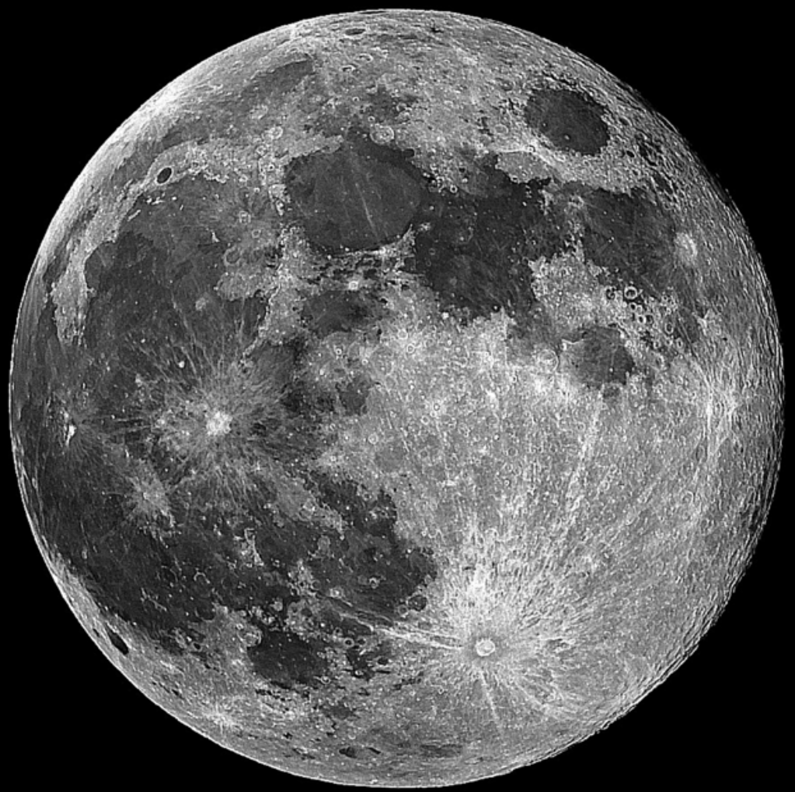
Lunar Geophysical Network

A New Frontiers Mission delivering Solar System Science



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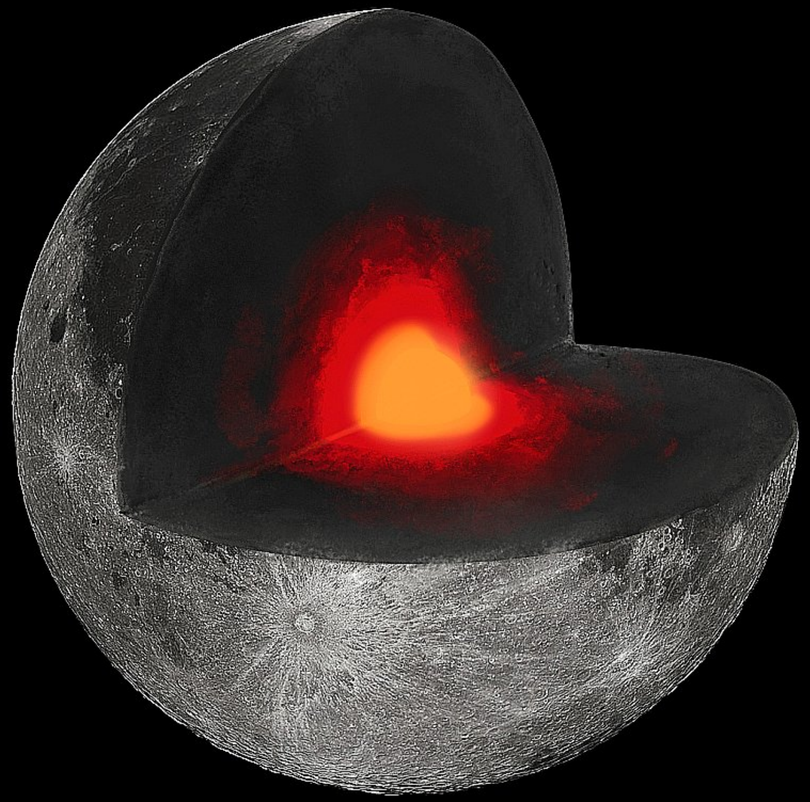

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Community Support

Key points from the 2018 LEAG SAT Report: Advancing Science of the Moon
(https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf)

GRAIL data improved lunar gravity, revealed features of the lunar crust in unprecedented detail (Inc. fractures and other tectonic structures, mascons, lava tubes & other volcanic landforms, impact basin rings, & the shape & size of complex to peak-ring craters.

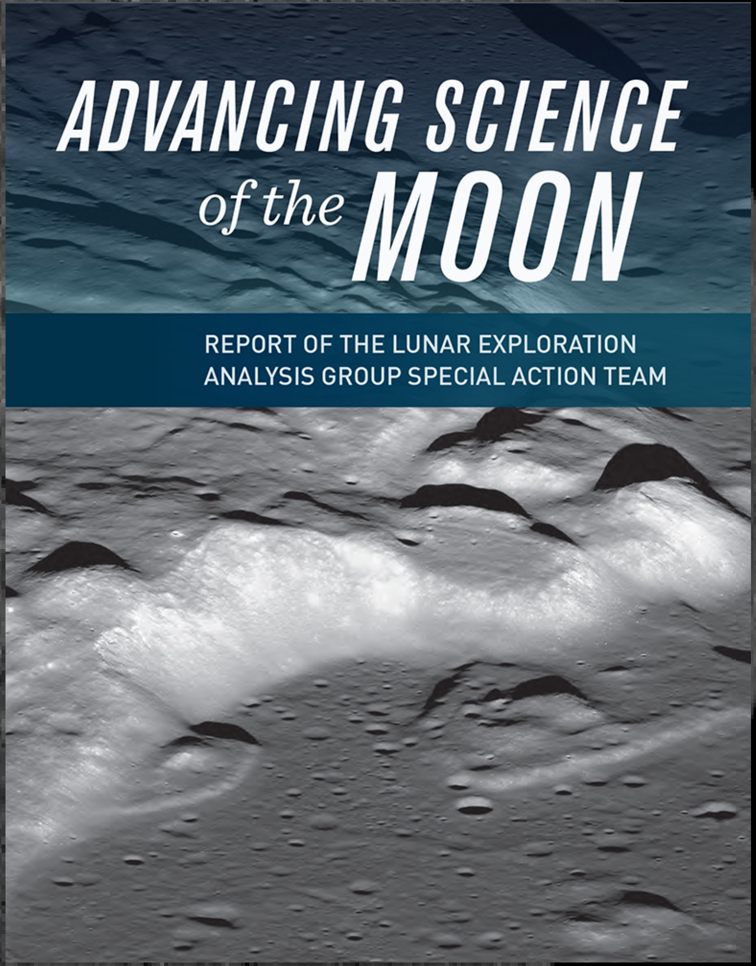
- ***A more nuanced view of the lunar interior drives new questions to be answered by an LGN in concert with GRAIL investment***

Applying terrestrial seismic techniques to Apollo data can quantify scattering effects in the shallowest layers of the lunar regolith (meter scale).

- ***Recent studies have made progress quantifying these effects, feeding instrument design and deployment needs***

GRAIL analysis produced a family of core models consistent with geodetic parameters (inc. constraints from LLR), but gravity data alone have not yet definitively identified the presence of an inner core. LLR data suggest the lunar core is liquid, although combining gravity, topography and laser ranging data to model the deep lunar interior produces a solid inner core and total core size akin to the core modeled using Apollo seismic data.

- ***Additional laser ranging stations would provide significant scientific return***



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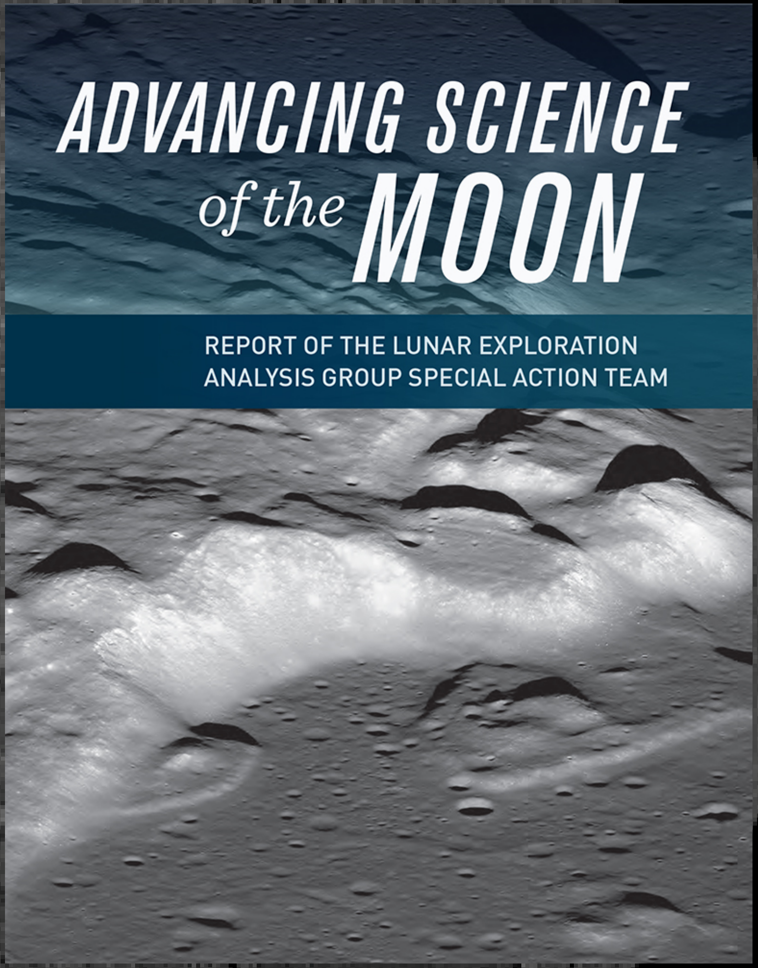
<u>Key points from the 2018 LEAG SAT Report: Advancing Science of the Moon</u>
(https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf)

Crustal Th in the PKT would lead to asymmetric mantle temperatures and cause a giant "mantle plume" below the PKT; the influence of ilmenite on mantle overturn may have also permitted a single upwelling plume. GRAIL data revealed a dyke system surrounding the PKT, calling into question the long-standing theory that the PKT is an ancient impact basin. Rather this work suggests it may be a magmatic-tectonic feature overlying the nearside "magma plumbing system" that supplied the mare with their basaltic infills. A thermal asymmetry that extended into the mantle may have produced true polar wander.

- ***Continued modeling efforts help define new hypotheses for heat-producing element distribution and updated landing site considerations***

Paleomagnetic studies of Apollo samples have demonstrated that the Moon had surface magnetic fields of ~30–100 μT between at least 4.2 and 3.56 Ga. The widely accepted theory for the generation of this field is an ancient core dynamo.

