Lunar Surface Geophysics

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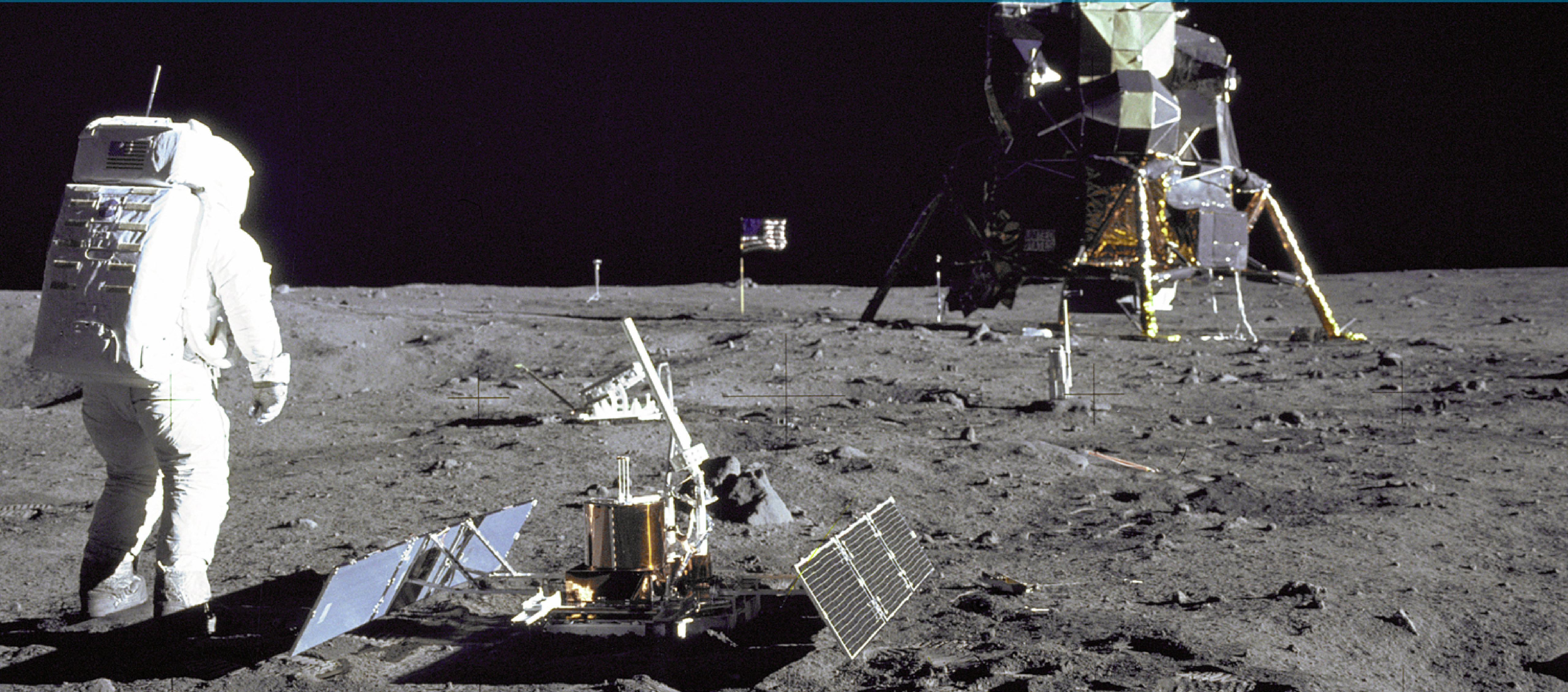
March 31, 2020

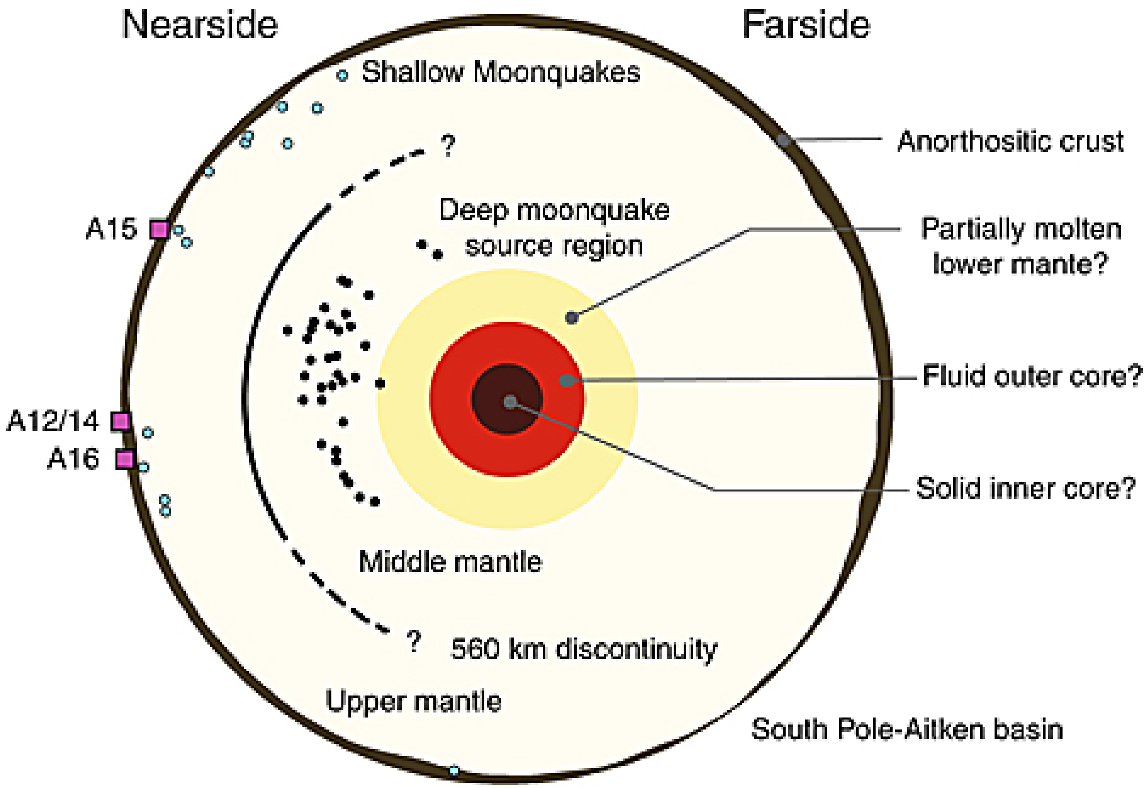
50 Years of Lunar Science: The Legacy of "One Small Step"



Geophysics: Elucidating planetary interiors

- Interior properties provide constraints on formation and evolution models, and possible indicators of an early dynamo for magnetic field generation.
    - Layering
    - Composition
    - Seismic velocity & density
    - Presence of partial melt
    - Core state

- Terrestrial planets all share a common structural framework (crust, mantle, core) which is developed shortly after formation and which determines subsequent evolution.

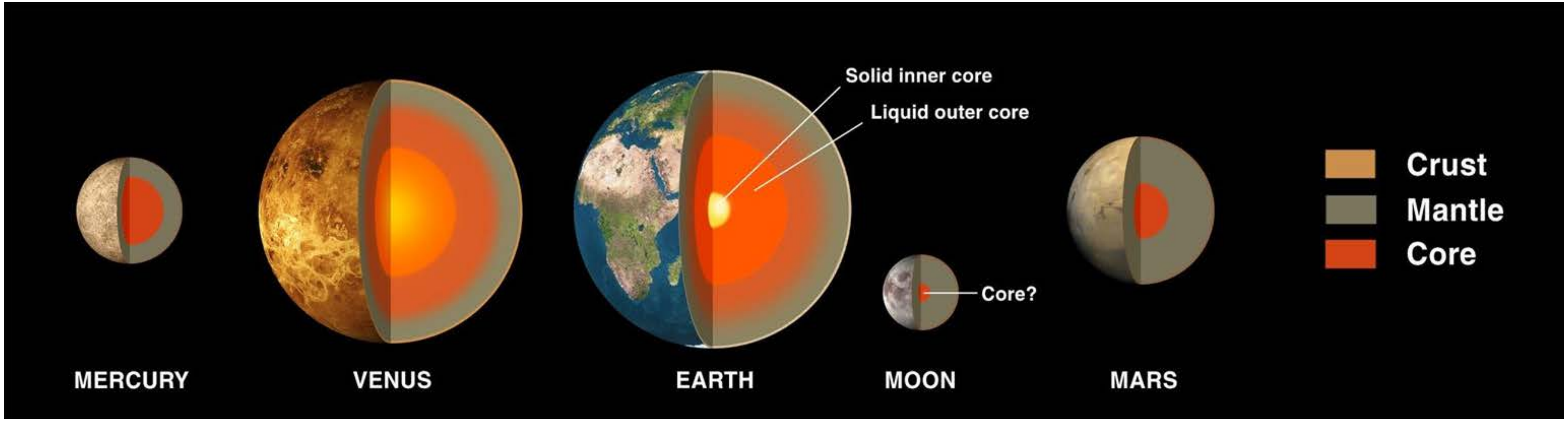


Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Lunar Science is Solar System Science

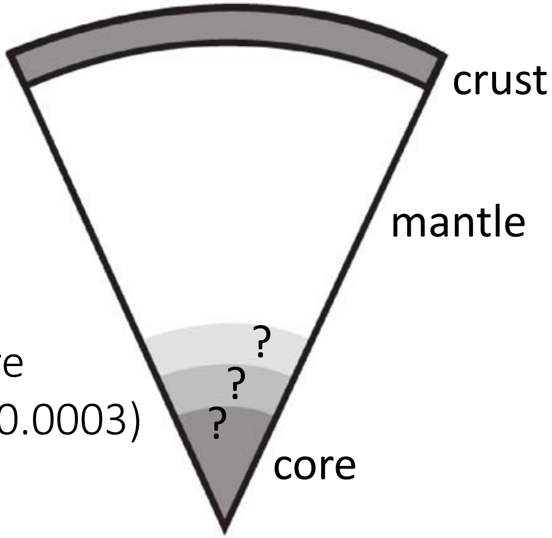
- While much of Earth's early structural evidence has been destroyed by plate tectonics, the so-called "ancient" planets retain more information about their early interior structure and are ideal bodies to explore to advance our understanding of all terrestrial planetary formation and evolution.

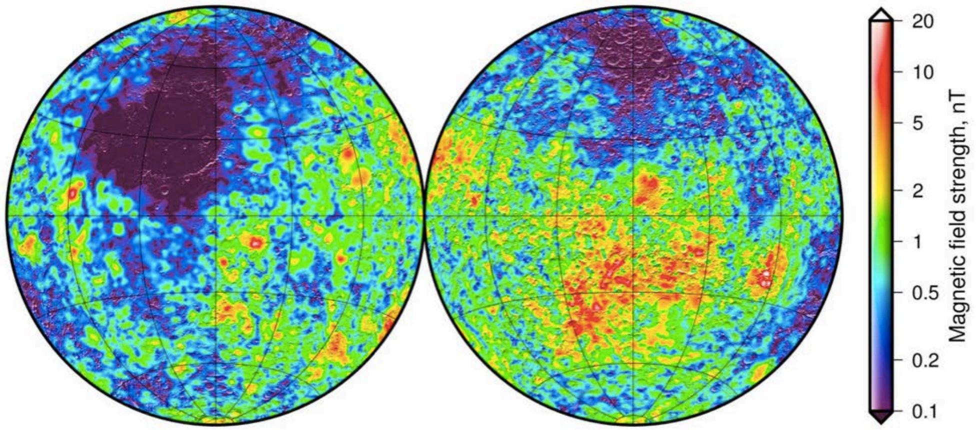
- Constraints on these properties arise from geophysical observations:
  - Geodetic parameters
  - Lunar laser ranging
  - Gravity field
  - Electromagnetic induction
  - Heat flow
  - Seismology



