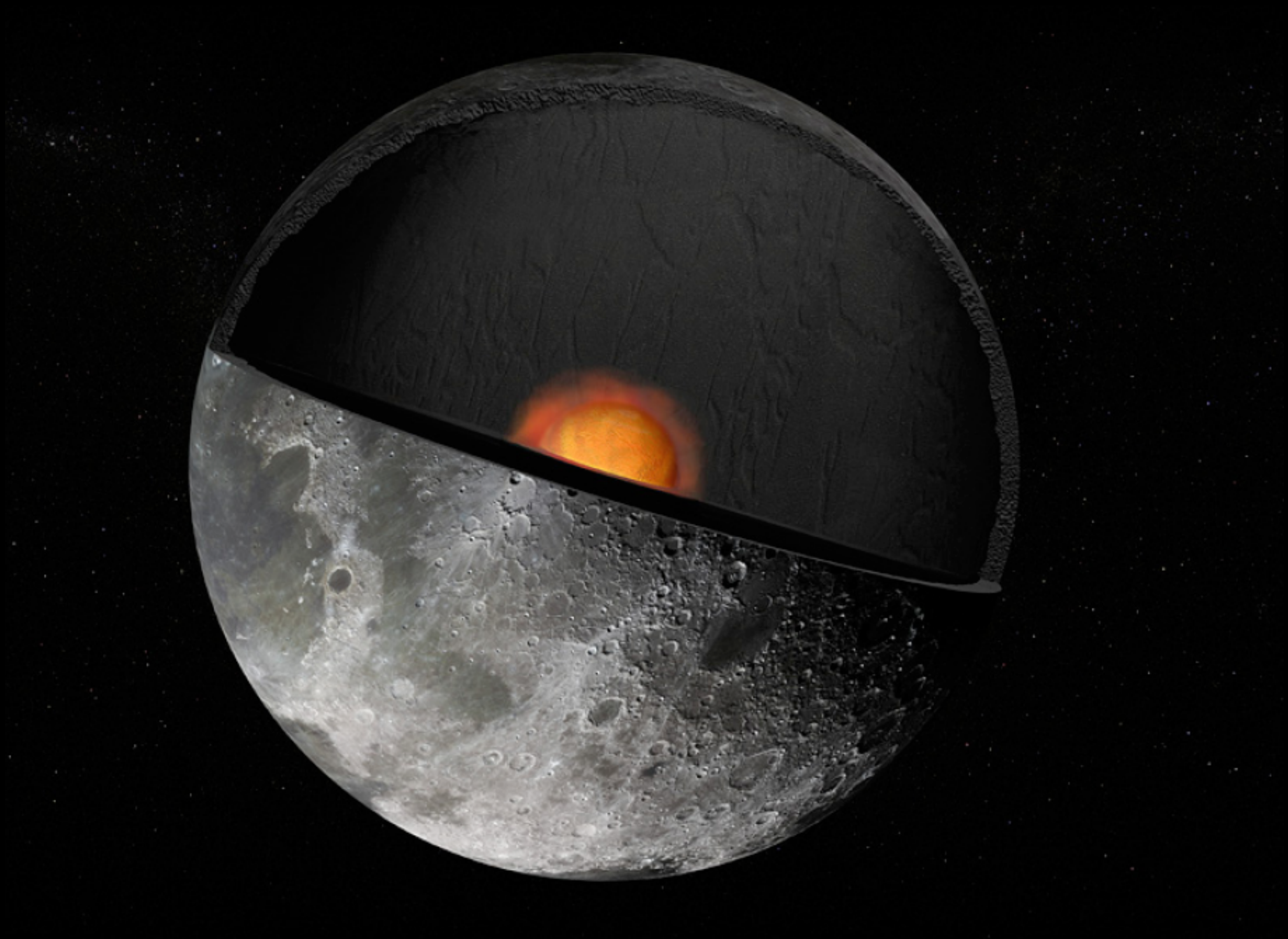
The interior structure and evolution of the Moon

A geophysical perspective…



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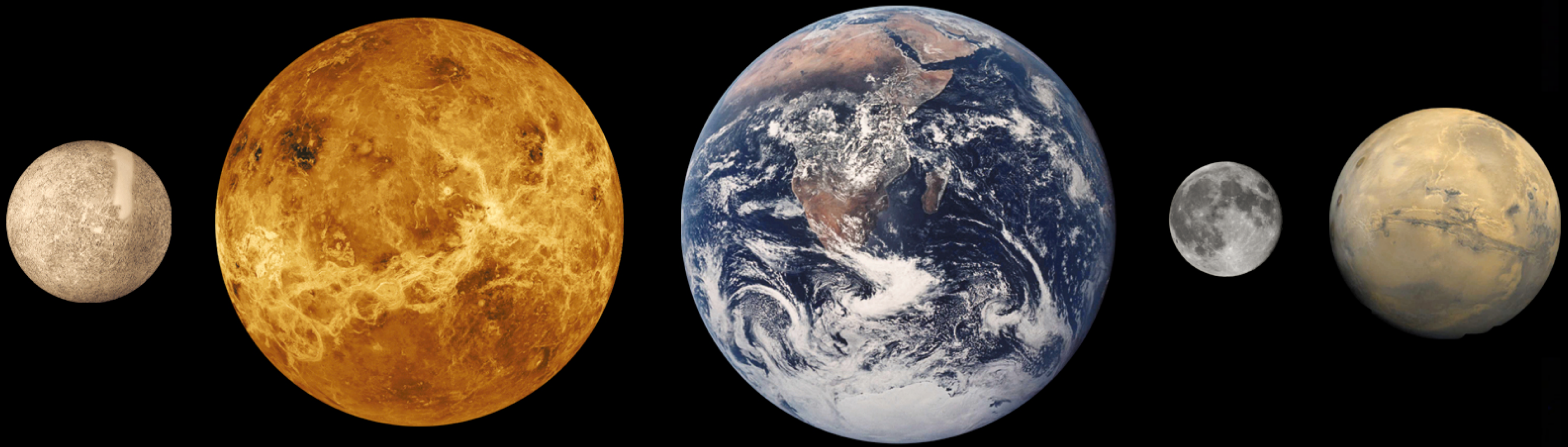
Comparative Planetology



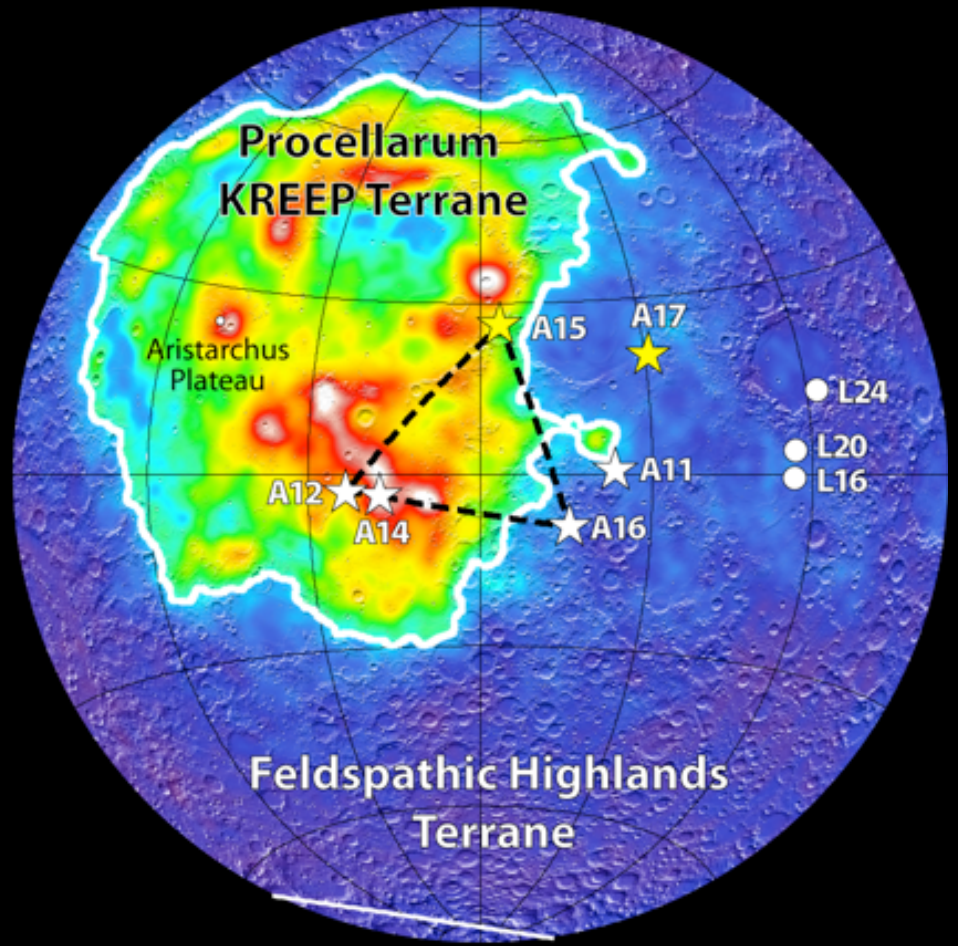
By studying the same physical process (such as mantle convection, dynamos, impact cratering) but with different boundary conditions, we can learn more about how these processes work on Earth.

The importance of the Moon in Earth and Planetary science

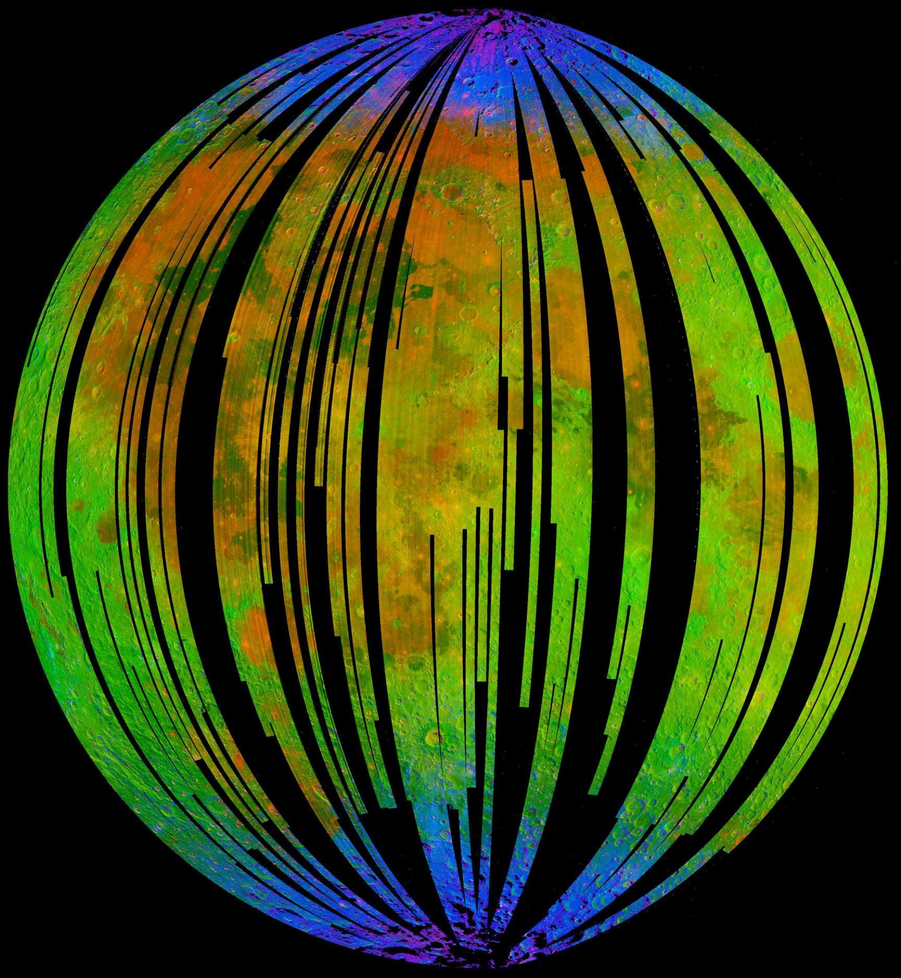
- The Earth and Moon formed together during a giant impact event 4.5 billion years ago.
- Both the Earth and Moon had large scale "magma oceans," but this event is preserved only on the Moon.
- The Moon has witnessed 4.5 billion years of impact cratering, and is the basis of the "crater chronology" method.
- The Moon is the only extra-terrestrial object for which we possess in situ samples with known geologic context.

