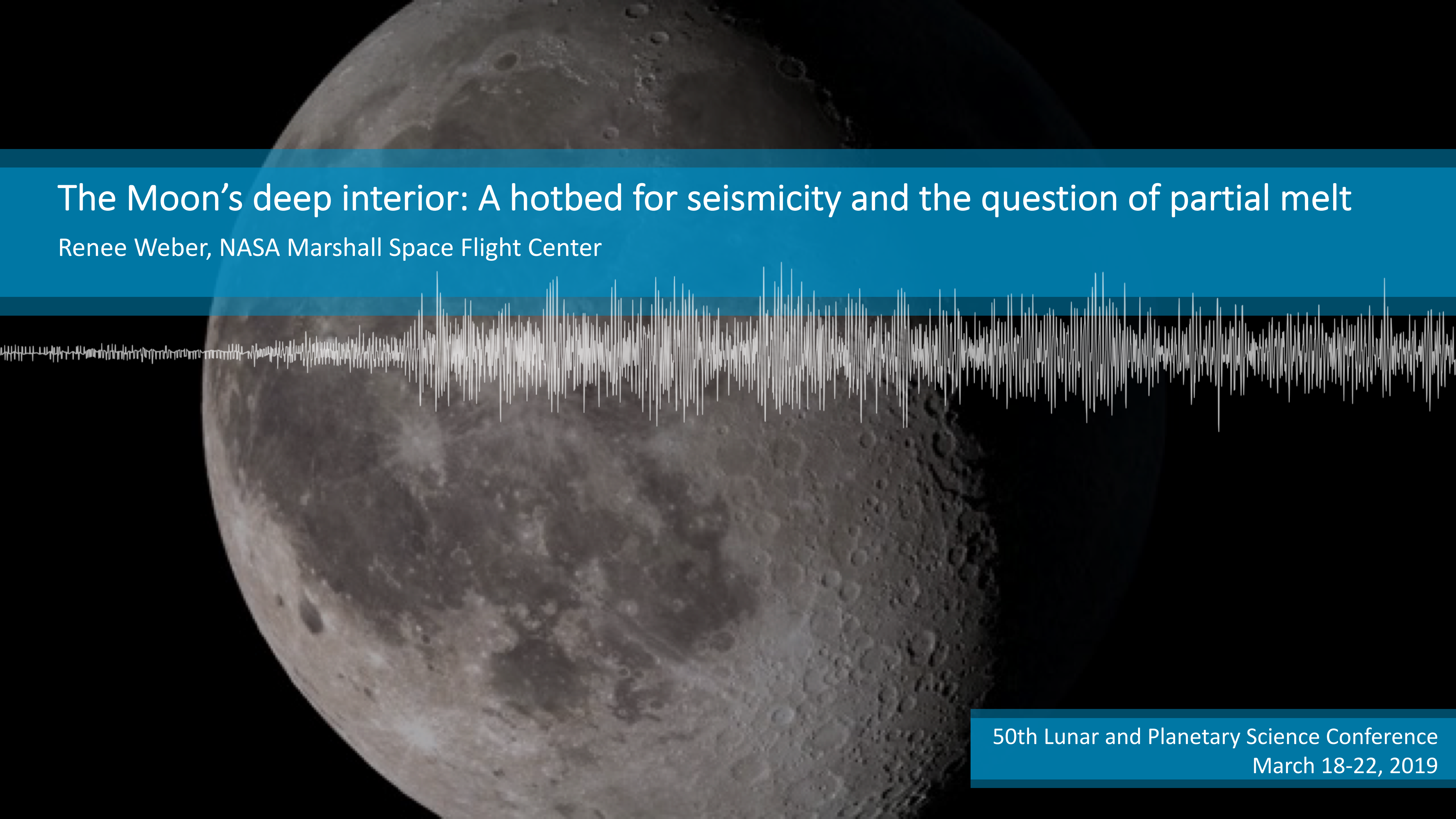
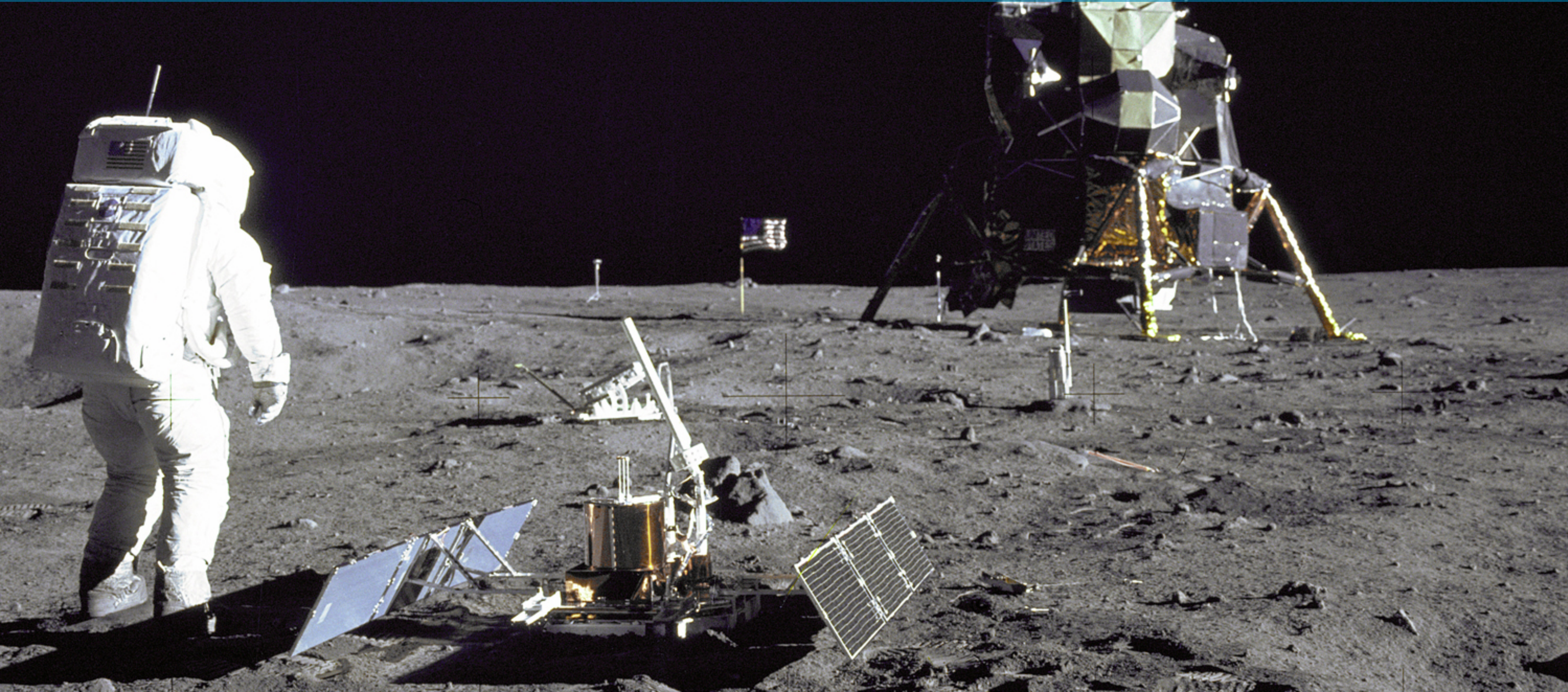


The Moon's deep interior: A hotbed for seismicity and the question of partial melt

Renee Weber, NASA Marshall Space Flight Center

50th Lunar and Planetary Science Conference
March 18-22, 2019

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

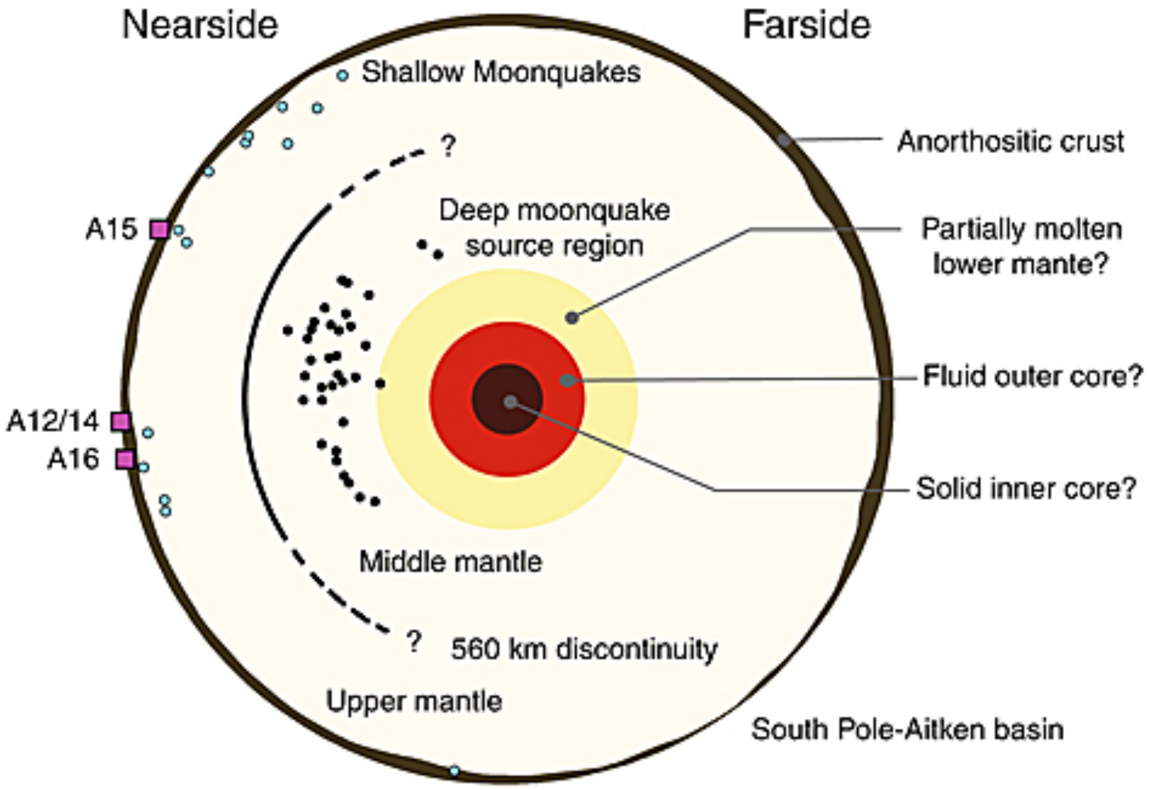


Geophysics: Elucidating the deep lunar interior

- Terrestrial planets all share a common structural framework (crust, mantle, core) which is developed very shortly after formation and which determines subsequent evolution. The Moon formed under very unique circumstances.