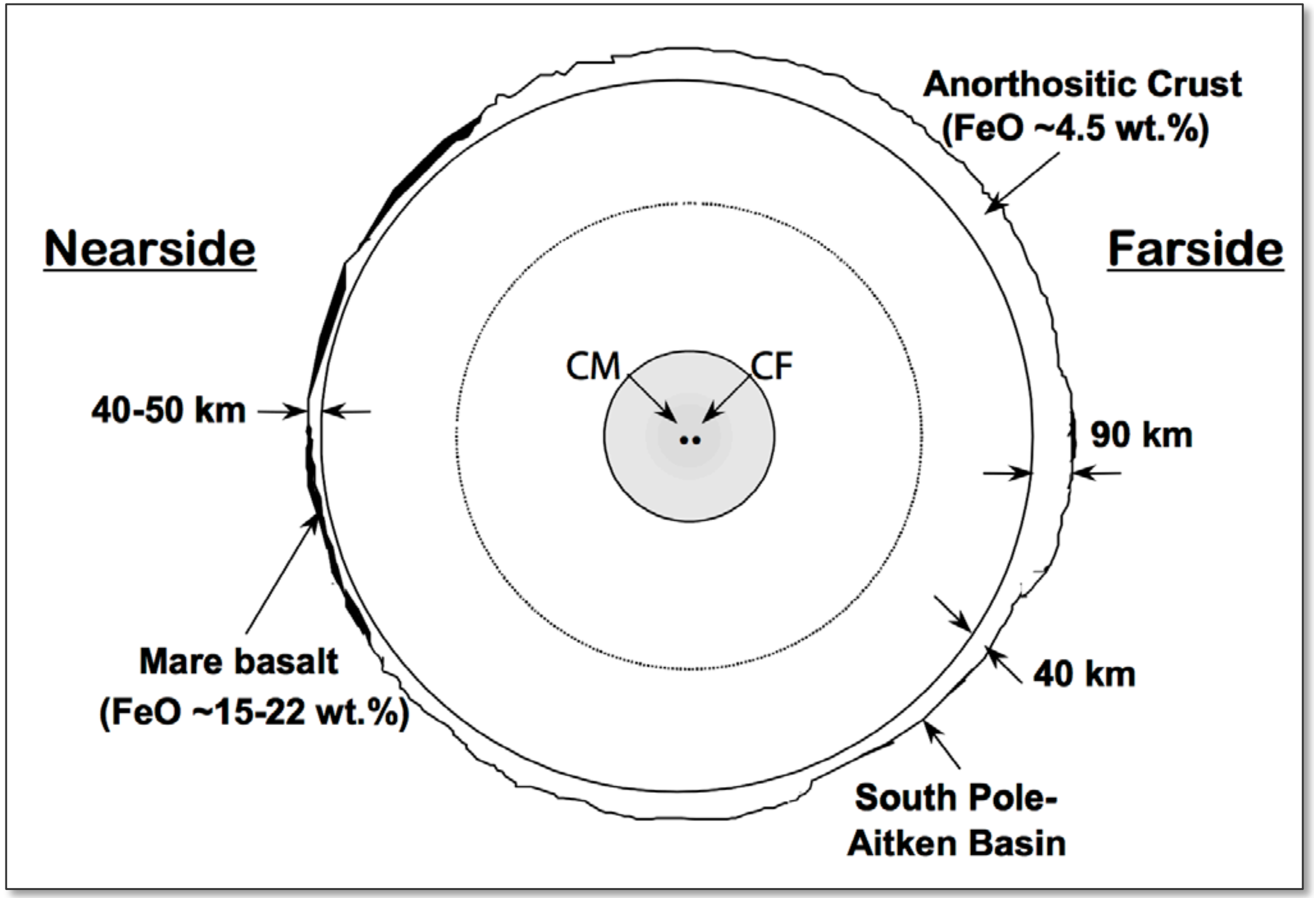
Lunar geodetic parameters

To first order, the Moon's moment of inertia is roughly approximated by homogeneous sphere ($I_{solid}/MR^2 = 0.3930 \pm 0.0003$)
~0.4





Global crustal magnetism – Wieczorek et al. (2017) *NVOTM2* #6036



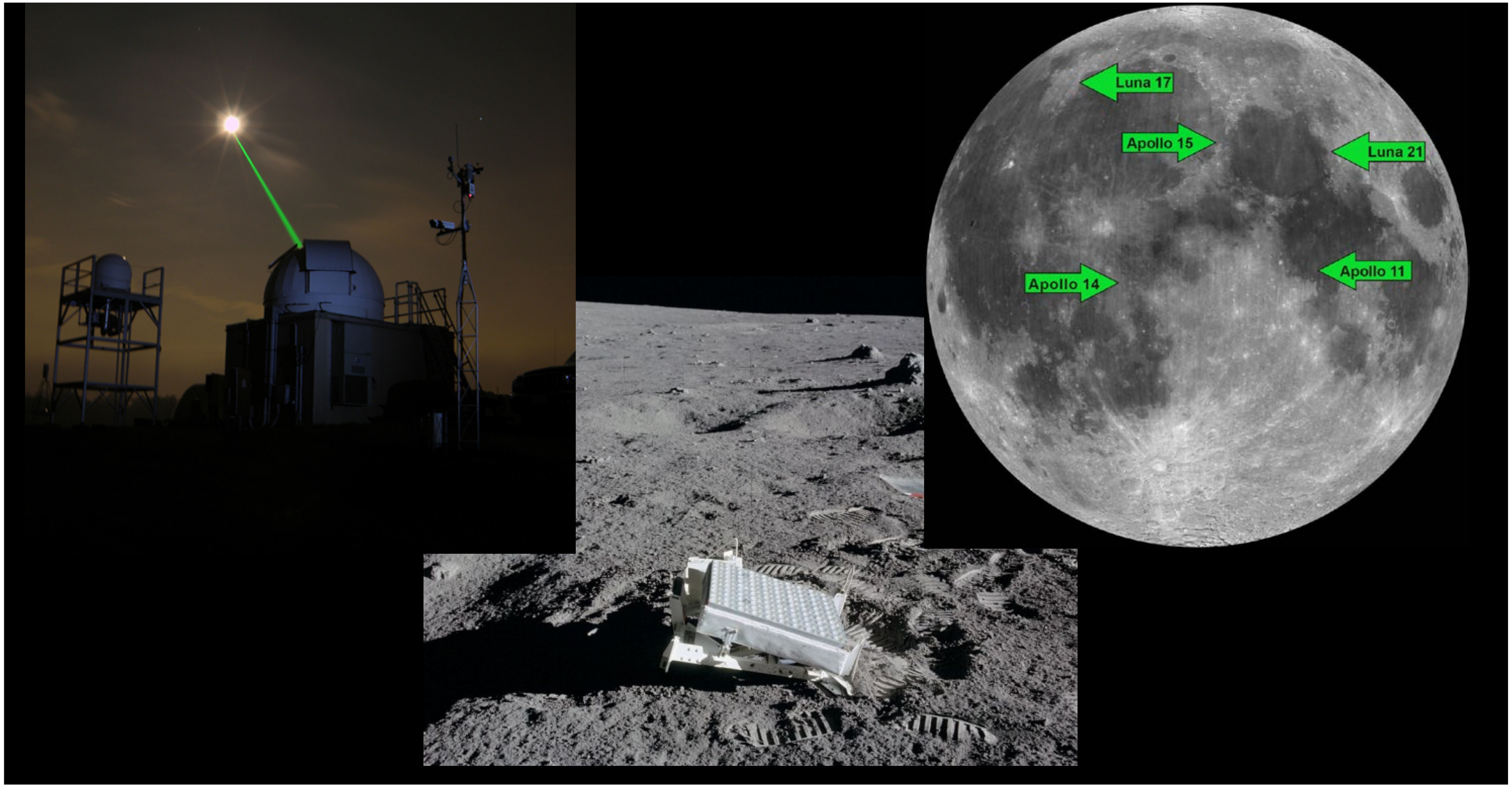
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Lunar Laser Ranging (LLR)

LLR has been precisely monitoring the Moon's geodetic parameters since 1969

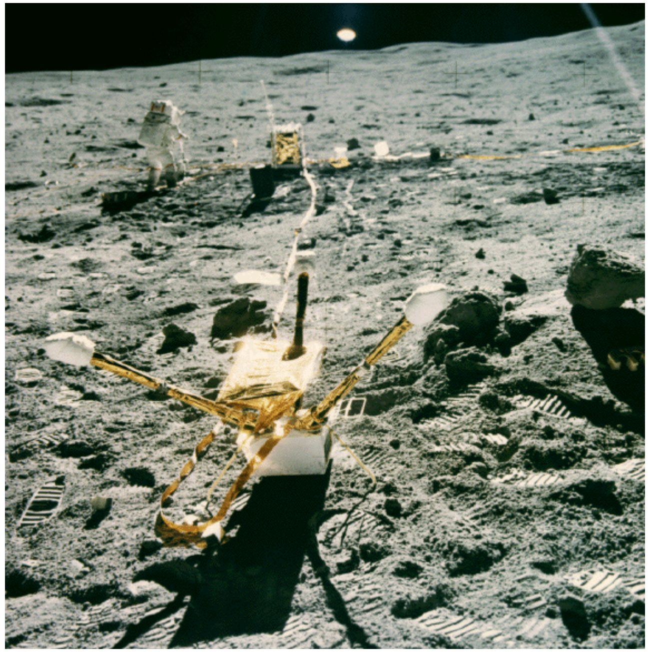
Dissipation provided the first LLR evidence for a fluid core

fluid core radius = 352km if iron, or 374km for a Fe-FeS eutectic composition

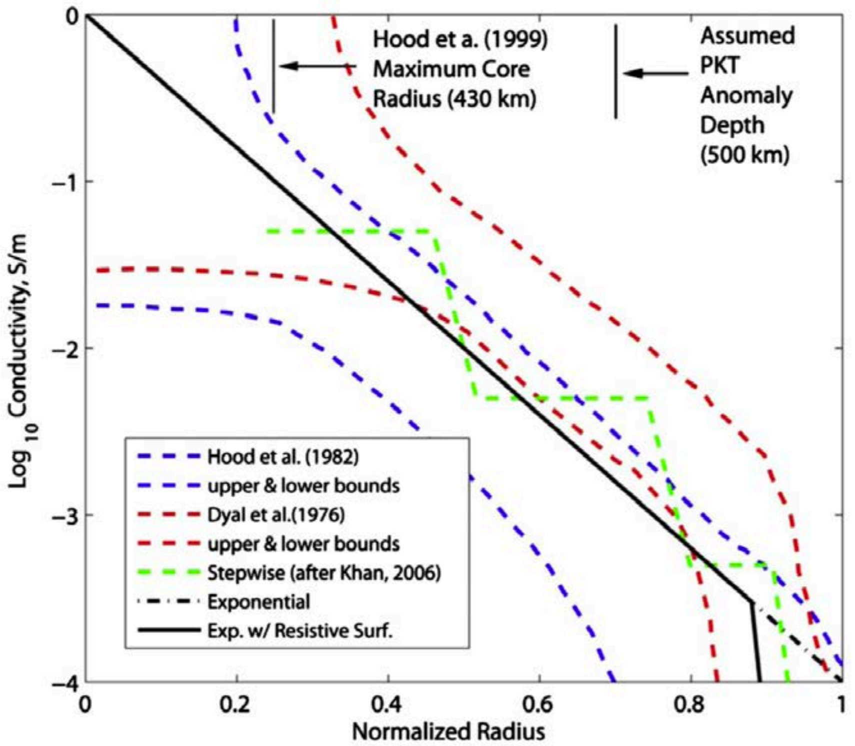


Lunar magnetic induction

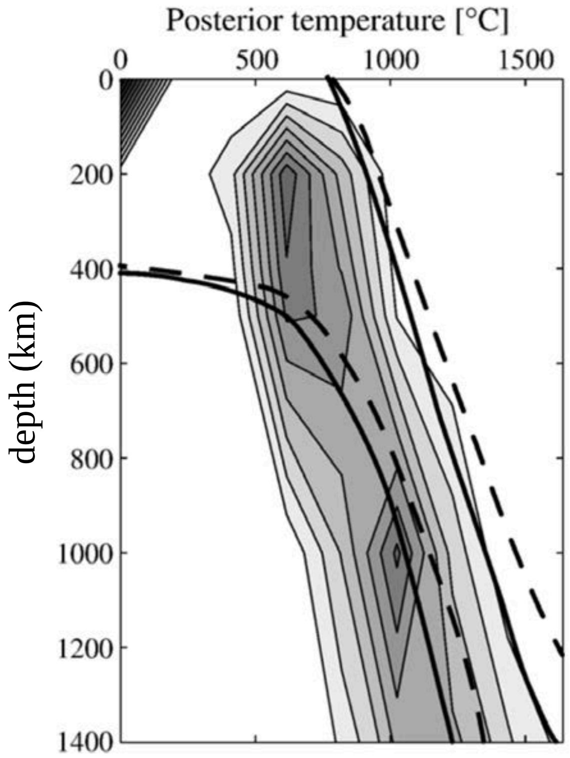
- EM sounding at Apollo 12 provided broad constraints on core size, mantle composition, and interior temperature (used concurrent orbital reference).
- The Lunar Prospector and Kaguya magnetometers detected an induced moment that independently constrained core size.
- Apollo 12 site may be anomalous as it is located within the PKT.