Lots of data have been collected, but most of these only tell us about the surface

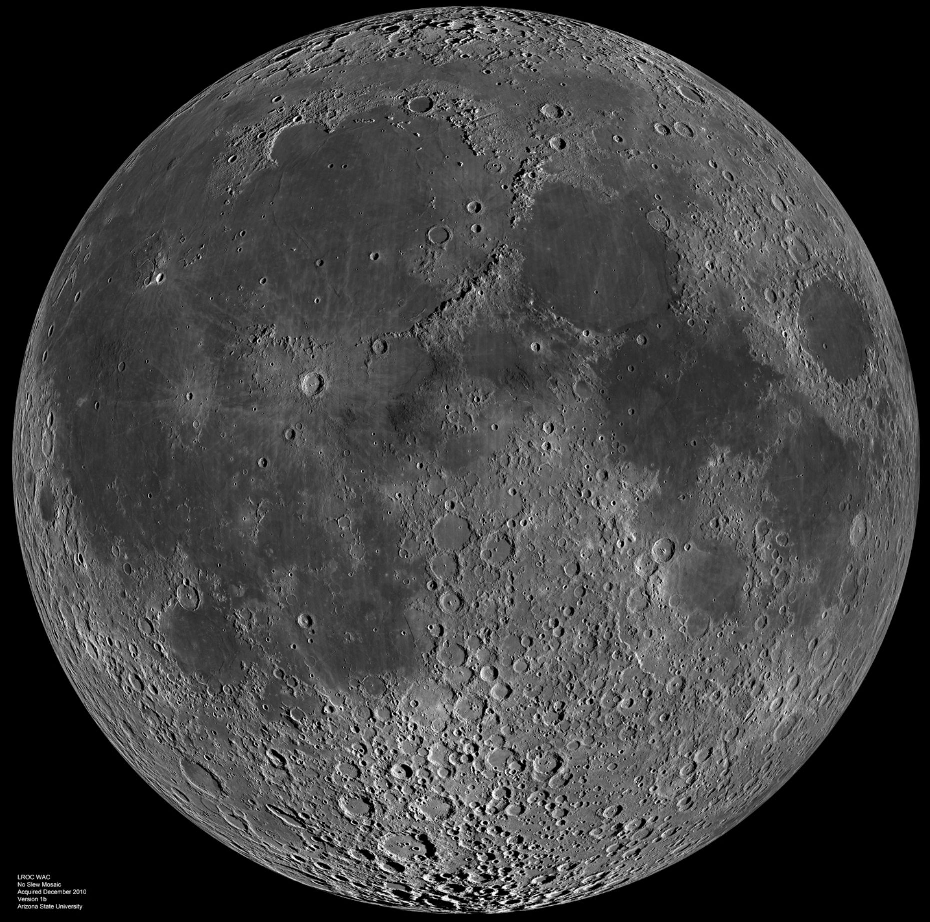
382 kg of samples (Apollo, Luna, Chang'e)



Global compositional mapping (Lunar Prospector, Kaguya)



Global spectral mapping (Kaguya, Chandrayaan-1, Chang'e)



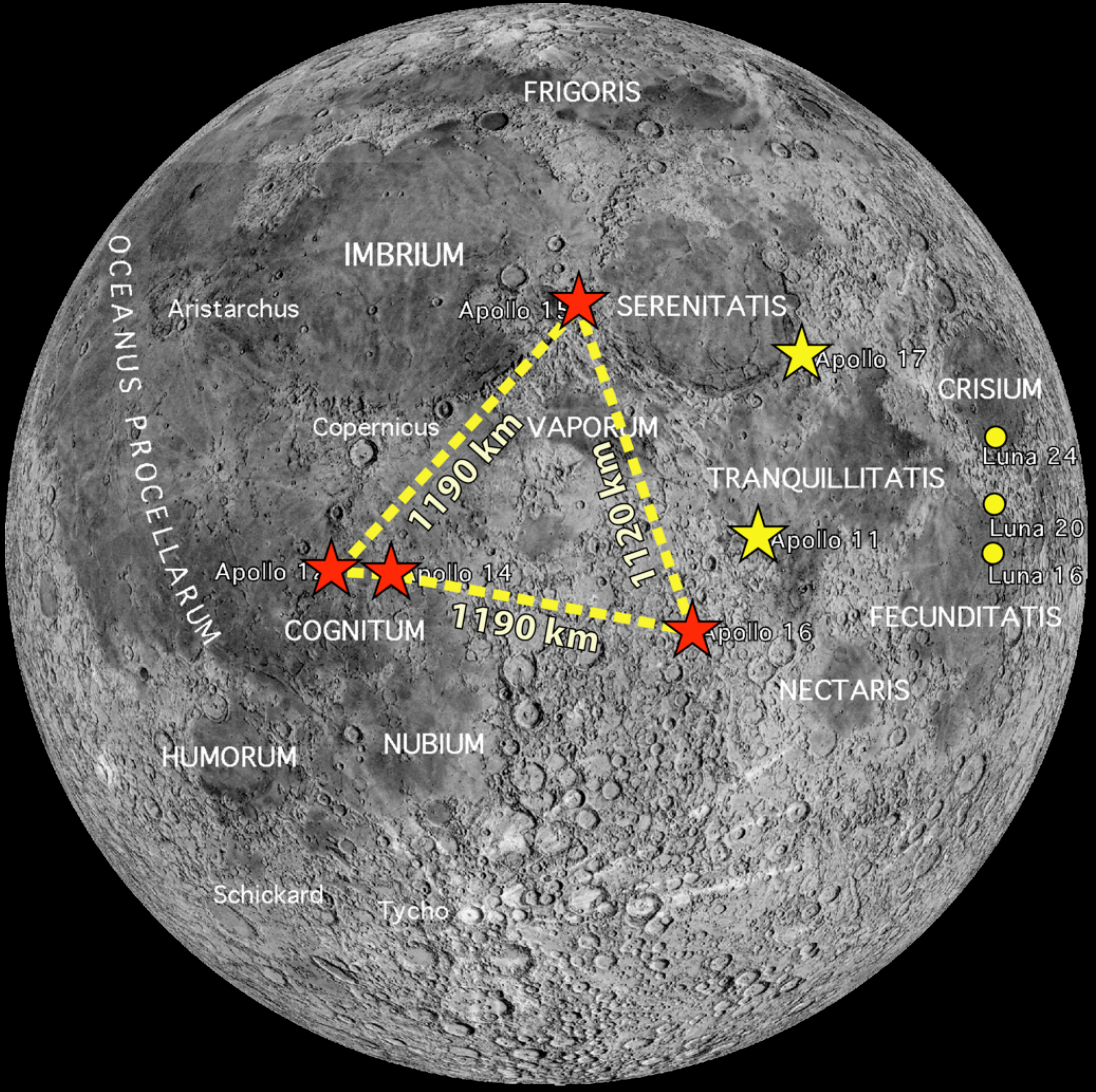
Global imaging of the surface (Lunar Reconnaissance Orbiter, Kaguya, Chang'e)

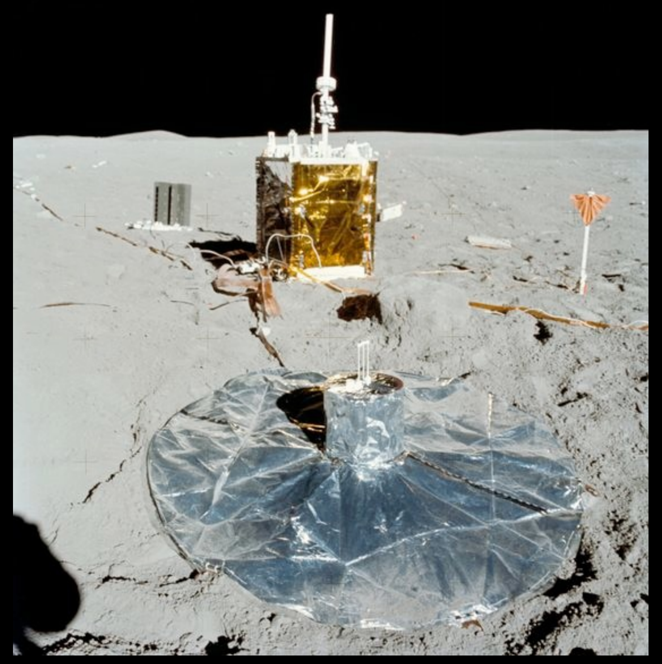
Geophysical data are required to see below the surface.

Key questions about the Moon

- Why are the nearside and farside hemispheres different?
- How thick is the crust?
- What is the composition of the mantle?
- Does the Moon have a core? And did it ever generate a magnetic field?
- How did external geologic process, such as impact cratering, affect the Moon's evolution?