- ***Sample studies continue to make surprising discoveries about the lunar dynamo, but need the global context of an LGN type mission***



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LEAG 2019 Annual Meeting Finding on New Frontiers 5

LEAG reiterates the importance of using the decadal survey process to identify science priorities that should be addressed within the New Frontiers program. This process is the best route for building community consensus for large, high-priority PI-led missions. Any changes to the New Frontiers target list should be made via a formal, community-focused process, as recommended in the Planetary Decadal Midterm Review. **NF5 is nominally scheduled to include a lunar geophysical network, and LEAG affirms the importance of such a mission for lunar and Solar System science, as articulated in the Lunar Exploration roadmap.**

LEAG reaffirms the high priority of the science goals for South Pole-Aitken basin Sample Return (SPA-SR), which would provide insight into Solar-System-wide bombardment, the conditions under which life emerged on Earth, and the lunar interior. Though the important nature of the science goals of SPA-SR have been reiterated in the last two decadal surveys, such a mission has not yet been selected. Inthe interim, multiple lunar orbital missions have provided a wealth of data that suggest SPA is not the only location on the Moon where these science goals could be addressed. In comparison to other NF targets that led to selected missions (e.g., Jupiter Polar Orbiter with Probes, Ocean Worlds), the mission implementation for SPA-SR that is laid out in the decadal is unduly restrictive.

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NAS Committee on Astrobiology and Planetary Science

<u>Options for the Fifth New Frontiers Announcement of Opportunity (2020)</u>

http://nap.edu/25868

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<u>Finding</u>: CLPS missions by their design (and current implementation approach) cannot replace the integrated New Frontiers–level science investigations of the LGN. But, the CLPS program, if so utilized, represents a potentially important risk reduction mechanism for LGN instruments and technologies.

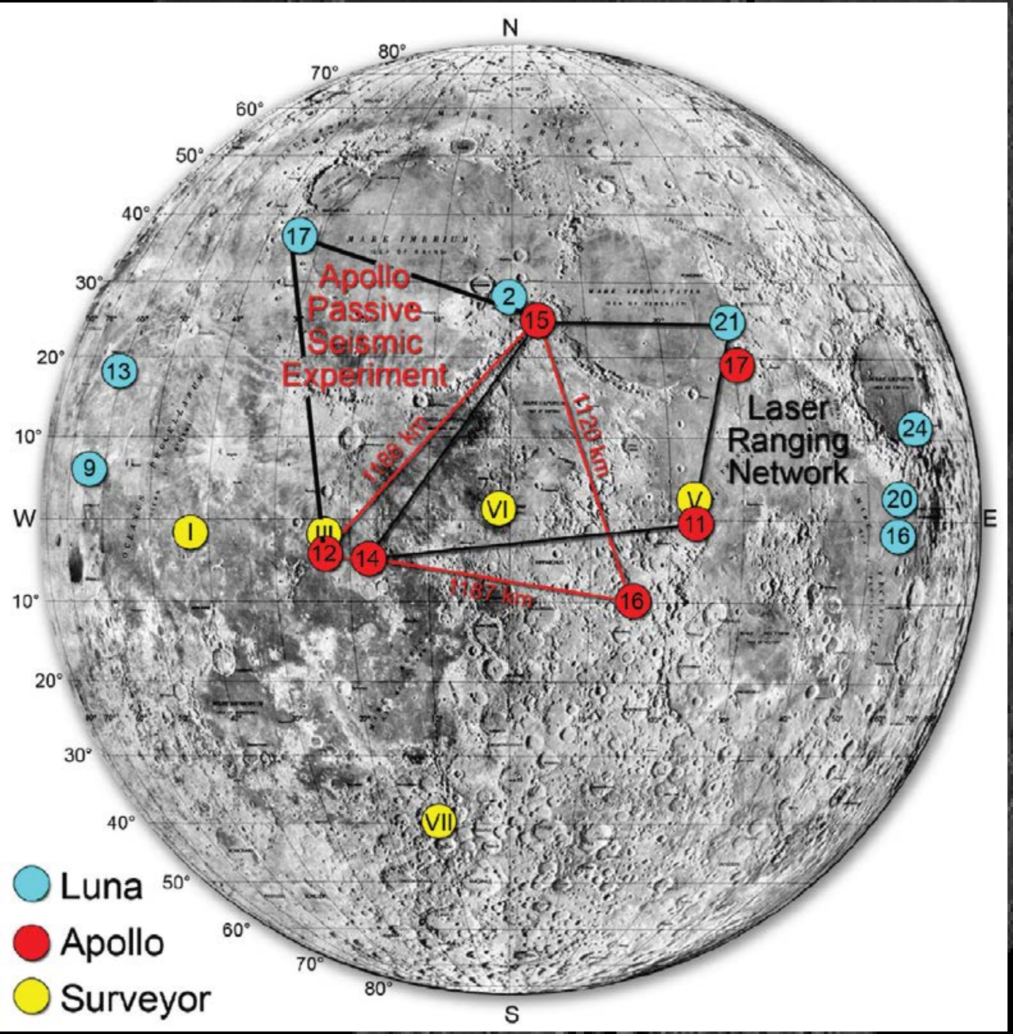
<u>Finding</u>: Scientific discoveries from lunar orbit or in terrestrial laboratories and technical advances in instrumentation since the 2011 decadal survey do not replace or obviate the need for the LGN.

<u>Finding</u>: The scientific rationale in V&V for the LGN has not changed, and if anything has become more compelling, so reconsideration by NASA of inclusion of LGN in the NF5 target list is not warranted. Substantial investment in deployable geophysical instrumentation for the lunar surface over the past decade has made the scientific case for LGN more robust in the sense of being more achievable.

[9]Committee member Clive Neal recused himself from discussion of, or contributions to, the findings in this section of the report

Lunar Geophysical Network

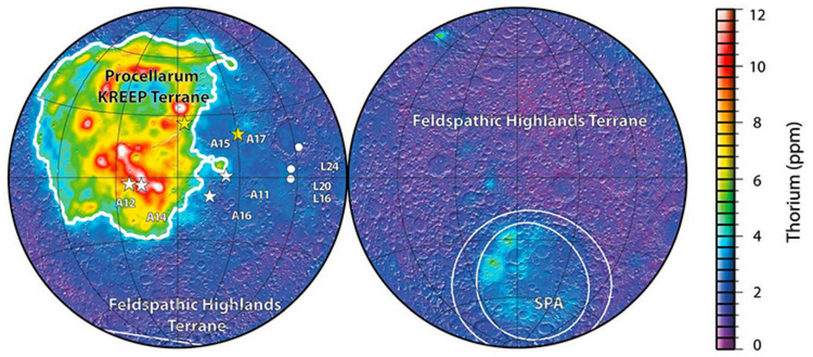
Must be better than Apollo (and Luna).



- Narrow aperture of the seismic network
- Heat flow only at Apollo 15 & 17 – across the PKT boundary
- Surface magnetometers only at Apollo 12 and 16
- EM sounding results ambiguous
- Laser ranging network only in the northern central nearside
- Instruments better than Apollo

Lunar Geophysical Network

New data since Apollo that support the need for a geophysical network



Recognition of lunar terranes.

- Surface only?

Jolliff et al. (2000) *JGR* **105**, 4197-4216; Laneuville et al. (2018) *JGR Planets* **123**, 3144-3166.

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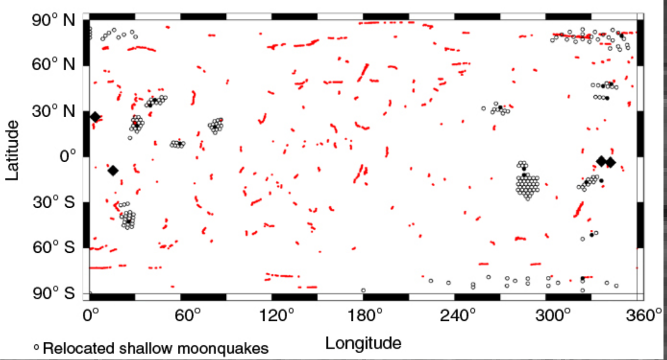


Lobate scarps.

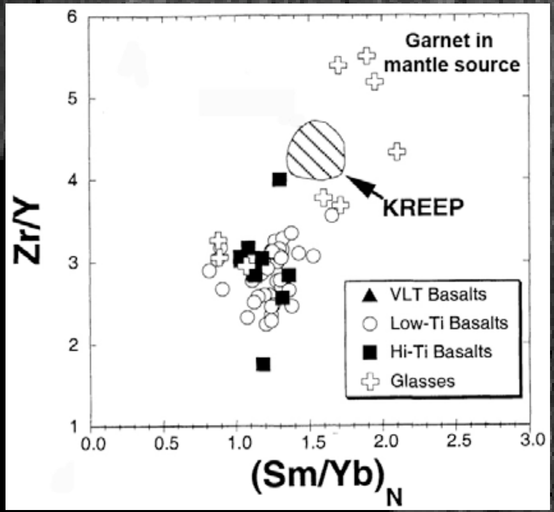
- Shallow MQ sources.
- Still active – producing boulder trails.

Watters et al. (2019) *Nat. Geosci.* **12**, 411-417
Kumar et al. (2019) *GRL* **46**, 7972-7981

Young basalts in Oceanus Procellarum.

- Implications for heat flow

Hiesinger et al. (2011) *GSA Spec.Pap.* **477**, 1-51



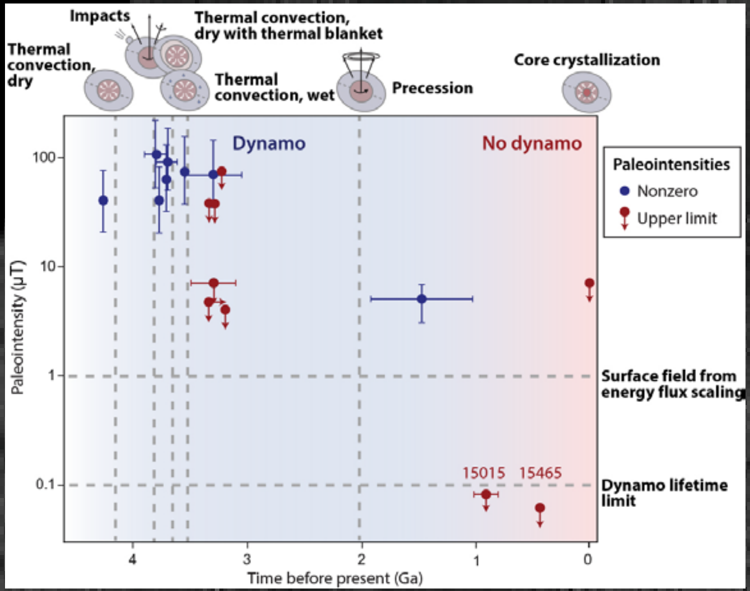
Garnet in the lunar interior.

- Lunar bulk composition

Neal (2001) *JGR* **106**, 27865-27885
Kuskov et al. (2019) *PEPI* **286**, 1-12

Lunar Geophysical Network

New data since Apollo that support the need for a geophysical network



Recognition of potential lunar dynamo.