Apollo Lunar Surface Magnetometer

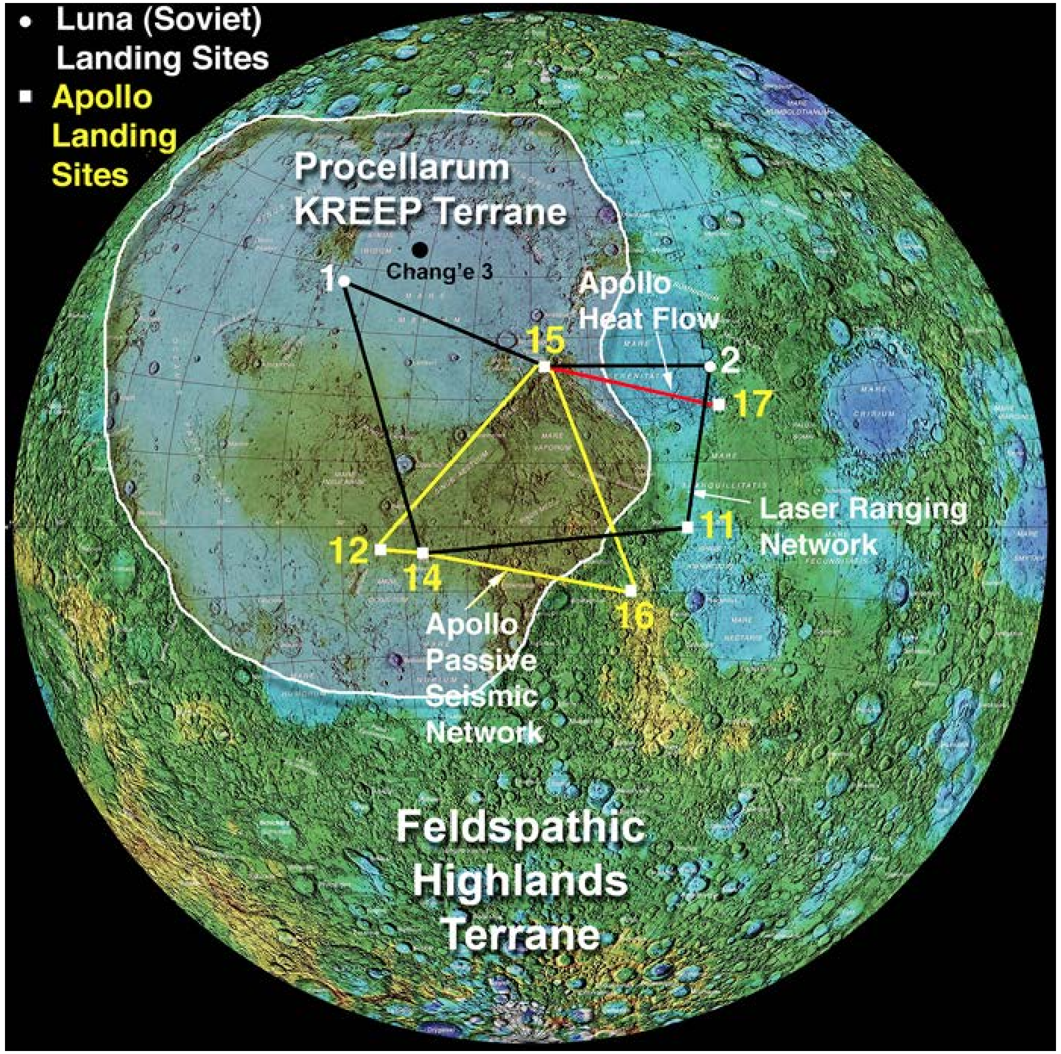


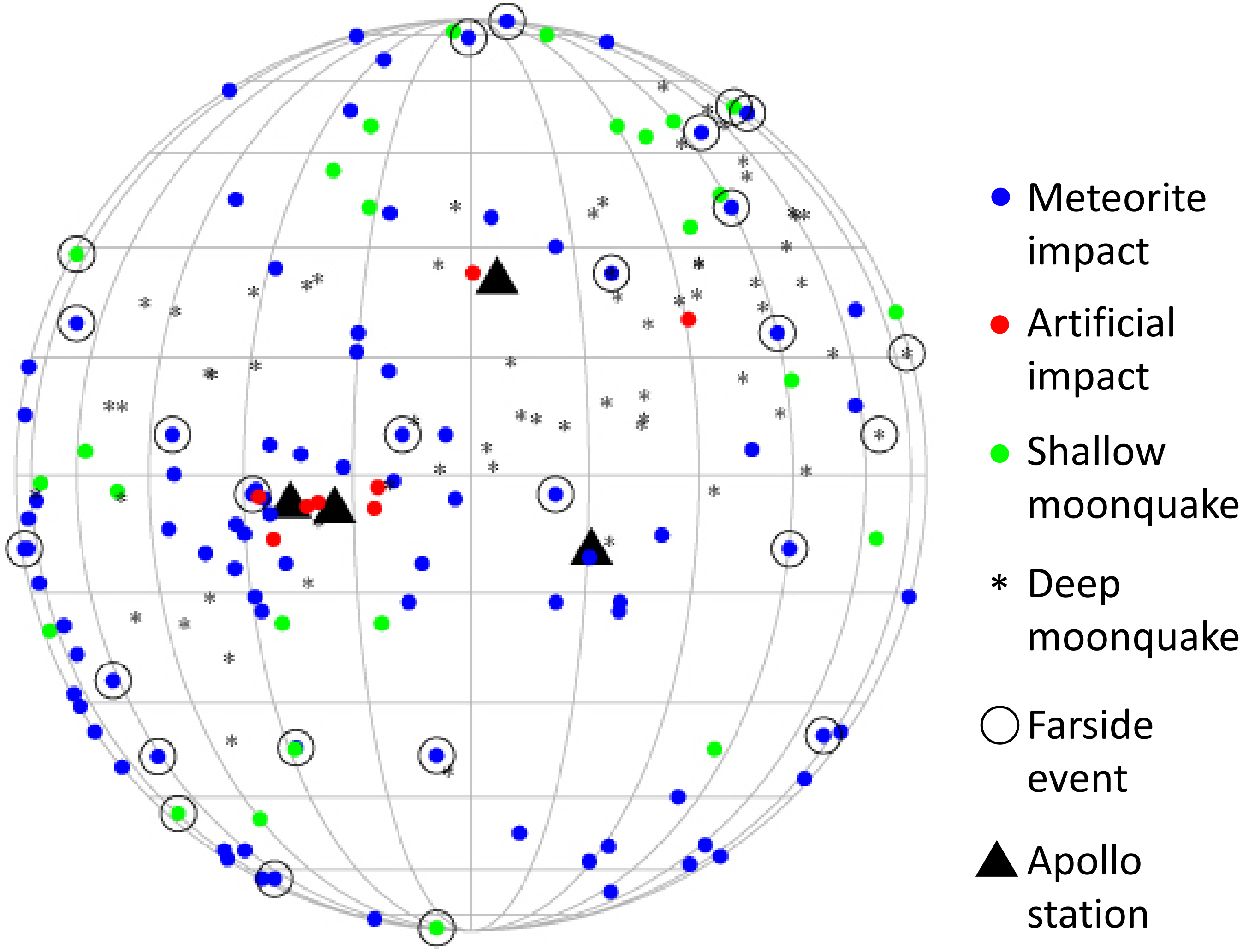
Grimm & Delory (2012) *ASR* **50**, 1687–1701



Khan et al. (2006) *EPSL* **248**, 579-598

Seismic measurements

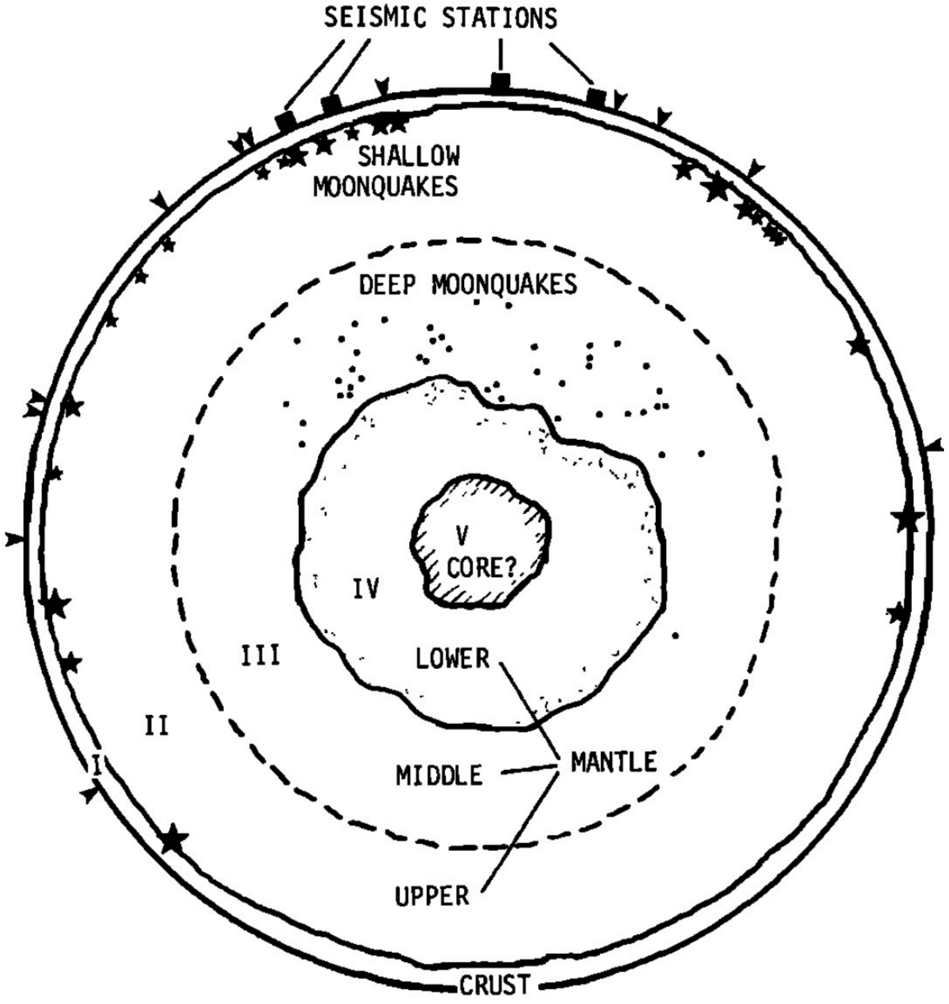




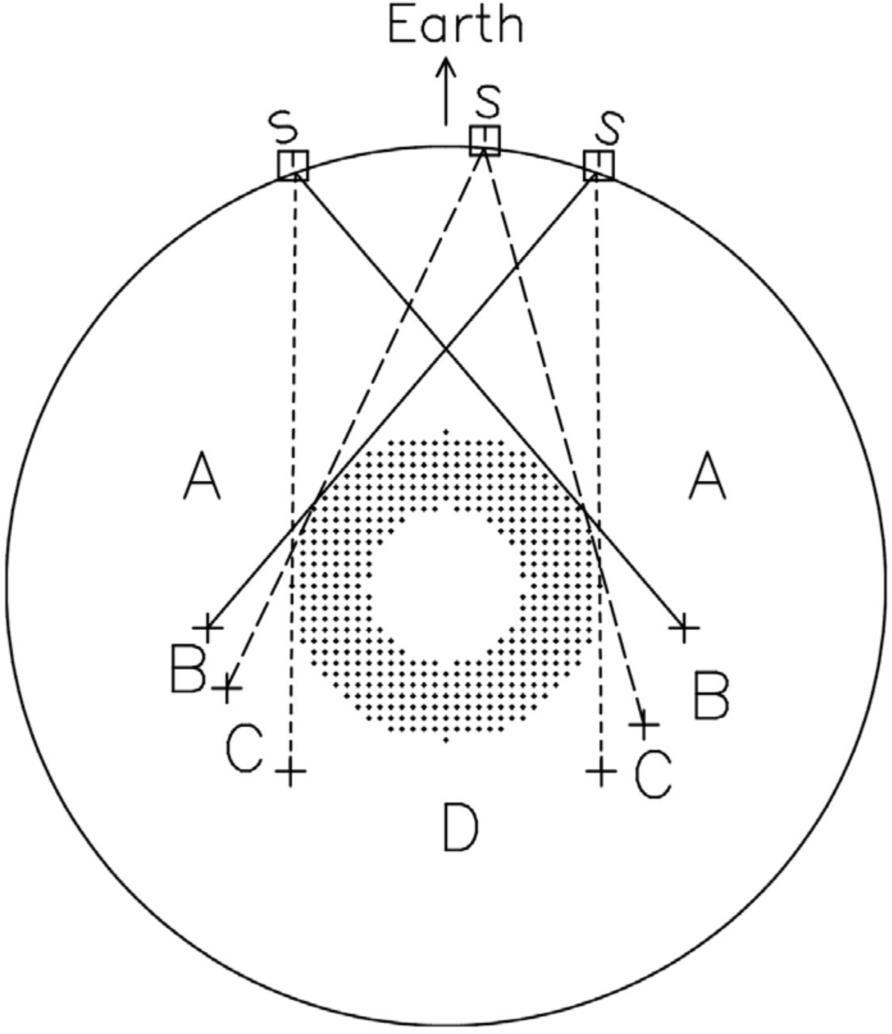
Seismic measurements

No seismic energy originating from far side penetrated the core, so it is likely attenuating

Deepest moonquake source regions ~1200-1400km depth; so core likely 300-500km radius