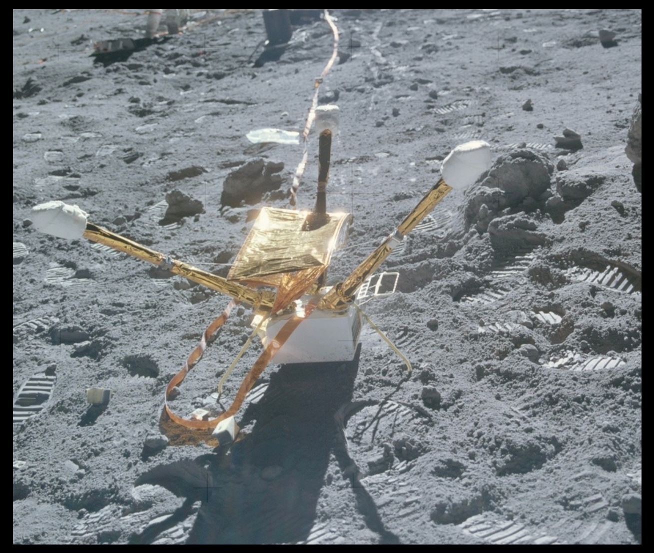
The ALSEP Network





A16 seismometer

A17 heat flow experiment



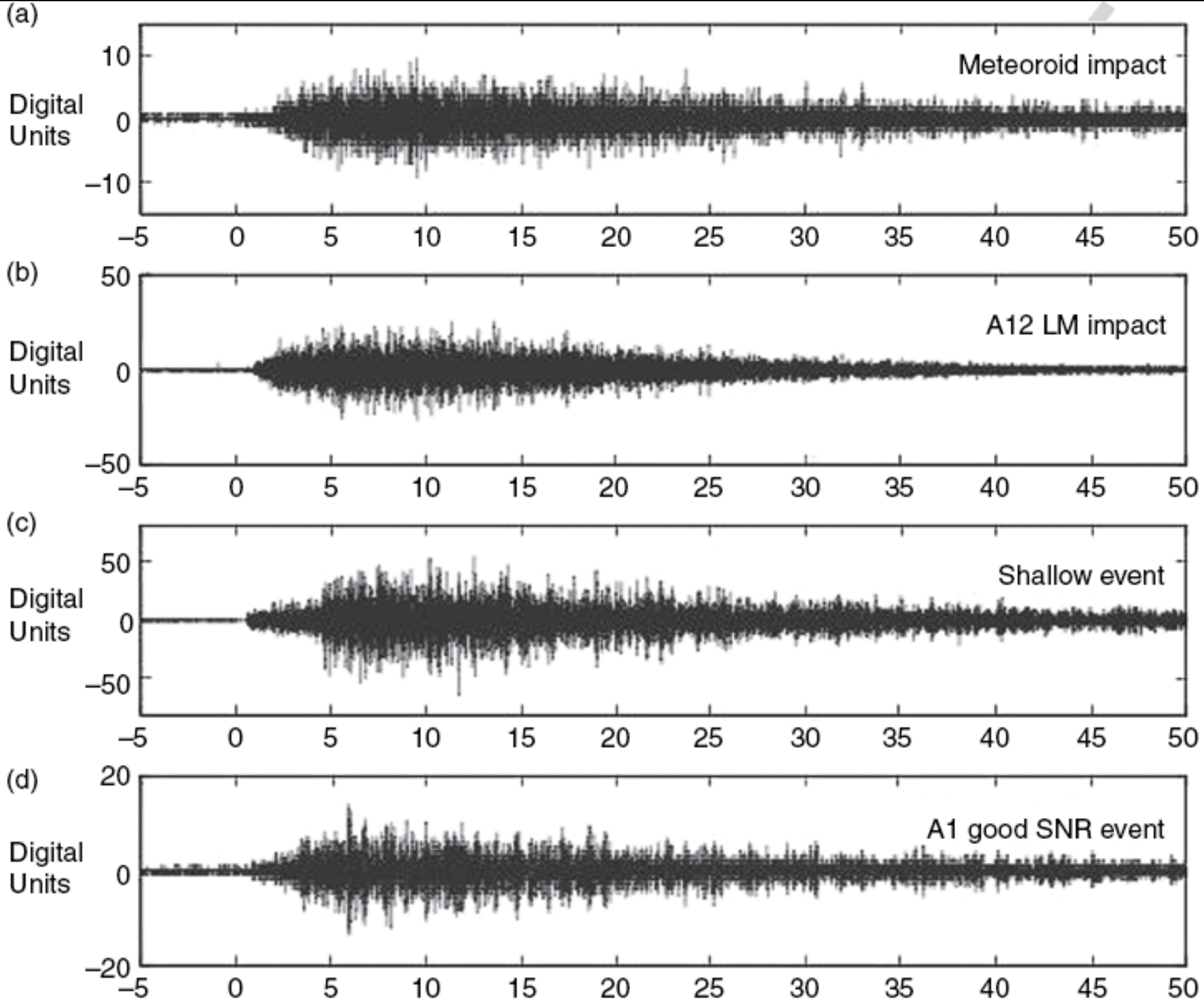
A16 magnetometer

A11 laser retroreflector

The Apollo Lunar Surface Experiment Package (ALSEP) operated for about 7 years, but covered only a small portion of the nearside hemisphere.

Wieczorek (2009)

Characteristics of moonquakes



~1700 meteoroid impacts.

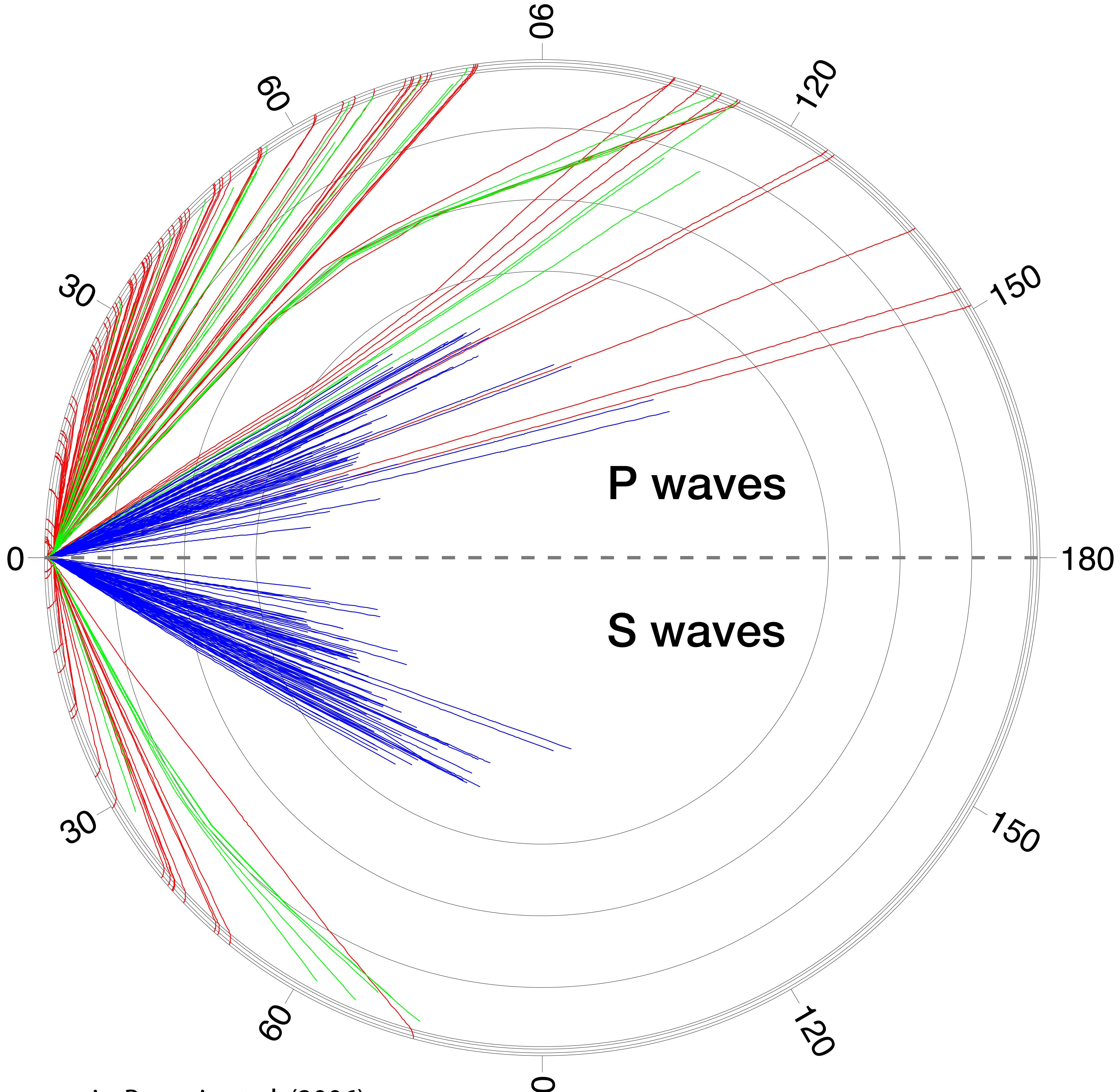
9 artificial impacts (locations imaged by LRO).

28 shallow "tectonic" moonquakes. (Most energetic, having magnitudes up to 5).

~7000 deep moonquakes originating from about 300 distinct source regions that are correlated with the tides.

Lognonné and Johnson (2007)

Seismic sampling of the deep interior

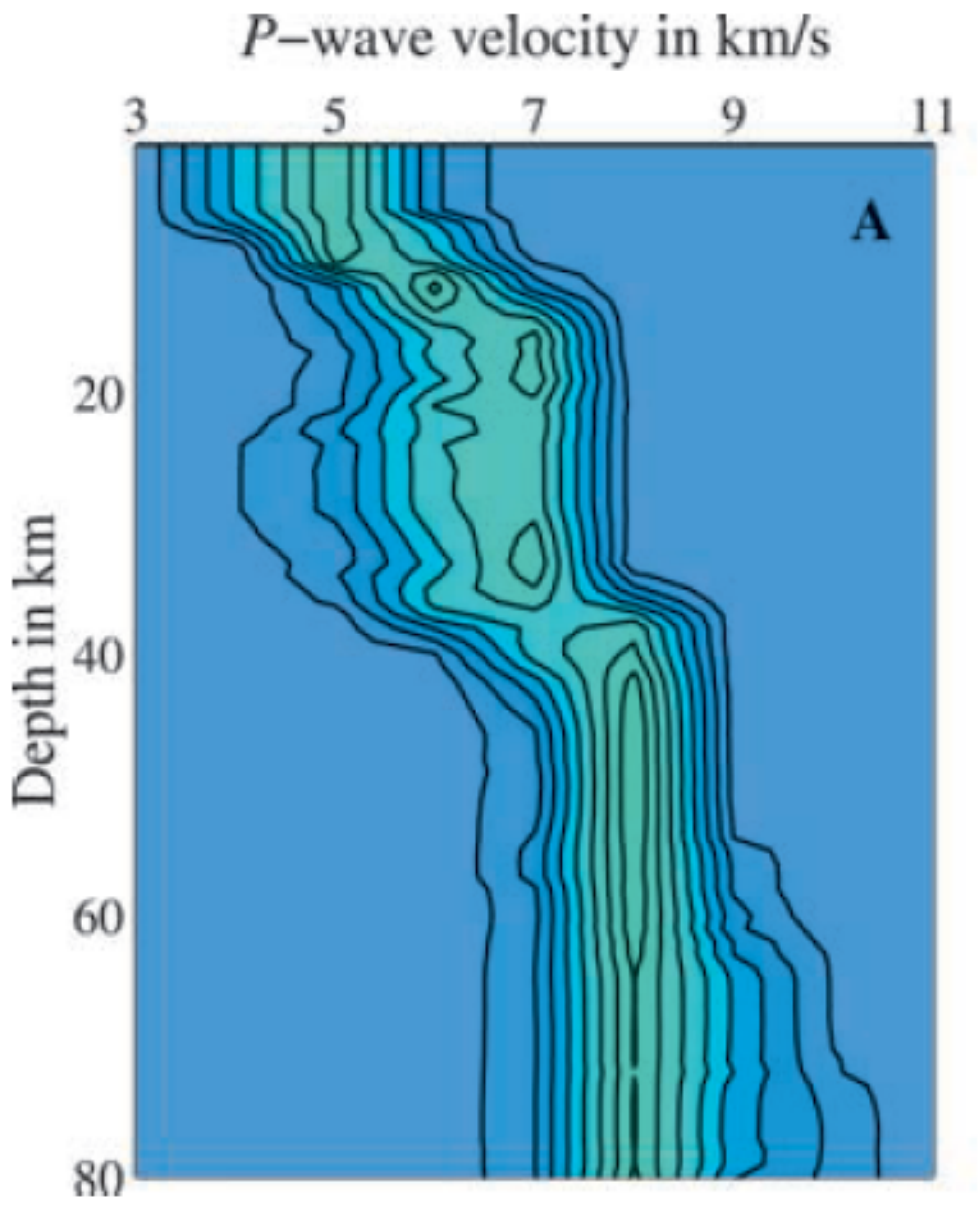


Gagnepain-Beyneix et al. (2006)

