GEOPHYSICAL INVESTIGATION OF THE MOON

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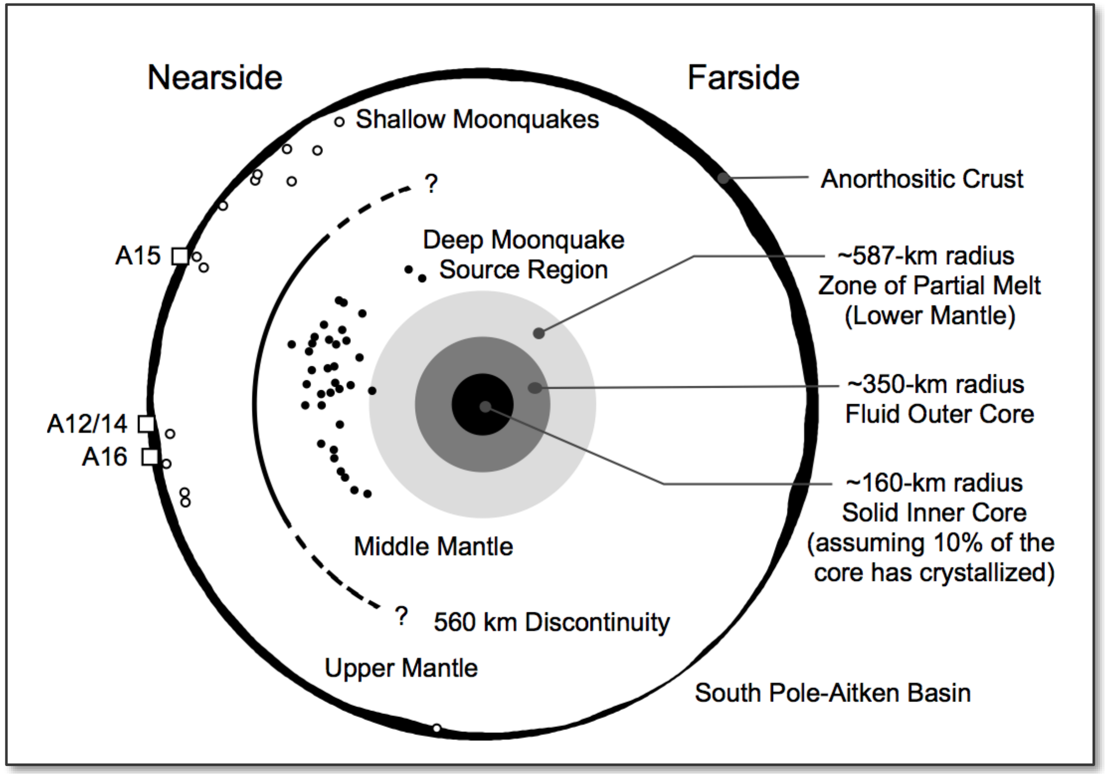
The Planetary Decadal Survey recognizes geophysics as a high-priority science objective for a future lunar landed mission. Why?

- Interior properties (layering, composition, seismic velocity and density, presence of partial melt, core state: liquid vs. molten) provide important constraints on lunar formation and evolution models, as well as possible indicators of an early dynamo for magnetic field generation.

- Constraints on these properties arise from geophysical observations:
  - Seismology
  - Heat flow
  - Lunar laser ranging
  - Magnetic induction studies
  - Gravity field

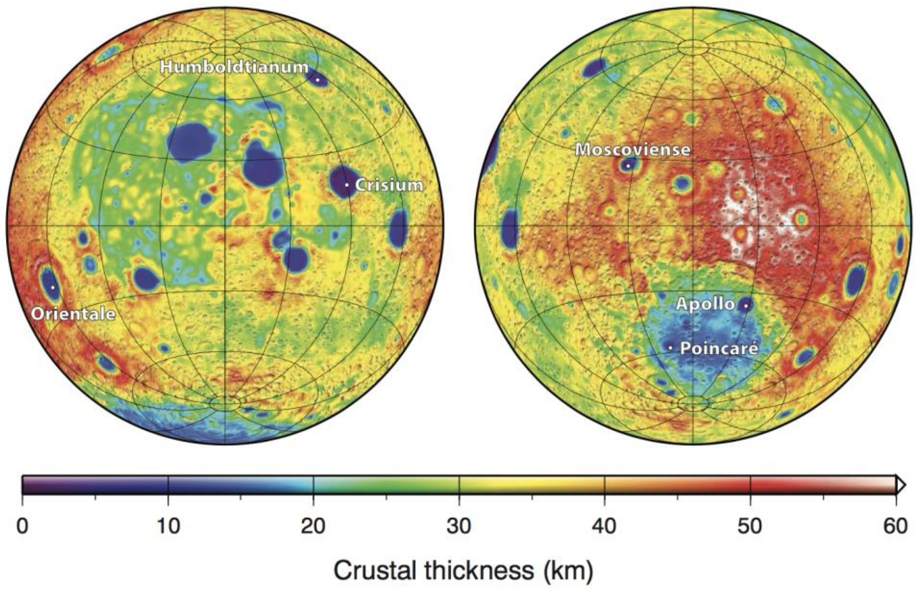


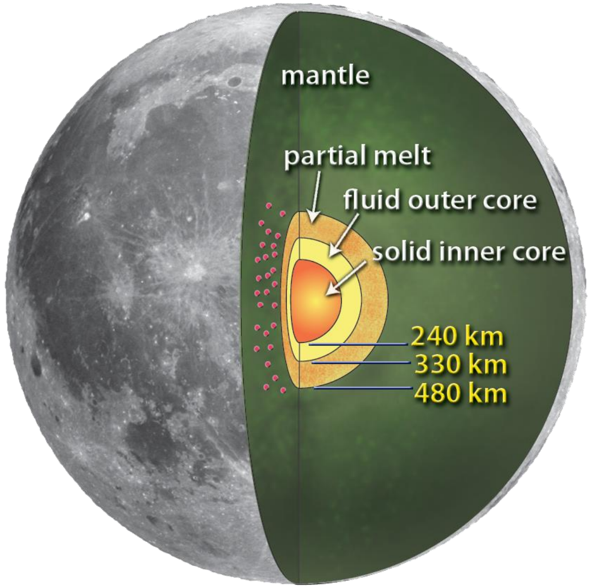
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Recent advances in lunar geophysics