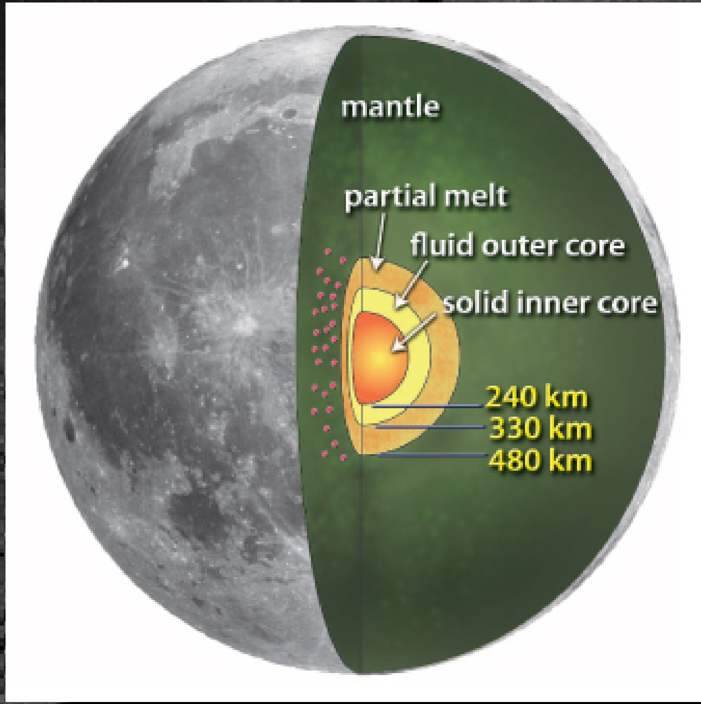
- Implications for the core and thermal budget

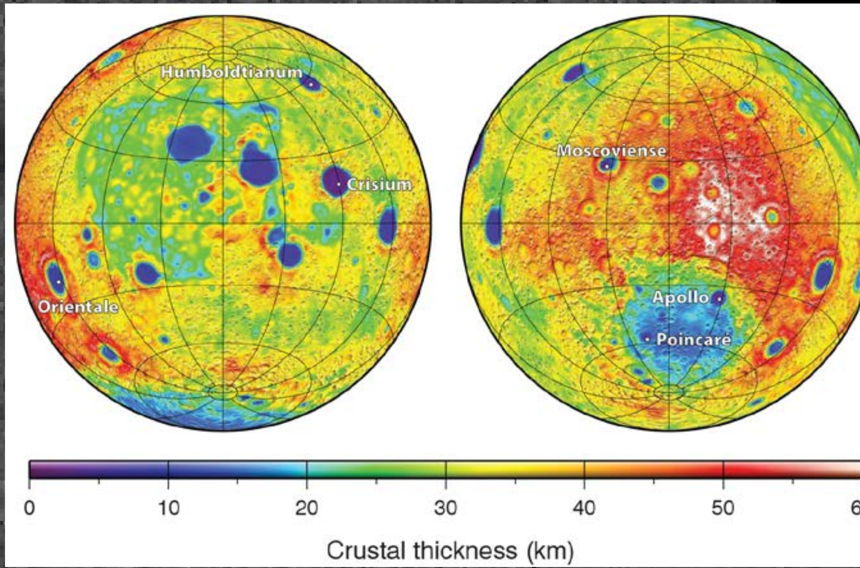
e.g., Mighani et al. (2020) *Sci. Adv.* **6**, eaax0883

Lunar core structure.

- Needs verification

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





Grail gravity data.

- New crustal thickness estimates
- Tied to Apollo seismic data

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

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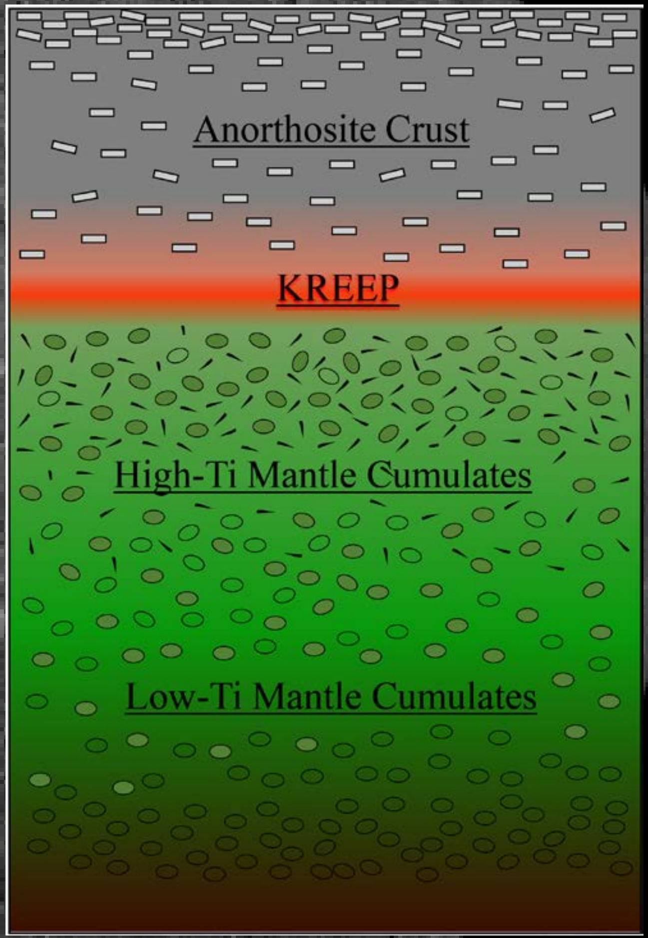
Questions that remain after Apollo

- How does the overall composition and structure of the Moon inform us about initial differentiation of terrestrial planets?
- What is the state, structure, and composition of the mantle and is it consistent with the lunar magma ocean hypothesis (or are there resolvable discontinuities)?
- What is the present heat budget and how could the Moon experience magmatism for >3 b.y.?
- What is the crust and mantle heterogeneity within and between different terranes?
- How did the lunar core form and could it have supported a global magnetosphere (indicated by sample analyses – e.g., Weiss & Tikoo, 2014, Science 346, 1246753, DOI: 10.1126/science.1246753; Mighani et al., 2020, *Sci. Adv.* **6**, eaax0883)
- What is the bulk composition of the Moon?

Lunar Geophysical Network

Goal: Understand the initial stages of terrestrial planet evolution.



Moon is ideal to test this:

- Source region modeling consistent with lunar magma ocean hypothesis.
- Magma oceans hypothesized as initial differentiation of terrestrial planets.

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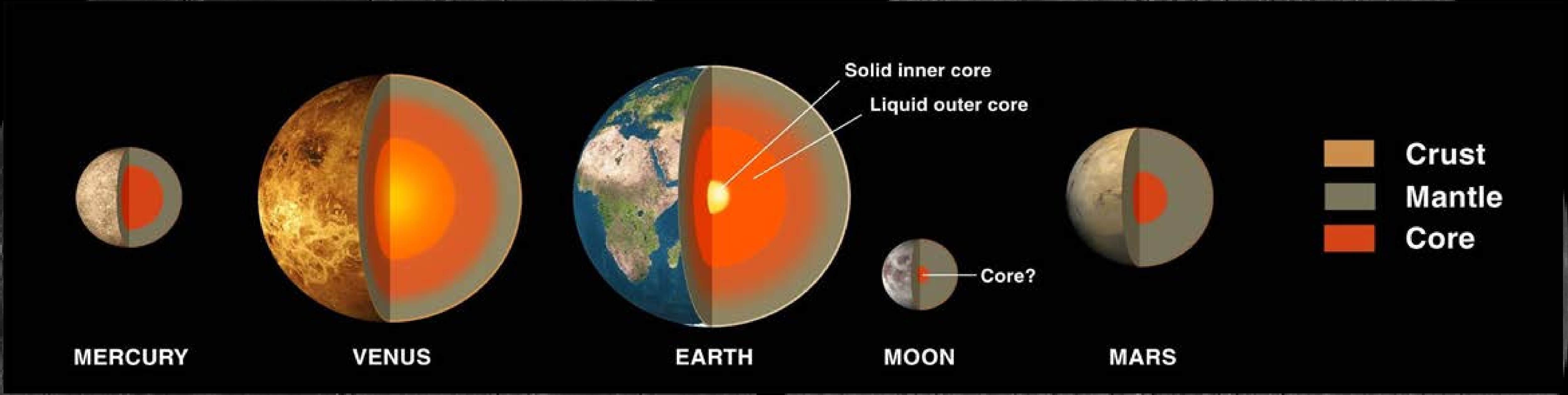
Goal: Understand the initial stages of terrestrial planet evolution.



- Moon forms the cornerstone for investigating this in the inner solar system.
- Implications for early evolution of Earth after the giant impact and formation of the lunar core and the core dynamo.

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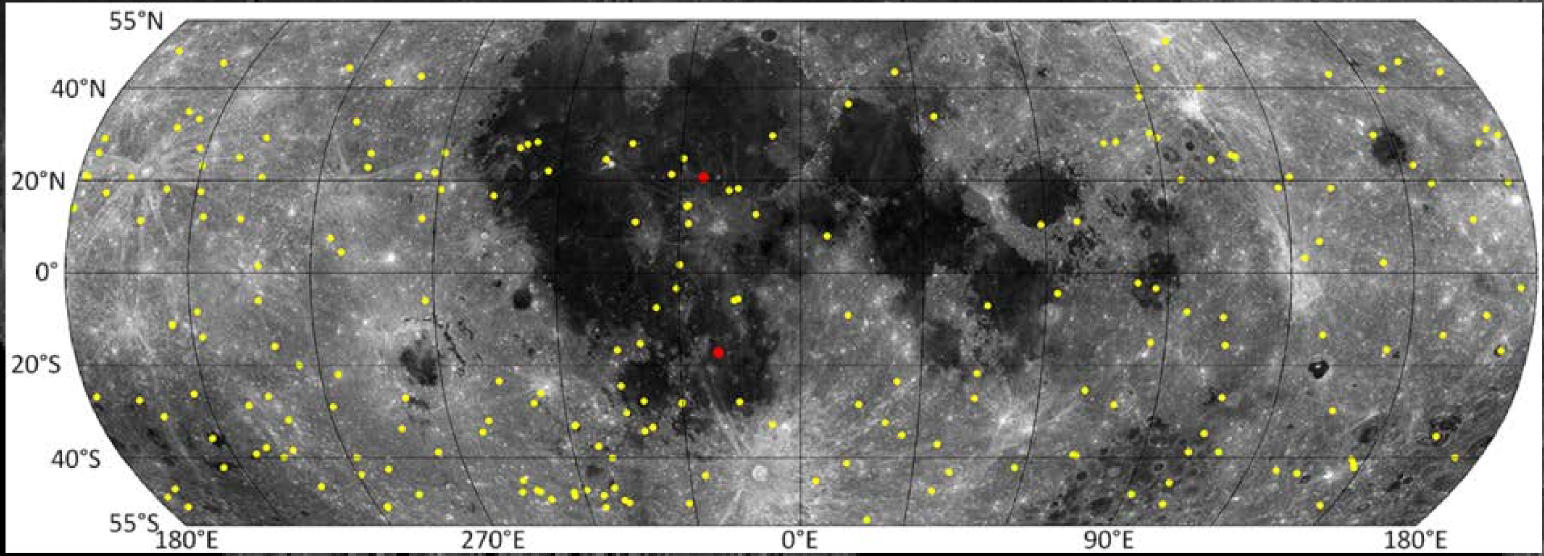
Lunar and Solar System science questions

What is the current impact flux in the inner solar system?