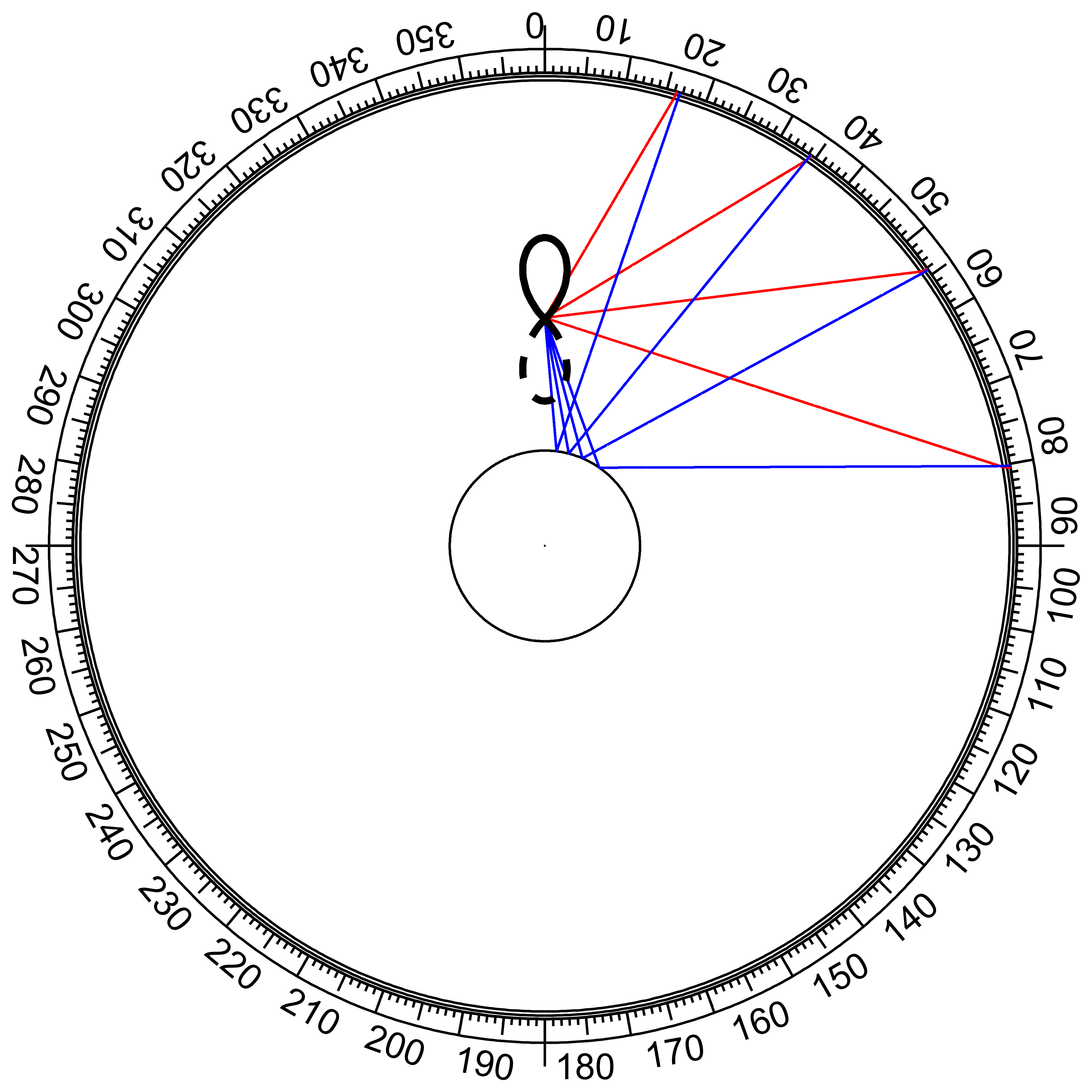
Three types of seismic events: deep (blue), shallow (green), and meteorite impacts (red).

Most deep moonquakes occurred on the nearside hemisphere. Is this an observational bias, or is the farside seismically inactive?

No direct seismic rays pass through the central portion of the Moon where a core might be present.



Khan and Mosegaard (2002)



Garcia et al. (2011)

The crust beneath the Apollo zone is either 30±3 km (Lognonné et al. 2003) or 38±3 km (Khan and Mosegaard 2002) thick.

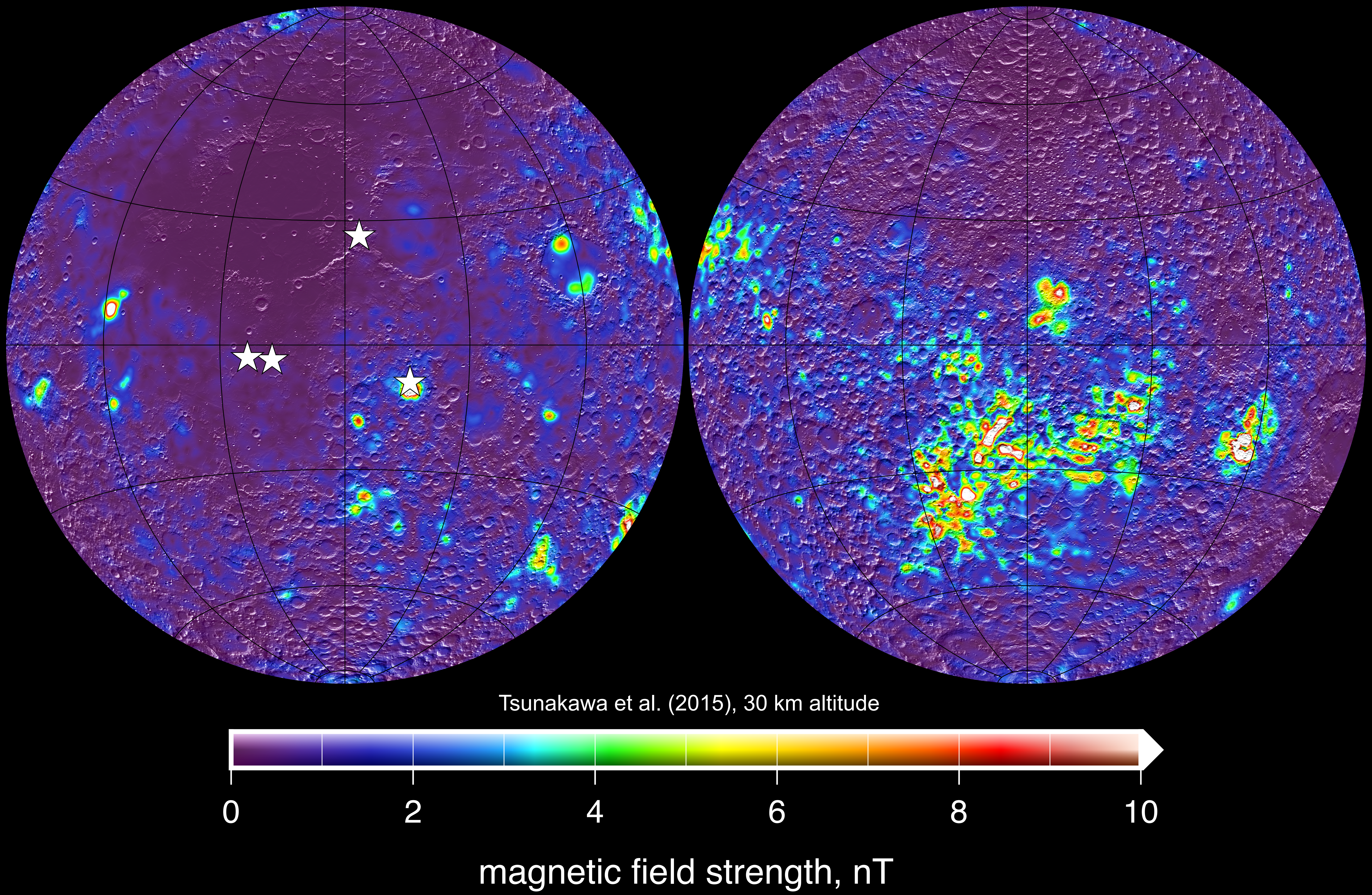
Energy from seismic S waves reflected off the core implies a core radius of 340-420 km.

Lunar surface magnetometer (Apollo 12, 15, 16): 6-231 nT

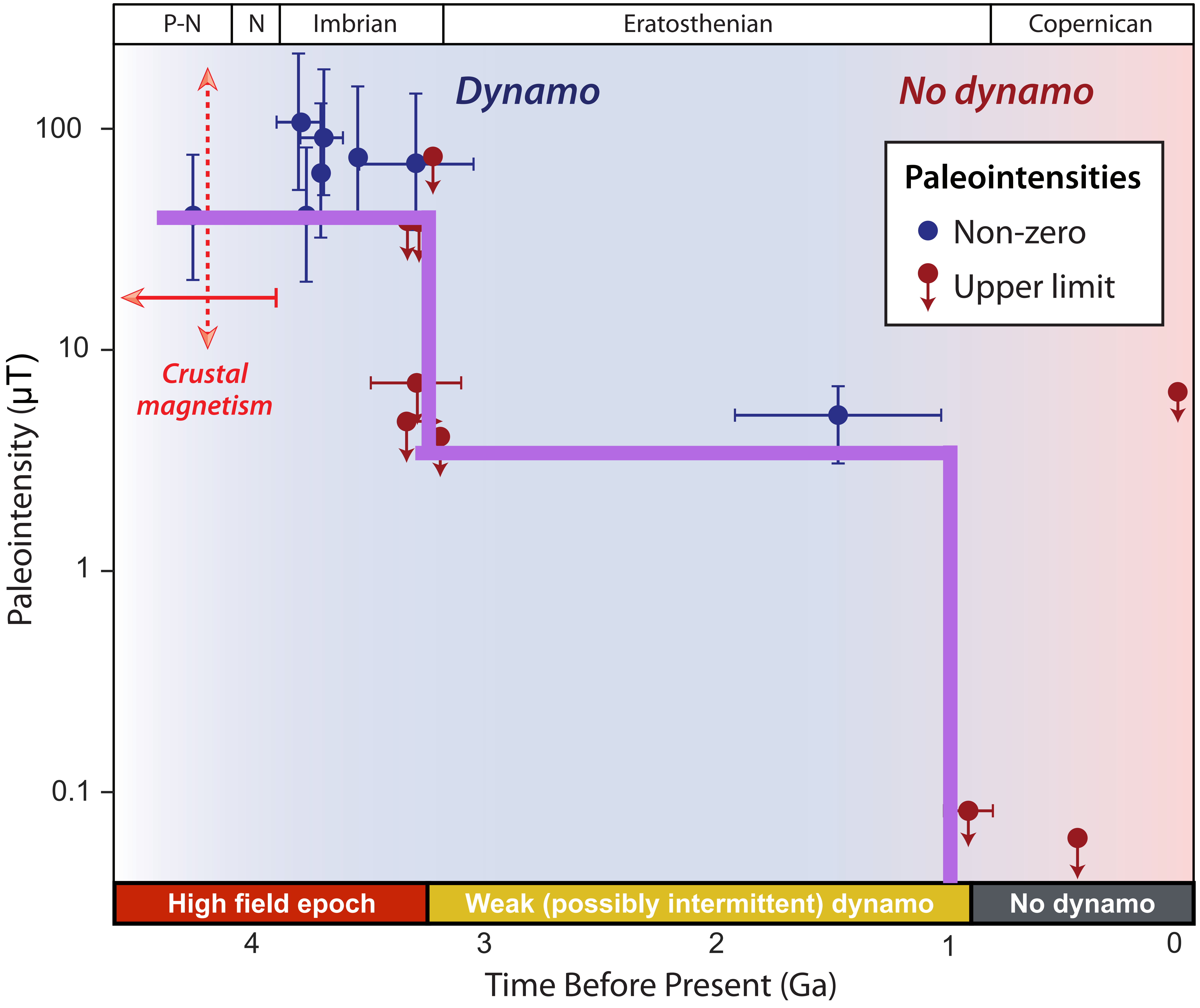
Lunar portable magnetometer (Apollo 14, 16): 43-313 nT

The Moon does not have a dipolar field like the Earth, but the strength of the lunar crustal fields is comparable to the Earth's lithospheric fields.