- GRAIL lunar gravity mission mapped the Moon's gravity field in extreme detail
  - ➢ Shallow (crustal) structure tightly constrained, but still tied to (uncertain) ground-truth seismic estimates from the Apollo landing sites
- Re-analyses of Apollo seismic data found evidence for core reflections, including the presence of a partial melt layer above the liquid outer core
  - ➢ Differing perspectives on whether a partial melt layer is required to satisfy available constraints (gravity, seismic, geodetic constraints, EM sounding data, phase-equilibrium models, dissipation)

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





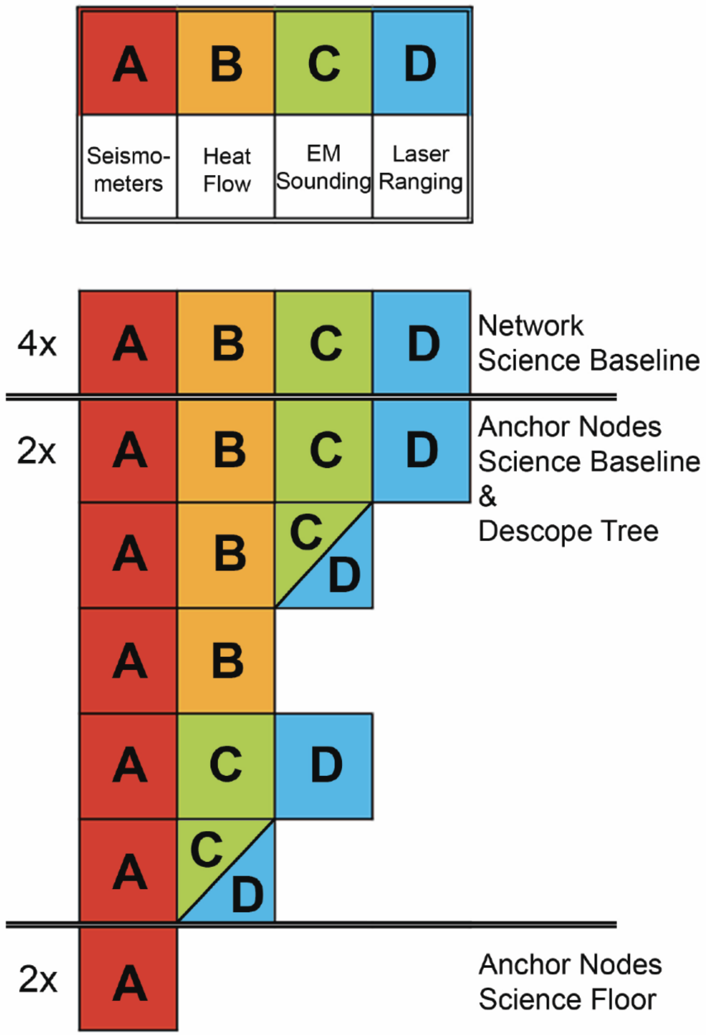
Weber et al. (2011) *Science* **331**, 309-312

Why go back?

- Apollo seismic data & GRAIL revolutionized our understanding of the Moon's interior and its formation/evolution. Nevertheless, many questions remain regarding the amount/distribution of seismicity, as well as the detailed structure of the crust, mantle, and core.

- ILN study: seismometers were deemed the most important instrument

- Future seismic mission
  - ➢ Wider aperture network (better locations for better interior models)
  - ➢ Far side coverage
  - ➢ Better sensitivity (although they were very sensitive, the Apollo seismometer LSB was above background noise level)
  - ➢ Wider frequency range (lower frequencies are less affected by scattering and suffer less attenuation)



The Lunar Geophysical Network – What is it?

- A network of geophysical "nodes" (at least 4) operating continuously for an extended period of time – at least 2 (ILN), 4 (LUNETTE), or 10 (LGN) years

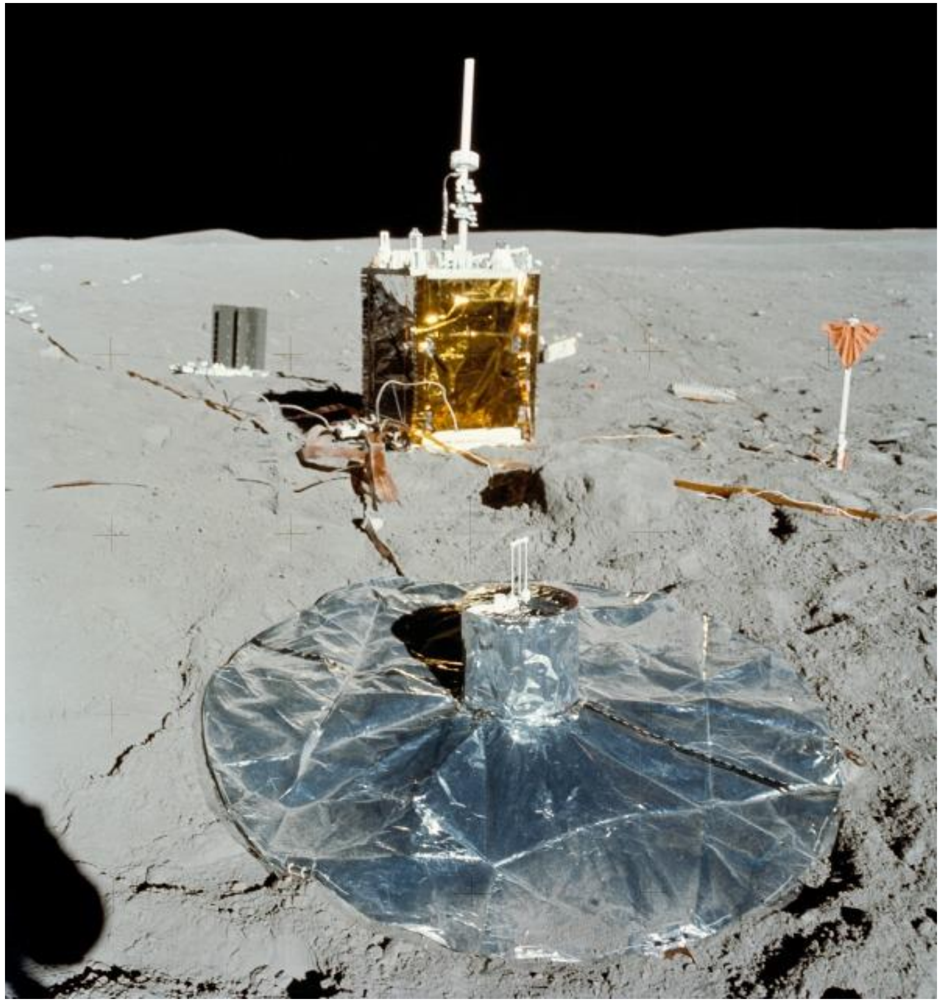
- Science objectives for each node:

Seismometer	Heat flow probe	Retroreflector	Magnetometer
• Understand the current seismic state and determine the internal structure of the Moon	• Measure the heat flow to characterize the temperature structure of the lunar interior	• Increase ability to determine deep lunar structure and conduct tests of gravitational physics by installing next-generation laser ranging capability	• Use electromagnetic sounding to measure the electrical conductivity structure of the lunar interior

Lunar seismology – what is it?

- Seismometers are stationary instruments that monitor the ground for seismic shaking induced by natural tectonism and meteorite impacts.

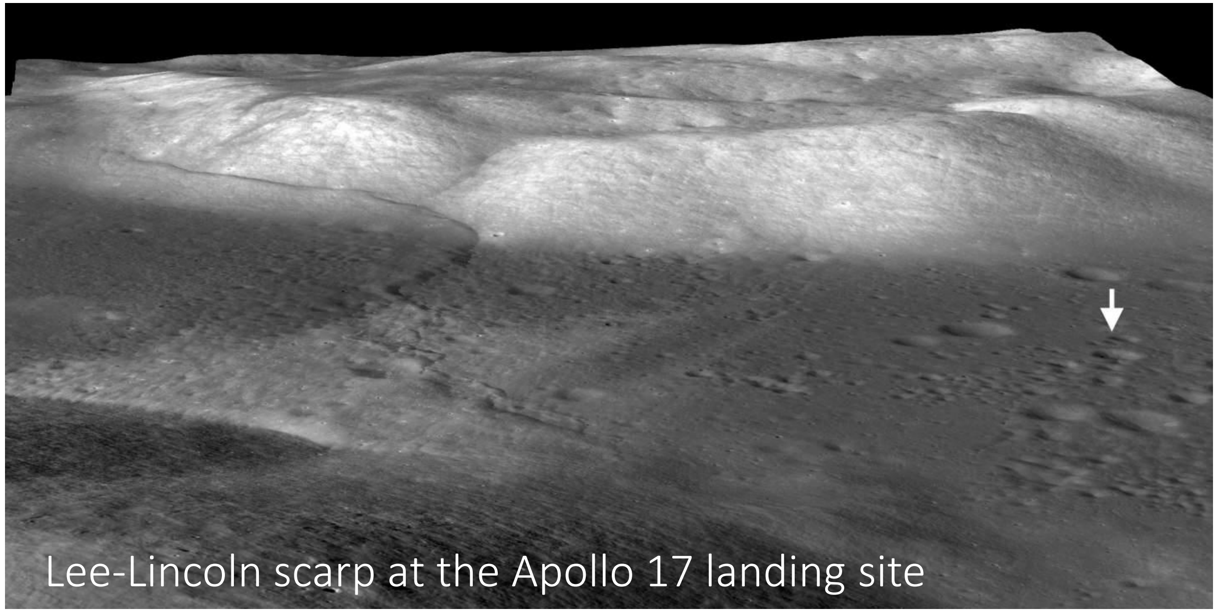
- Ideal deployment conditions:
    - Good ground coupling
    - Continuous data collection/transmission
    - Longevity (several years)



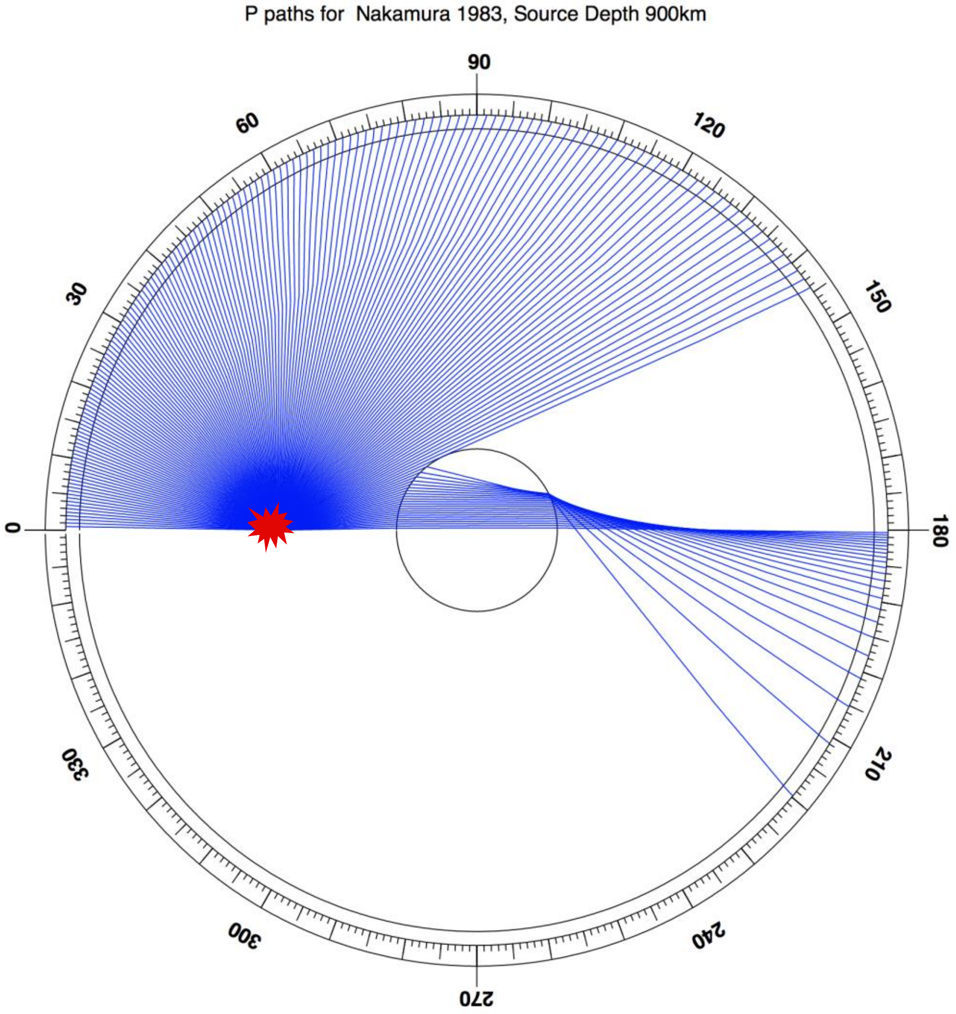
Lunar seismology – what is it?