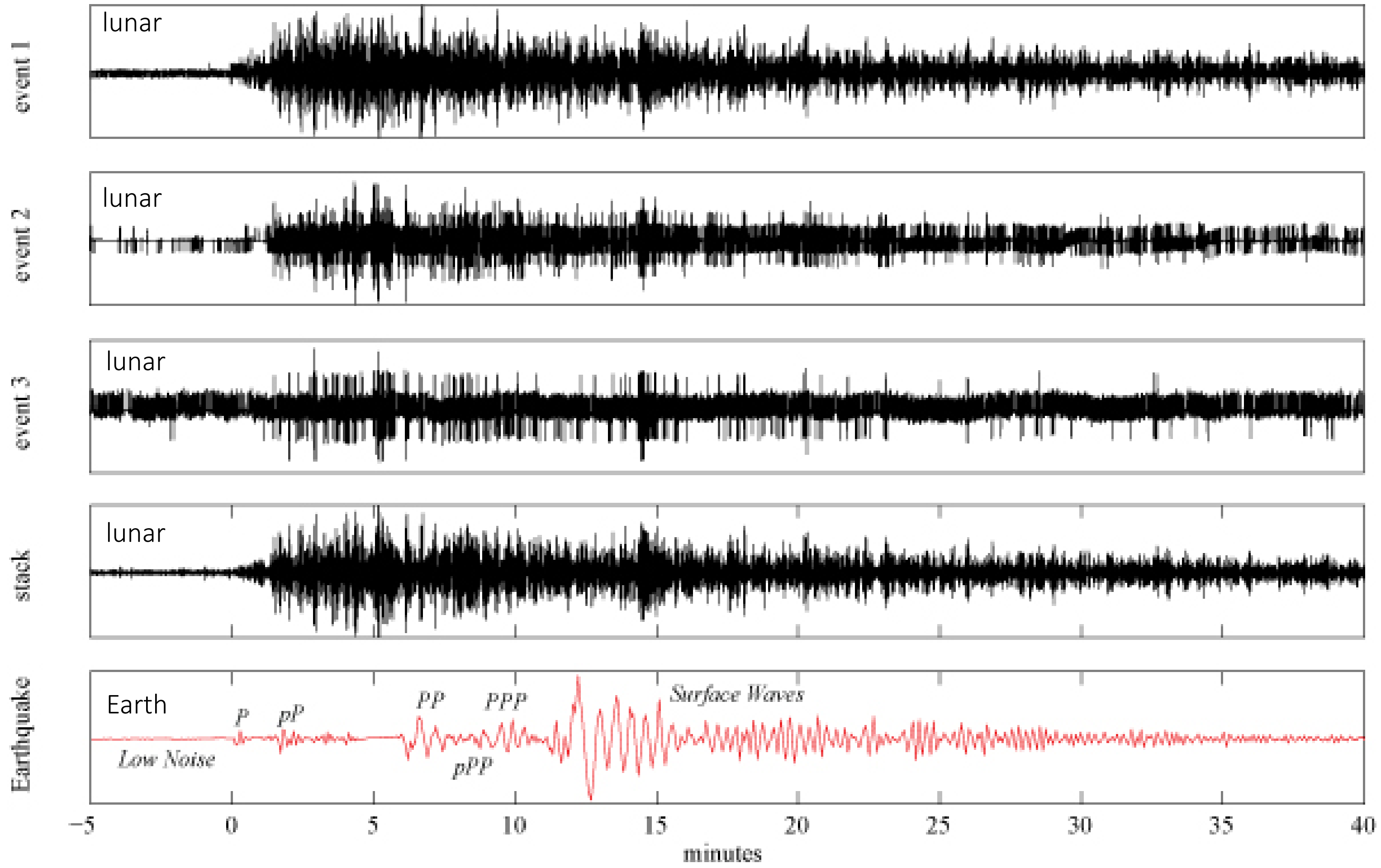


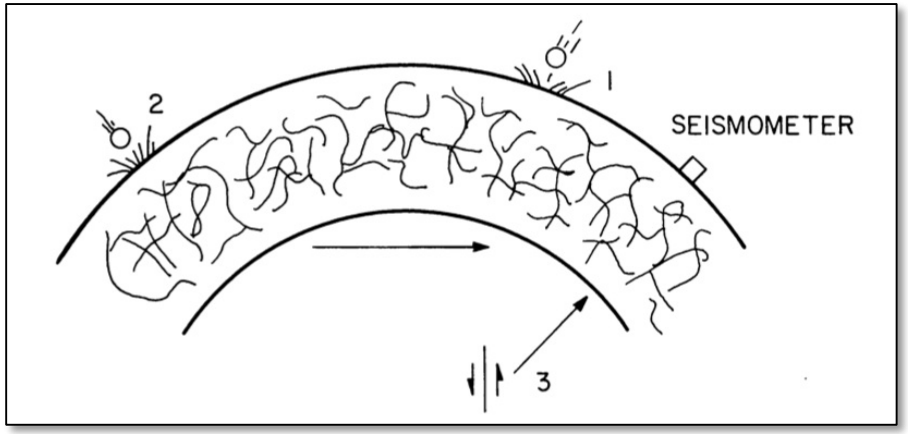
Nakamura (1983) *JGR* **88**, 677-686



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

Seismic scattering





Dainty et al. (1974) *The Moon* **9**, 11-29.

- The lunar regolith intensely scatters seismic energy.
- Lunar seismograms are of limited quality compared to their modern terrestrial counterparts.
- Secondary phases which contain information on deep structure are masked by ringy codas.

Seismic model uncertainty

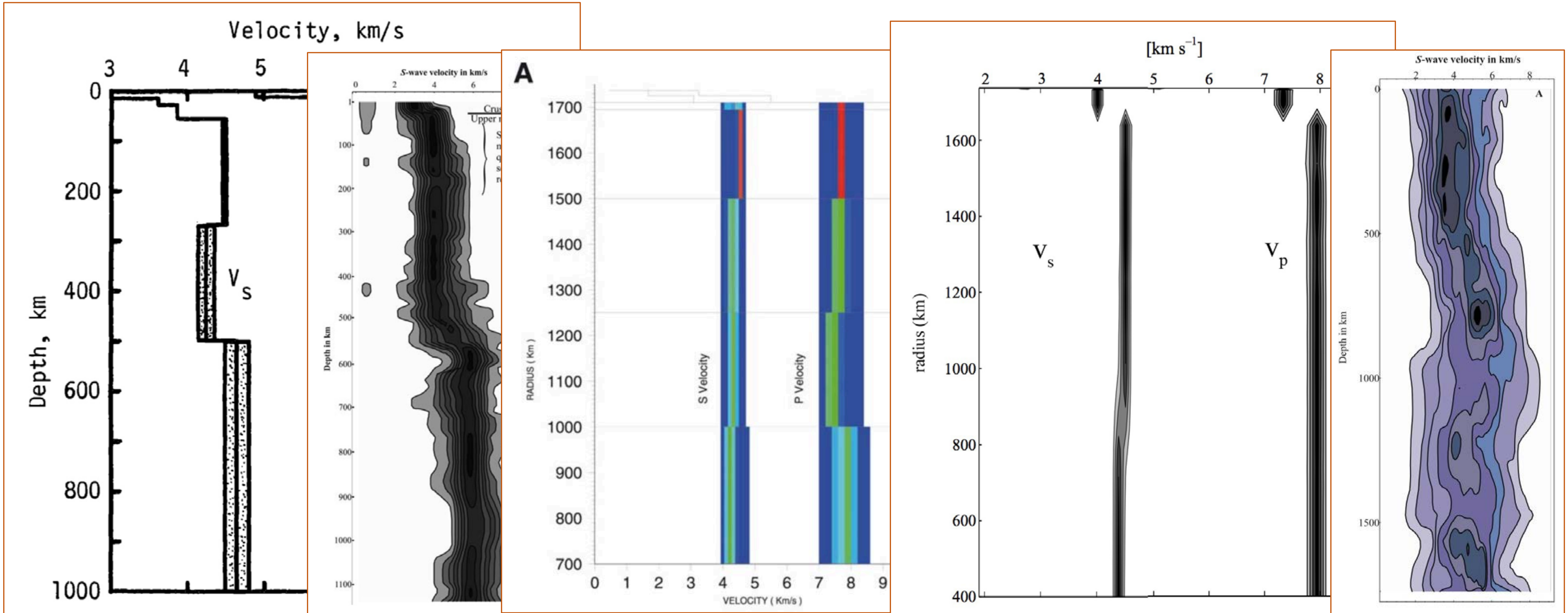
Nakamura (1983) *JGR* **88**, 677-686

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



Seismic model uncertainty

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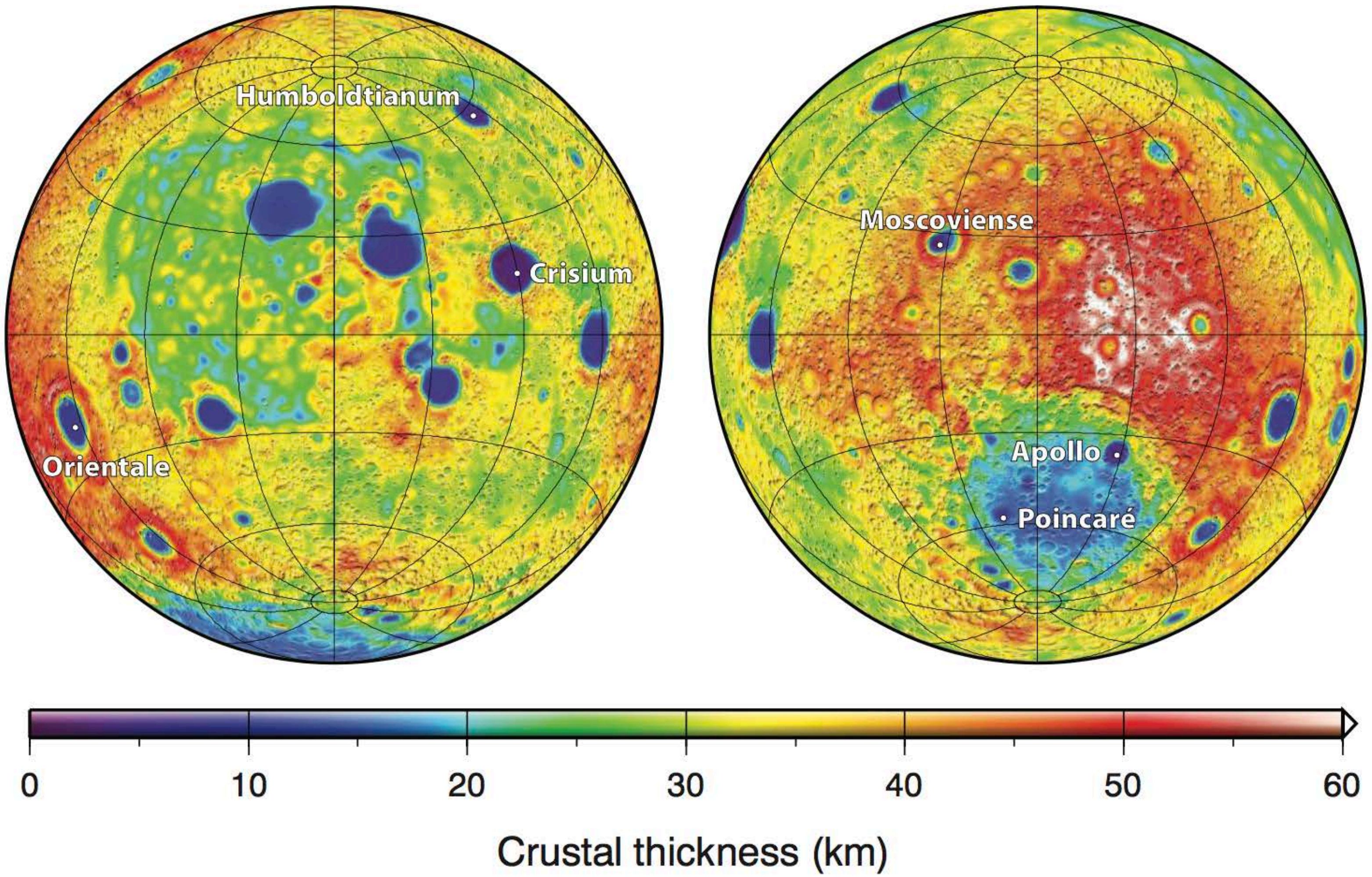
- Crustal thickness estimates have decreased over the years as newer and more computationally expensive techniques were applied.
- Early models based on arrival time inversion alone were supplemented by newer models using maximum likelihood estimates, joint seismic and pre-GRAIL gravity inversion, and free oscillations.
- Newer models mostly agree that the only major discernable discontinuity in the lunar interior is the crust-mantle boundary located around 30km deep.
- There is no consensus among models regarding the presence of a mid-mantle seismic discontinuity, which has been used in the past to suggest the lower bound of an ancient magma ocean.

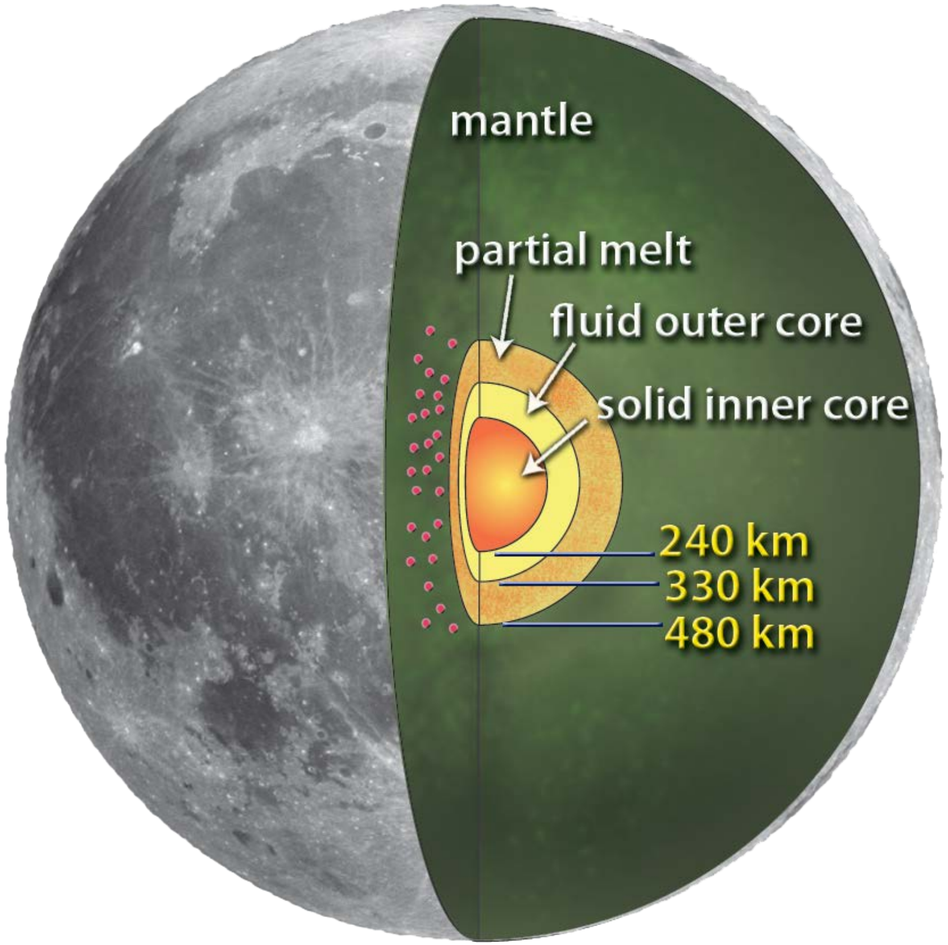
Recent advances in lunar geophysics



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

- GRAIL lunar gravity mission mapped the Moon’s gravity field in extreme detail
- Shallow crustal structure is tightly constrained, but still tied to (uncertain) ground-truth seismic estimates at the Apollo landing sites

