Lunar Interior

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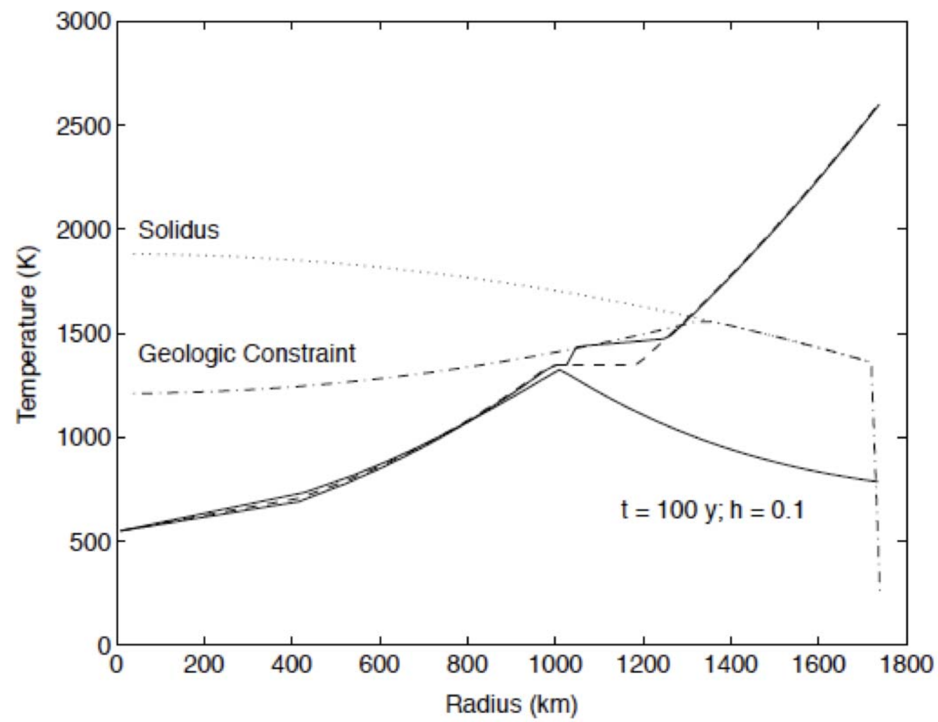
History of the Moon

