR **88**, 677-686.
- Others use the same seismic data to infer the presence of garnet >500 km within the Moon.
  Hood (1986) in *Origin of the Moon*, 361-410; Hood &Jones (1987) *PLPSC* **17** in *JGR* **91**, E396-E410.

Why is Another Lunar Geophysical Network Needed?

Evaluate the seismic hazard to human exploration and human permanence on the Moon

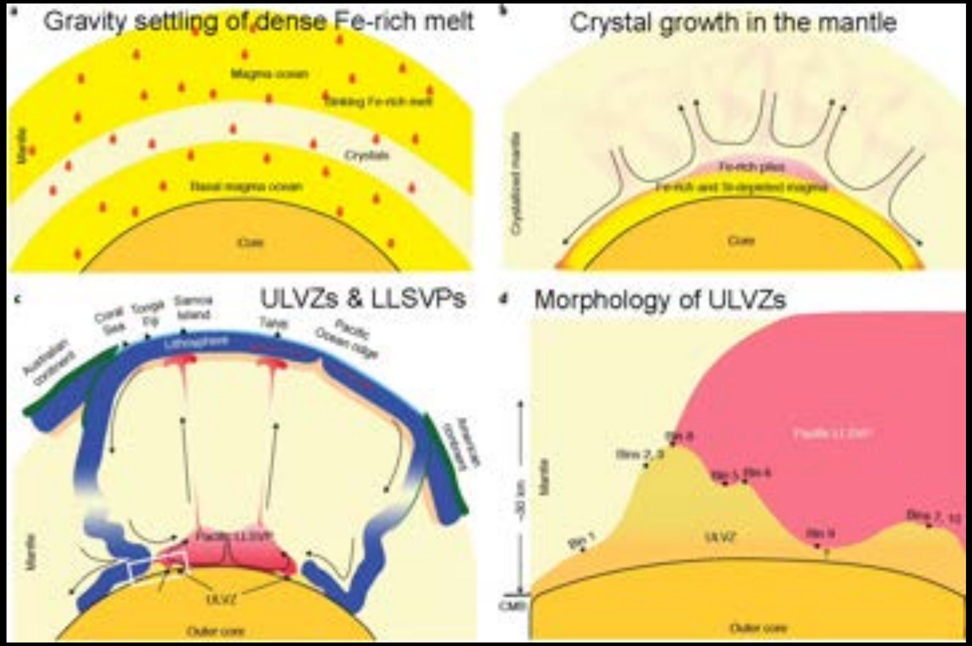


Oberst & Nakamura (1992) A Seismic Risk for the Lunar Base. 2nd Conference on Lunar Bases & Space Activities, 231-233



Nakamura et al. (1974) *PLSC* **5th**, 2883-2890

Using the Moon to Explore the Origin of LLSVPs



Primordial Magma Ocean Cumulates

- Assumed to be compositionally dense leftovers from the magma-ocean phase that are formed to dense accumulations (piles) by mantle flow.
- Magma ocean crystallization leads to a massive mantle overturn that may set up a stably stratified mantle.
- Could lead to significant delays or total prevention of plate tectonics on some planets.

Kreielkamp et al. (2022) *EPSL* **579**, 117357. Pachhai et al. (2022) *Nat. Geosci*. **15**, 79-84. Schaefer & Elkins-Tanton (2018) *Phil Trans. Roy. Soc. A* **376**, 20180109.

The Lunar Geophysical Network Mission

- Planetary Mission Concept Study funded in 2019 https://science.nasa.gov/science-pink/s3fs-public/atoms/files/Lunar%20Geophysical%20Network.pdf
- Globally distributed network of seismometers, heat flow probes, electromagnetic sounders, laser retroreflectors