Lunar Prospector (1994) and Kaguya (2007) orbital magnetometer data



- **Mare basalts have no magnetic signature.**
- **A few large impact basins are weakly magnetized, but most aren't.**
- **Most strong anomalies have no correlation with geologic features.**

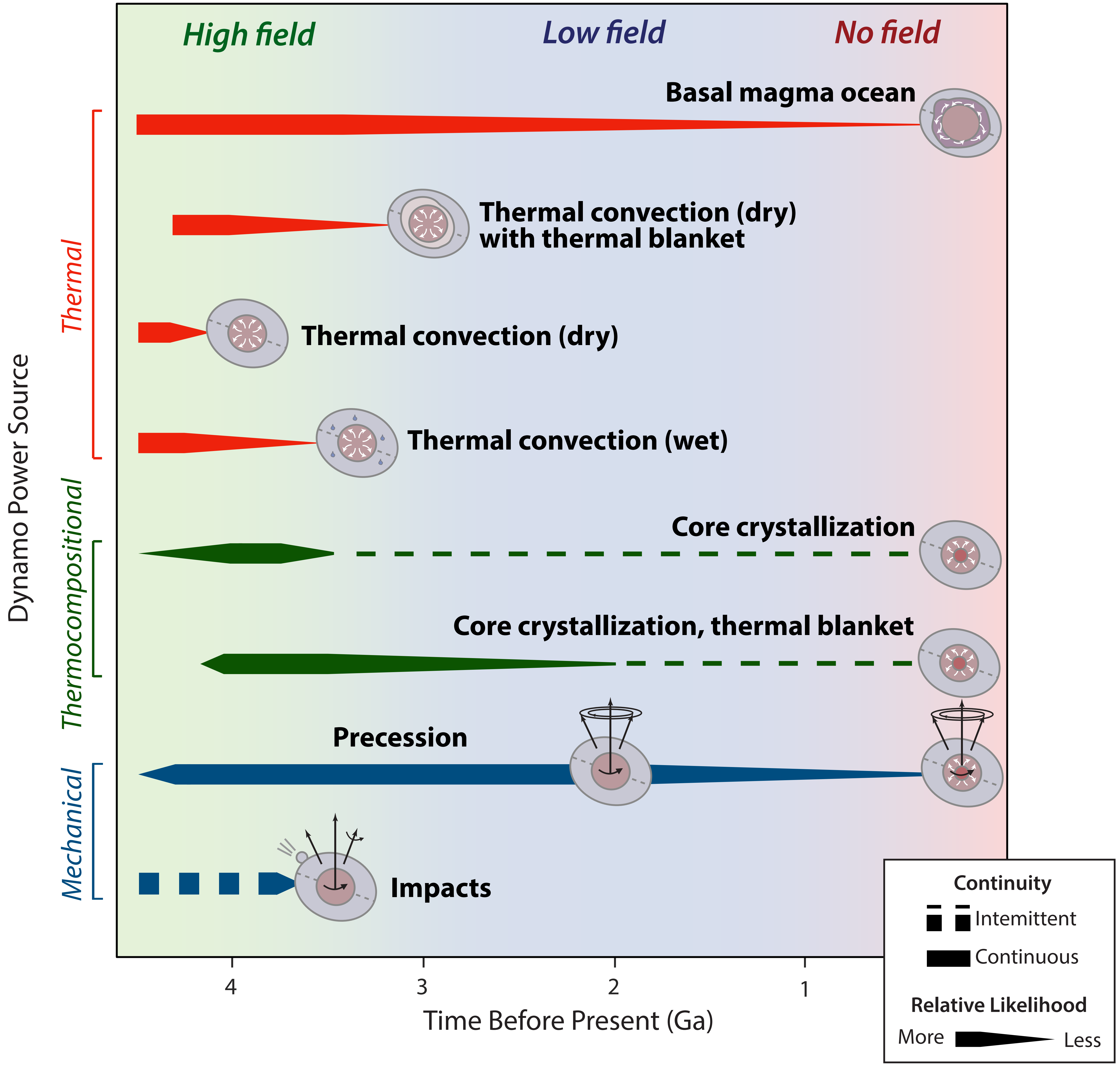


Wieczorek et al. (2020), after Weiss and Tikoo (2014)

Modern paleomagnetism results

- Strong, Earth-like fields from ~4.2 to ~3.5 Ga.
- Dynamo field strength decreased by a factor of 10 from 3.5 Ga to 0.9 Ga.
- No dynamo after 0.9 Ga.

Summary of dynamo models

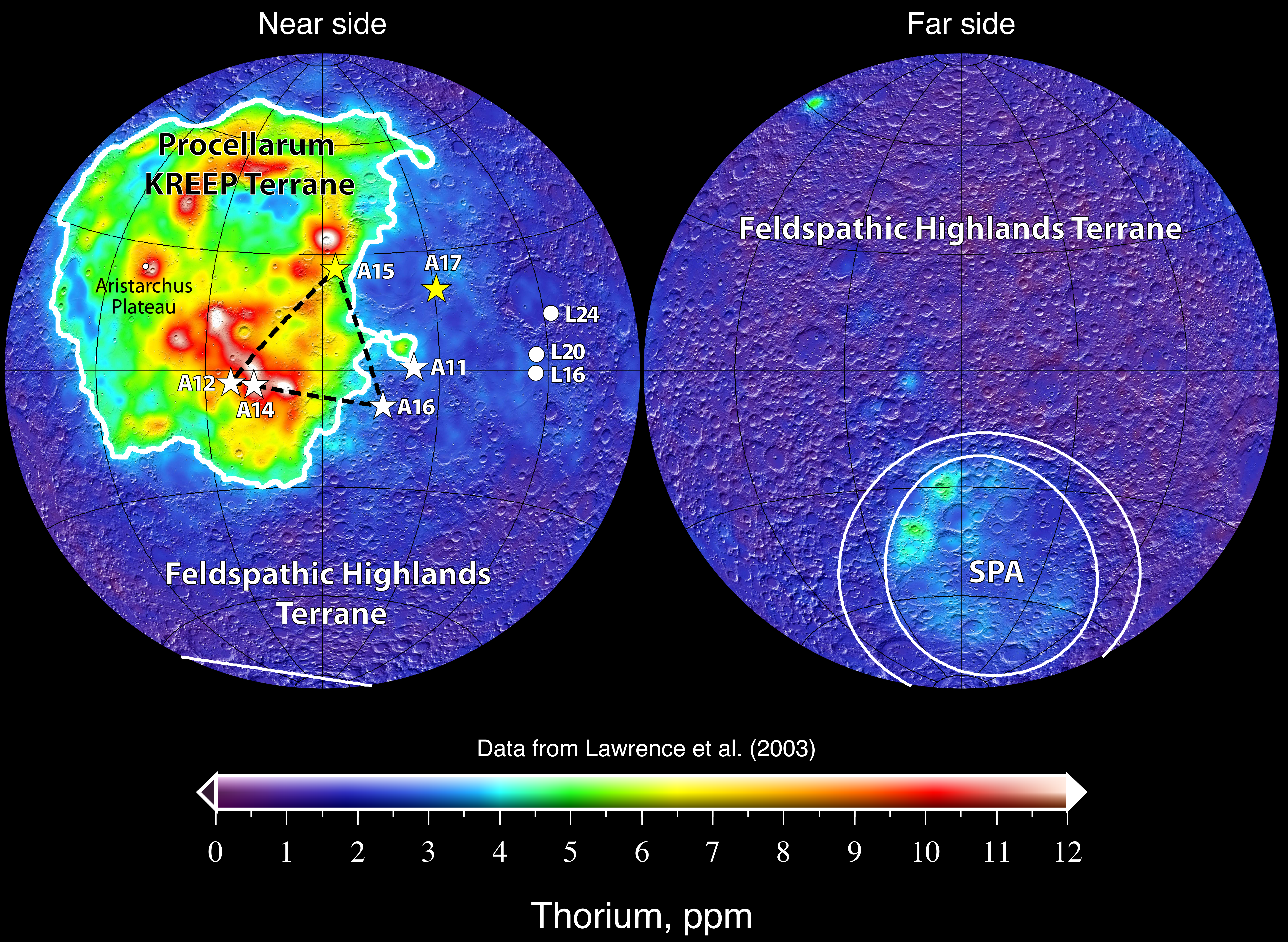


- Thermal convection and core crystallization can account for a magnetic field up to ~2-3 Ga, with perhaps later episodic activity. However, the predicted field strengths are too weak.
- Precession of the liquid core can potentially account for a magnetic field up to about 2 Ga, and precession of a solid inner core even later. The field strengths are unknown, but arguably could be much stronger.
- No models predict a weakening of the field strengths near 3.5 Ga.

The heat flow was measured at two locations on the Moon: Apollo 15 and 17

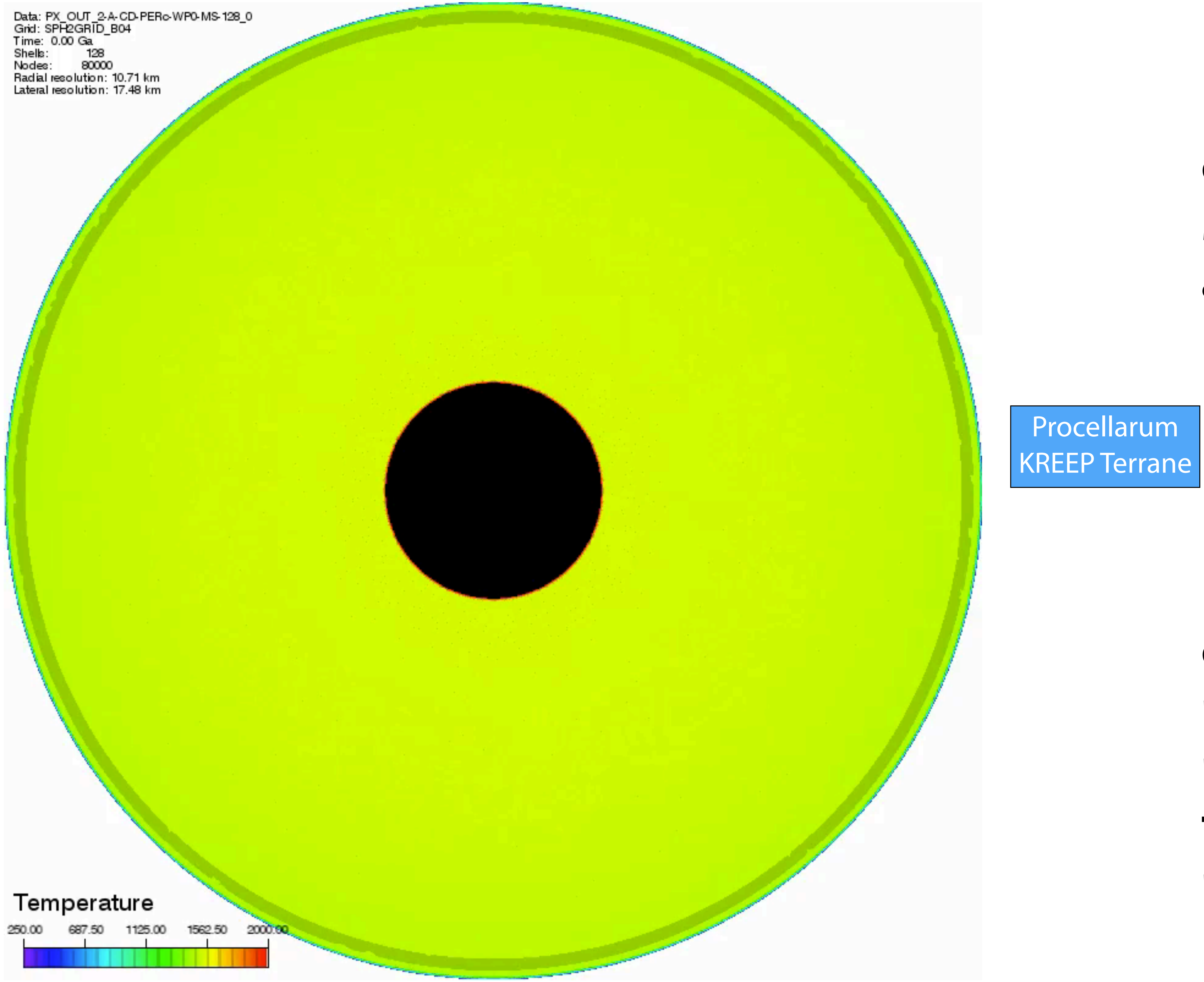
Surface heat flow is sensitive to the abundance of heat-producing elements in the crust and mantle, and is a critical constraint for thermal evolution models.

Lunar Prospector Thorium abundances



The two Apollo heat flow measurements were made at the boundary of two distinct geologic terranes.