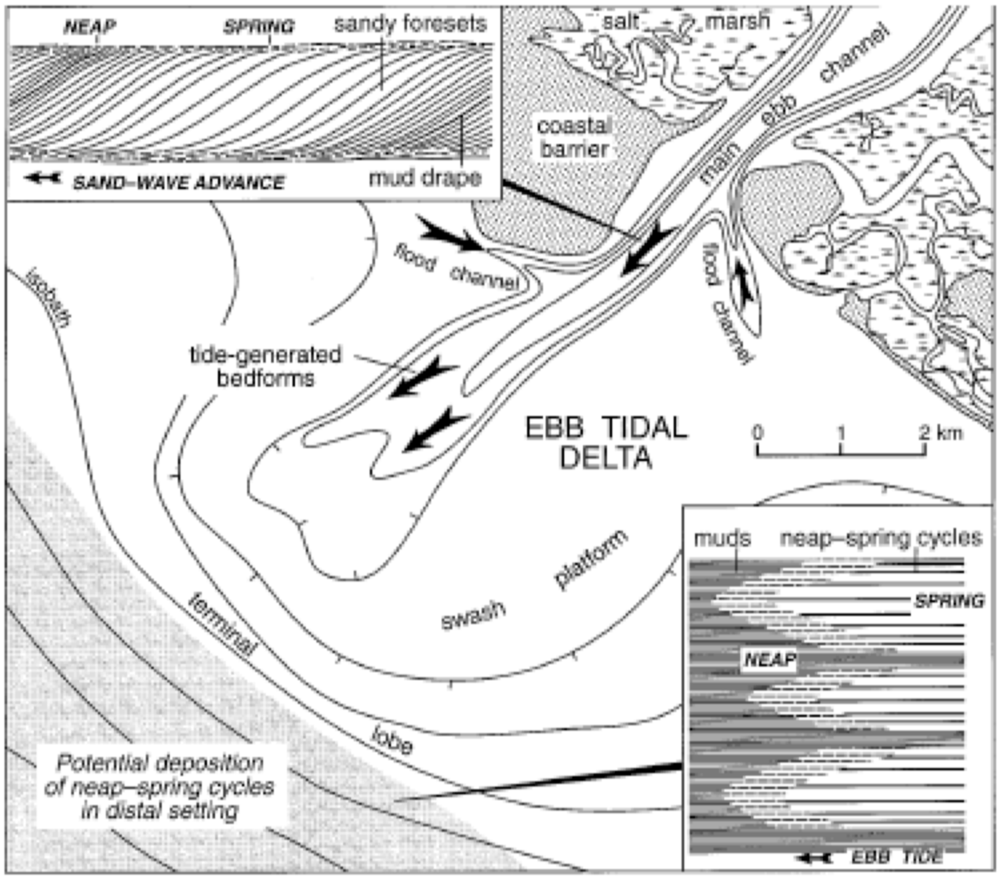
- Giant impact, 4.5 Gya
- Moon almost entirely molten, 4 – 4.5 Gya
- Fractional Crystallization in Magma Ocean, > 4 Gya
  - Floating anorthosite crust
  - Partitioning of heat producing materials between crust and mantle
- Impact dominated (giant basin formation), 3.5 – 4 Gya
  - Interior melting from radioactive decay
  - Mantle partially melts, erupt as mare
- Geologically boring, < 3.5 Gya
  - Small craters
  - Last lava, 1 Gya