- 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

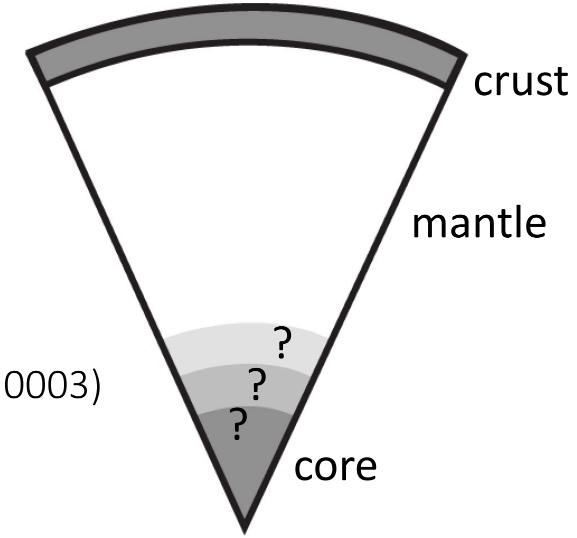
- Constraints on these properties arise from geophysical observations:
  - ➢ Geodetic parameters
  - ➢ Lunar laser ranging
  - ➢ Gravity field
  - ➢ Magnetic induction
  - ➢ Heat flow
  - ➢ Seismology

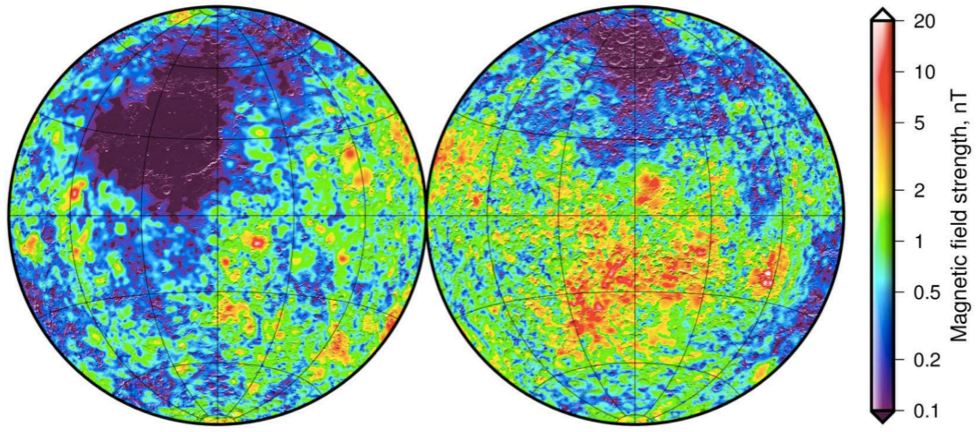


Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Geodetic parameters

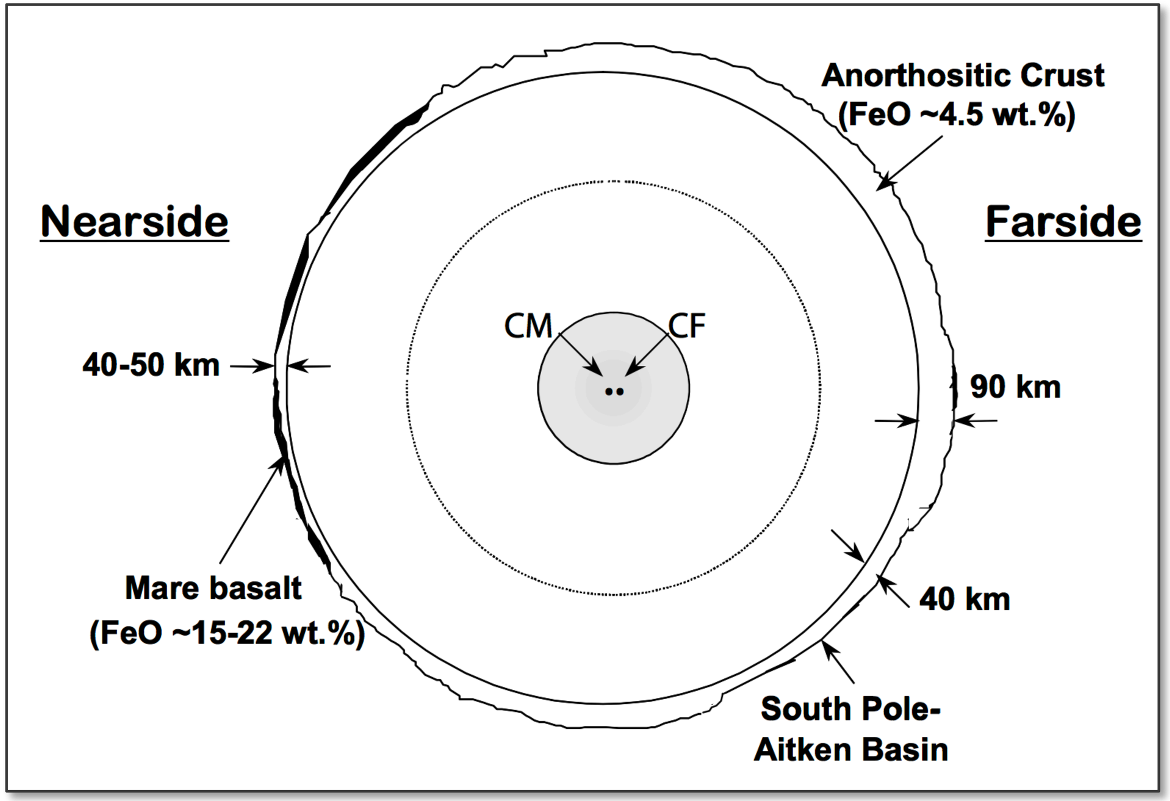
To first order, the Moon's moment of inertia is roughly approximated by homogeneous sphere (I_{solid}/MR^2 = 0.3930±0.0003) ≈0.4





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

Real Moon: Dichotomies in crustal thickness, volcanism, magnetism, and the distribution of heat-producing elements. How do these dichotomies propagate into the interior?



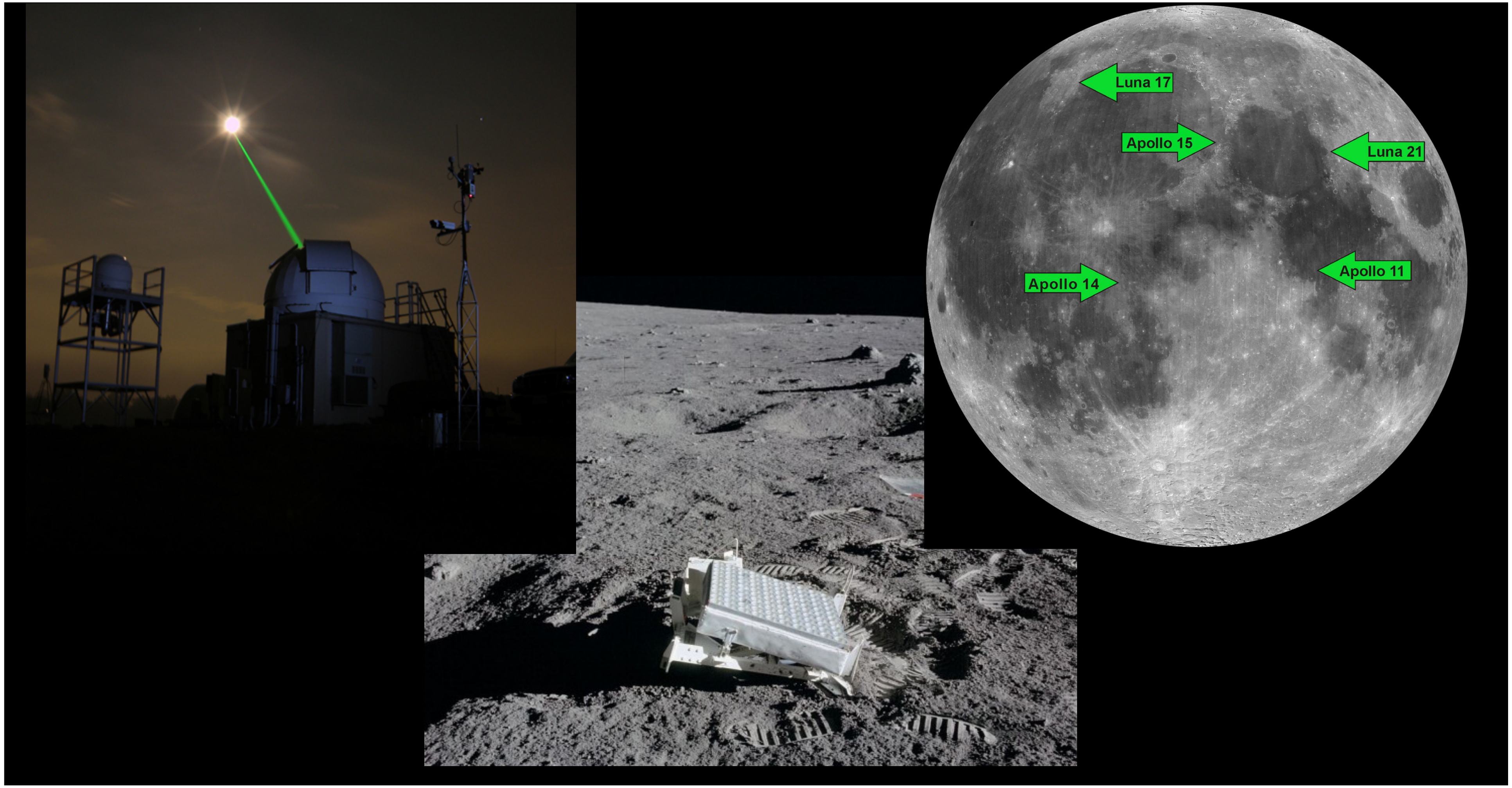
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.