Data recorded by seismometers can be used to study:

- The transmission of seismic energy through the planet, allowing recovery of structural properties and layering (crust, mantle, core)
- The amount and distribution of seismicity (ground shaking), which can illuminate tectonic processes and quantify potential threats to future landed assets.



Lee-Lincoln scarp at the Apollo 17 landing site



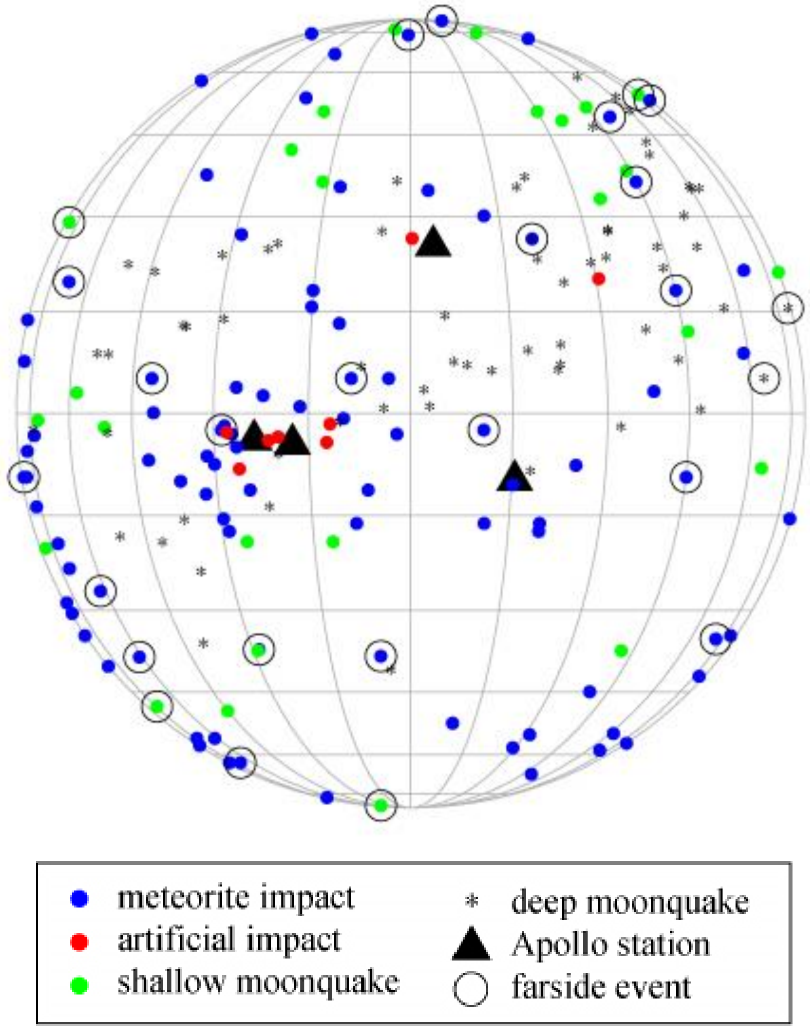
Lunar seismology – types of seismicity

Known lunar seismicity consists of four primary types:

1. Shallow moonquakes (large but rare “tectonic” events similar to intra-plate quakes on Earth)
2. Deep moonquakes (small but frequent events that occur monthly according to the tidal cycle)
3. Meteorite impacts (much more frequent than on Earth due to lack of atmosphere)
4. Thermal events (localized cracking of rocks and regolith movement induced by large day/night temperature swings)

and

5. Artificial impacts (e.g., lunar modules, Saturn IVB stages)



Landing site selection for optimal geophysical observations

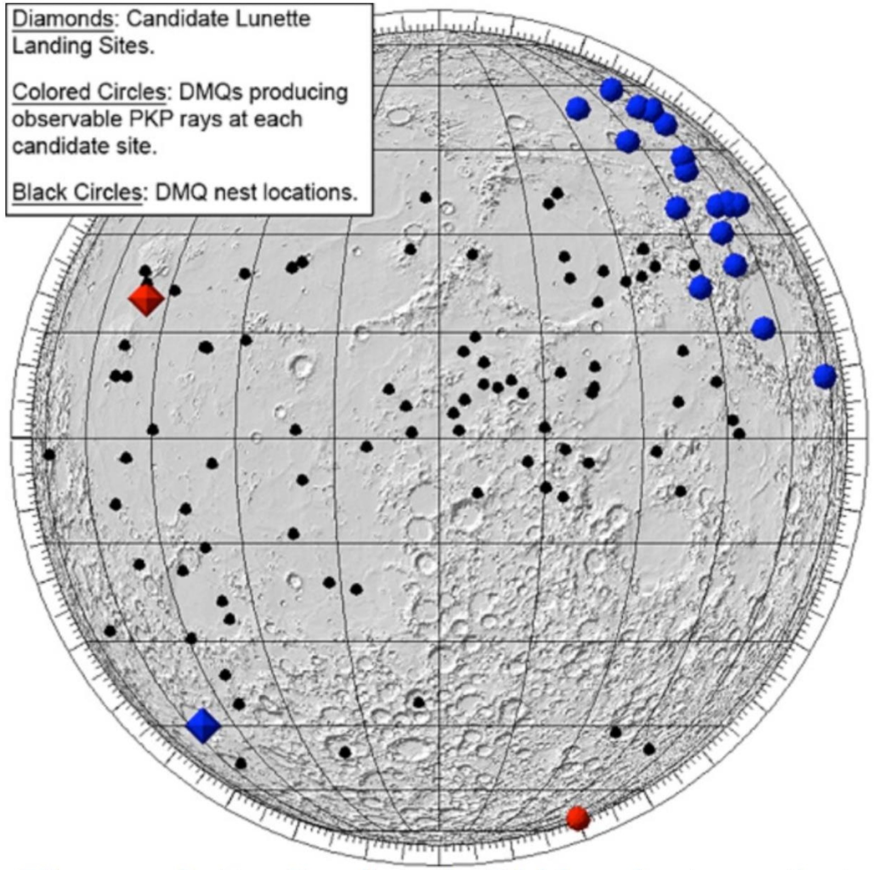
Seismometers are often packaged with other geophysical instruments. Joint consideration of landing site requirements maximizes science return.