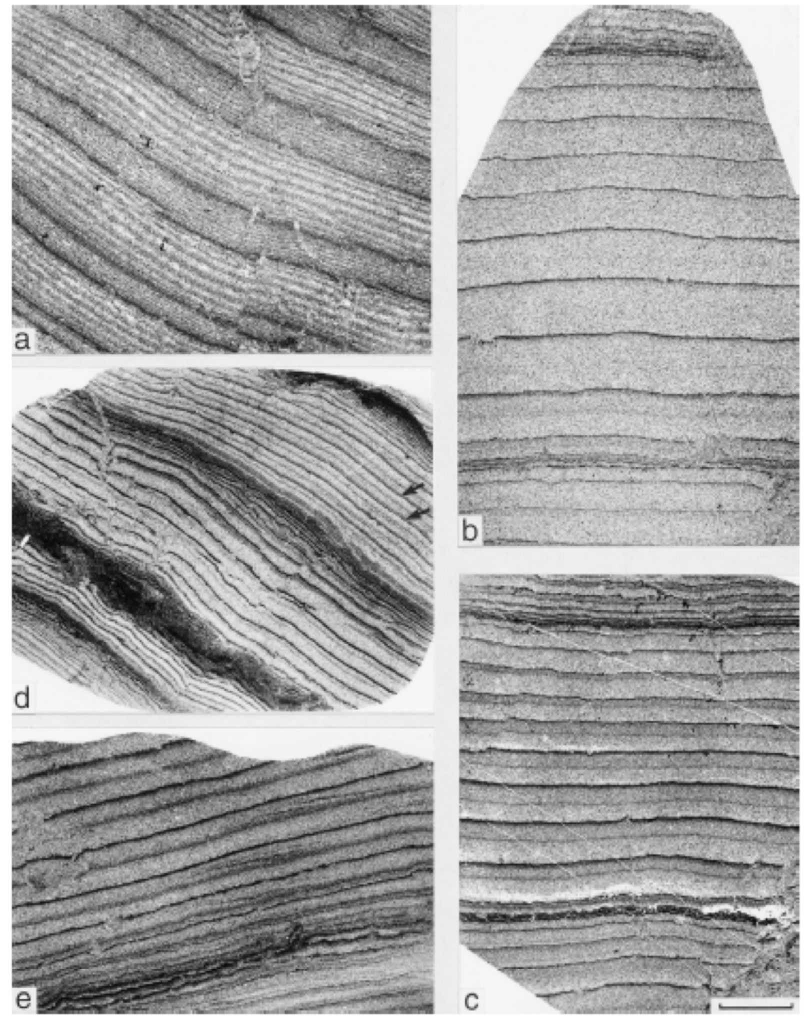
Accretion of the Moon



- Timescale of accretion determines whether the moon begins with a magma ocean
- Tidal evolution models disagree on whether the moon started with a magma ocean

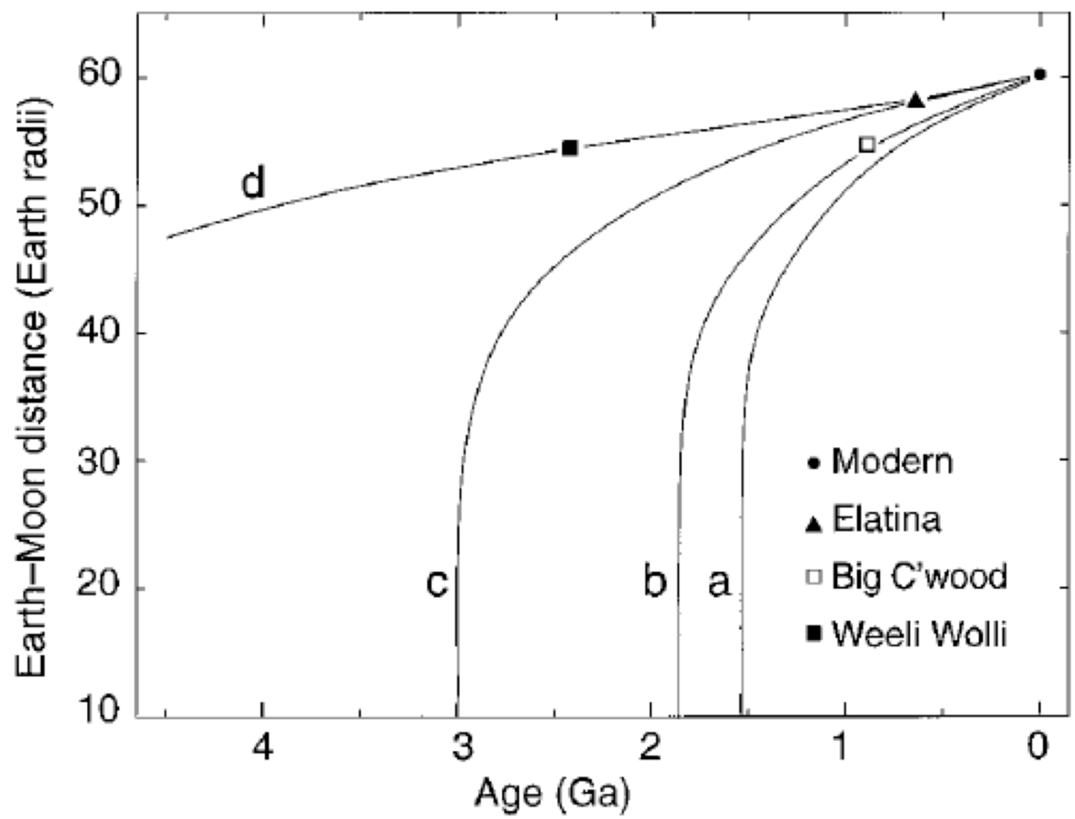
Tidal Record





Tidal Evolution of the Moon

- Tidal Quality factor must change or the moon would be at the Earth's surface, 2 Gya
  - Continent and Ocean arrangement play a big role
- Tidal record indicates a changing tidal dissipation rate