Recent advances in lunar geophysics

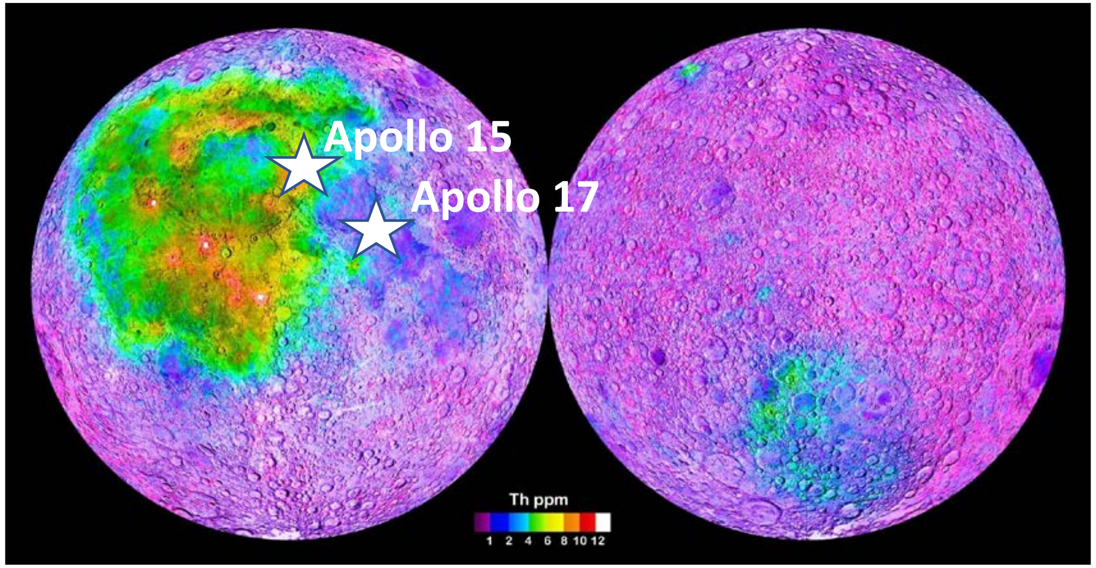


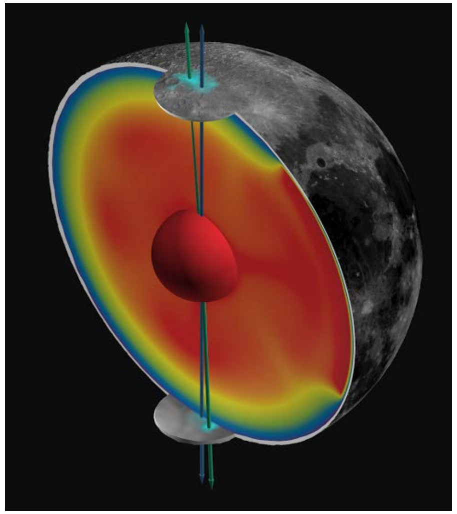
Weber et al. (2011) *Science* **331**, 309-312

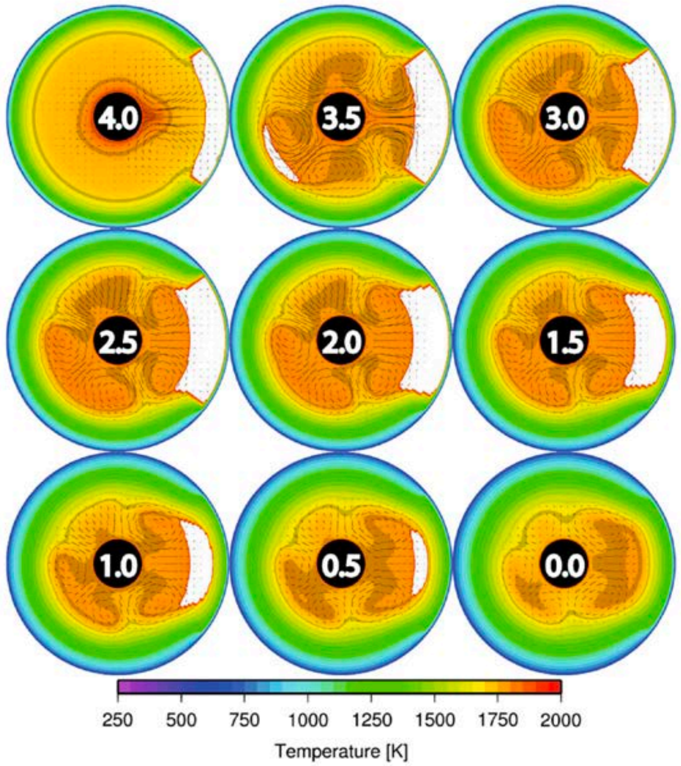
- Re-analyses of Apollo seismic data found evidence for core reflections, both including (Weber et al., 2011) and not including (Garcia et al., 2011) the presence of a partial melt layer above the liquid outer core.
- Differing perspectives on whether a partial melt layer is required to satisfy available constraints (gravity, seismic, geodetic constraints, EM sounding data, phase-equilibrium models, dissipation, volatile content)

Synergy with geothermal measurements

- Geothermal measurements track heat production and interior temperature distribution.
- The Apollo Heat Flow Experiments were both within areas dominated by Thorium-rich crust. How the PKT came to exist depends on internal structure.
- Determining the physical and thermal structure of the lunar core and deep interior is critical for understanding the Moon's formation. Geophysical data reveal the evolution of the lunar dynamo, by which the Moon may have generated and maintained its own magnetic field. They also provide context for thermal emission and volcanism studies.



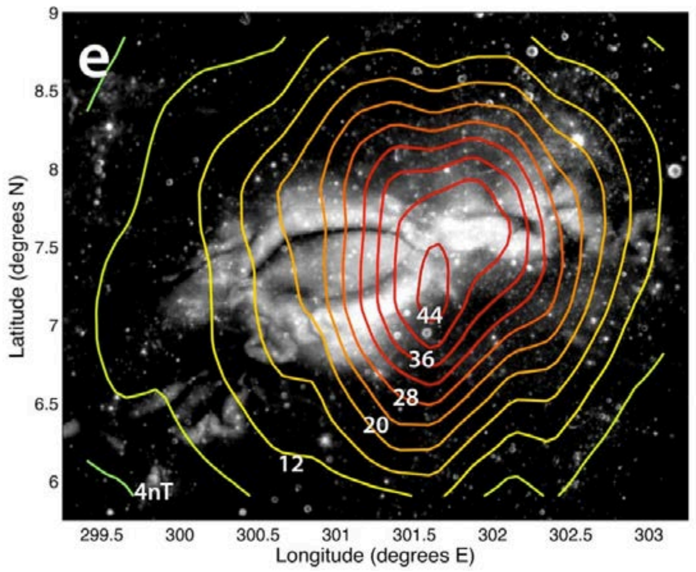




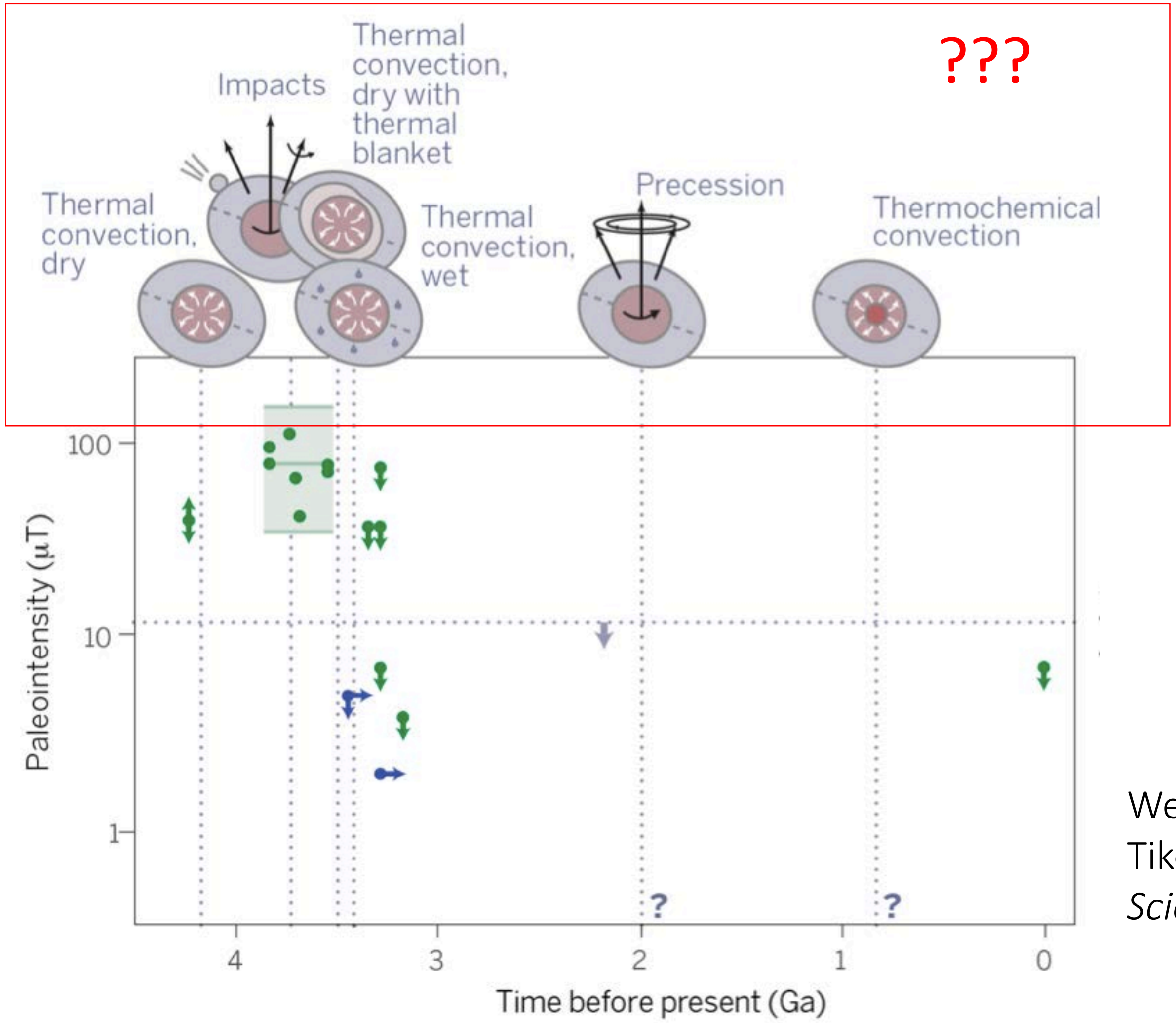
Laneuville et al. (2014) *EPSL* **401**, 251-260.

Synergy with paleomagnetic measurements

- Magnetism is ubiquitous in the Solar System.
- Just beginning to constrain the nature of the extinct lunar dynamo
- We don't know the origin of magnetic anomalies or swirls



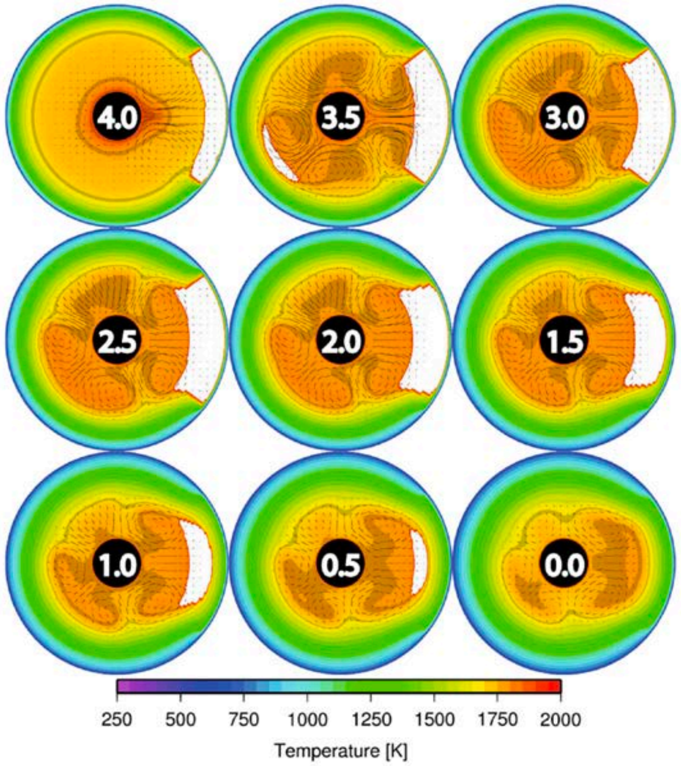
Local crustal magnetism – Hemingway & Garrick-Bethell (2012) *JGR* **110**



Weiss & Tikoo (2014) *Science* **346**.

How to develop an internal structure model consistent with all observations?

Complex internal processes drive the distribution of surface observables. If the PKT is indicative of thermal upwelling and mantle overturn, a potential partially molten region could act as a thermochemical blanket preventing the core from cooling.