Lunar Laser Ranging (LLR)

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

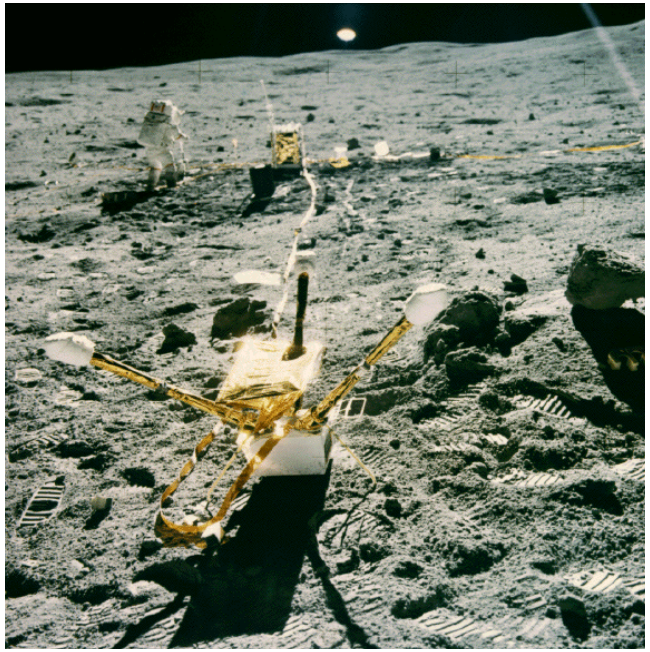
Dissipation provided the first LLR evidence for a fluid core

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

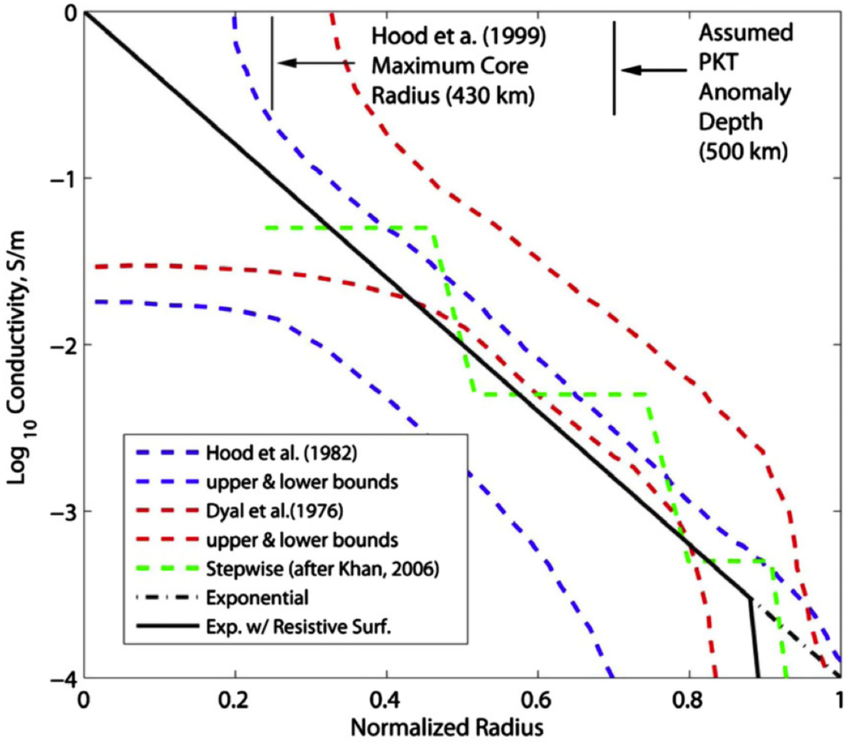


Magnetic induction

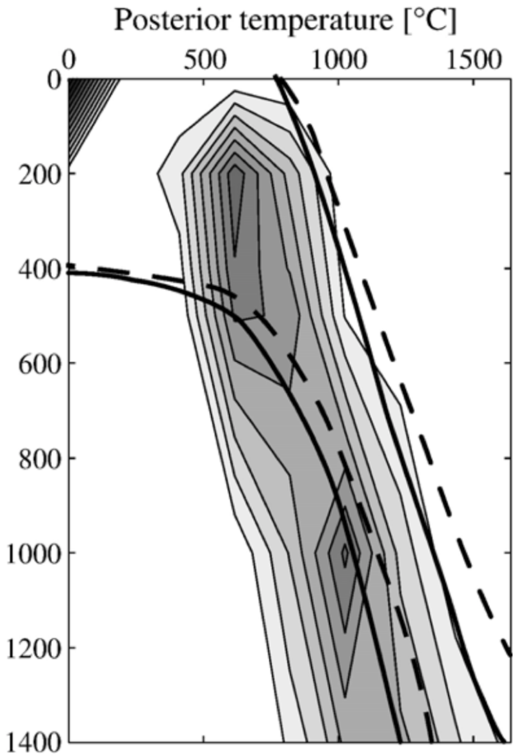
- EM sounding of the Moon during & after Apollo provided constraints on core size, mantle composition, and interior temperature.
- Electrical conductivity and mantle temperatures were constrained at single points at the Apollo stations, using concurrent surface and orbital magnetometer measurements. The observed lateral heterogeneity in conductivity is consistent with the presence of the PKT.
- The Lunar Prospector and Kaguya magnetometers detected an induced moment within the Moon, observed in the Earth's geomagnetic tail