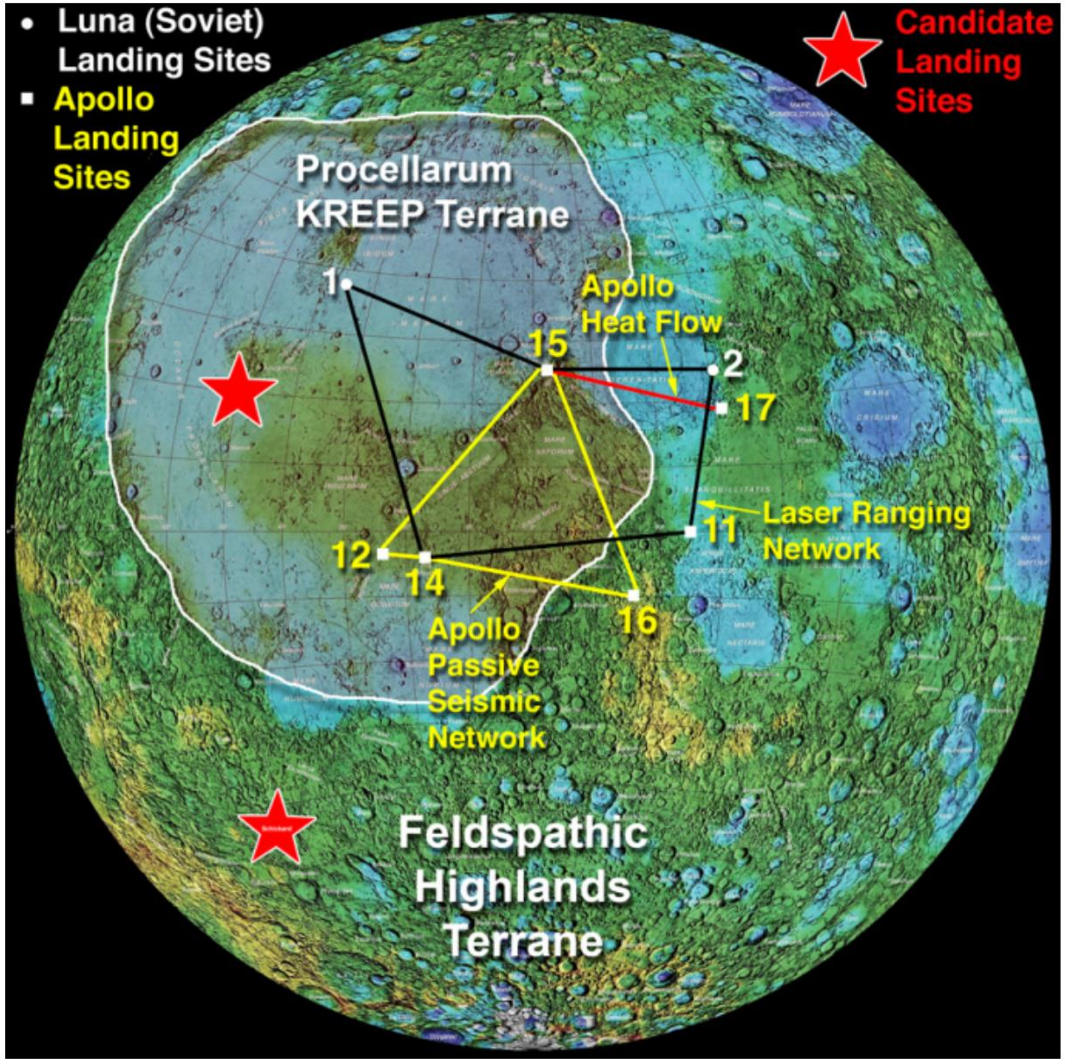
Seismology	Heat flow	Laser ranging	EM sounding
• Detect the maximum number of sources • Multiple instruments with a geographically wide (global) footprint, including observations from the far side	• Land >200 km away from boundaries between regions with disparate thermal properties	• Increase the footprint of current network of retroreflectors • Near side sites only to take advantage of Earth-based lasers	• Co-location with other experiments. • Studies of crustal magnetism and plasma interaction studies would benefit from measurements at sites of strong DC magnetization and/or albedo anomalies

General site considerations: few boulders, slopes <10°, near lobate scarps/thrust faults to test ongoing seismicity

Previous landing site suggestions

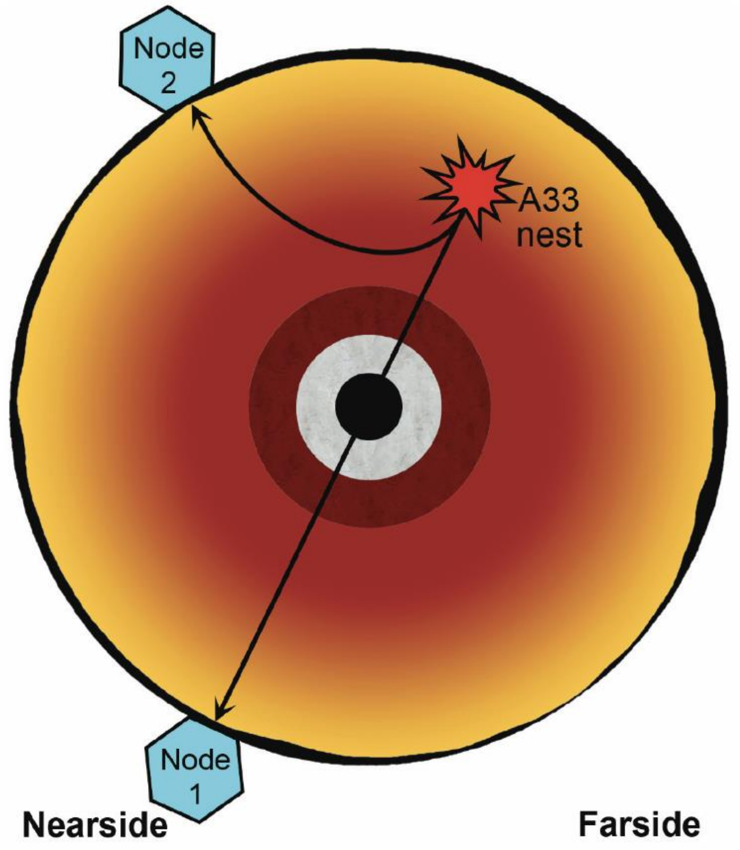
Landing sites suggested by previous mission concept LUNETTE: A Lunar Geophysical Network