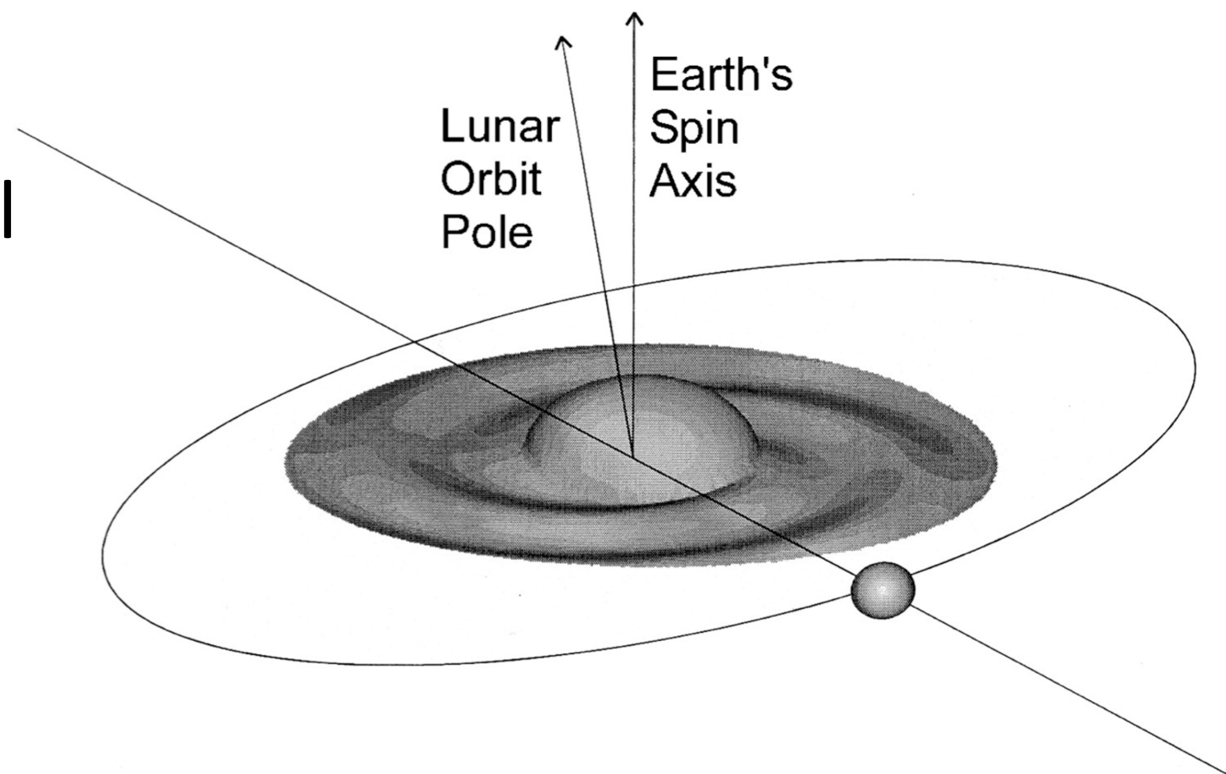


Inclination Problem

- Moon seems to start in inclined orbit
  - Hypothesis: Well-placed giant impact (second)
- Energy needed to change the moon's orbit appropriately is very large
- "Thus, even an optimally aligned impact to the Moon capable of producing the lunar *I* could also cause significant disruption, and to the degree to which this occurred, reaccretion would tend to realign the Moon in the Laplacian plane."