Apollo Lunar Surface Magnetometer



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

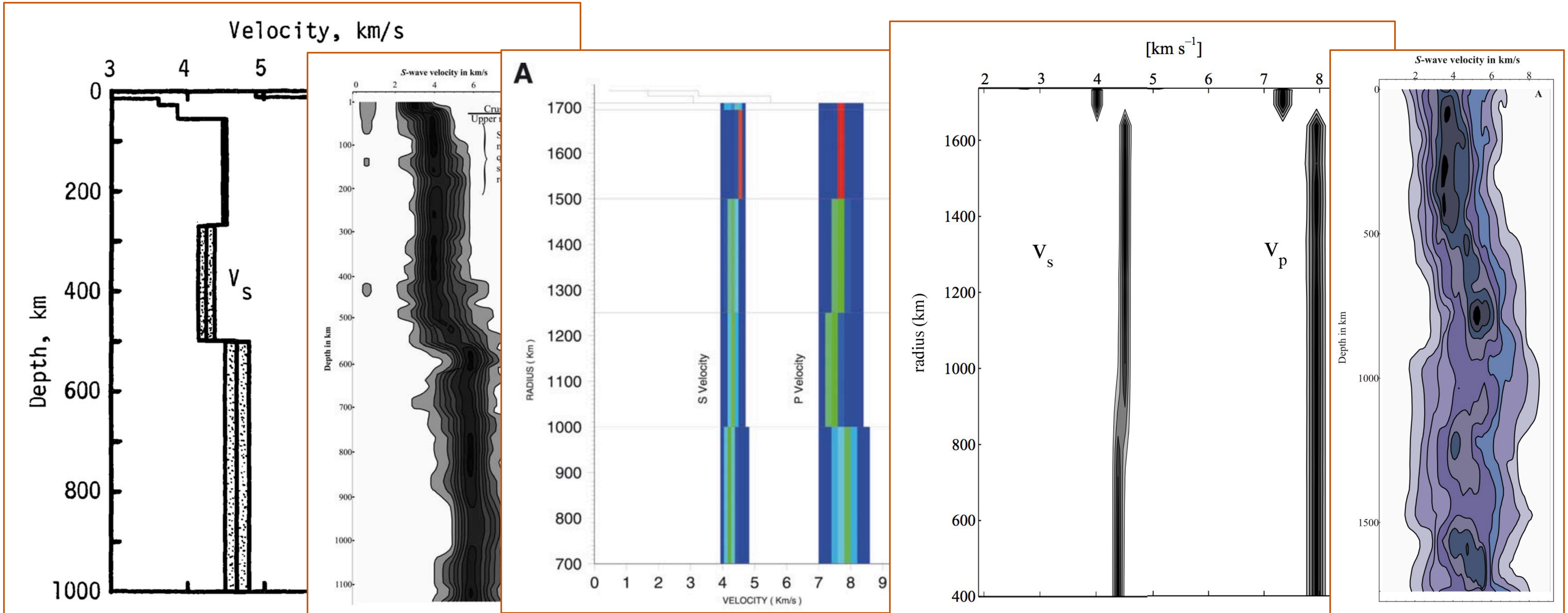


Khan et al. (2006) *EPSL* **248**, 579-598

Seismic measurements

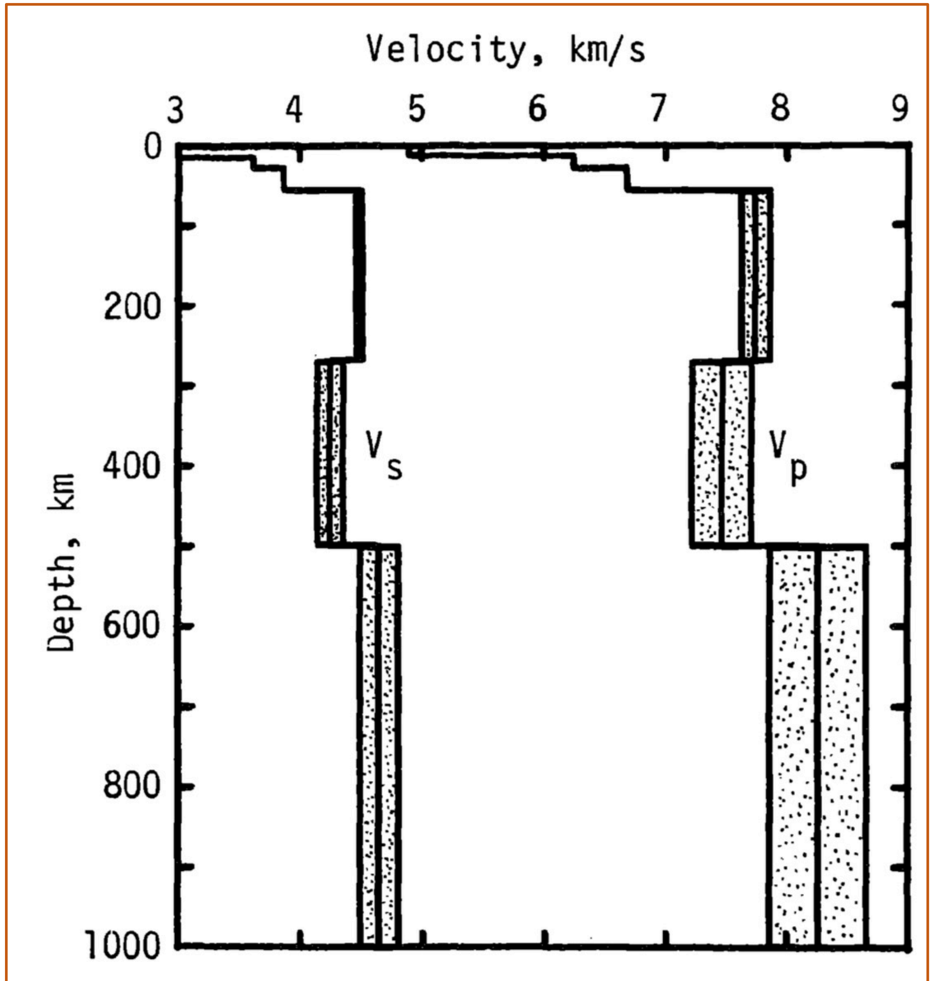
Nakamura (1983) *JGR* **88**, 677-686 Lognonné et al. (2003) *EPSL* **211**, 27-44 Khan & Mosegaard (2001) *GRL* **28**, 1791-1794