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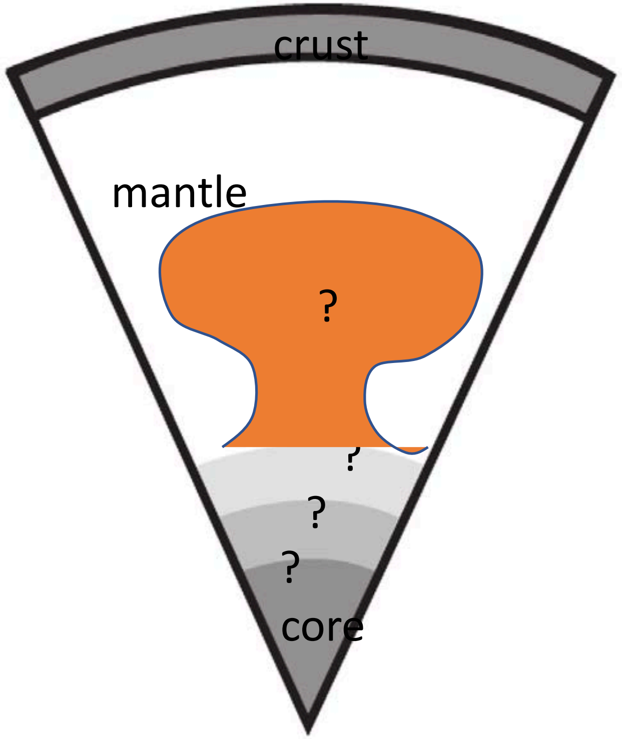
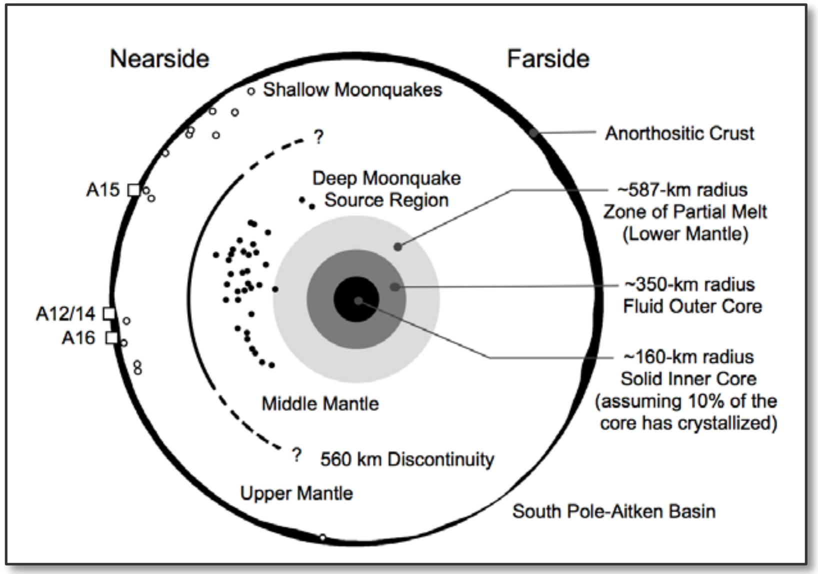
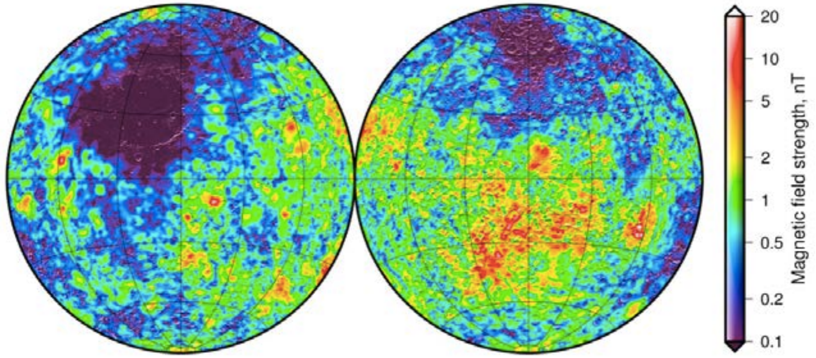


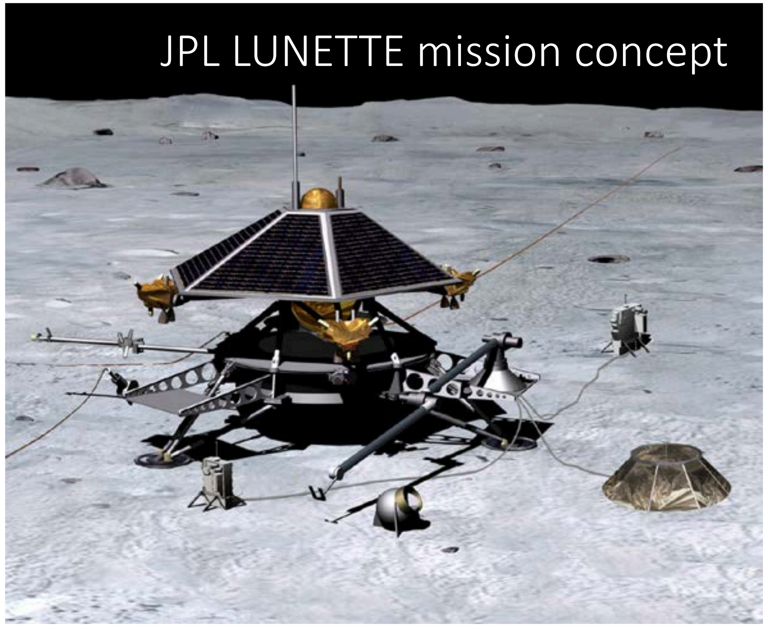


Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.



Wieczorek et al. (2017) *NVOTM2* #6036

The Lunar Geophysical Network

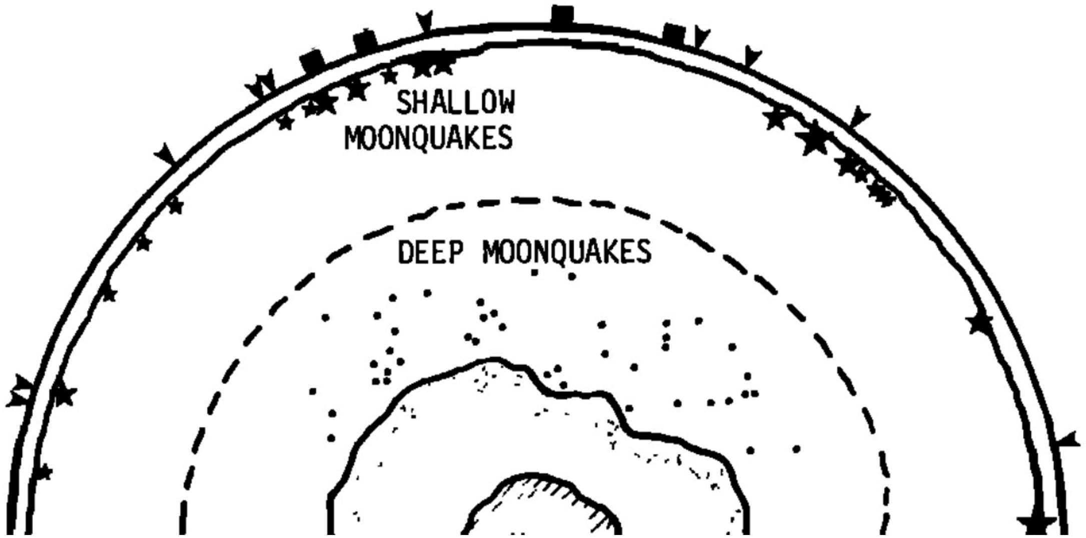


- A network of geophysical "nodes" (at least 4) operating continuously for an extended period – at least 2 (ILN), 4 (LUNETTE), or 6 (LGN threshold) years
- Science objectives for each node:

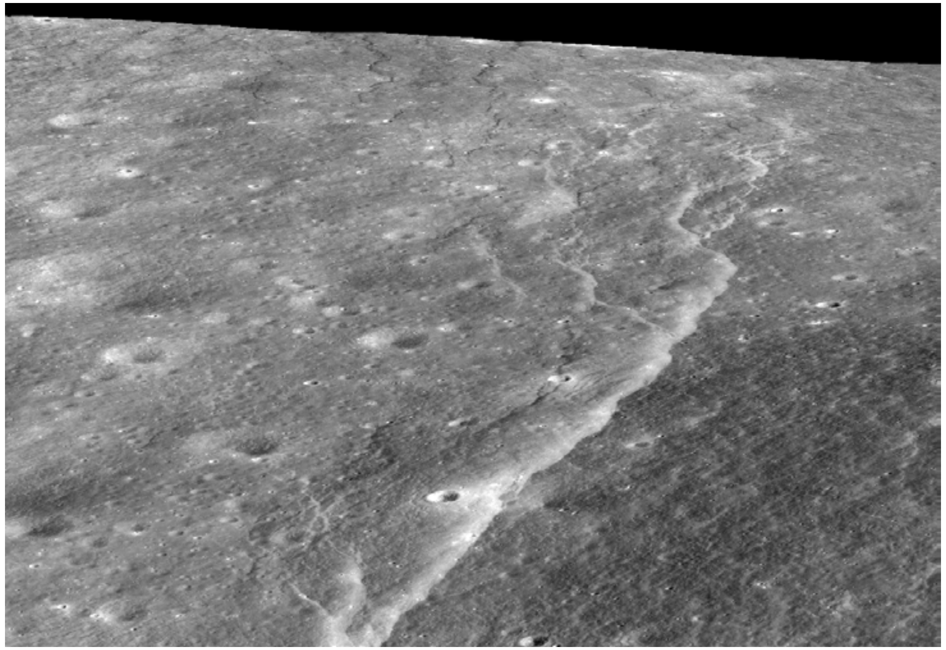
Seismometer	Heat flow probe	Retroreflector	Magnetometer
• Understand the current seismic state and determine the detailed internal structure of the Moon	• Measure the heat flow to characterize the temperature structure of the lunar interior	• Increase ability to determine deep lunar structure and conduct 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 scientific understanding – outstanding issues

- 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



Deep moonquakes: brittle failure in the ductile regime?



Shallow moonquakes: lobate scarp slip?

Planetary scientific understanding – outstanding questions

Terrestrial planet hypotheses that can be tested with new geophysical data from the Moon:

1. How do solar systems form and evolve over time, and when did major solar system events happen?
   - What is the tidal relationship between parent bodies and their satellites, and the internal evolution and structure of these systems?
2. How did the early terrestrial planets form and differentiate?
   - The Moon preserves a record of early terrestrial planet differentiation; imaging the core, mantle, crust provides a window into these early processes and how the planets evolve from an initial magma ocean.
3. What processes shape planetary surfaces and how do these surfaces record solar system history?
   - Stagnant lid conduction is assumed to be the norm for smaller bodies, as is global contraction. The thermal evolution of terrestrial objects is tied to their tectonic evolution, and the rate of heat loss is determined by their internal dynamics.
4. How do worlds become habitable, and how is habitability sustained over time?
   - We know the core dynamo is important for magnetic field generation, which is relevant for habitability. At what point did a core dynamo form (if it ever did), and how long was it operational?
5. What are the hazards of the Solar System for human exploration?
   - Seismology can assess risk from shaking, which is needed as we push toward a sustained human presence on the Moon.

CAPS committee questions for New Frontiers targets

1. Has scientific understanding or external factors such as programmatic developments or technological advances, significantly changed since the release of the planetary science decadal survey or its midterm review?

2. Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial to warrant reconsideration of the four targets for inclusion in the New Frontiers 5 announcement of opportunity, scheduled for release in early 2022?

CAPS committee questions for New Frontiers targets

1. Has scientific understanding or external factors such as programmatic developments or technological advances, significantly changed since the release of the planetary science decadal survey or its midterm review? YES

    1. Advancements in our scientific understanding of the lunar interior
    2. Technologic advancements in geophysical instruments
    3. Programmatic considerations and NASA activities

Advancements in our scientific understanding of the lunar interior

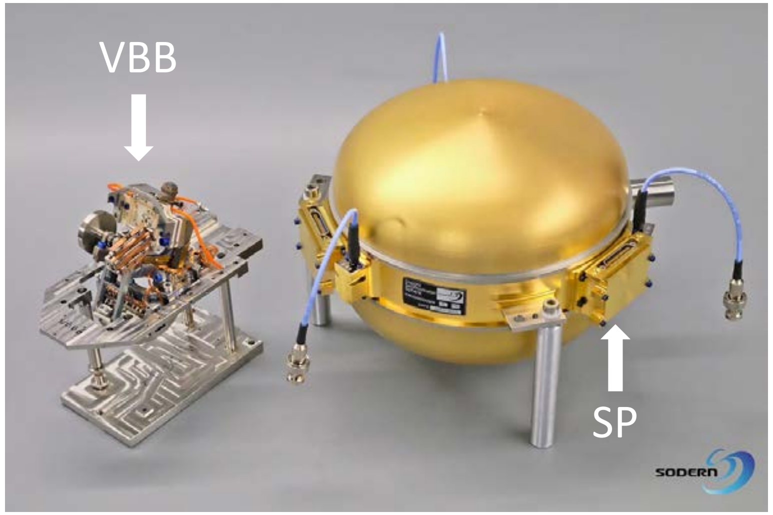
Key points from the 2018 LEAG Special Action Team: Advancing Science of the Moon (https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf)

- GRAIL data improved lunar gravity field map and revealed features of the lunar crust in unprecedented detail, including fractures and other tectonic structures, mascons, lava tubes and other volcanic landforms, impact basin rings, and the shape and size of complex to peak-ring lunar 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 (including constraints from LLR), but gravity data alone have not yet definitively identified the presence of an inner core. Laser ranging data suggest the lunar core is liquid, although combining gravity, topography and laser ranging data to model the deep interior of the Moon 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*
- 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. While large surface impacts can also generate transient magnetic fields, recent analyses of Apollo samples require a slow cooling timescale that excludes impact field origins.
  - ➢ *Sample studies continue to make surprising discoveries about the lunar dynamo, but need the global context of an LGN type mission*

Technologic advancements in geophysical instruments

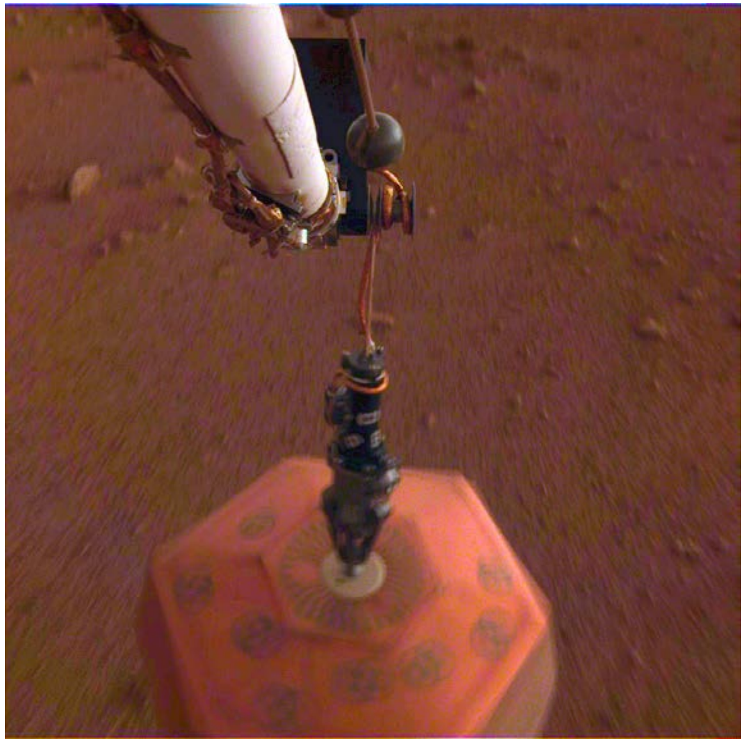
Seismology

- Development of the InSight Very Broad Band (VBB) and Short Period (SP) flight seismometers.



http://seis-insight.eu

- The first placement of a seismometer on the surface of an extraterrestrial body since the Apollo & Viking era.