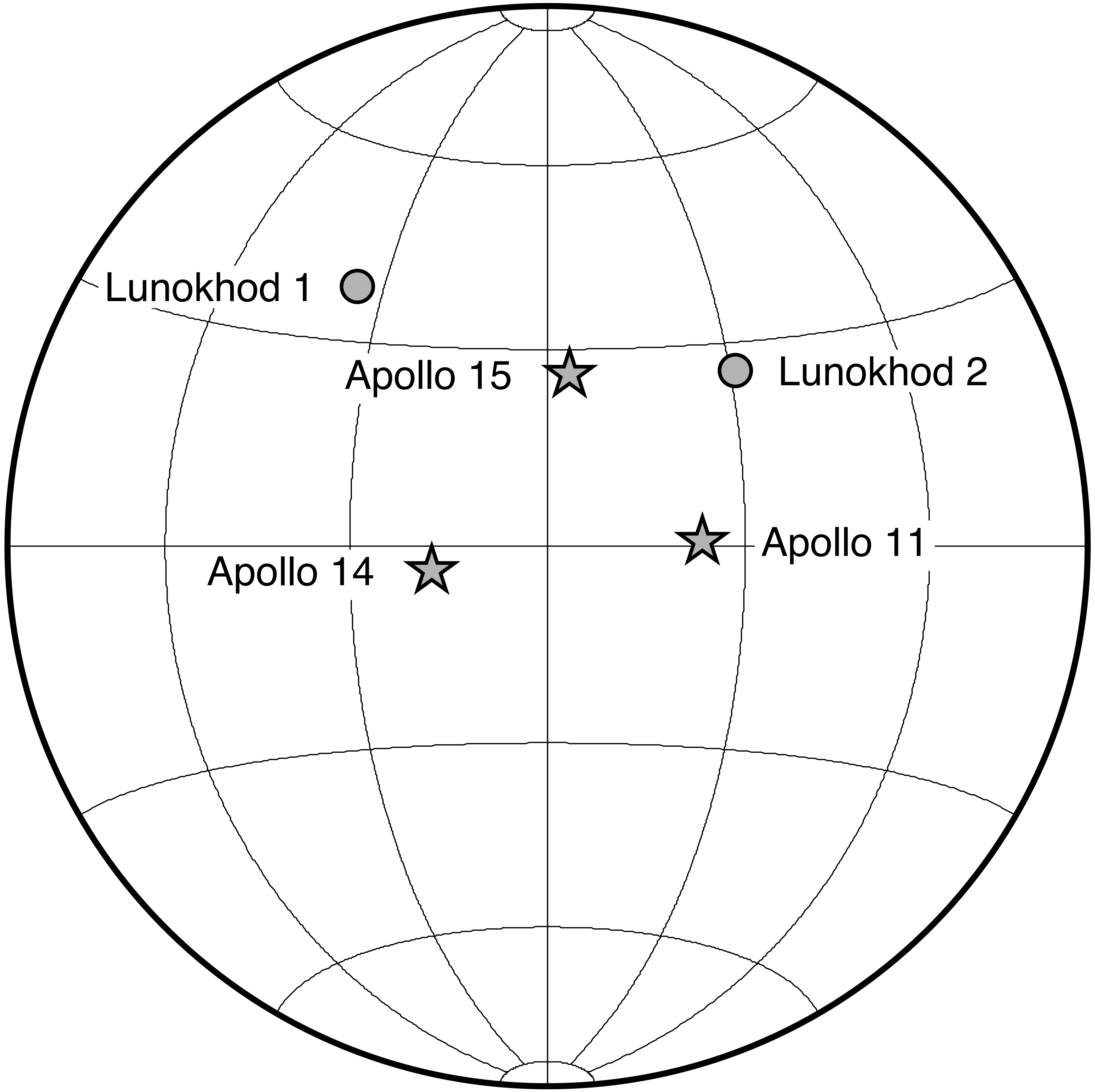
Are either of the measurements representative of the Procellarum KREEP Terrane or Feldspathic Highlands Terrane?



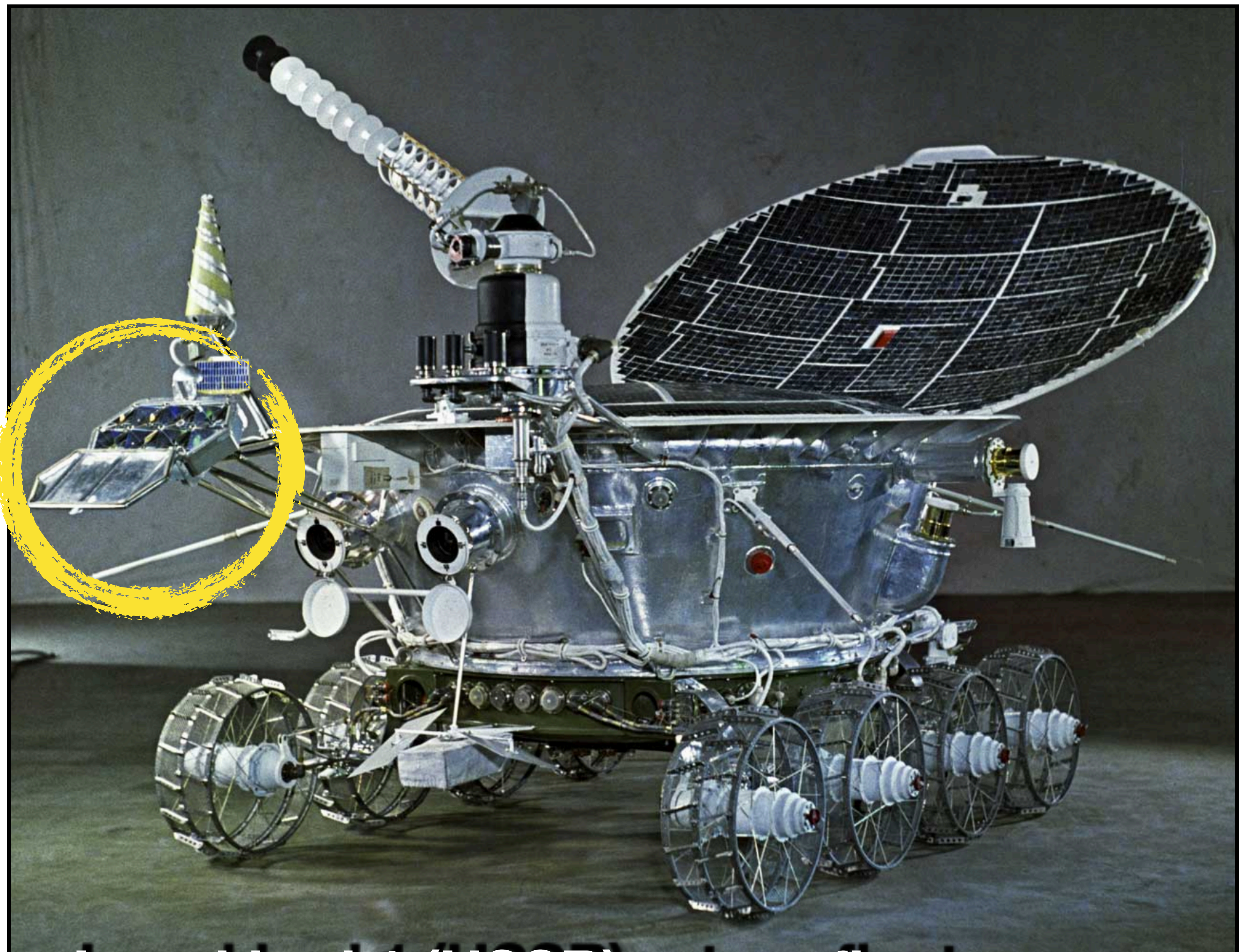
Heat flow measurements constrain models of the Moon's thermal evolution and dynamo generation.

In this model, the high concentration of crustal radioactive elements on the nearside gives rise to a thermal anomaly that persists to the present day.

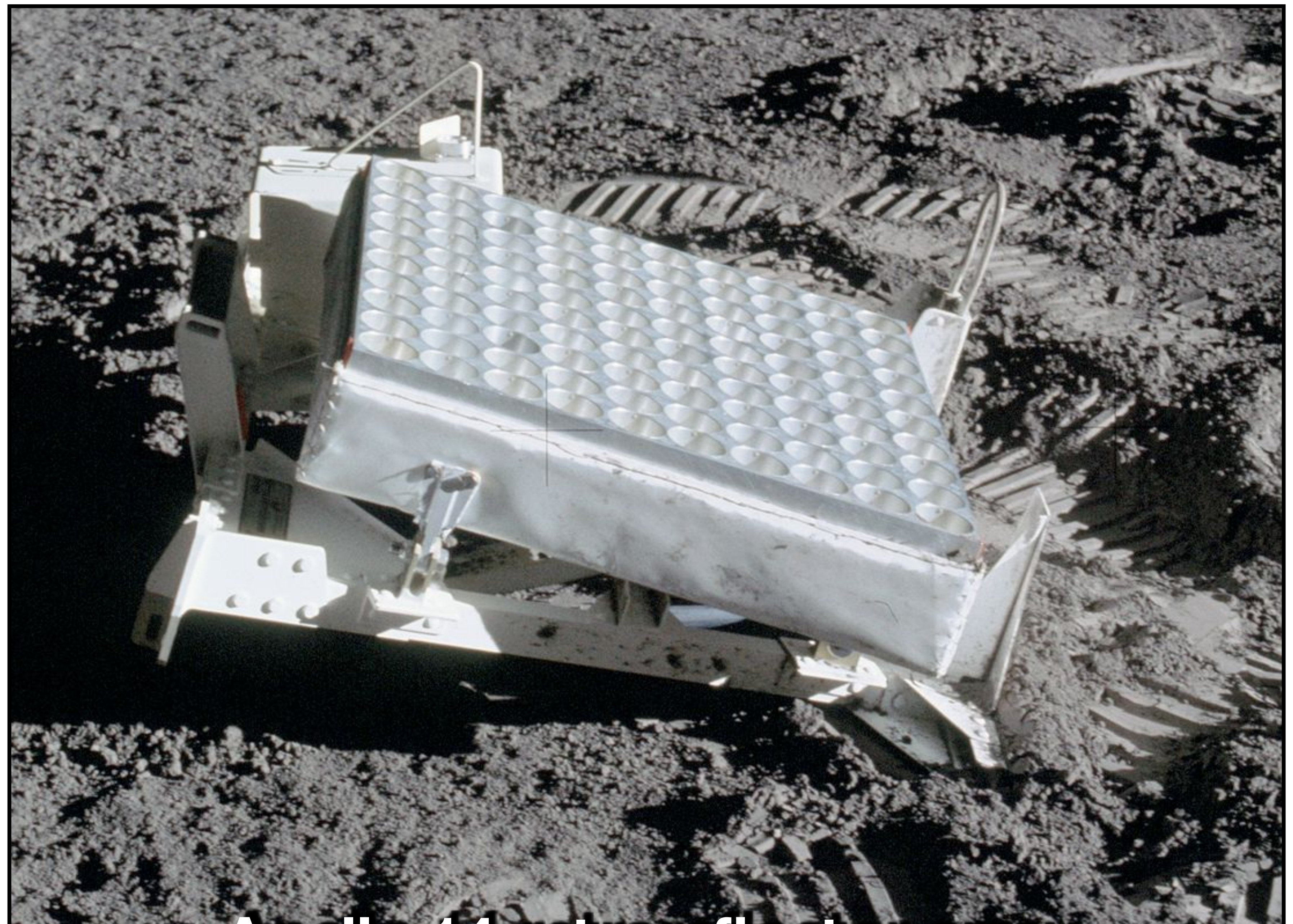
Laneuville et al. (2013)



Lunokhod 1 was "lost" and not ranged to until it was imaged by Lunar Reconnaissance Orbiter in 2010.