LGN in New Frontiers 5

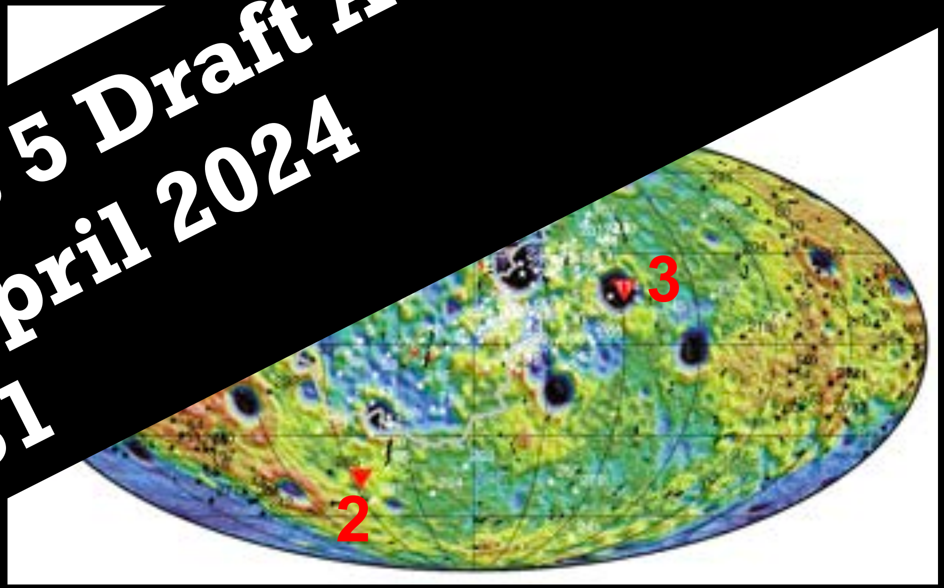
UPDATE! 10 Jan 2023, New Frontiers 5 Draft AO Released

Proposal Due Date: April 2024

Launch: 2031

Baseline Mission:
- 4 identical landers globally deployed around the Moon.
- Long-lived: 6-year mission with a goal of 10 years.
- Will allow other nodes to be added to strengthen s… return (*cf*. the International Lunar Network).
- 4 landers launched together, deployed …

Threshold Mission:
- 2 identical landers deploy… 60) and 2 (Schickard…
- 2 sites distinctl…
- Sites dete… A33 nest (cor…
- … distinct terranes.



- The parent spacecraft = communications relay for all landers.
- Each lander will be able to send data direct to Earth, so the communications relay orbiter acts as a back-up for near side landers.

Summary & Conclusions

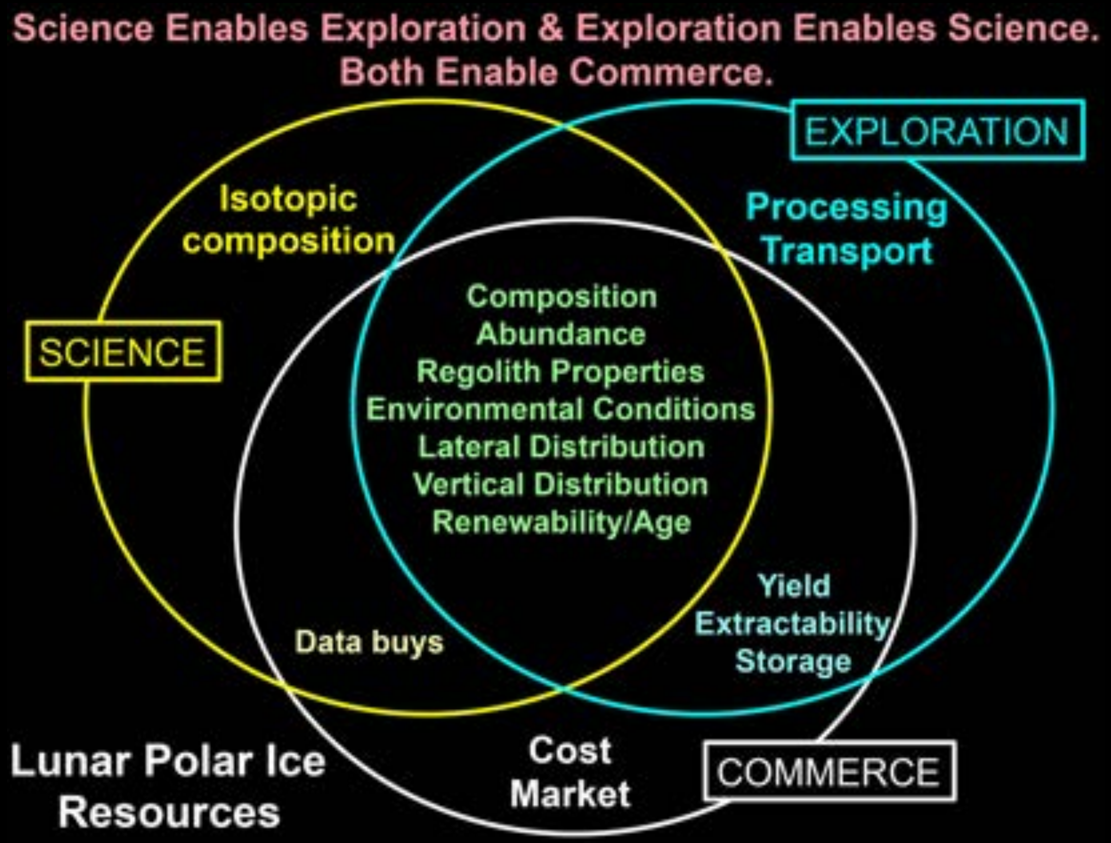
Sample Return:

- Technology developed by JAXA (Hyabusa) – opportunities for scientific and technology collaborations.
- Develop reliable fetch rover and sample transfer & return mechanisms.
- Useful for establishing strong scientific collaborations.

Summary & Conclusions

Resource Prospecting:

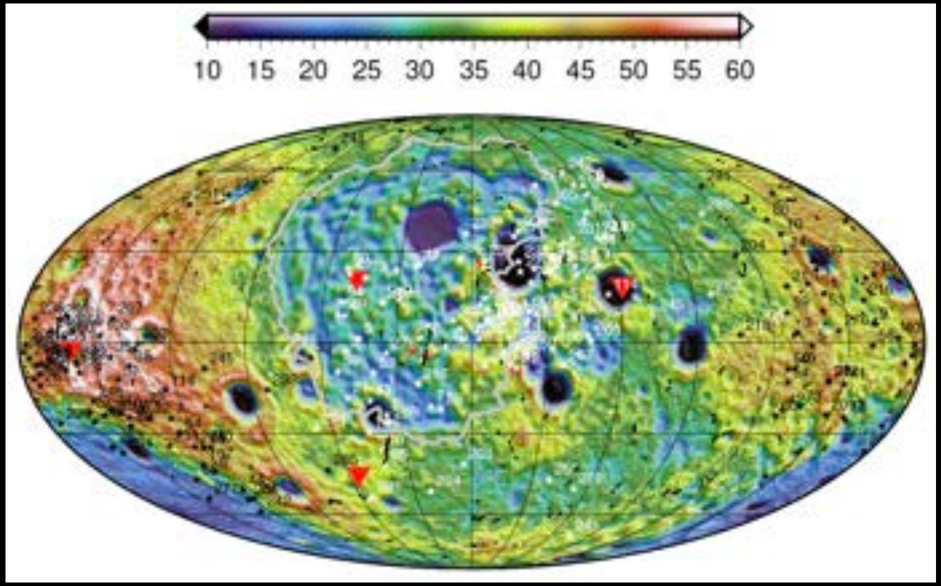
- Promotes international scientific and technological cooperation and collaboration.
- Technology needed to work in shadowed craters (~40 K).
- Data returned serves a number of different stakeholders.
- Potentially can establish strong commercial involvement and job growth IF resources = reserves.



Summary & Conclusions

Lunar Geophysical Network:

- International team assembled with commercial and government participation.
- In the last 20 years new instruments developed (heat flow probe, seismometer, laser retroreflector, electromagnetic sounder).
- New batteries and landers developed.
- Critical for safety of humans on the lunar surface.



Questions?