- Is the current flux observed by impact flashes and new craters from LRO observation the correct one?
- Opportunistic seismic sources to study the structure of the Moon – need to accurately locate impact sites.



Distribution of new impact craters from LROC:
http://lroc.sese.asu.edu/posts/943

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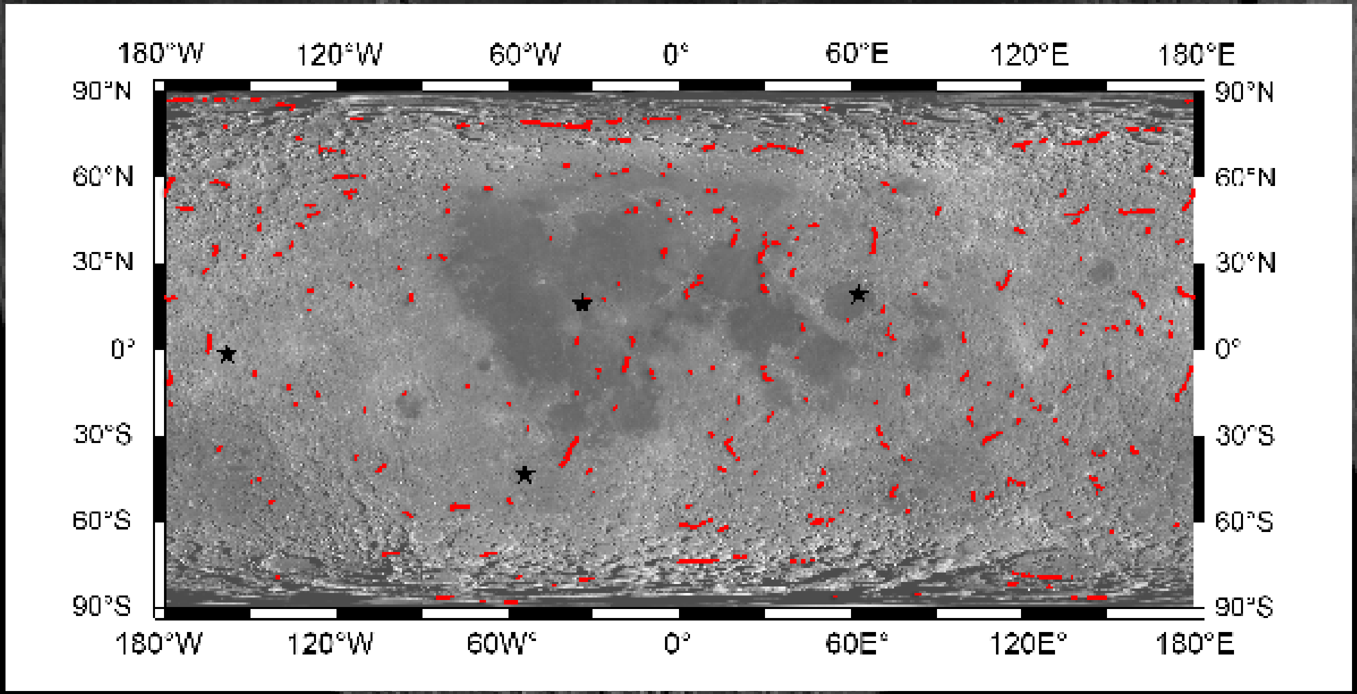
Shallow Moonquakes

- Do shallow moonquakes represent movement along thrust faults (e.g., Watters et al., 2019, *Nat. Geosci.* **12**, 411-417)?
- Do moonquakes present a threat to future human infrastructure (Oberst and Nakamura, 1992, 2nd *Lunar Bases Space Activ. Conf.*, 231-233)?



Global distribution of lunar lobate thrust fault scarps (red lines >3500 have been detected). These are found predominantly in the highlands, at all latitudes.

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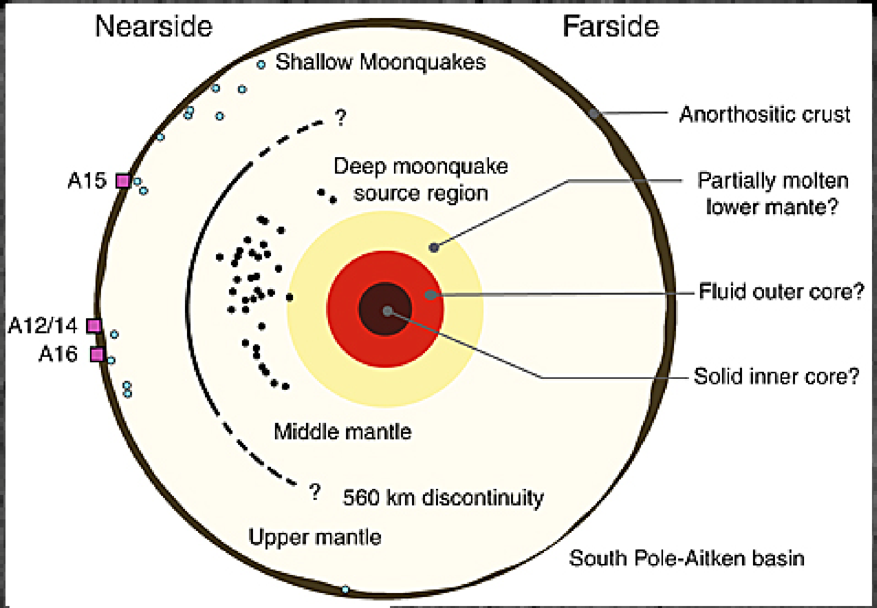
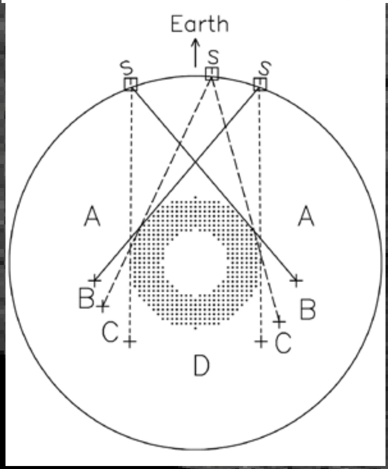
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Deep Moonquakes

- Do deep moonquakes occur on the farside of the Moon (Nakamura et al., 1982, *PLPSC 13th*, in *JGR* **87**, A117-A123; Nakamura, 2005, JGR 110, E01001, doi:10.1029/2004JE002332)?
- Is the appearance that the farside is aseismic an artifact of network aperture, interior structure, or is it linked to the presence of maria on the nearside only (e.g., Laneuville et al., 2018, *JGR Planets* **123**, 3144-3166)?
- What is the mechanism for triggering deep moonquakes (Weber et al., 2009, *JGR* **114**, E05001, doi:10.1029/2008JE003286; Kawamura et al., 2017, *JGR Planets* **122**, 1487–1504)?





Nakamura (2005) *JGR* **110**

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Internal Structure – current uncertainty

Are there global discontinuities in the mantle and do they relate to the lunar magma ocean?

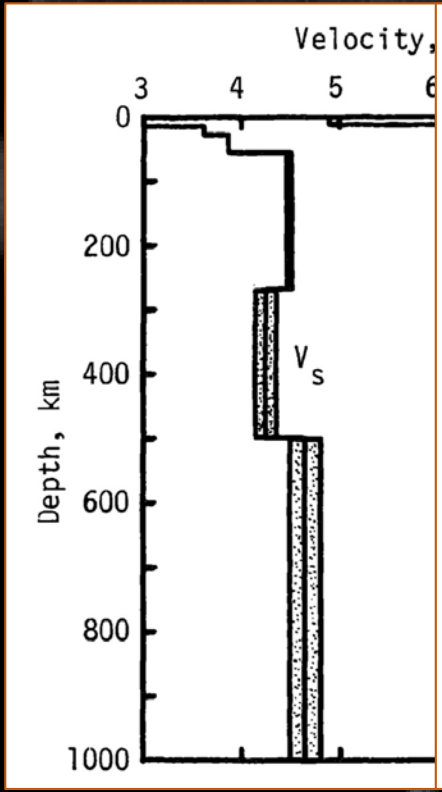
Nakamura (1983) *JGR* **88**, 677-686

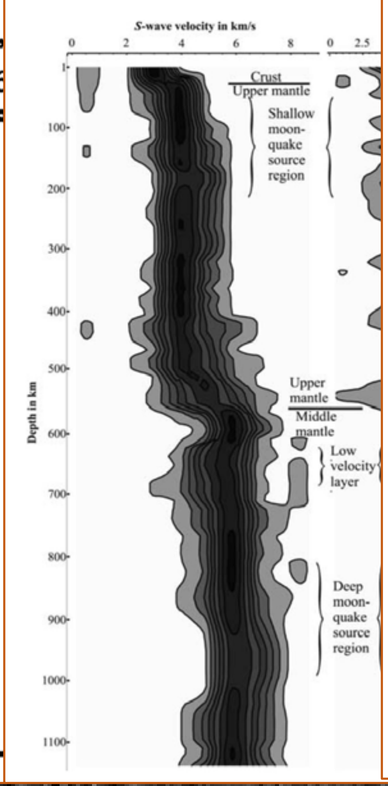
Lognonné et al. (2003) *EPSL* **211**, 27-44

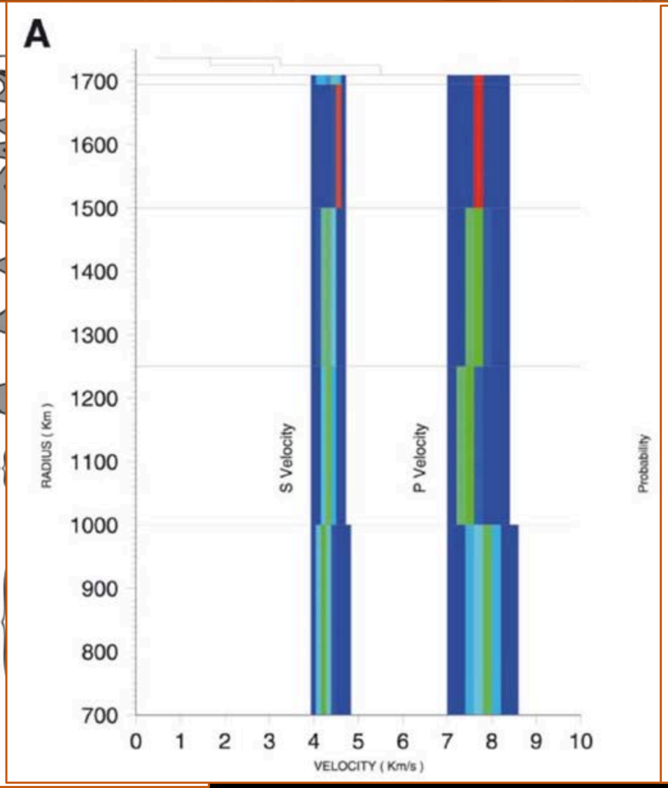
Khan & Mosegaard (2001) *GRL* **28**, 1791-1794