Khan & Mosegaard (2002) *JGR* **107** Khan et al. (2007) *GJI* **168**, 243-258



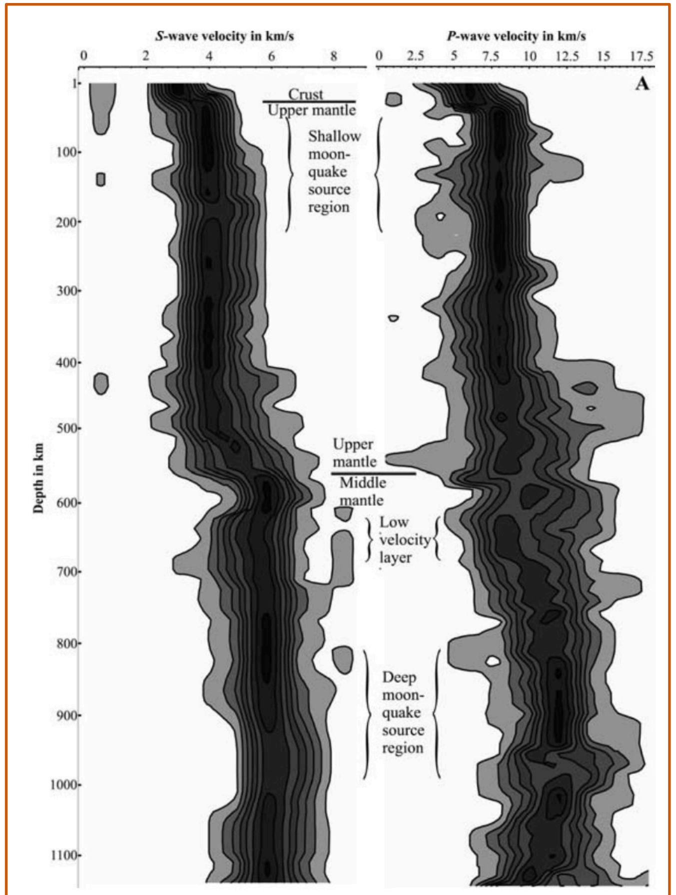
Seismic measurements

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



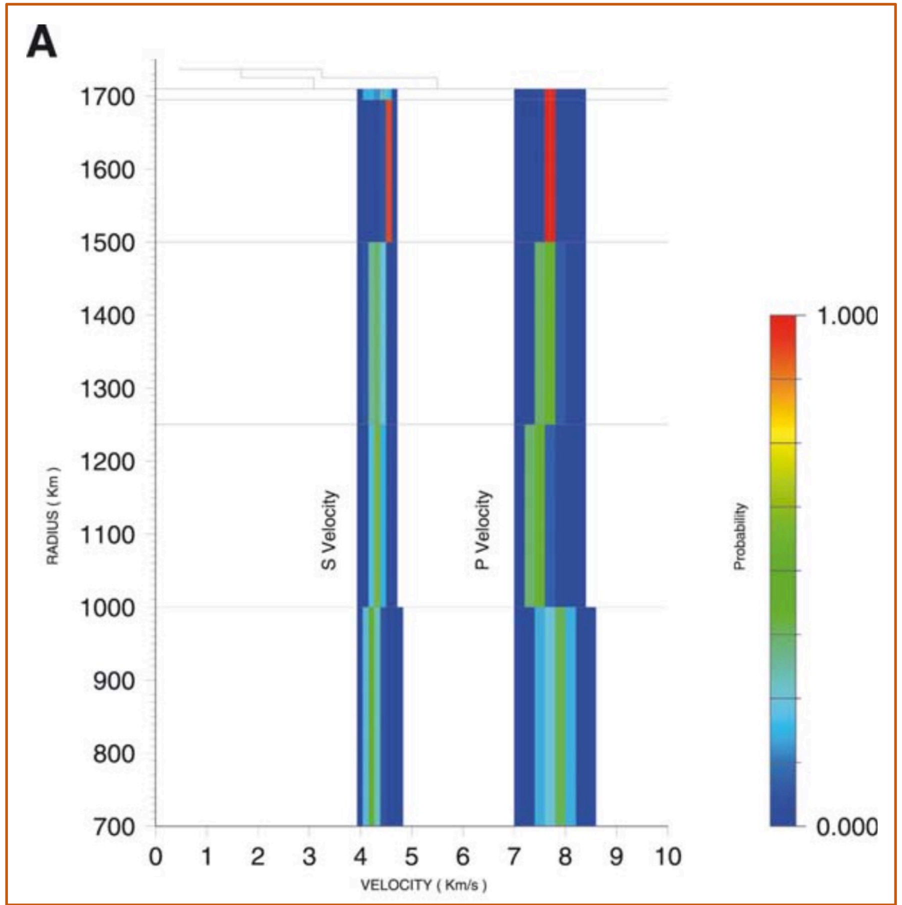
Seismic measurements

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



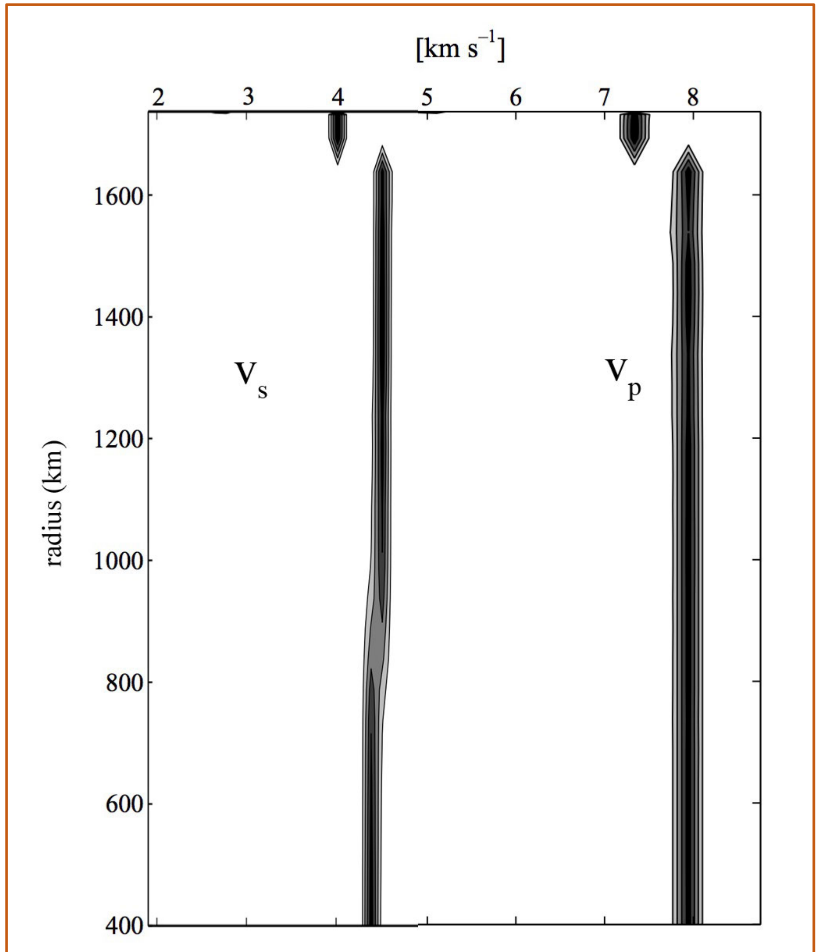
Seismic measurements

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



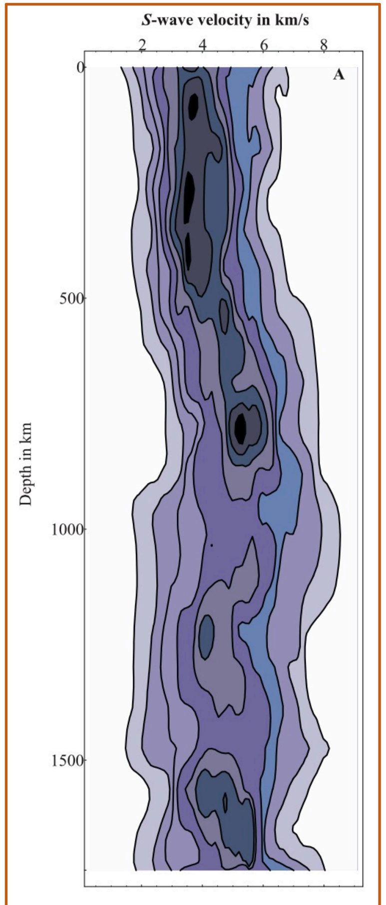
Seismic measurements

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



Seismic measurements

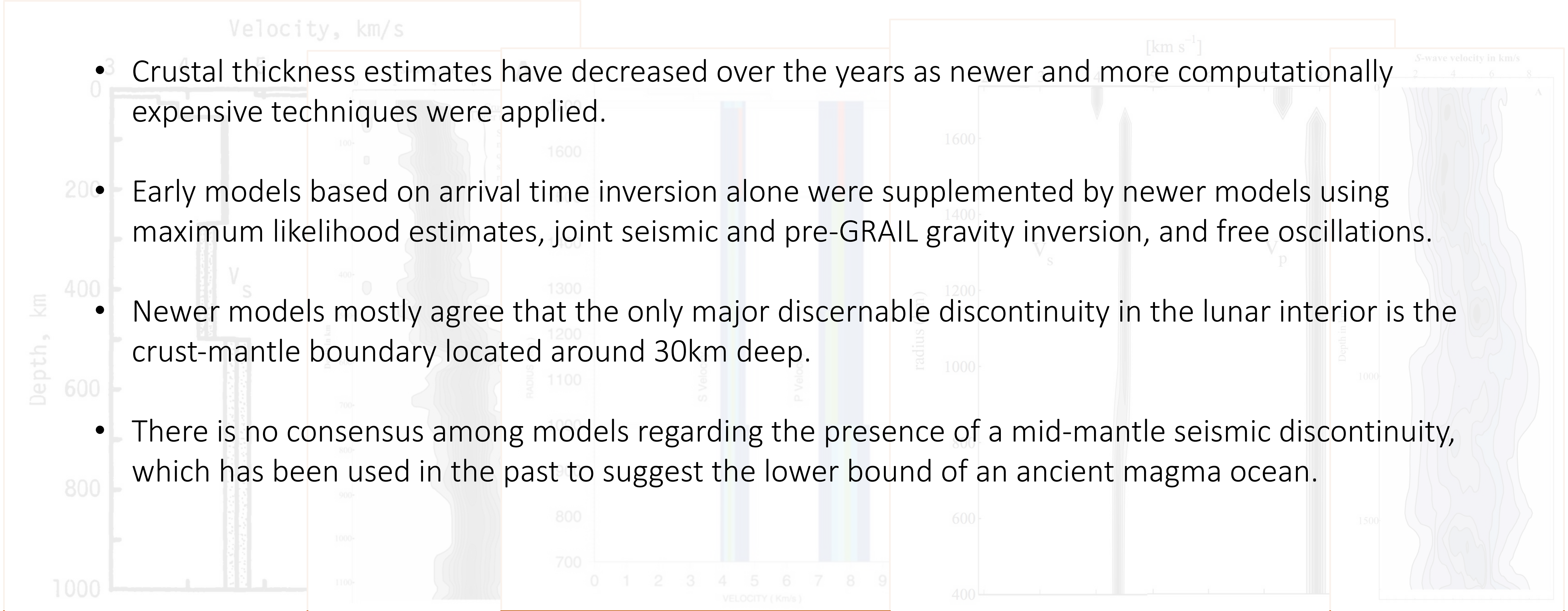
Khan & Mosegaard (2001) *GRL* **28**, 1791-1794



Seismic measurements

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

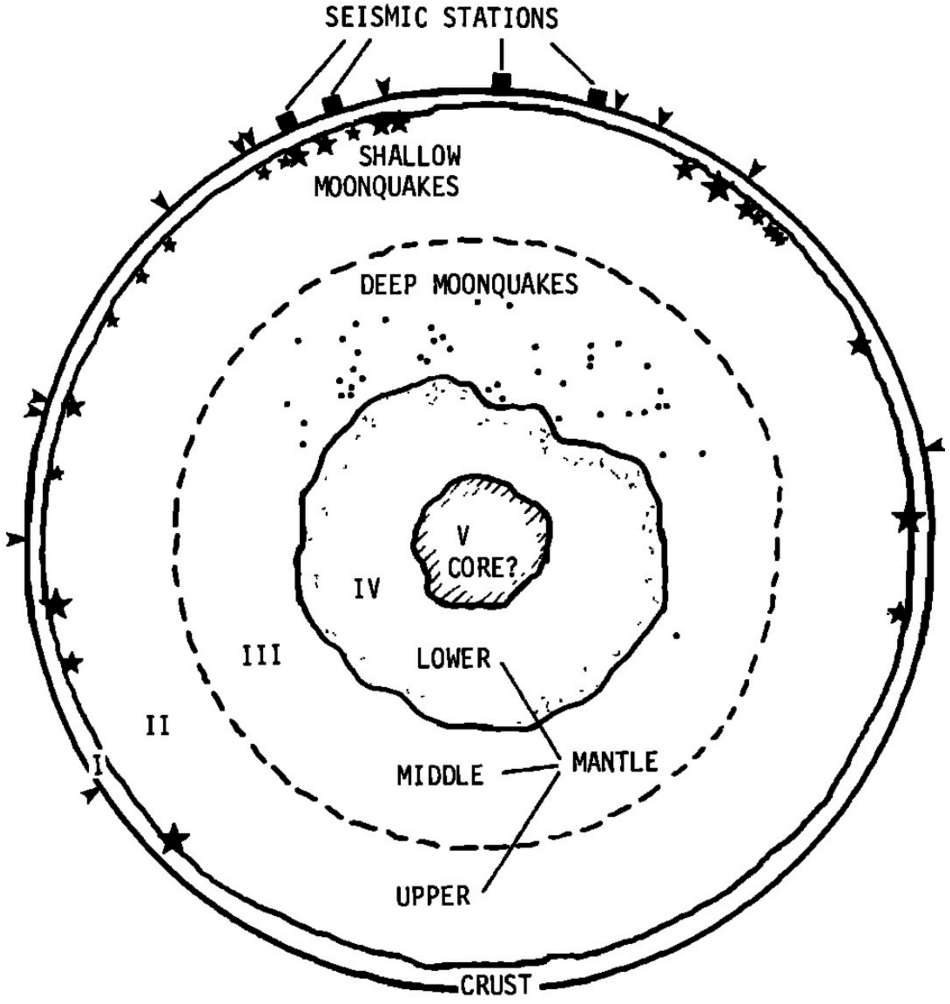


- Crustal thickness estimates have decreased over the years as newer and more computationally expensive techniques were applied.
- Early models based on arrival time inversion alone were supplemented by newer models using maximum likelihood estimates, joint seismic and pre-GRAIL gravity inversion, and 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.