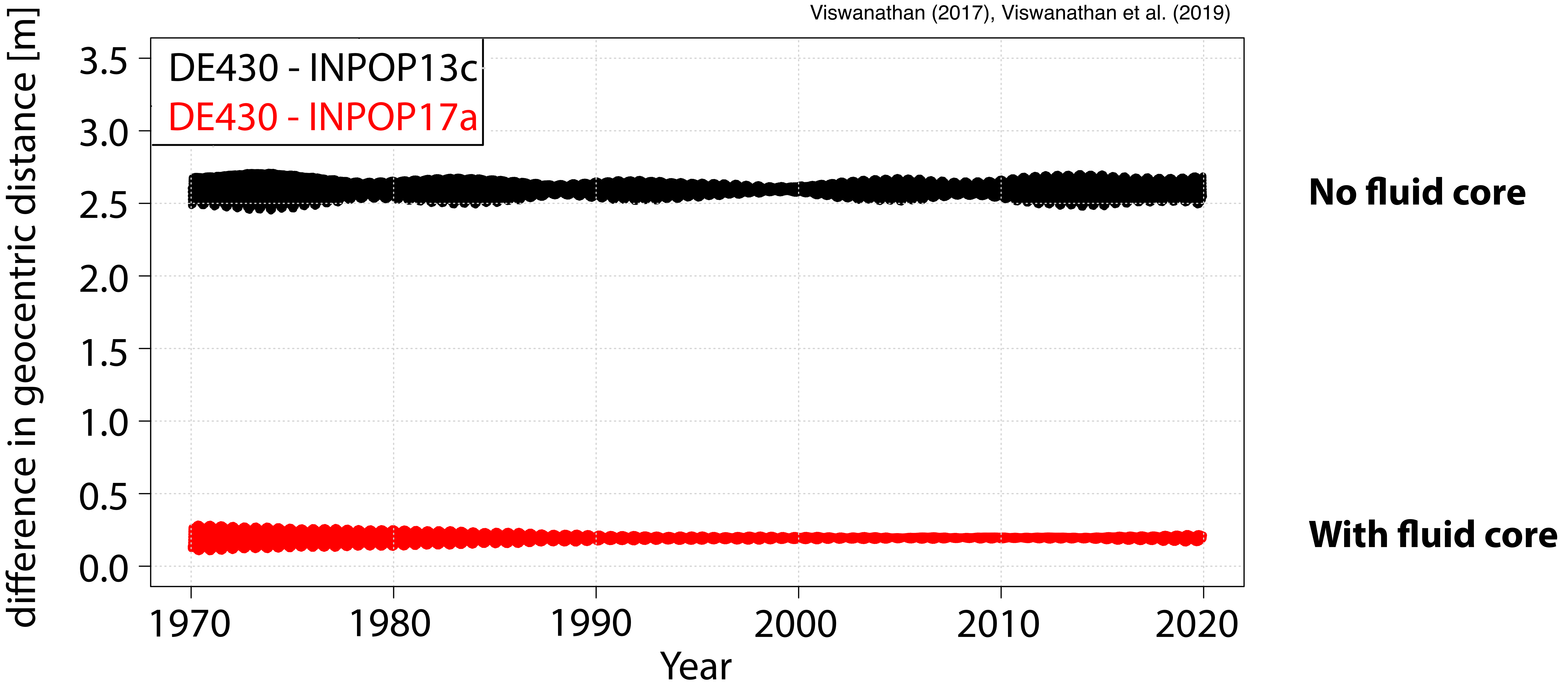


Lunokhod 1 (USSR) retroreflector array



Apollo 14 retroreflector array

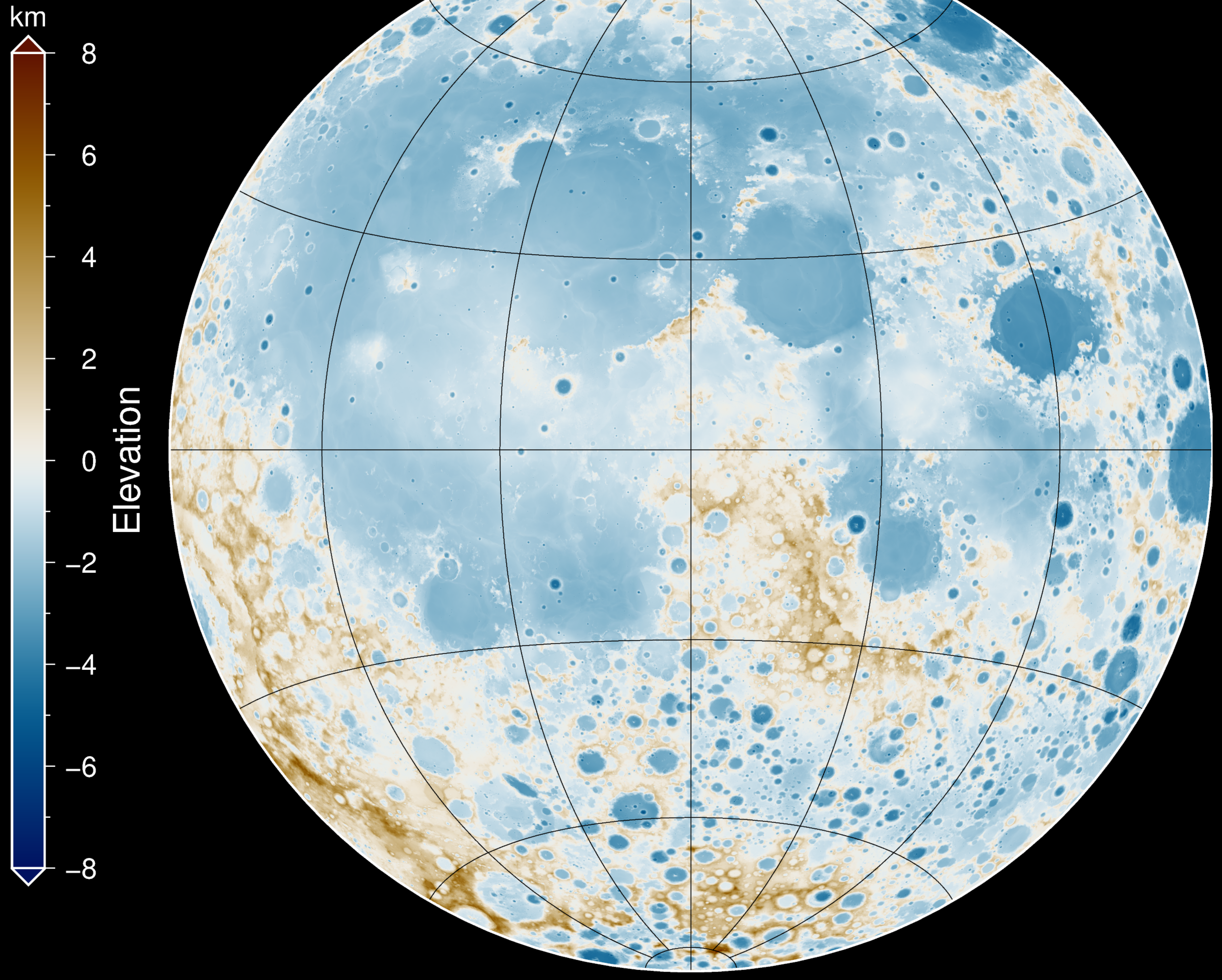
Signature of a fluid core in the LLR range residuals



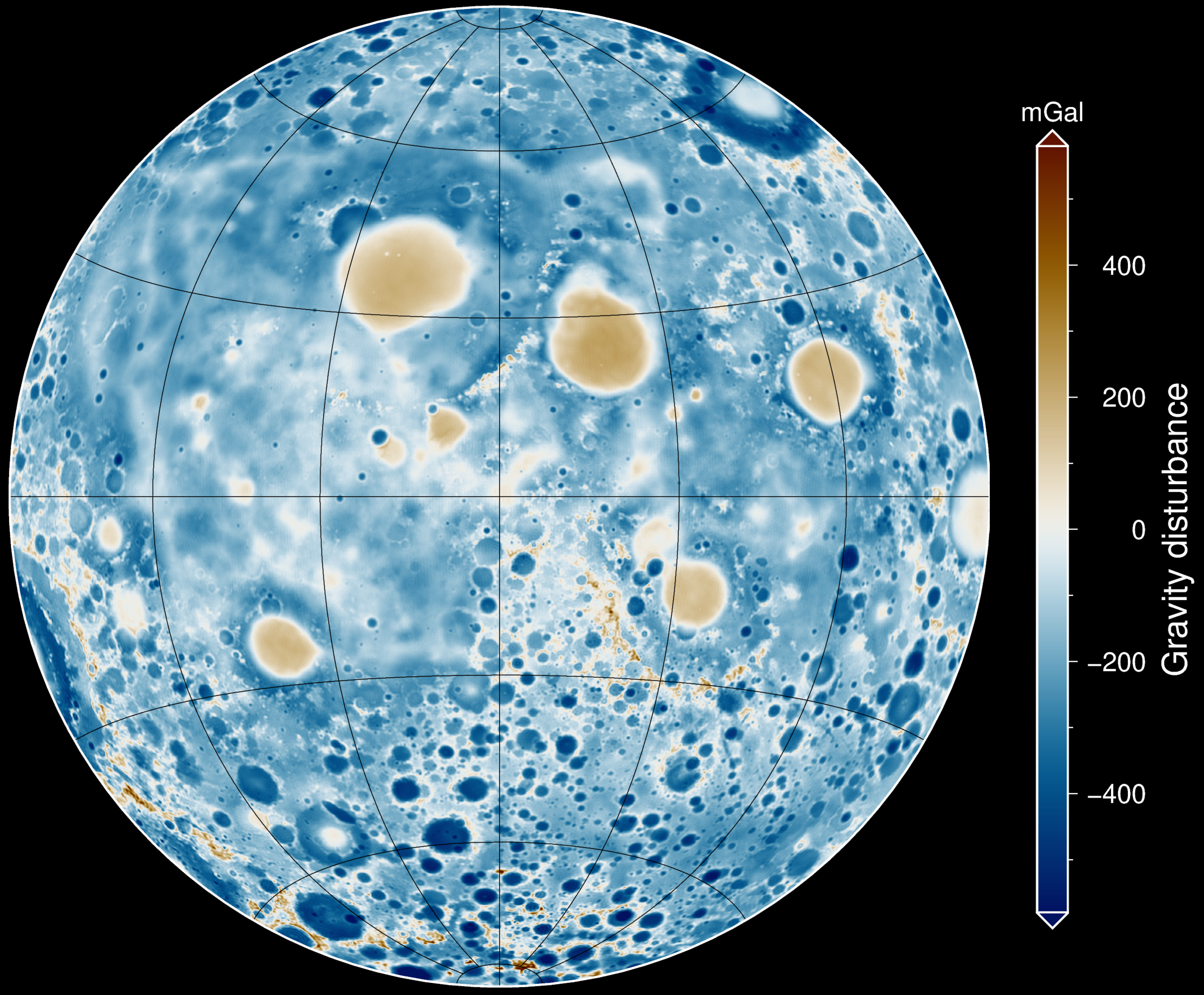
Analysis of LLR data provides the flattening of the core, as well as the core radius (for an assumed density). The bulk dissipation in the Moon suggest a highly dissipative layer above the core-mantle boundary.