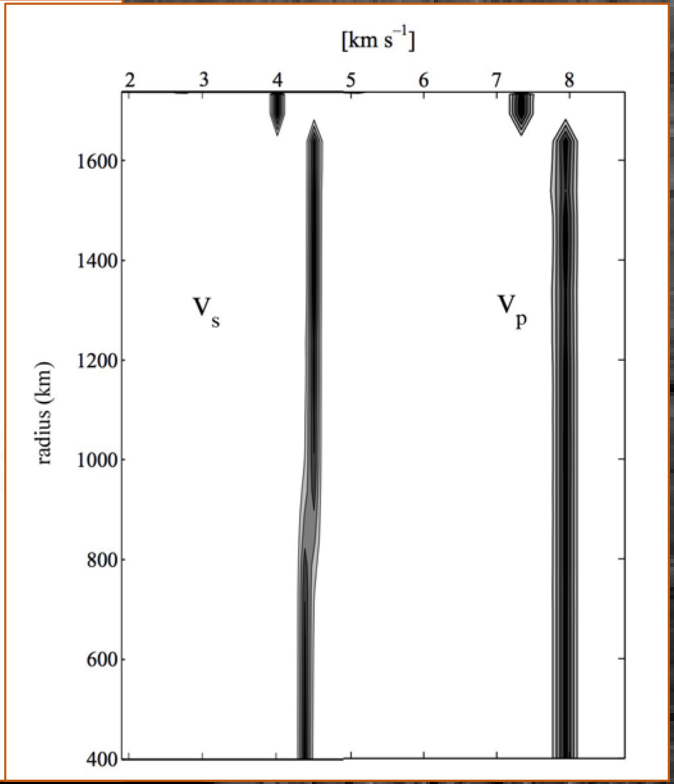
Khan & Mosegaard (2002) *JGR* **107**

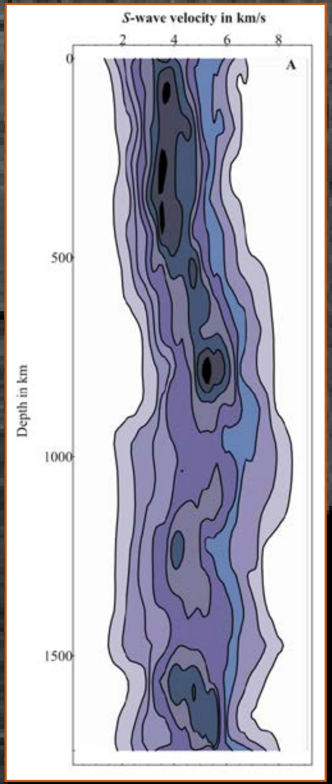
Khan et al. (2007) *GJI* **168**, 243-258











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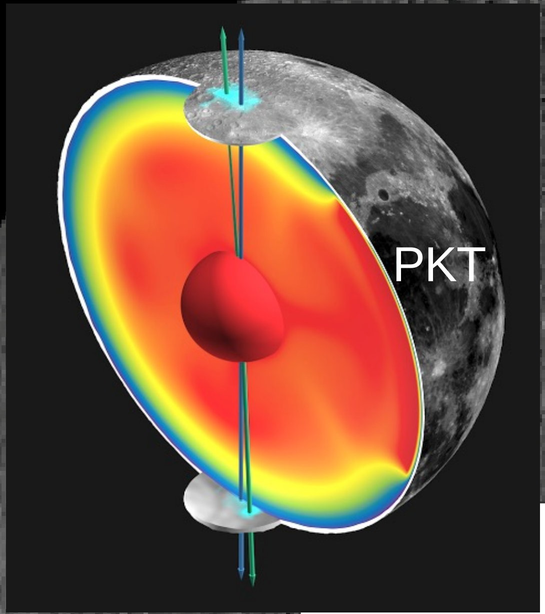
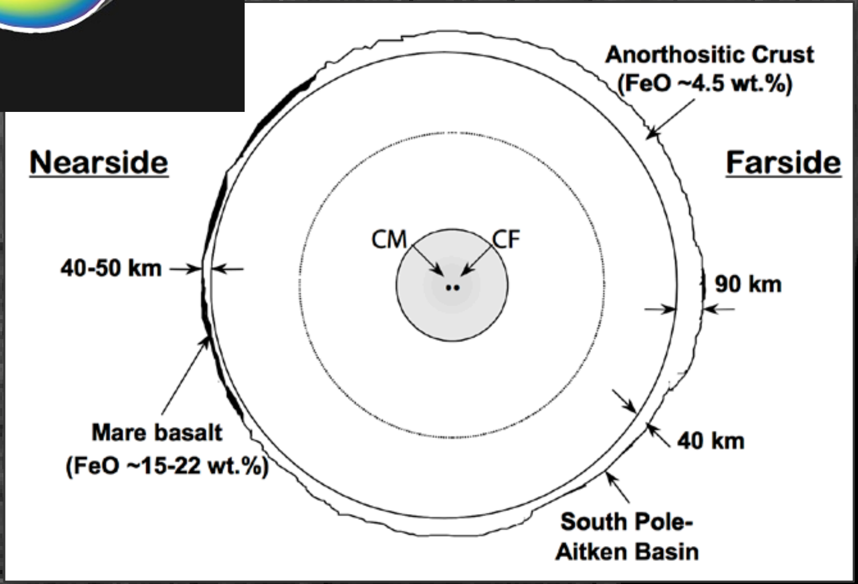
Lunar Terranes

- Do different lunar terranes have unique heat flow budgets and what does this imply about the bulk geochemical composition of the Moon (Laneuville et al., 2018, *JGR Planets* **123**, 3144-3166)?
- What is the lateral/vertical structure and composition as revealed by electrical conductivity (Hood et al., 1982, *JGR* **87**, 5311-5326; Grimm, 2013, *JGR* **118**, 768–777)?
- What are the differences between near and farside hemispheres? (e.g., Jolliff et al., 2000, *JGR* **105**, 4197-4216) Are differences observed at the surface manifest in the interior and if so, how? (e.g., Wieczorek and Phillips, 2000, *JGR* **105**, 20417-20430).





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

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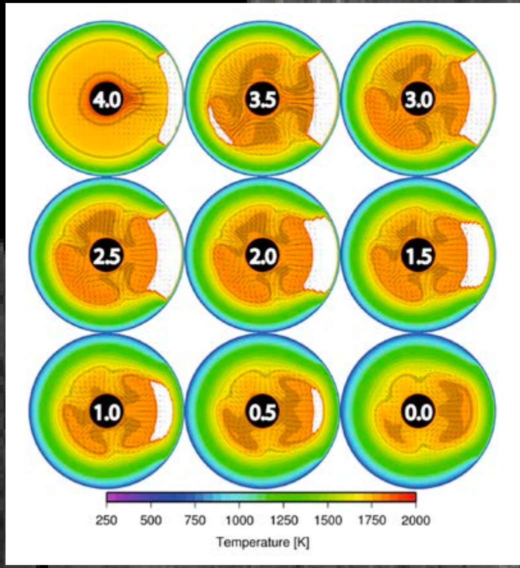
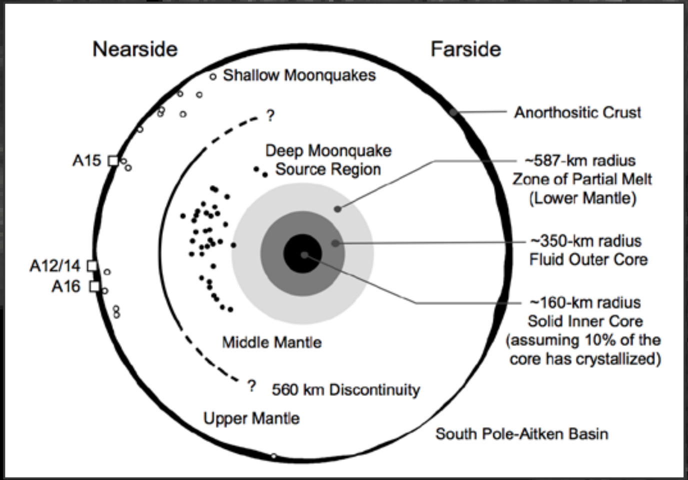
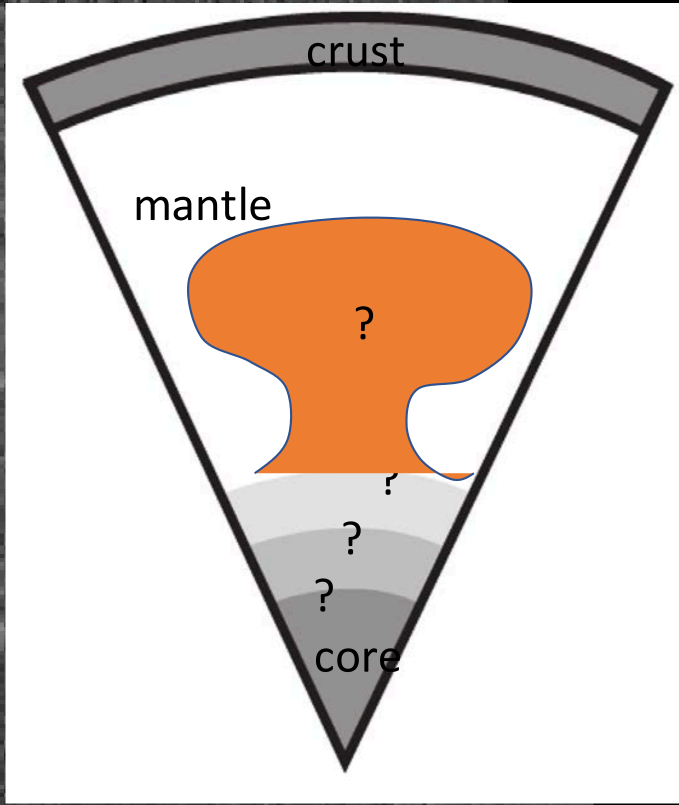
Core-Mantle Boundary

- What is the nature of the presumed "partial melt layer" on top of the core mantle boundary, and why does it exist? (e.g., Elkins-Tanton et al., 2002, EPSL 196, 239-249; Weber et al., 2011, *Science* **331**, 309-312; Khan et al., 2014, JGR Planets 119, 2197–2221)
- Can brittle failure occur at depths where the mantle should be hot? (e.g., Nimmo et al., 2012, JGR 117, E09005, doi:10.1029/2012JE004160).

Laneuville et al. (2014) *EPSL* **401**, 251-260.







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

Lunar Geophysical Network

Goal: Understand the initial stages of terrestrial planet evolution.

Objectives:

- Evaluate the interior structure and dynamics of the Moon.
- Constrain the interior and bulk composition of the Moon.
- Delineate the vertical and lateral heterogeneities within the interior of the Moon as they relate to surface features and terranes.
- Evaluate the current seismo-tectonic activity of the Moon (SMQ, DMQ, Thermal, Impacts).