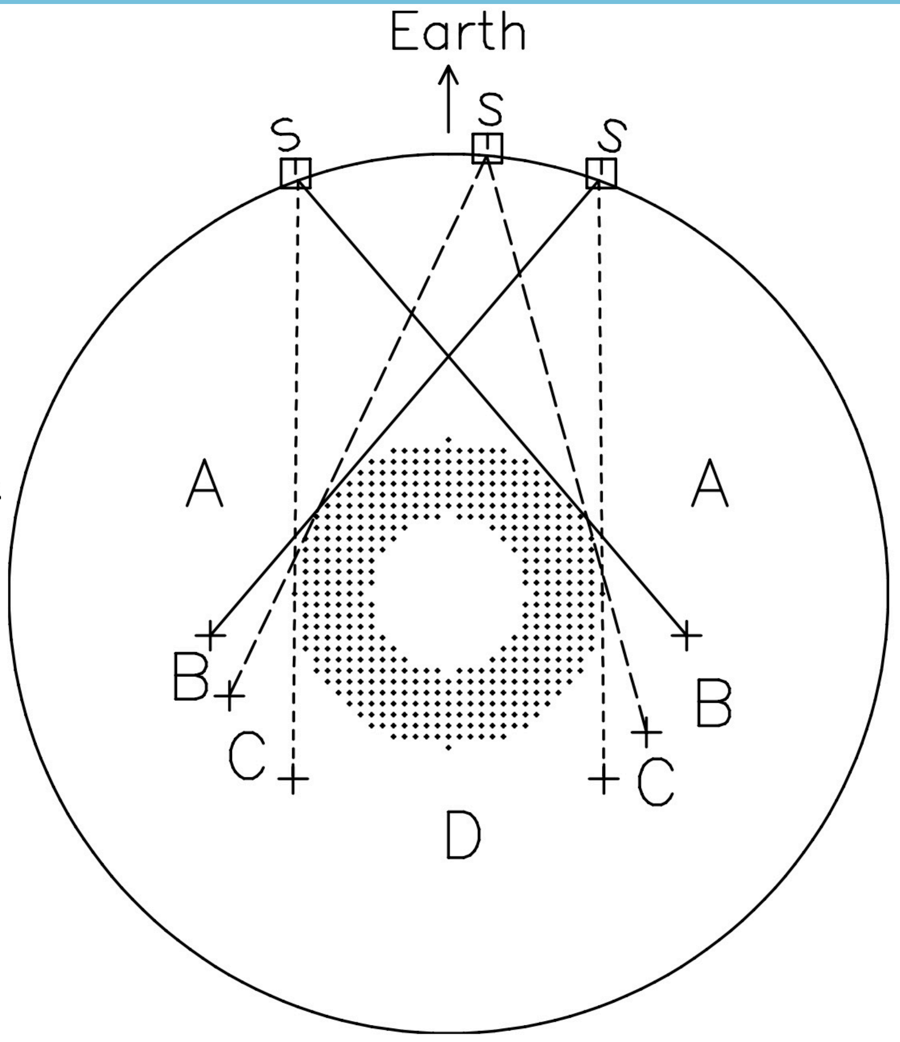
Seismic measurements

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



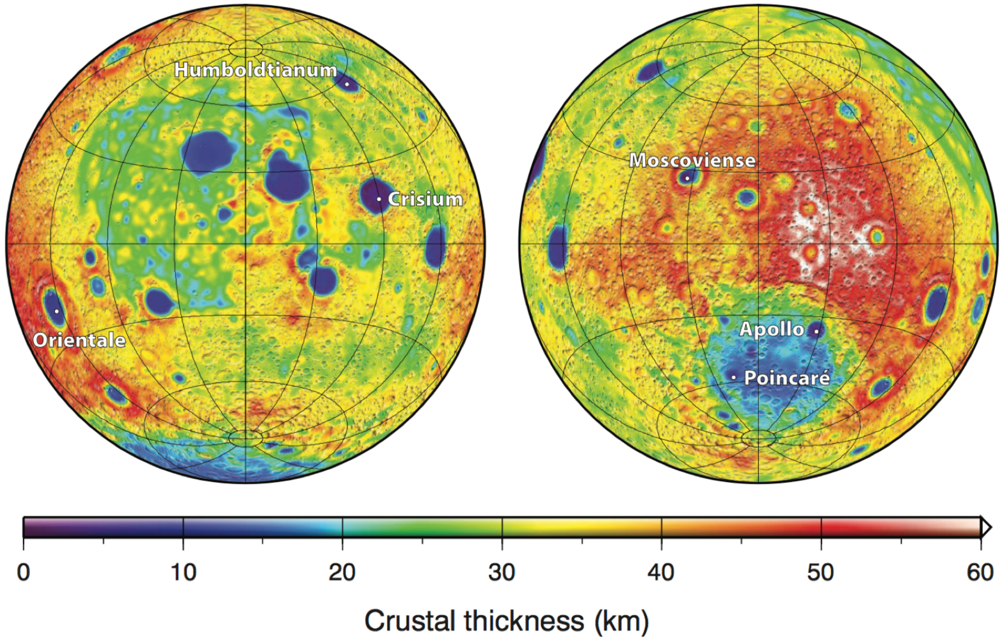
Nakamura (1983) *JGR* **88**, 677-686



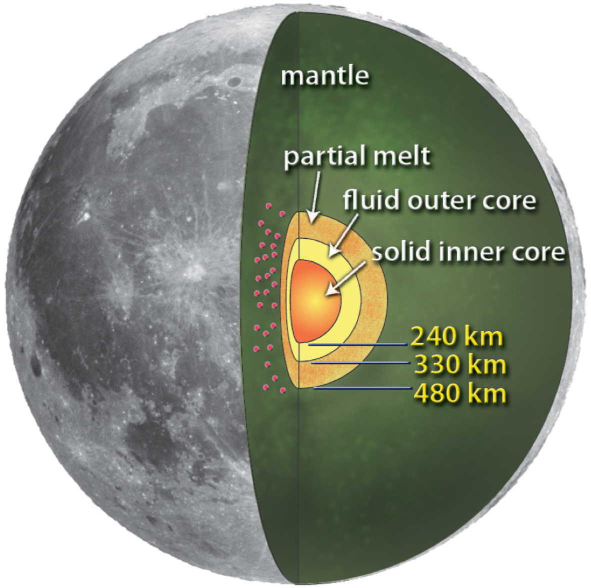
Nakamura (2005) *JGR* **110**

Recent advances in lunar geophysics

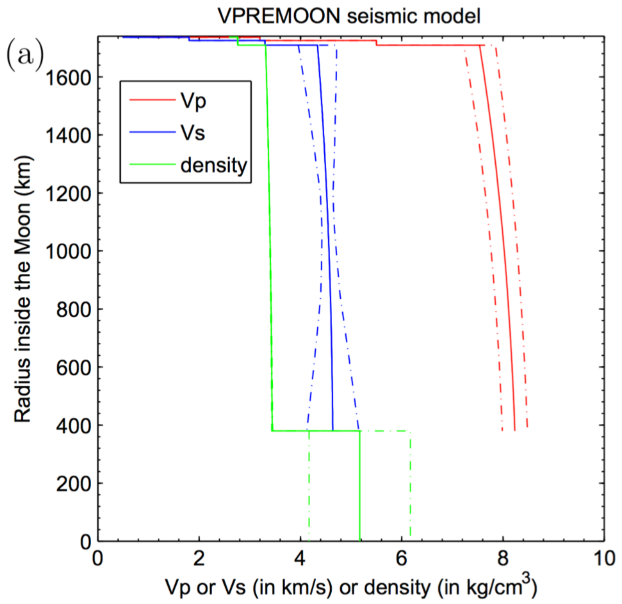
- GRAIL lunar gravity mission mapped the Moon's gravity field in extreme detail
- Re-analyses of Apollo seismic data found evidence for core reflections, both including (Weber) and not including (Garcia) the presence of a partial melt layer above the liquid outer core
    - ➢ Differing perspectives on whether a partial melt layer is required to satisfy available constraints (gravity, seismic, geodetic constraints, EM sounding data, phase-equilibrium models, dissipation, volatile content)



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



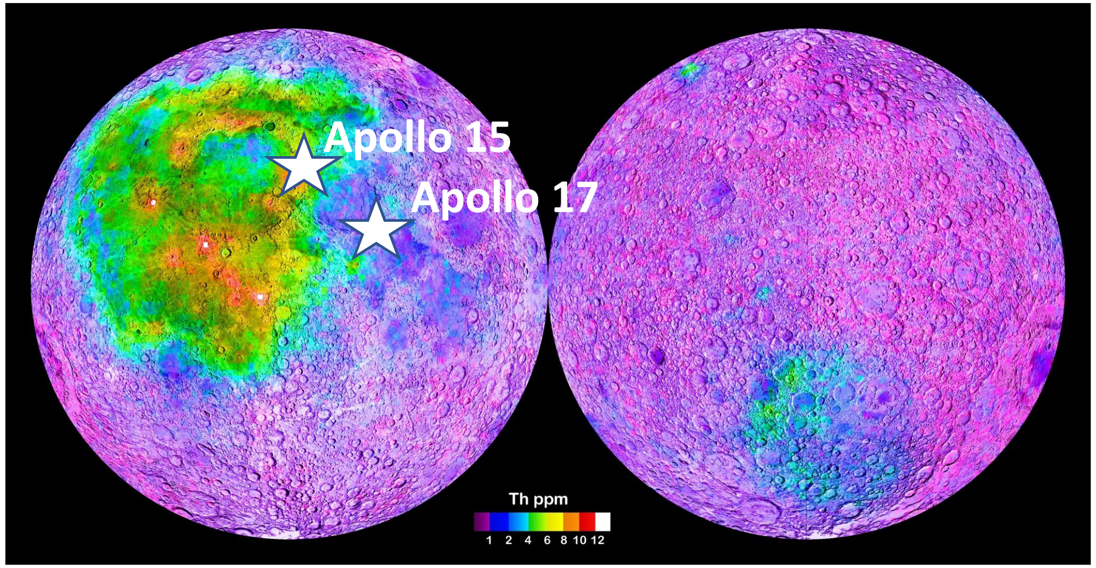
Weber et al. (2011)
Science **331**, 309-312