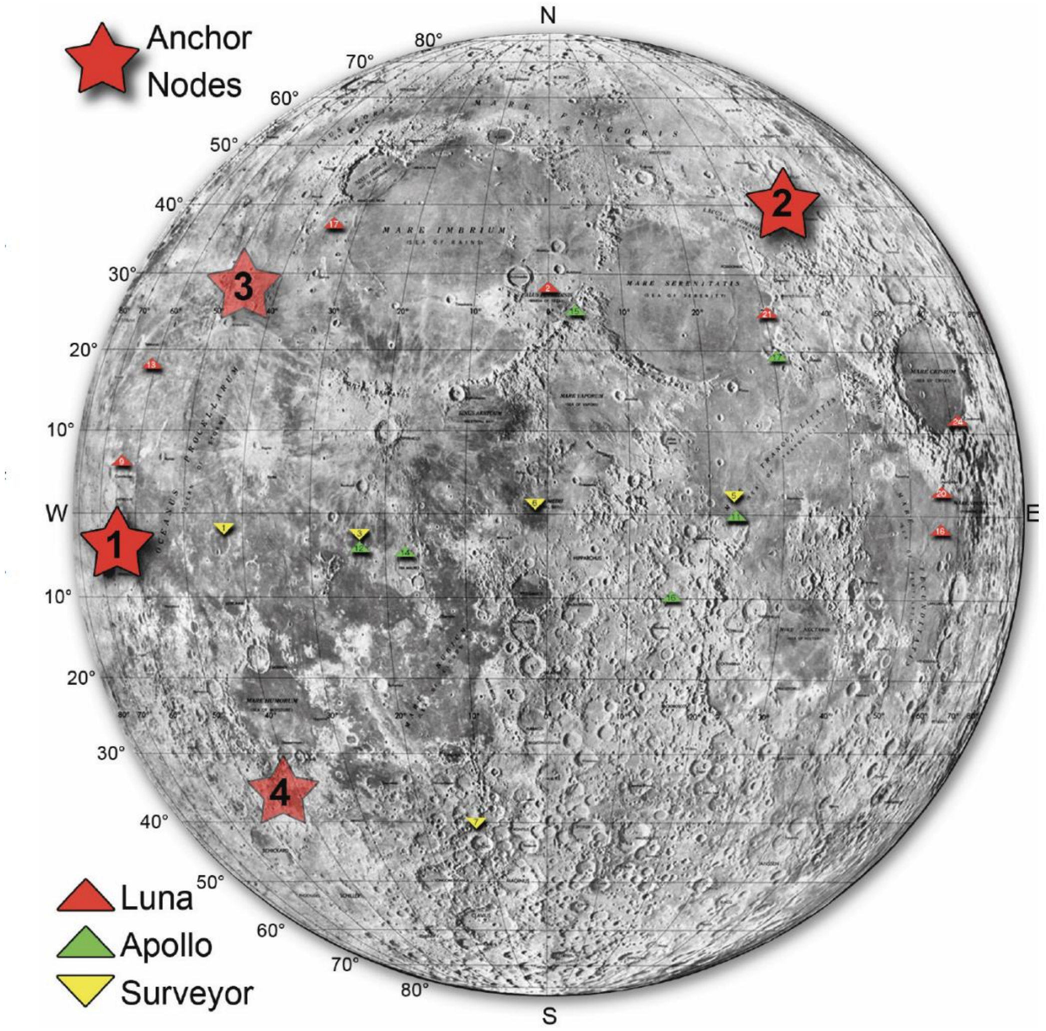




Previous landing site suggestions

Landing sites suggested by previous mission concept
ILN: The International Lunar Network