Image Credit: National Geographic

Lunar Geophysical Network

Goal: Understand the initial stages of terrestrial planet evolution.

Investigations:

- Determine the size, state, and composition of the lunar core (building on the work of Weber et al., 2011, *Science* **331**, 309-312; Garcia et al., 2011, *PEPI* **188**, 96-113).
- Determine the state and chemical/physical stratification of the lunar mantle.
- Determine the thickness of the lunar crust and characterize its vertical and lateral variability (refining and adding fidelity to the GRAIL results of Wieczorek et al., 2013, *Science* **339**, 671-675).
- Determine the thermal state of the lunar interior and elucidate the workings of the planetary heat engine.
- Monitor impacts as an aid to exploring the lunar interior.
- Characterize the seismo-tectonic properties at the lunar surface in support of future human infrastructure (e.g., Oberst & Nakamura, 1992; Ortiz et al., 2006, *Icarus* **184**, 319-326)?

Lunar Geophysical Network

Mission Outline:

- **Baseline Mission** = 4 identical landers position around the Moon containing seismometers, laser retroreflectors, heat flow probes, and magnetotelluric instruments, plus communication satellite.
- **Threshold Mission** = 2 identical landers on the lunar nearside.
- **Mission lifetime**: 6 years with a goal of 10.

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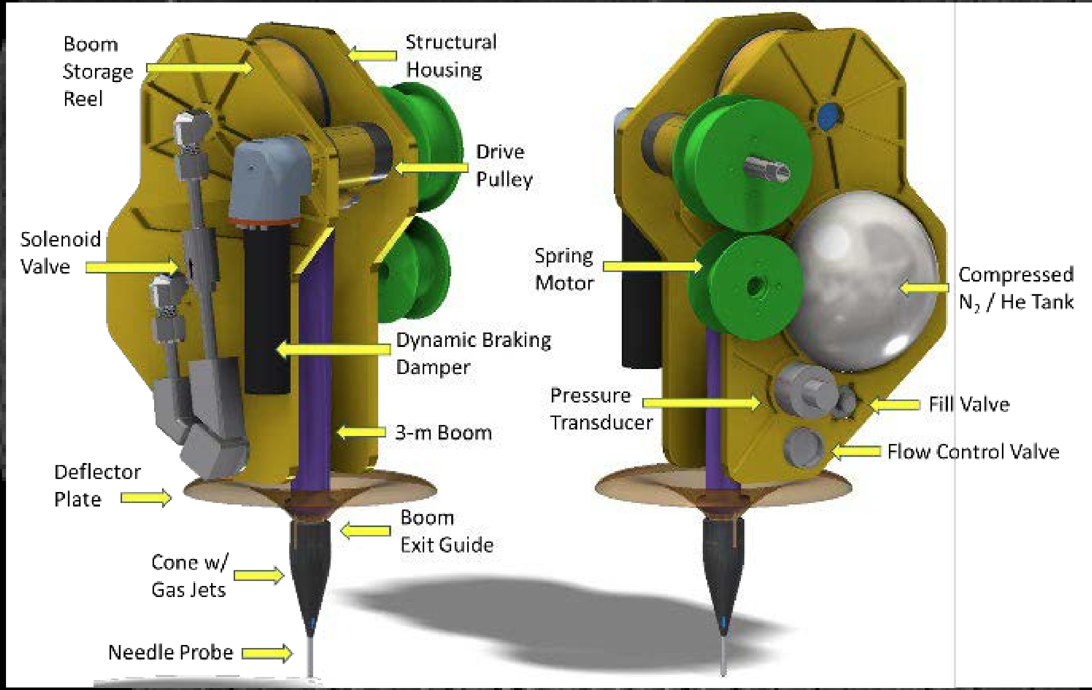
Instruments: Must be better than Apollo

1. Lunar additional mass (+59gr per axis),
2. Larger Displacement Voltage (40 Volt),
3. Larger integrator (80 mF),
4. Resistors tuning

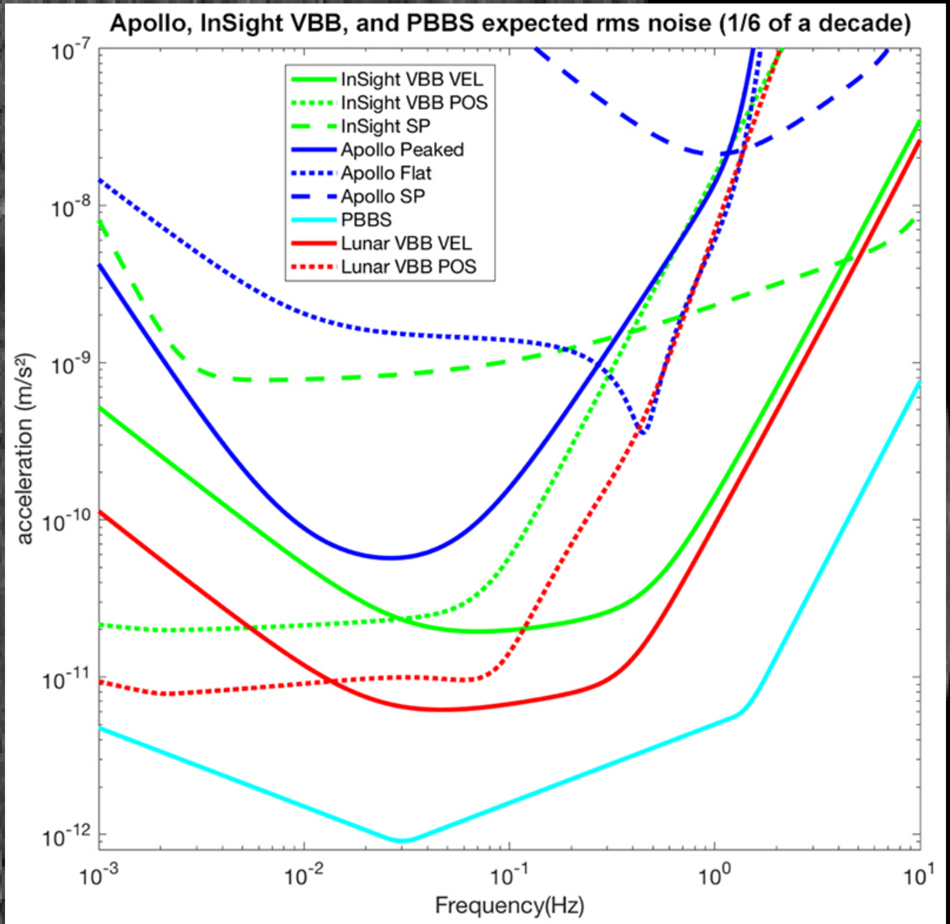


Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER)

Performance

$< 3.5\ 10^{-11}\ m/s^2/Hz^{1/2}$

0.01-0.8 Hz



InSight seismometer adapted for the Moon

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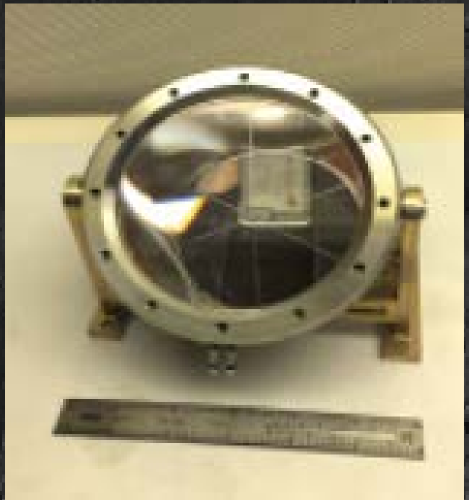
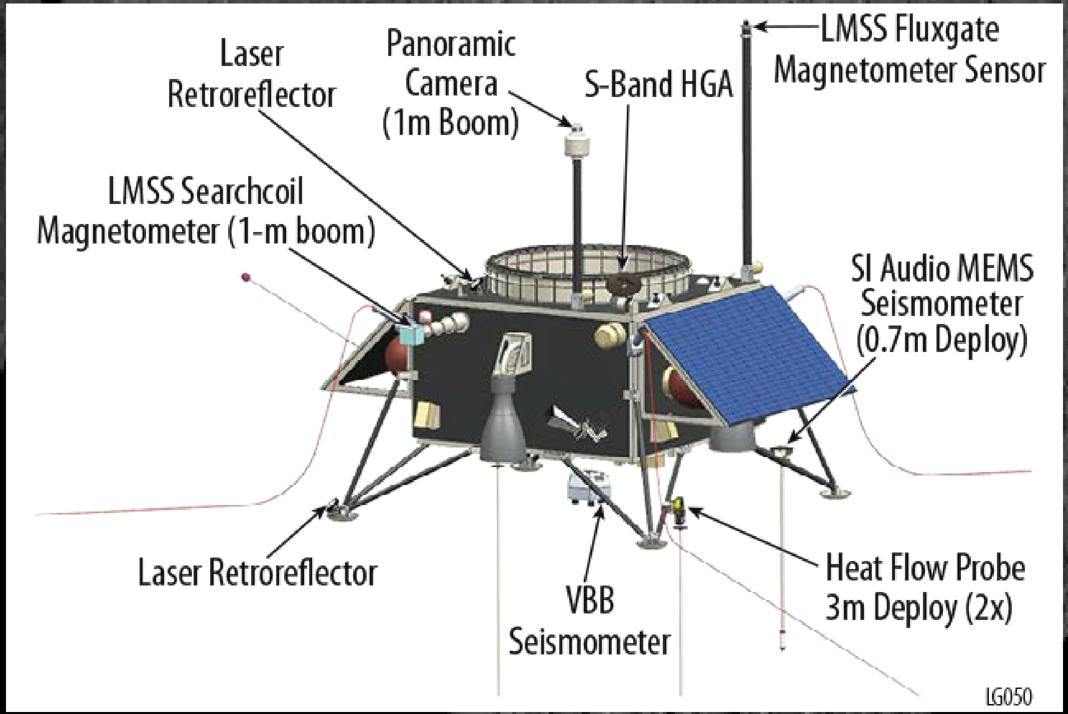
Instruments: Must be better than Apollo

Next Generation Laser Retroreflector (NGLR)



Lunar Magnetotelluric Sounding Suite (LMSS):

- 4 electrodes,
- Mast-mounted fluxgate magnetometer
- Boom-mounted search coil magnetometer
- Plasma detector



Lunar Geophysical Network

Landing Site Requirements

- Broader coverage than Apollo
- Low-risk landing sites
- Well within terrane boundaries (≥200 km)
- Presence of regolith that allows a 3 meter deployment of a heat flow probe
- Proximity to known seismic sources

	Landing Site Requirements	
Overarching Criteria	Broader coverage than Apollo	
	Low-risk landing sites (i.e., low boulder and crater density)	
Measurement Type	**Primary**	**Secondary**
Seismicity	Use known seismic sources to examine the core, mantle, and crust	Proximty to thrust faults (lobate scarps, wrinkle ridges)
Magnetotelluric	Location well within terrane boundaries	Benign magnetic signature at the surface
Heat Flow	Location well within terrane boundaries	Regolith available for full deployment
Laser Retroreflectometry	Expansion of the existing network	Place nearside stations near as possible to the limb