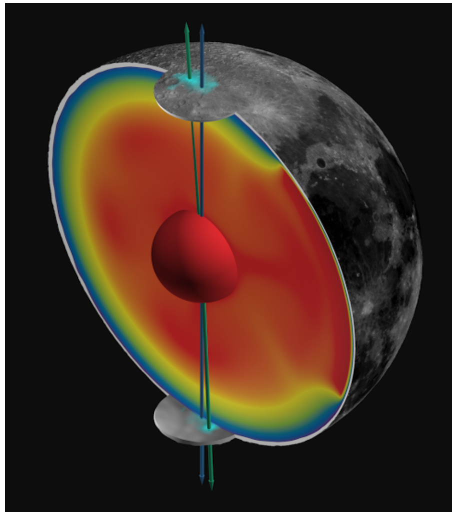


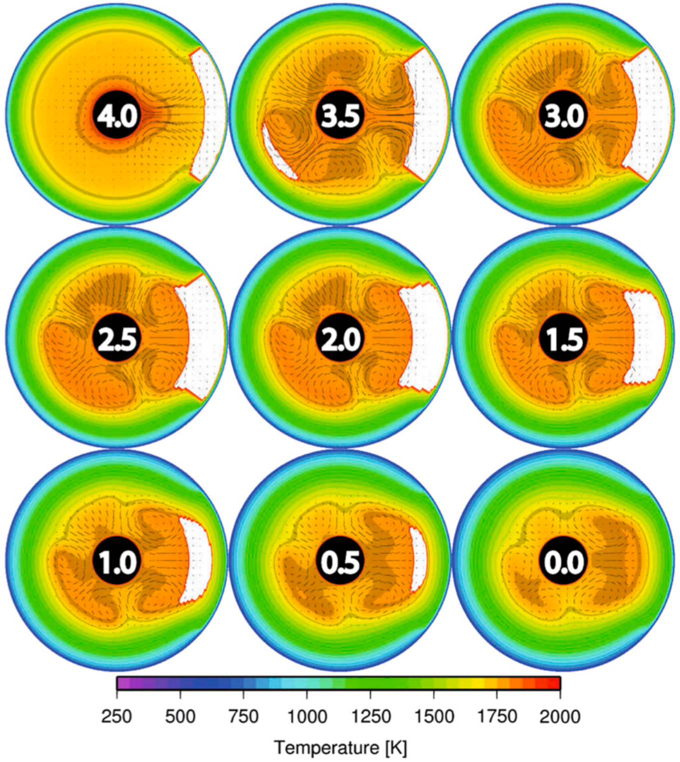
Garcia et al. (2011)
EPSL **188**, 96–113

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.
- 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.



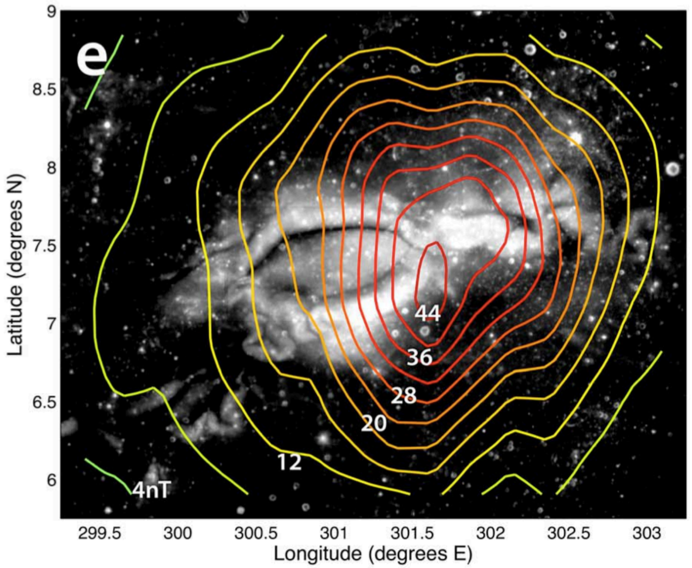




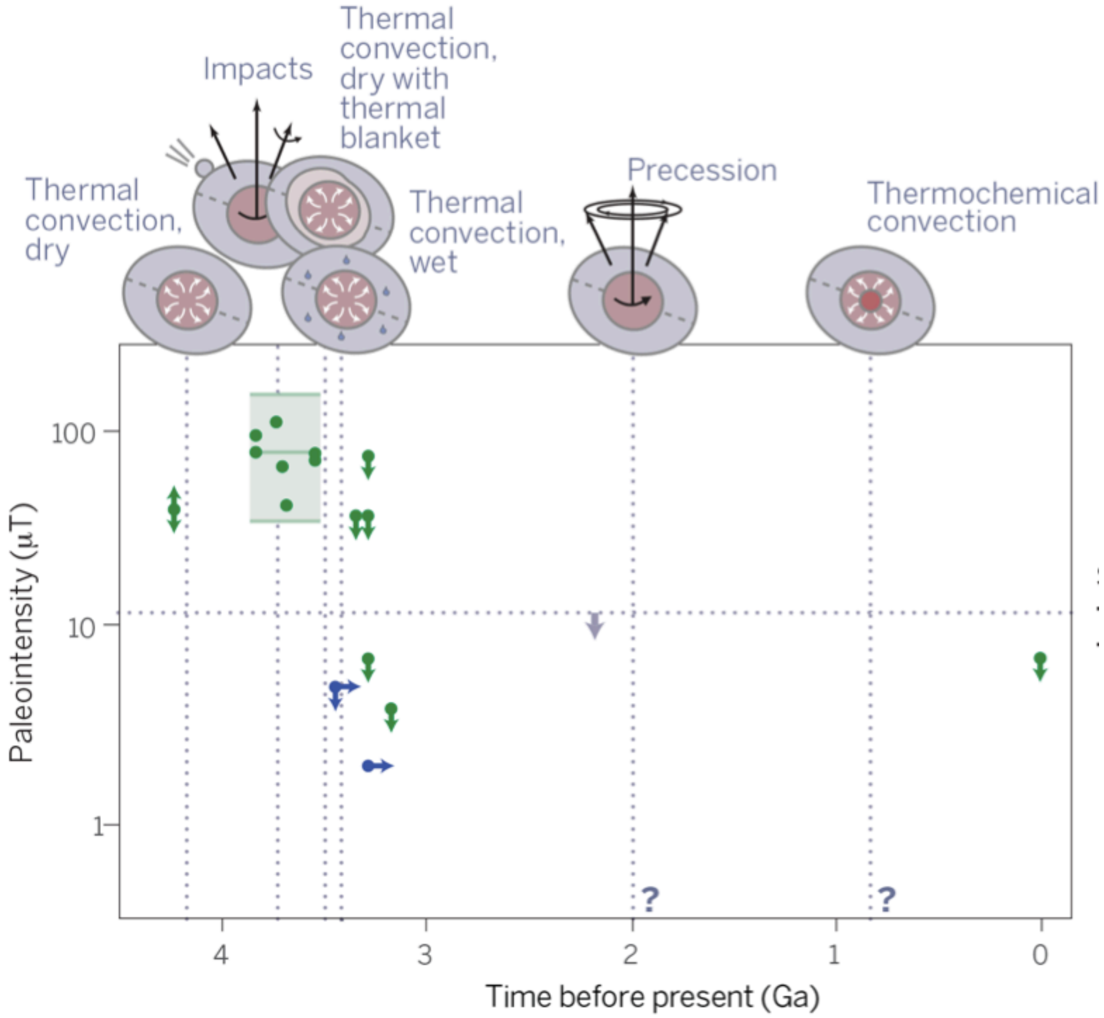
Laneuville et al. (2014) *EPSL* **401**, 251-260.

Synergy with paleomagnetic measurements

- Apollo samples record the Moon’s magnetic history, which strongly suggest the Moon once sustained a dynamo. Just beginning to constrain its nature.
- We can constrain dynamo history with paleomagnetism and via crustal magnetism studies, but we also don’t know the exact origin of the Moon’s magnetic anomalies



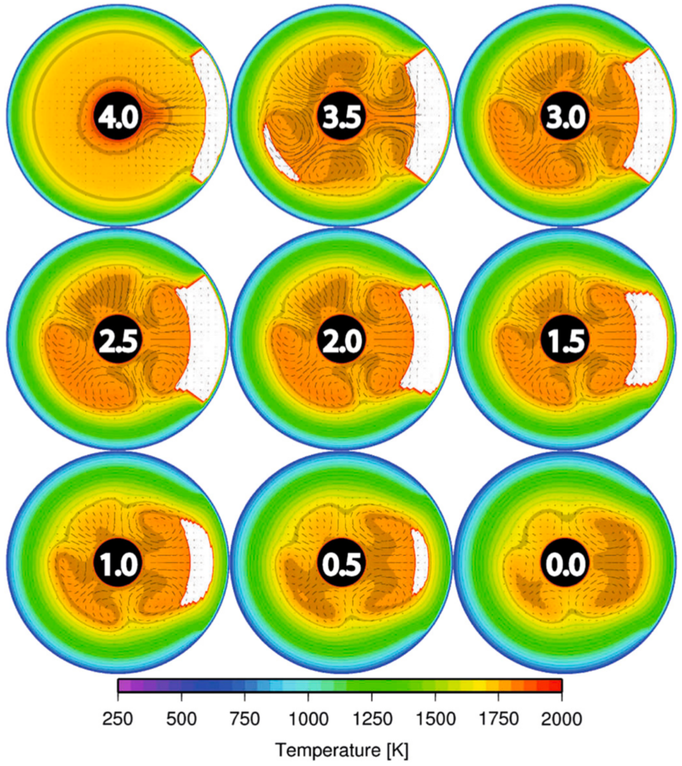
Local crustal magnetism – Hemingway & Garrick-Bethell (2012) *JGR* 110



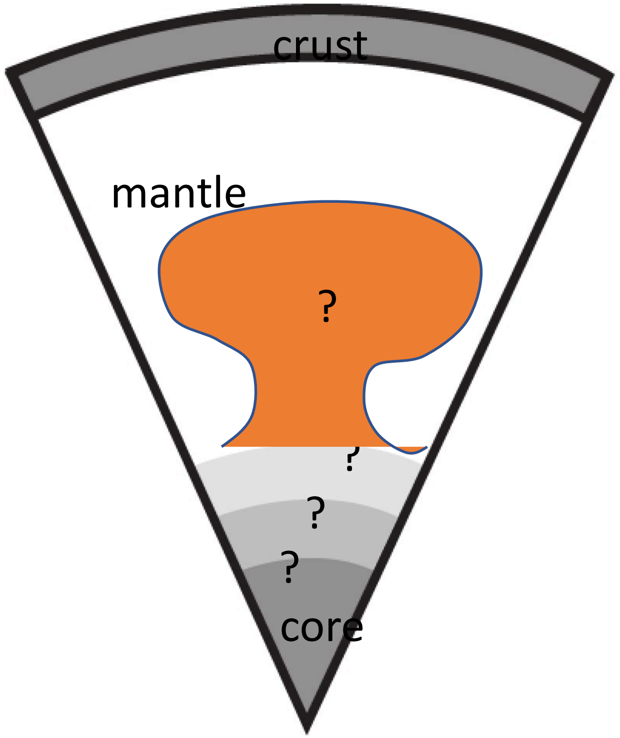
Weiss & Tikoo (2014) *Science* 346.