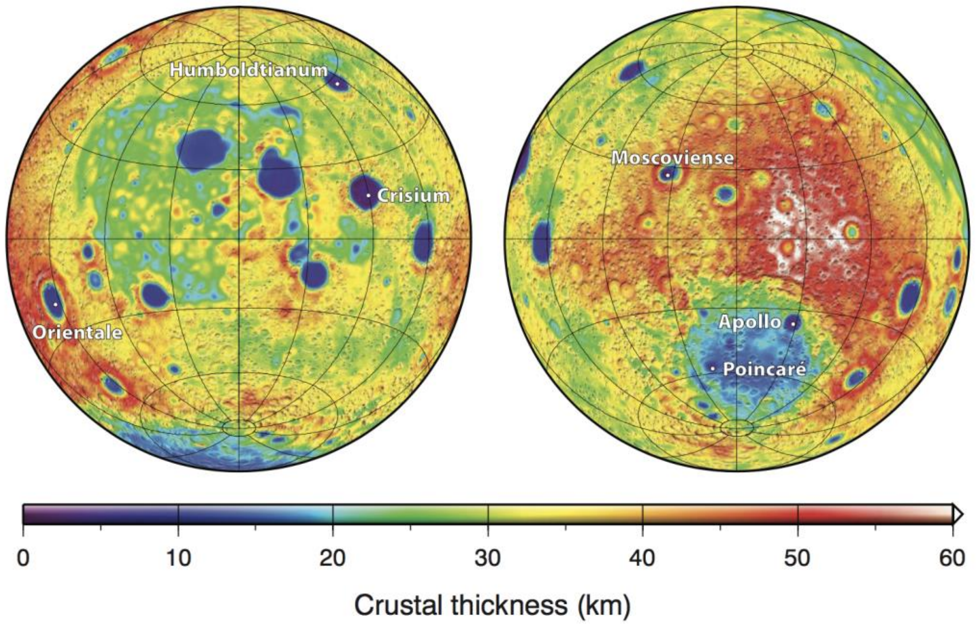


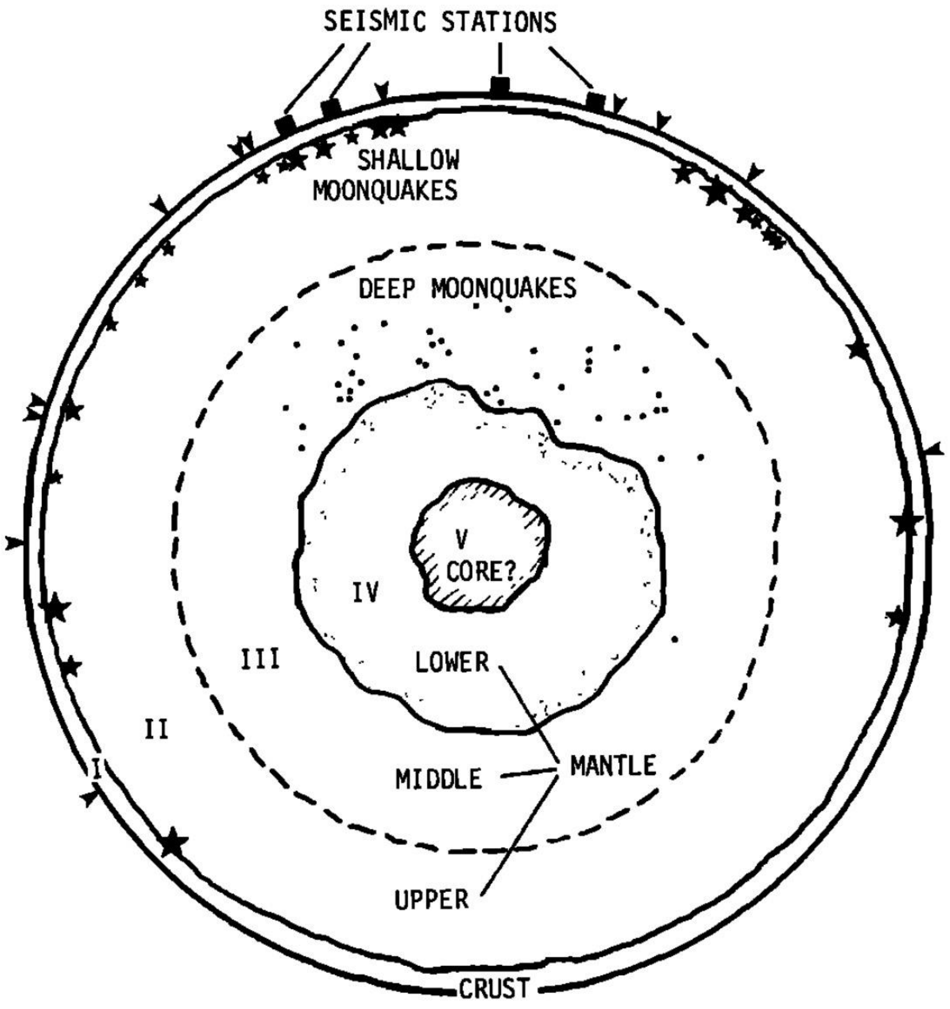


Landing on the far side

Requires orbital relay for communications, but enables observations to address key unknowns regarding:

- Far side seismicity
- Global dichotomies
  - ➢ Crustal thickness
  - ➢ Mare volcanism & related geochemical signatures