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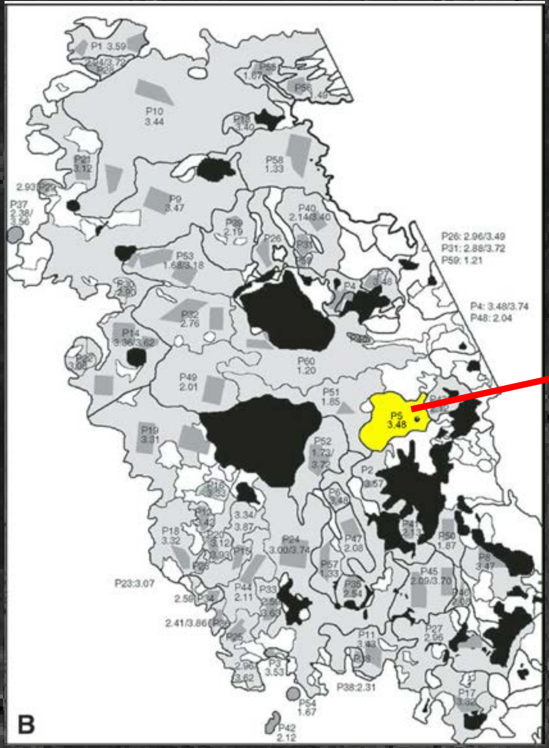
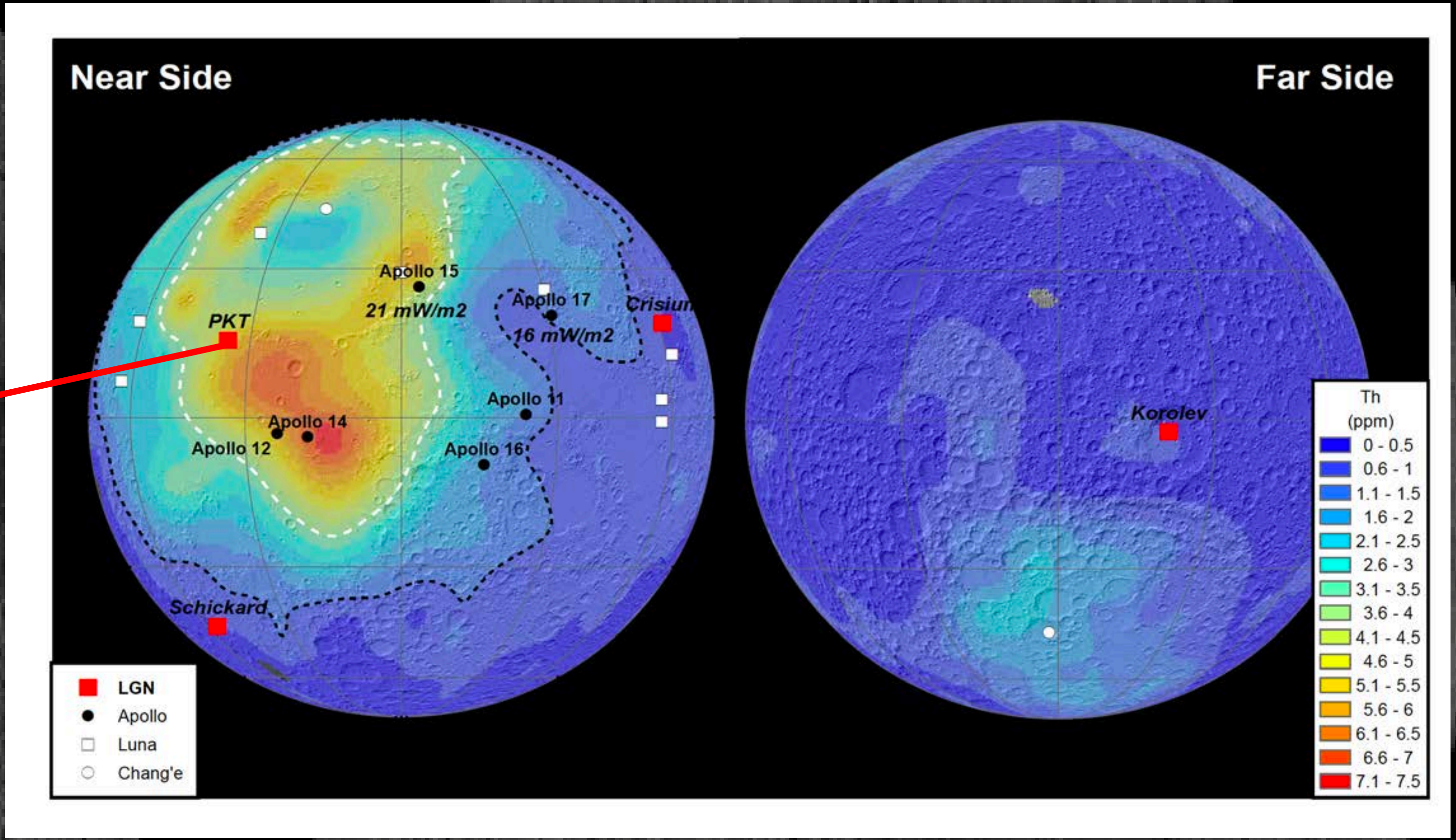
Example Landing Sites





PKT Site: P-5 basalt field site SE of Aristarchus Plateau (lat. = 14.9˚; long. = -35.5˚). Relatively flat volcanic terrain, few craters and boulders, & has a crater size frequency distribution age of 3.48 Ga. Regolith is well developed. Well-situated to detect both direct and core-reflected arrivals from the known nearside deep moonquake clusters. Lobate scarps present just to ESE.

Lunar Geophysical Network

Example Landing Sites

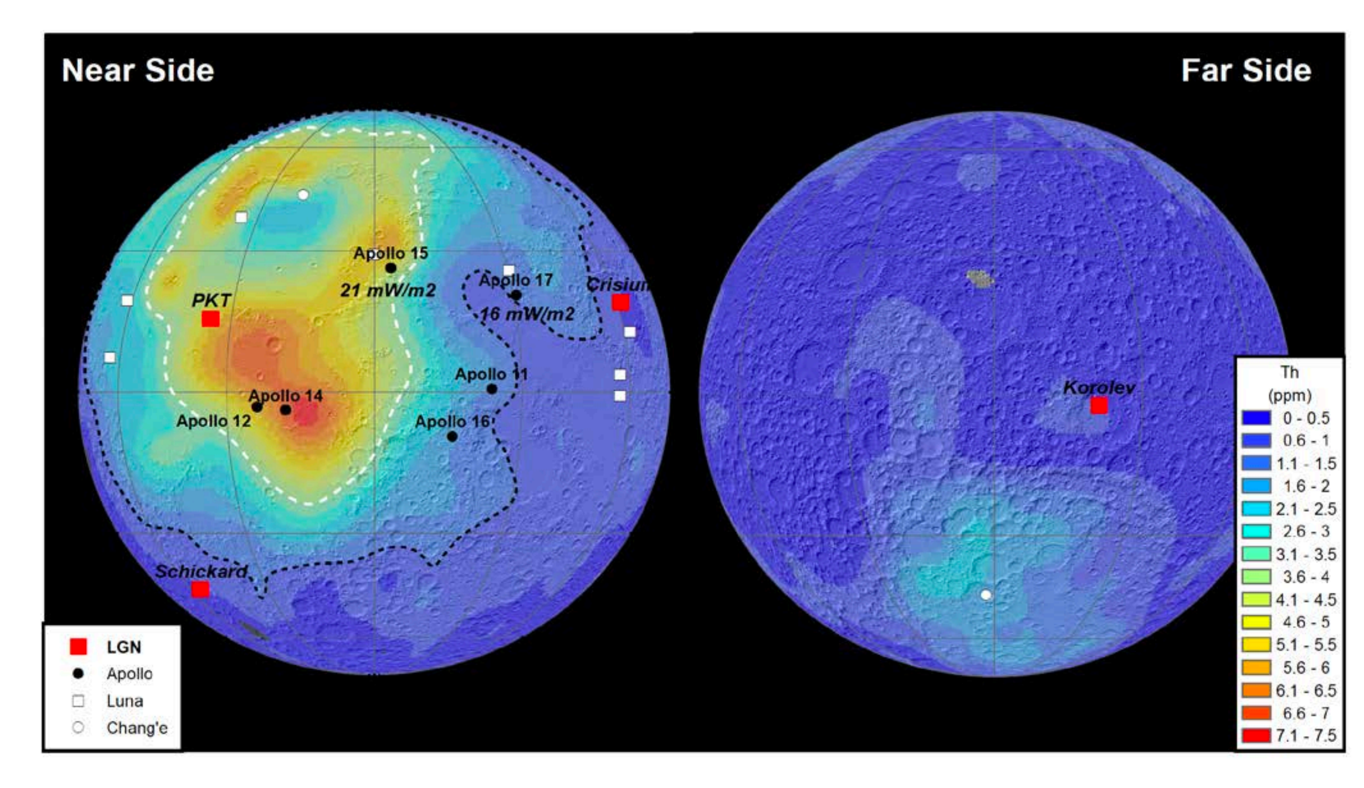
Schickard Basin (latitude = -44.3˚; longitude = -55.1˚): This site is in the southern hemisphere of the Moon and the floor is partially flooded with basaltic lava flows (3.62-3.75 Ga) that form a relatively flat landing site, with few craters and boulder fields.

Regolith well developed. Well outside PKT.

Expands LLR network.