LOLA topography & GRAIL gravity (centered over nearside)

Topography

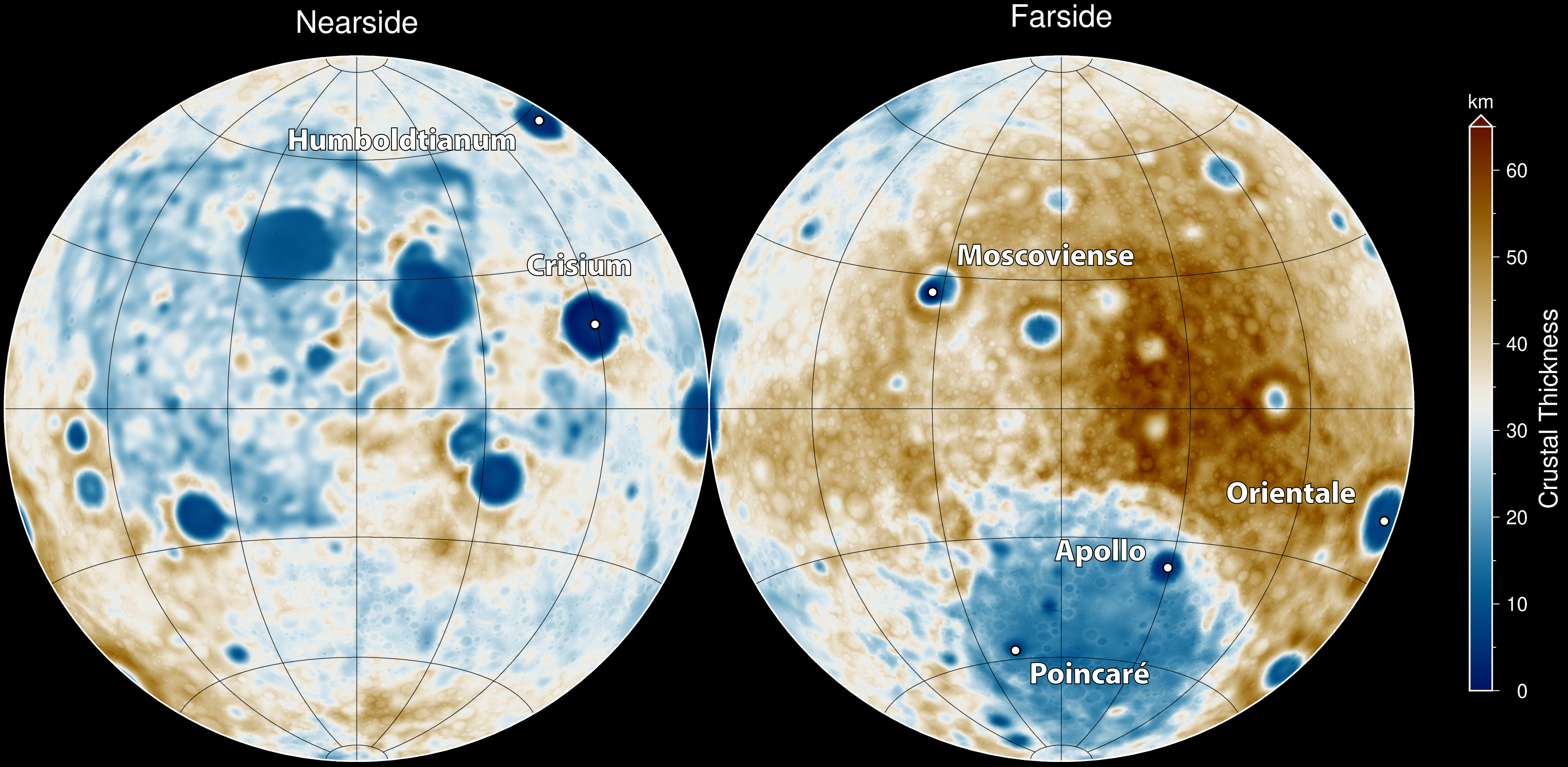


Free-air gravity



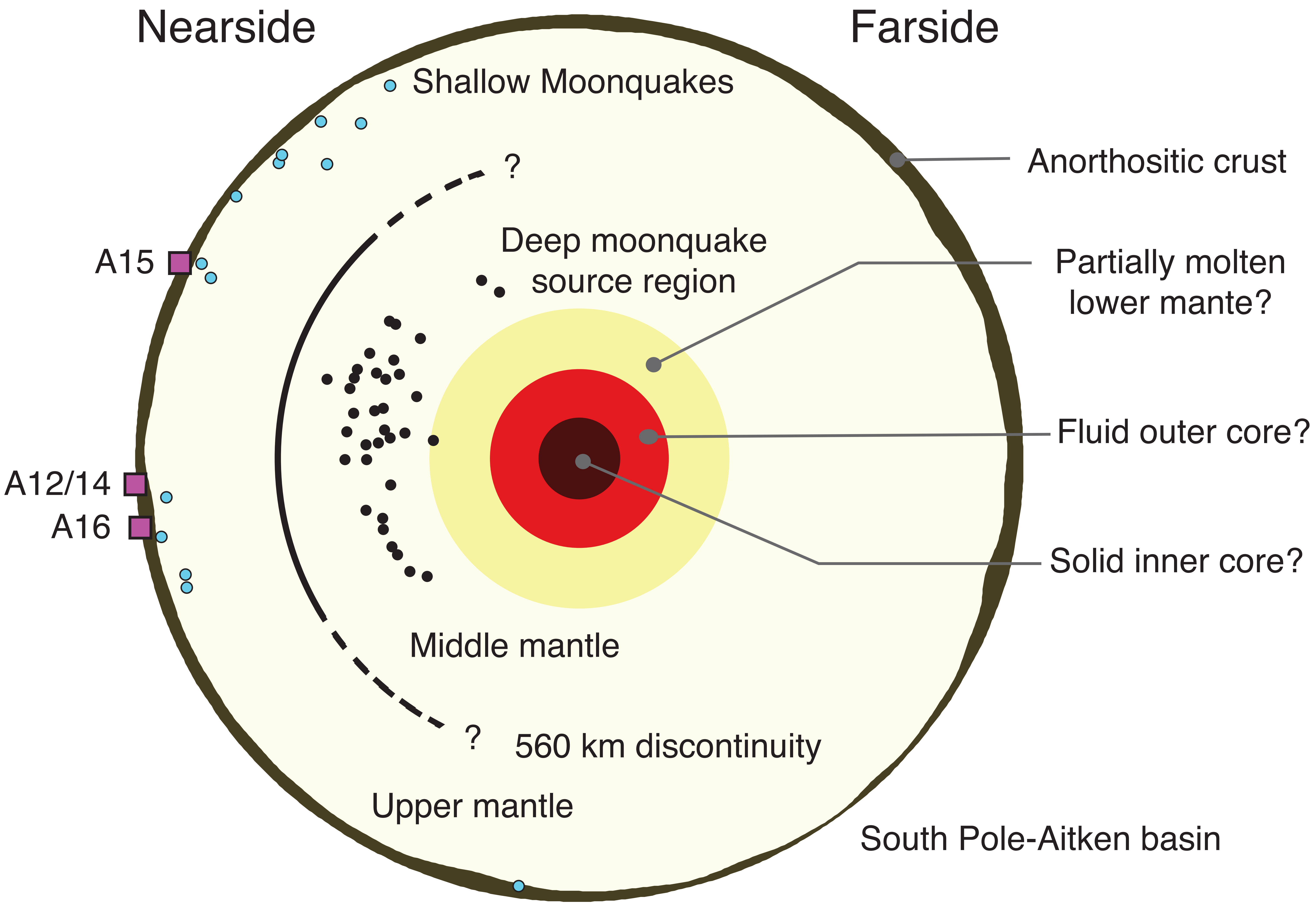
LOLA topography & GRAIL gravity (centered over farside)

GRAIL Crustal Thickness



The crustal thickness is very thin in the interiors of impact basins, as a result of crustal excavation. The crust is predicted to be absent within the Crisium and Moscoviense basins!

What we know about the Moon's interior structure



Wieczorek et al. (2006)

- <u>The Moon is seismically active.</u> *But no moonquakes were detected on the farside. Is this a detection bias, or is the farside not seismically active?*
- <u>The Moon has a liquid core that likely powered a geodynamo.</u> *But, the size of the core and timing of the dynamo are uncertain.*
- <u>There is good reason to believe that the Moon has a solid inner core.</u> *But, so far it has not been detected.*
- <u>The thickness of the crust was measured.</u> *But only with precision at one location.*
- <u>The heat flow of the Moon was measured at two places.</u> *But, these two places were probably the worst place to make this measurement!*

ESA Geophysics topical team (in support of Large Logistics Lander)

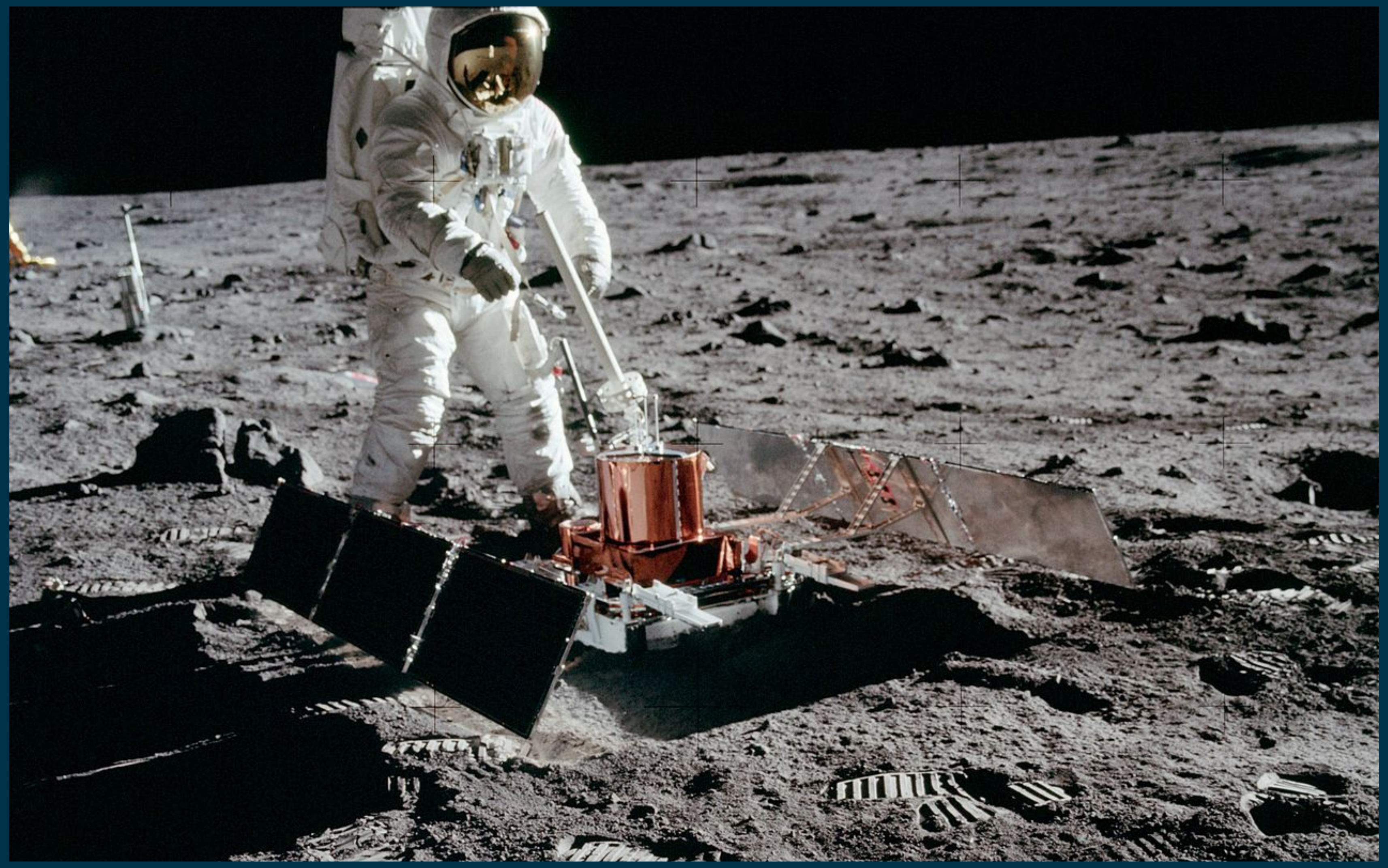
1. Justify the science case for each of the proposed geophysical instruments.

2. Define the requirements that these instruments would place on a Large Logistics Lander mission, before it is too late (mass, electromagnetic cleanliness, power, thermal, etc.).

3. Define strategies for deploying geophysical instruments on the lander deck, on the surface, and far from the lander with rovers.

4. Investigate synergies that could exist between instruments, as well as the coordination of measurements with other stations on the Moon, from orbit, and from Earth.

5. Ensure coordination with other international agencies (primarily NASA and China), and the scientific community.



Apollo 15 ALSEP layout