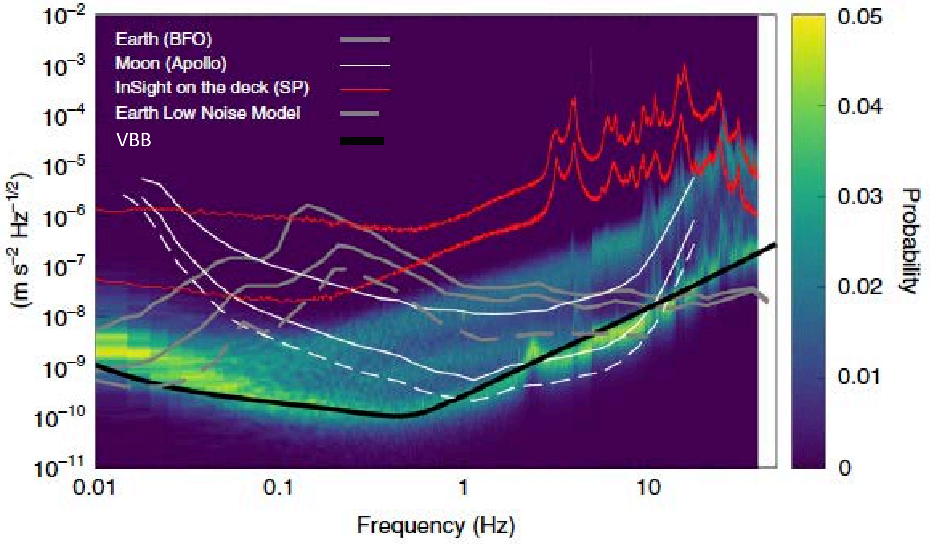


http://mars.nasa.gov/insight

- The discovery of marsquakes and characterization of the seismicity of Mars

Banerdt et al. (2020) *Nature*

Statistical Comparison of Martian, terrestrial and lunar seismic noise



Lognonne et al. (2020) *Nature*

Technologic advancements in geophysical instruments

Seismology

- Planetary Broadband Seismometer (PBBS) – JPL
- Molecular Electronic Transducer (MET) Seismometer – ASU
- Seismometer for Lunar Network (SLN) – University of Arizona
- Ultra-low frequency atomic lunar seismometer – JPL
- Universal MEMS Seismometer (UMS) – JPL

Technologic advancements in geophysical instruments

Heat Flow

- We now have a heat flow instrument deployable from a small robotic lander, and it is more robust in its ability to penetrate regolith than the mole-based system used for the InSight mission.

- The new heat flow instrument (LISTER) has been selected to fly on a CLPS mission in 2022 and will reach TRL-9 in time for New Frontiers 5.

- Recent lunar orbital missions (LRO and GRAIL in particular) have global data coverage and the Arecibo Radar has near complete coverage on the near side. These data enable us to select landing sites that would maximize science return.

The Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (LISTER)

Technologic advancements in geophysical instruments

Electromagnetic Sounding

Surface magnetometer measurement must be supplemented with another constraint in order to perform EM sounding:

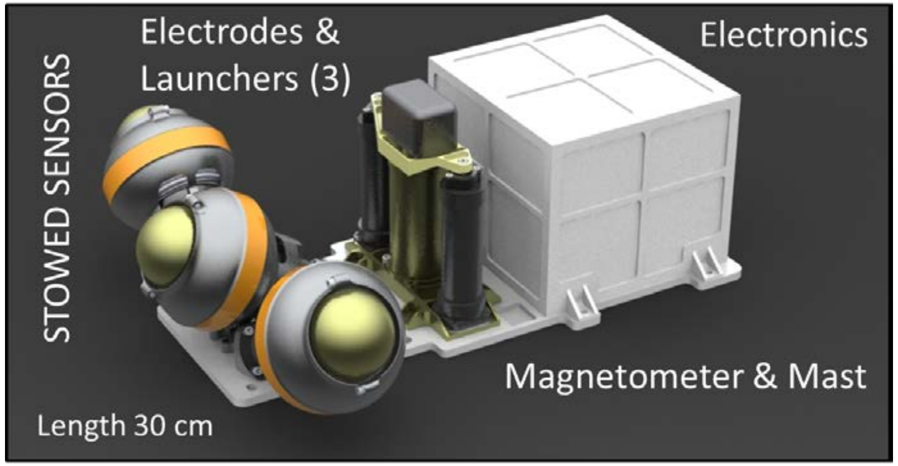
- Geometrical information on source field (quasi-DC fields observed by Galileo, Lunar Prospector, Kaguya).
- Direct measurement of AC source field at large distance from target (Apollo-Explorer)

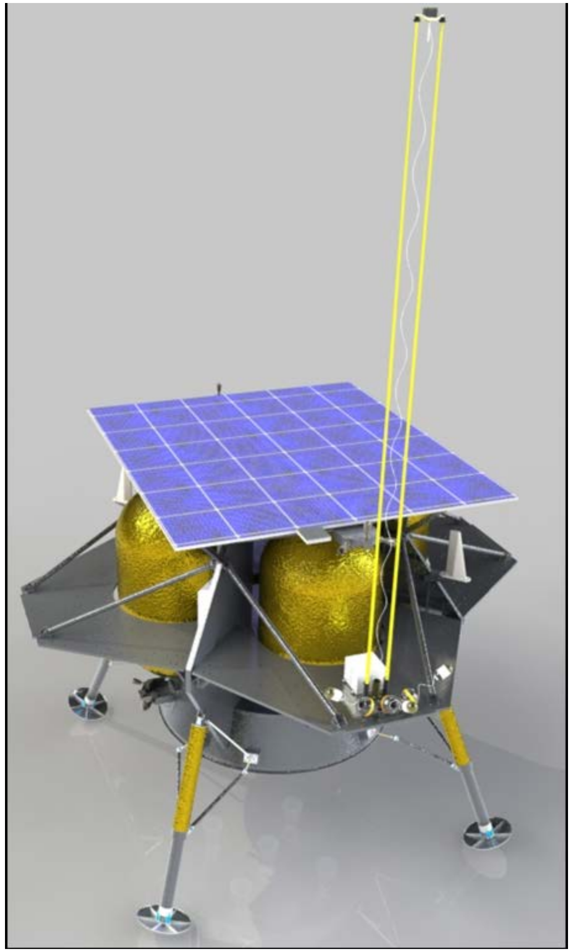
Measurement of the electric field can also be done using the magnetotelluric method (MT).

- *MT has been used on Earth for more than 50 years and provides soundings from a single surface station without any knowledge of the source field.*

Lunar Magnetotelluric Sounder (LMS)

- Compact instrument combining fluxgate magnetometer with ballistically launched electrodes.
  - Electric field determined from voltage drop across electrodes 10-20 m apart.
- Selected for CLPS flight to the Moon in 2022.
- High heritage for LGN.





Technologic advancements in geophysical instruments

Lunar Laser Ranging

Technical Advancements

- Development of Next Generation Lunar Retroreflector for CLPS lander
- Upon deployment in 2022 will support factor of 100 improved range accuracy and science parameter uncertainty

Lunar Scientific Advancements

- Strong tidal dissipation from partial melt at bottom 200 km of mantle. Dissipation 1/Q peaks around 3 months period
- Improved shape & dissipation of liquid-core/solid-mantle boundary
- Collaboration with GRAIL improves principal moments of inertia

Programmatic considerations and NASA activities

- Discovery 2019 Selection Statement on NanoSWARM, a Category I investigation: "NASA is already making significant investments in lunar exploration and investigation, making NanoSWARM a lower priority than the selected investigations for the programmatic reason of maintaining scientific balance."
- What are these investments, and do they *enable* or *replace* Discovery and New Frontiers proposals?
  - ➢ SMD: Lunar Discovery and Exploration Program (LDEP)
    - Development of Advanced Lunar Instrumentation (DALI)
    - NASA-Provided Lunar Payloads (NPLP), Lunar Surface Instrument and Technology Payloads (LSITP), and Payloads and Research Investigations on the Surface of the Moon (PRISM)
    - Commercial Lunar Payload Services (CLPS)
  - ➢ STMD: Lunar Surface Initiative (LSII)
  - ➢ HEOMD: Artemis

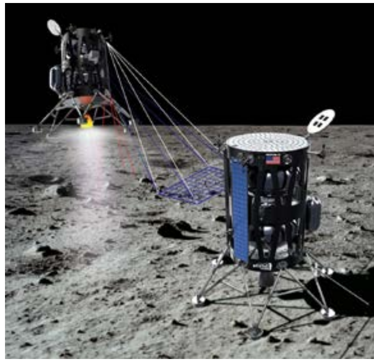
Programmatic considerations and NASA activities

- NASA selected first the two Commercial Lunar Payload Services (CLPS) landers to deliver individual instruments to the Moon in 2021 (Astrobotic, Intuitive Machines), and is reviewing the next two now
- CLPS landers carry ~35 kg of total payload and last 1 lunar day; NASA is the marginal customer – meaning that these are delivery trucks, not integrated science missions
- We are excited about this model, but it is not yet proven, and the scope is very different – these missions *do not replace* the function of Discovery and New Frontiers to enable Decadal-level science investigations
- CLPS missions can *enable* LGN by retiring key risks such as deployment strategy, lander noise characterization, and thermal and power performance
- Multiple new lander providers may eventually *enable* a mission like LGN to shop around and save on mission bus costs

CLPS announcement May 2019

Astrobotic

Intuitive Machines

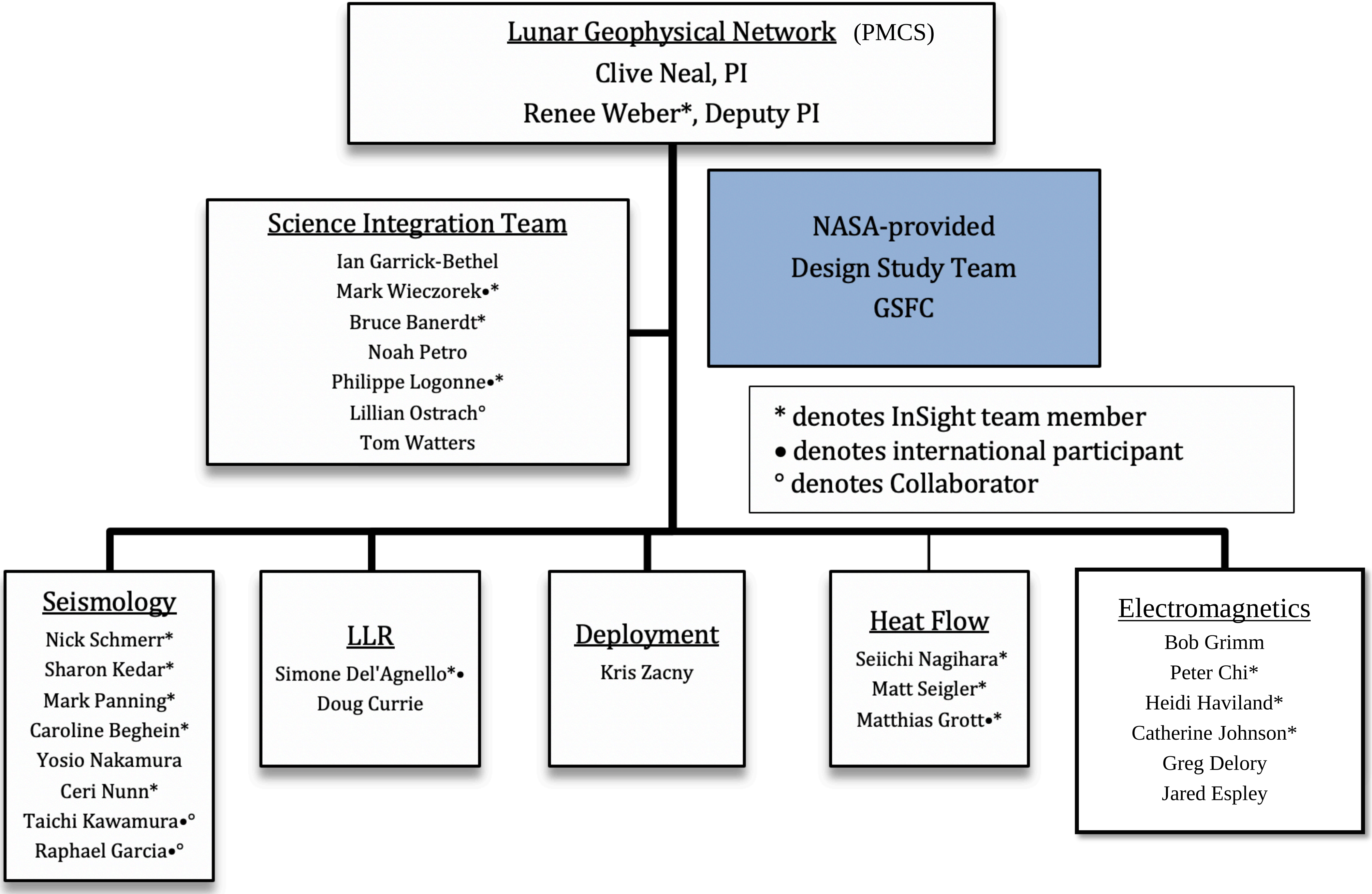


Programmatic considerations and NASA activities

Instruments in development or manifested on CLPS landers *enable* more sensitive or longer-lived instruments to be ready for an LGN