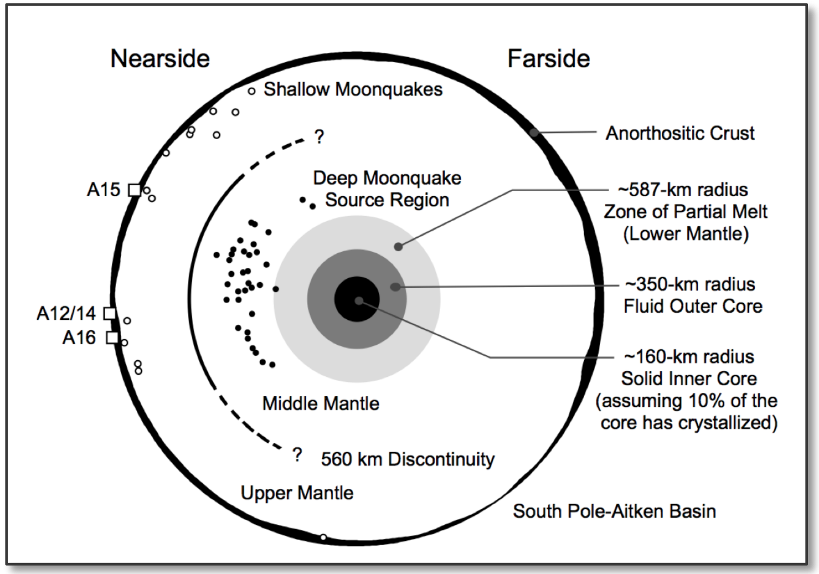
How to develop an internal structure model consistent with all observations?

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.

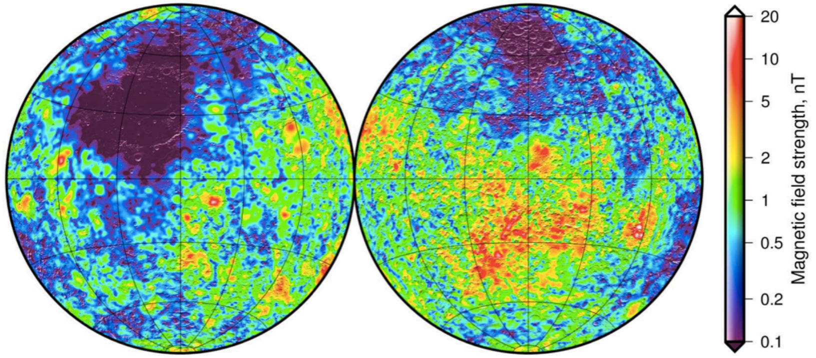


Laneuville et al. (2014) *EPSL* **401**, 251-260.





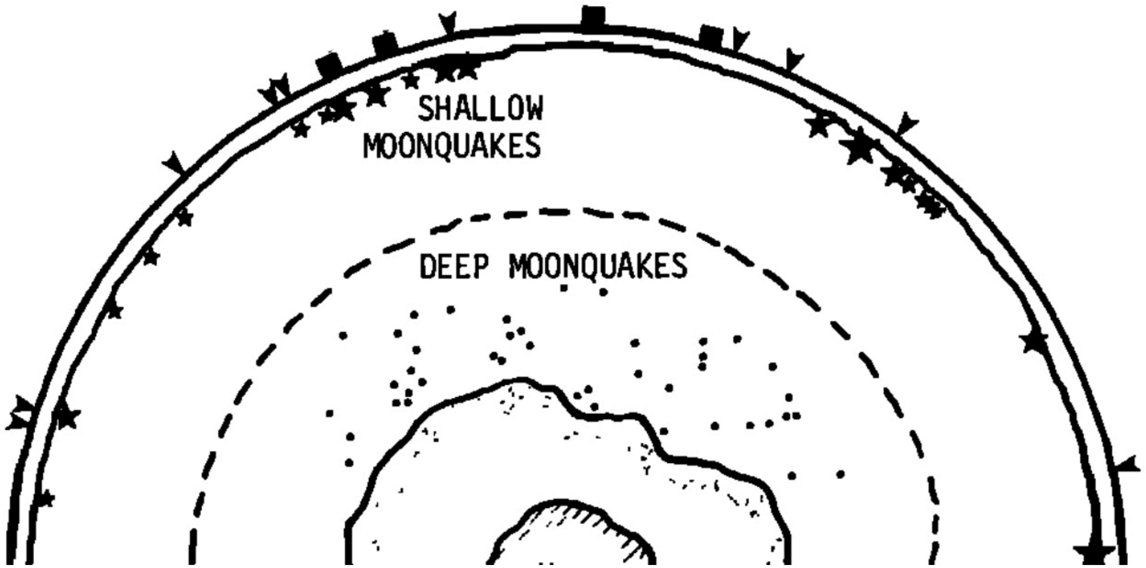
Wieczorek et al. (2006) *Rev. Mineral. Geochem.* **60**, 221 – 364.



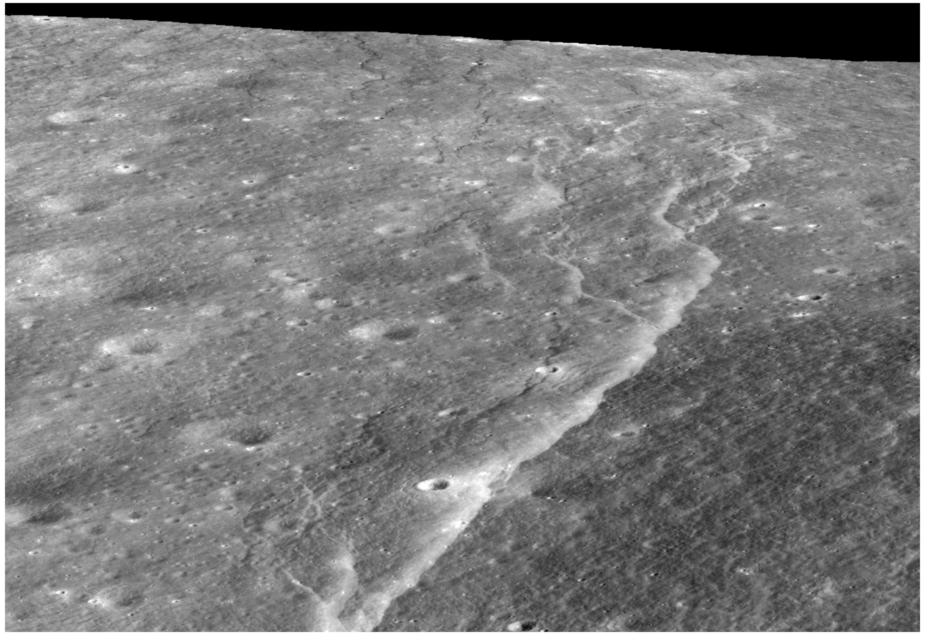
Wieczorek et al. (2017) *NVOTM2* #6036

Outstanding questions

- We don’t know the full nature of the extinct lunar dynamo
- We don’t know the exact origin of the Moon’s crustal magnetic anomalies
- We don’t have unambiguous observations of a mid-mantle discontinuity, a partial melt layer, or an inner core
- We don’t know how surface hemispherical dichotomies propagate into the interior
- We don’t understand why some moonquakes occur

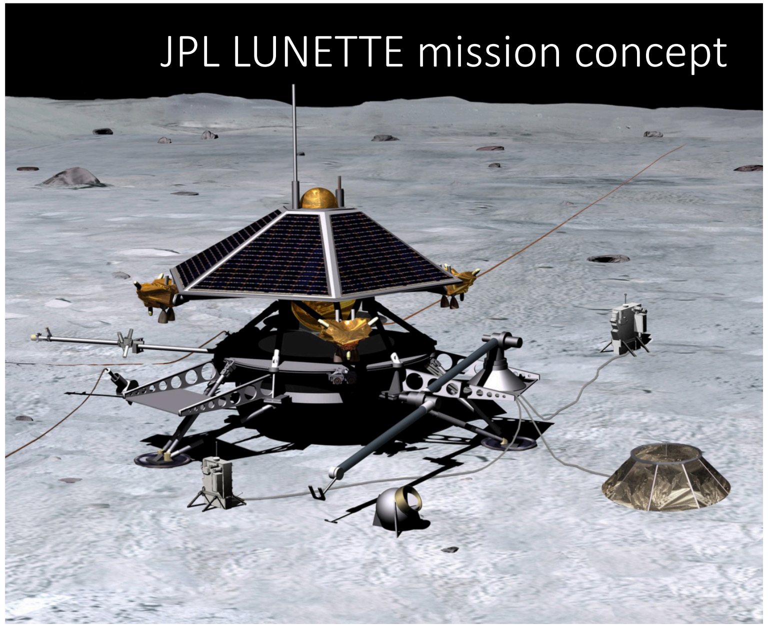


Deep moonquakes: brittle failure in the ductile regime?



Shallow moonquakes: lobate scarp slip?

The Lunar Geophysical Network



- 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 detailed internal structure of the Moon	• Measure the heat flow to characterize the temperature structure of the lunar interior See abstract #2455	• 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