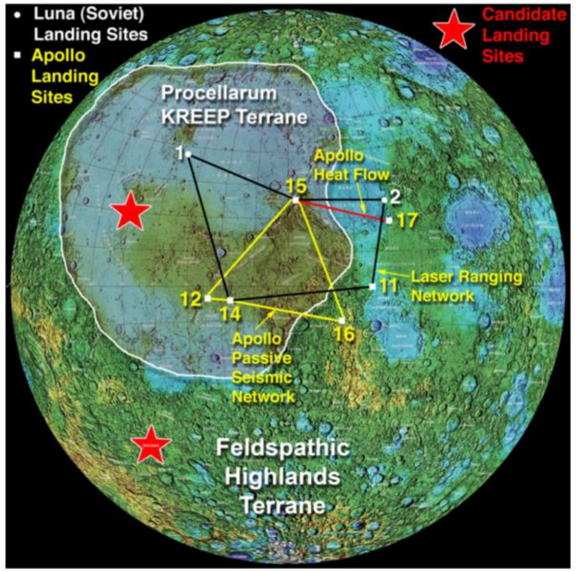


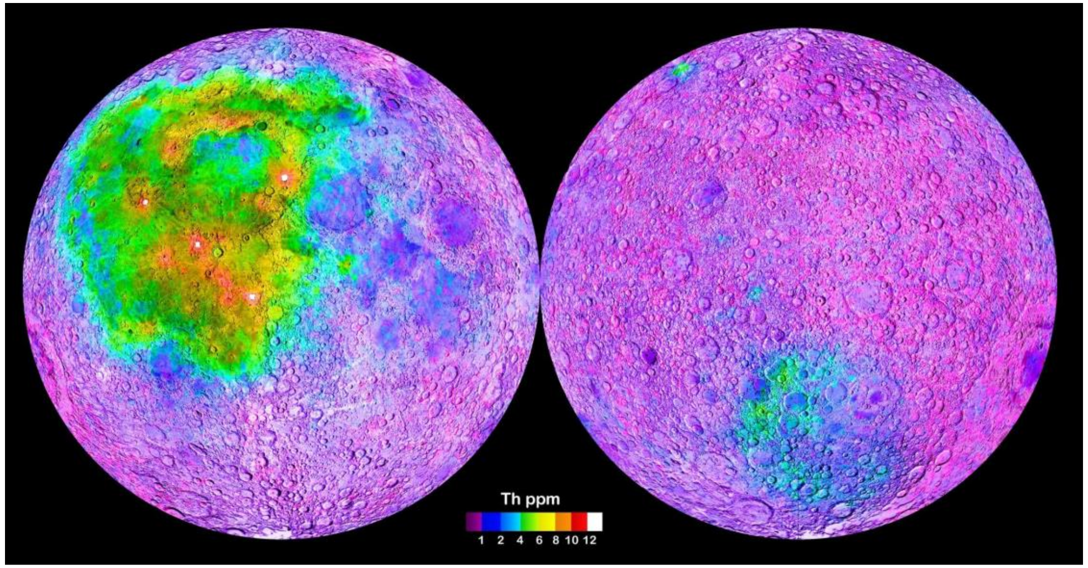
Synergy with geothermal measurements

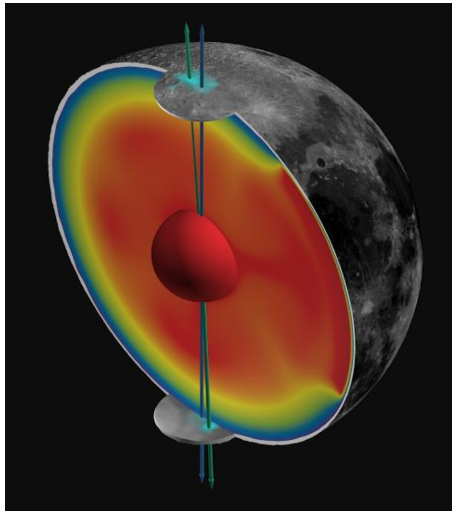
Obtaining measurements both inside and outside of the PKT is also important for understanding geothermal heat production and interior thermal distribution.

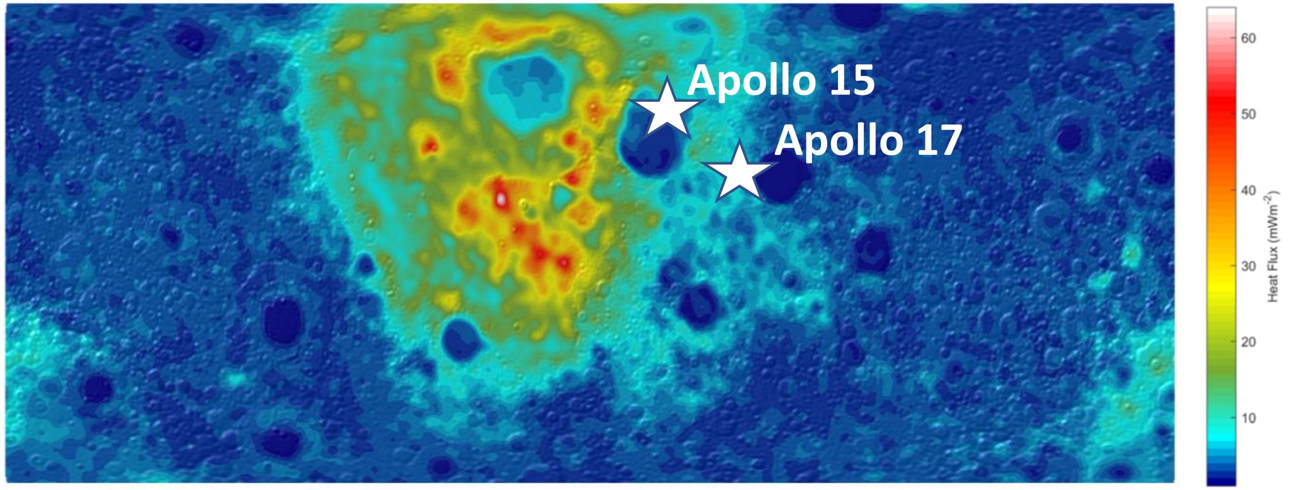
The Apollo Heat Flow Experiments were both within areas dominated by Thorium-rich crust; a heat flow probe outside this region would more tightly constrain mantle heat production and composition.

The PKT could also create a hot mantle region, which may be detectable in both heat flux and seismic measurements.









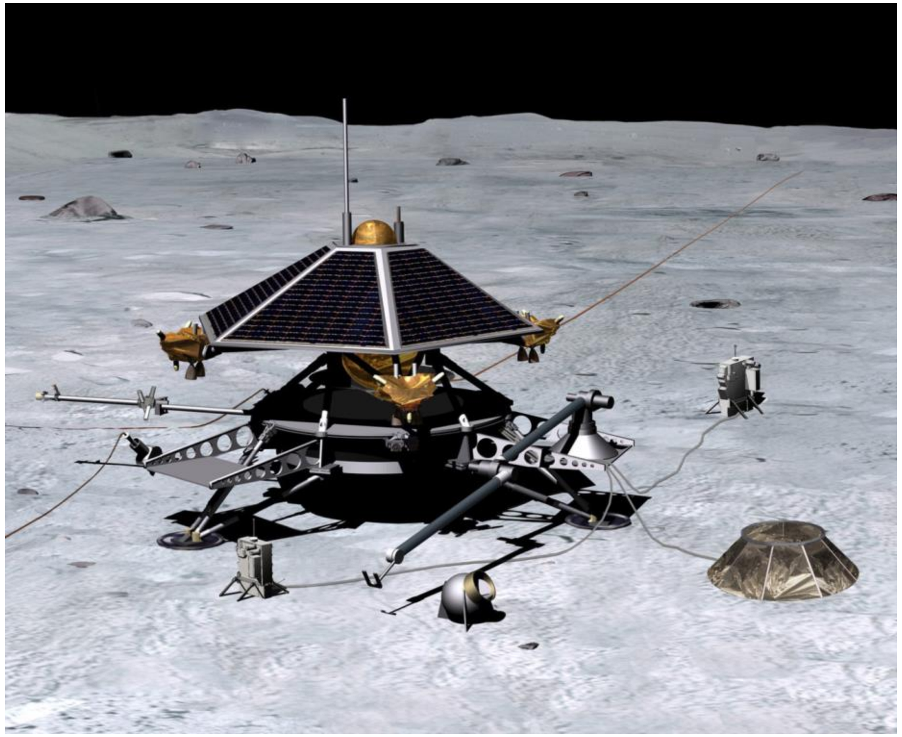
Conclusions

Seismology benefits science

- Modern, broadband scientific instrumentation and innovative robotic deployment mechanisms are currently under development by several U.S. and international teams
- NASA's New Frontiers 5 AO will target a Lunar Geophysical Network
- Favored landing sites are either internal or external to the Procellarum KREEP Terrane (not at boundaries), close to the lunar limbs, and on the far side

Seismology benefits exploration

- Seismic hazard can also be assessed with small, lightweight accelerometers that can easily be accommodated in lander structural components
- Any lander at any location on the lunar surface should have a seismometer!



JPL LUNETTE mission concept