- DALI
  - LEMS: Lunar Environment Monitoring Station, long-term monitoring of the lunar exosphere and seismic activity (Benna, GSFC/UMBC)
  - SLN: Seismometer for a Lunar Network (Bailey/ Univ. of Arizona)

- NPLP/LSITP (instruments in CLPS landers)
  - LMS: Lunar Magnetotelluric Sounder (Grimm / SwRI)
  - NGLR: Next Generation Lunar Retroreflector (Currie / Univ. of Maryland)
  - LISTER: Lunar Instrumentation for Subsurface Thermal Exploration with Rapidity (Nagihara / Texas Tech.)
  - LuSEE: Lunar Surface Electromagnetics Experiment (Bale / UC Berkeley)
  - Fluxgate Magnetometer (Purucker / GSFC)



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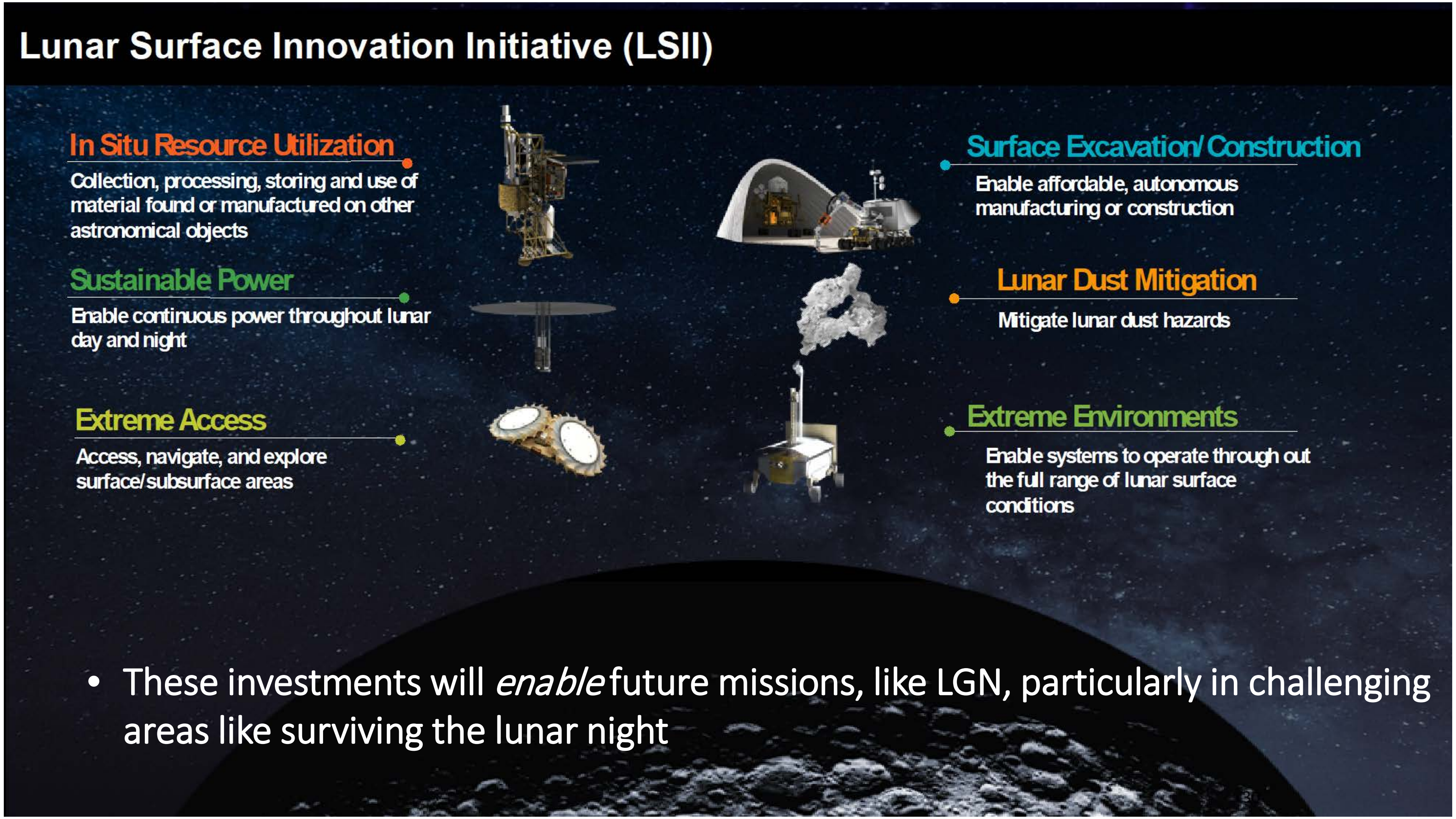
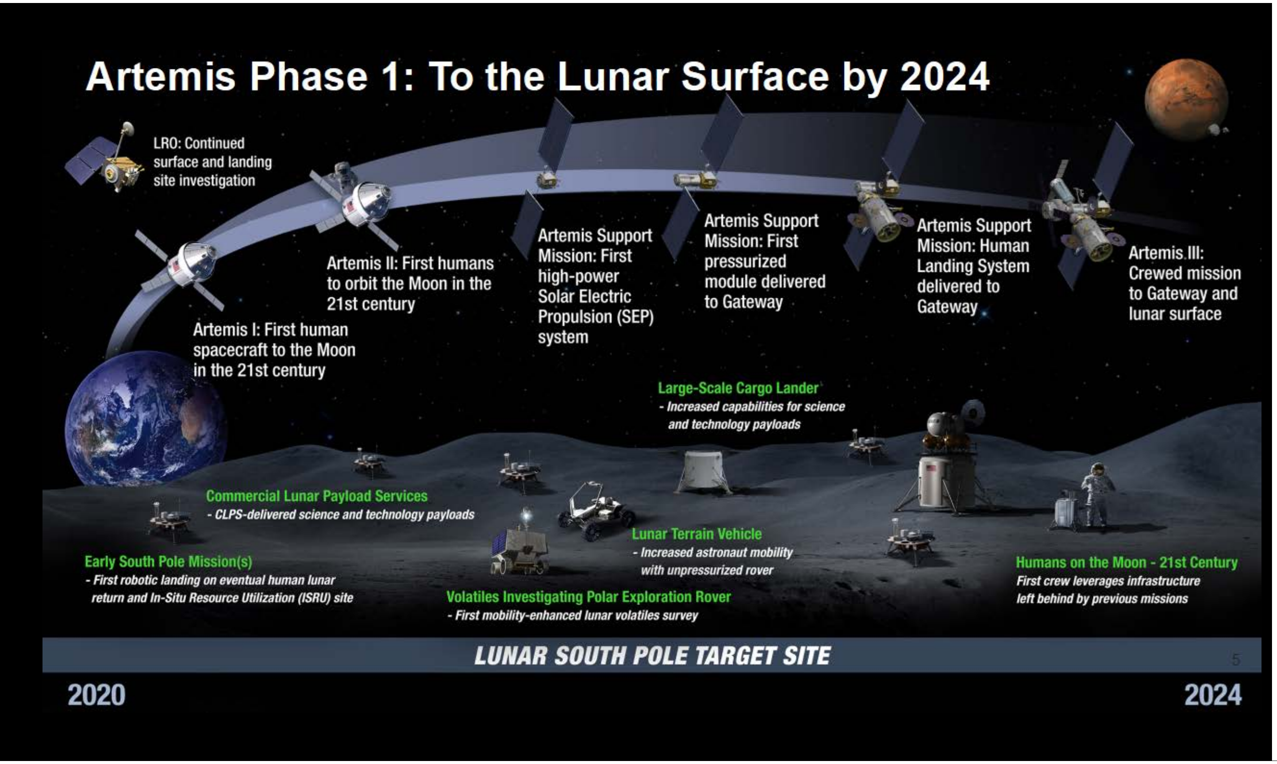
Programmatic considerations and NASA activities

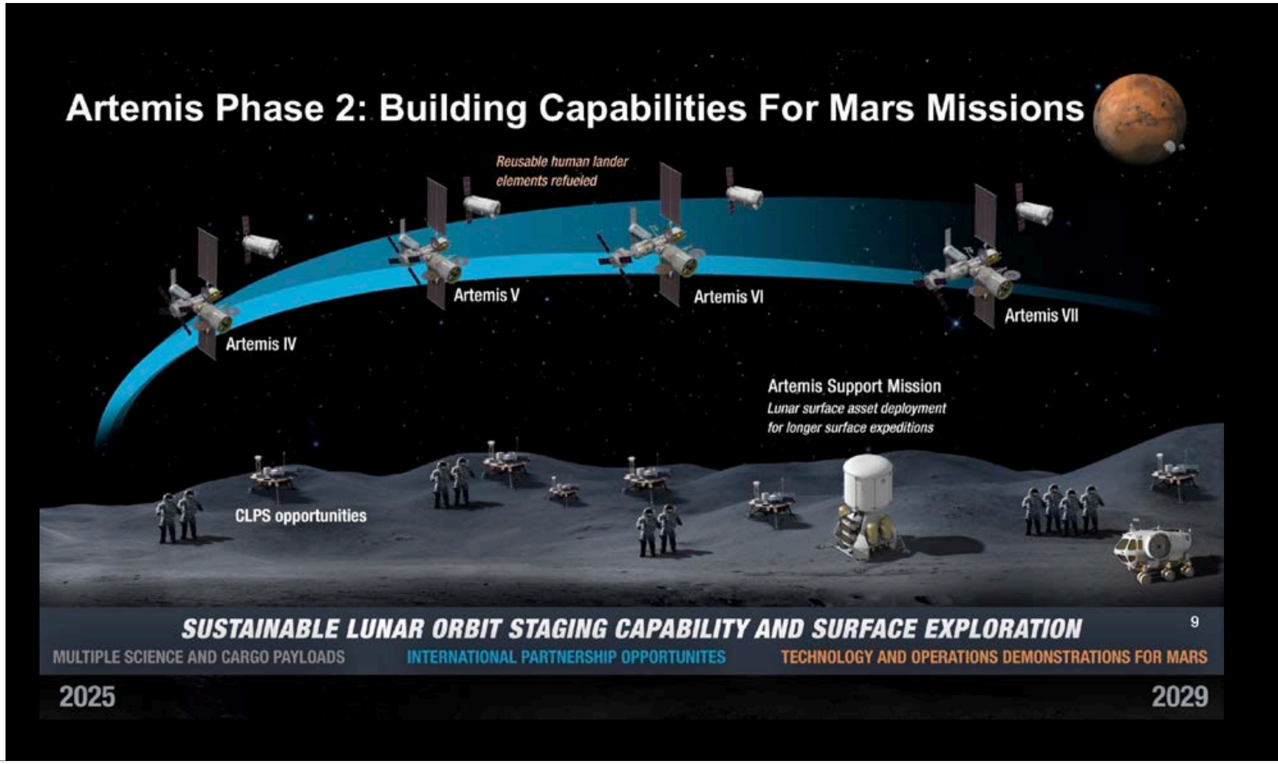


- These investments will *enable* future missions, like LGN, particularly in challenging areas like surviving the lunar night

Programmatic considerations and NASA activities

- HEOMD: Artemis Program is focused on human landing by 2024
- Landing at a single site will not fulfill network goal, but if there are opportunities to deploy a long-lived geophysical node at the human landing site, this would be *enabling* for broader LGN coverage





CAPS committee questions for New Frontiers targets

2. Has scientific understanding or external factors, such as programmatic developments or technological advances, been sufficiently substantial to warrant reconsideration of the four targets for inclusion in the New Frontiers 5 announcement of opportunity, scheduled for release in early 2022? NO

Advancing Science of the Moon, 2018
https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

In order to make significant progress toward addressing the fundamental questions related to the lunar interior, the recommendations for implementation in the 2007 NRC report remain valid. These recommendations include emplacement of instruments such as a simultaneous, globally distributed seismic and heat flow network and/or an expanded retroreflector network, as well as strategic collection of samples from terrains of different ages that can provide constraints on lunar geochemistry and new information on the history of the lunar dynamo.

Lunar Exploration Analysis Group 2019 finding regarding LGN:

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.