Ideally situated to detect seismic phases:

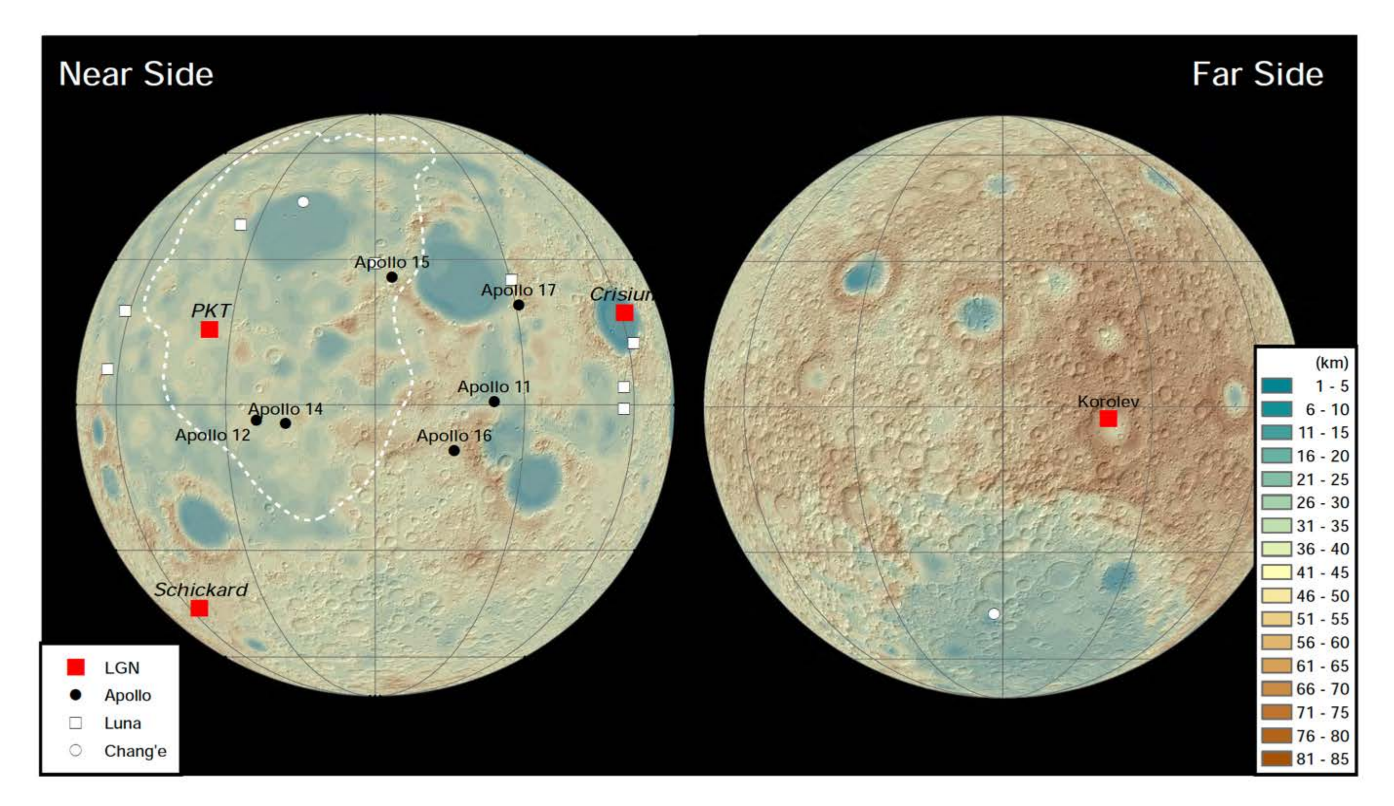
- reflected by the lunar core by known nearside deep moonquake clusters;
- refracted waves through the core from the farside A-33 deep moonquake cluster.



Lunar Geophysical Network

Example Landing Sites

<u>*Crisium Basin*</u> (latitude = 18.5˚; longitude = 61.8˚): Basaltic lavas (~3.65 Ga) form a relatively flat terrain, but contain secondary crater populations that will need to be avoided. The primary crust is essentially absent allowing mantle heat flow and structure to be directly measured without distortion by the fractured crust. Known magnetic anomalies need to be avoided. Expands LLR network to the east. Lobate scarps are located in the south of the basin and just to the east.



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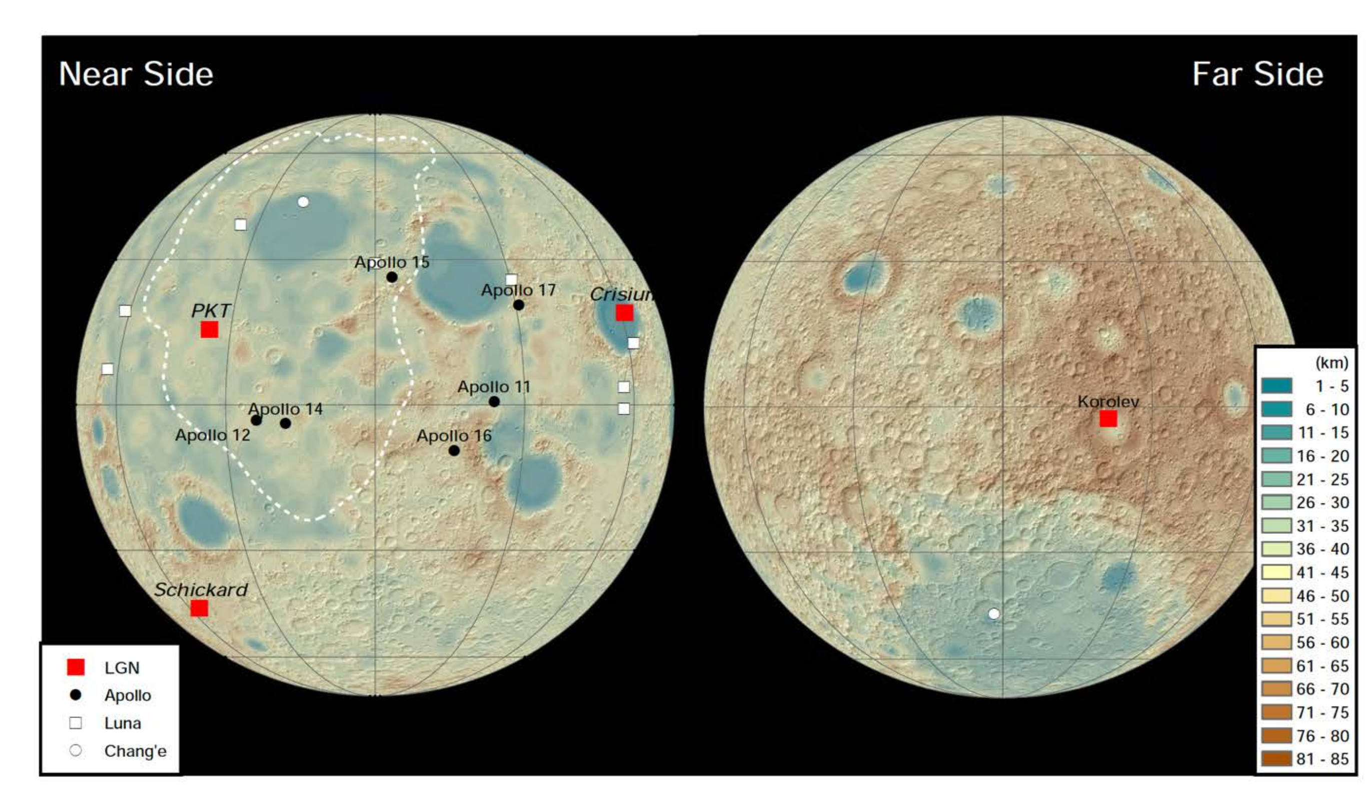
Example Landing Sites

<u>*Korolev Basin*</u> (latitude = -2.4˚; longitude = -159.3˚): This site will allow the first surface geophysical measurements to be made on the farside of the Moon. The Korolev Basin is a Nectarian-age basin (3.85-3.92 Ga) and affords a relatively flat and boulder-free landing area that is in the vicinity of a lobate scarp.

Well within FHT on some of the thickest crust.

Approximately antipodal to many nearside deep moonquake clusters, again improving ray coverage for core-traversing seismic phases.



A lobate scarp is close to the western margin of the basin

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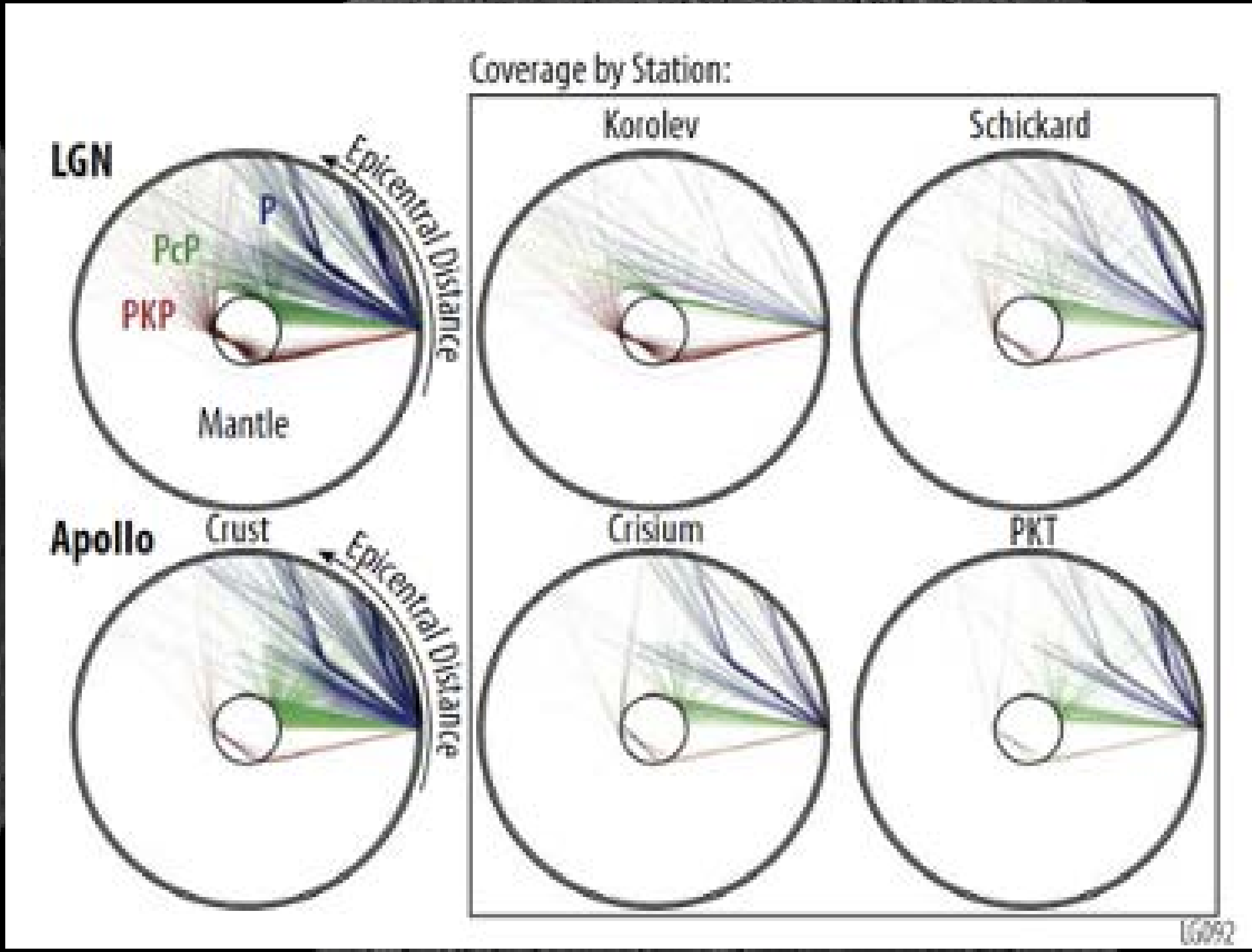
Better than Apollo

- Ray path coverage for P (blue), PcP (green), and PKP (red) phases from the known distribution of deep moonquake clusters, rotated such that the station is fixed at 0 degrees and stacking all stations in the array for LGN (top left) and Apollo (bottom left).
- Note LGN's wider coverage in epicentral distance, and denser sampling of the deep interior.
- The box on the right shows ray coverage for each of the LGN stations separately.



Lunar Geophysical Network

Summary

- Will deliver lunar and Solar System science – will inform about the initial differentiation of the Moon and other terrestrial planetary bodies
- Benefitted from a Planetary Mission Concept Study
- Instruments are/will be at high TRL
- Will also inform human exploration in term of hazards (SMQs, impacts)
- Important for the next decadal if not selected in NF-5