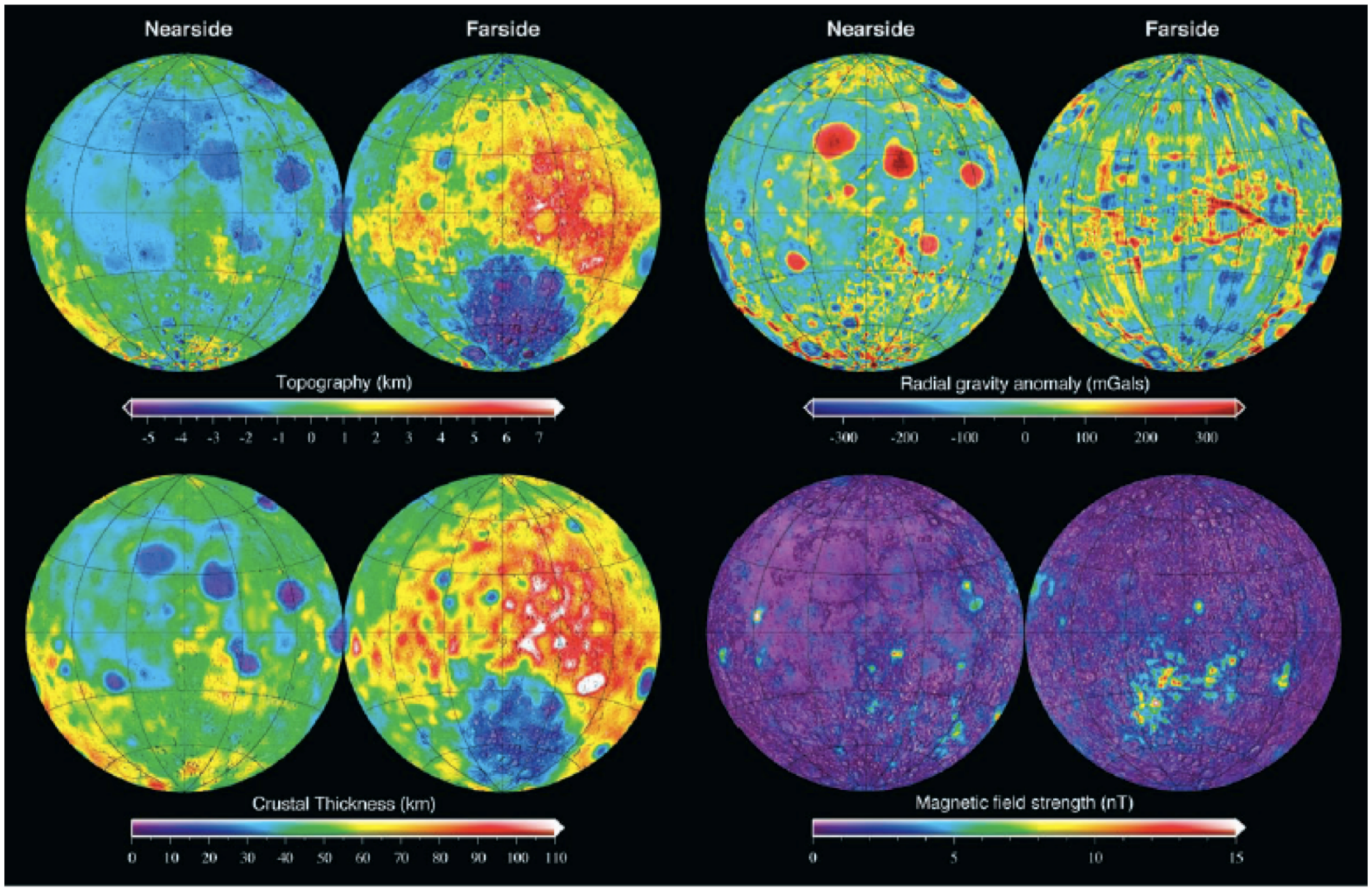
Disk Torque

- Resonant interactions between the disk and the moon
- Resonances interact with rings of disk material
- The last big resonance is a 3:1 vertical resonance



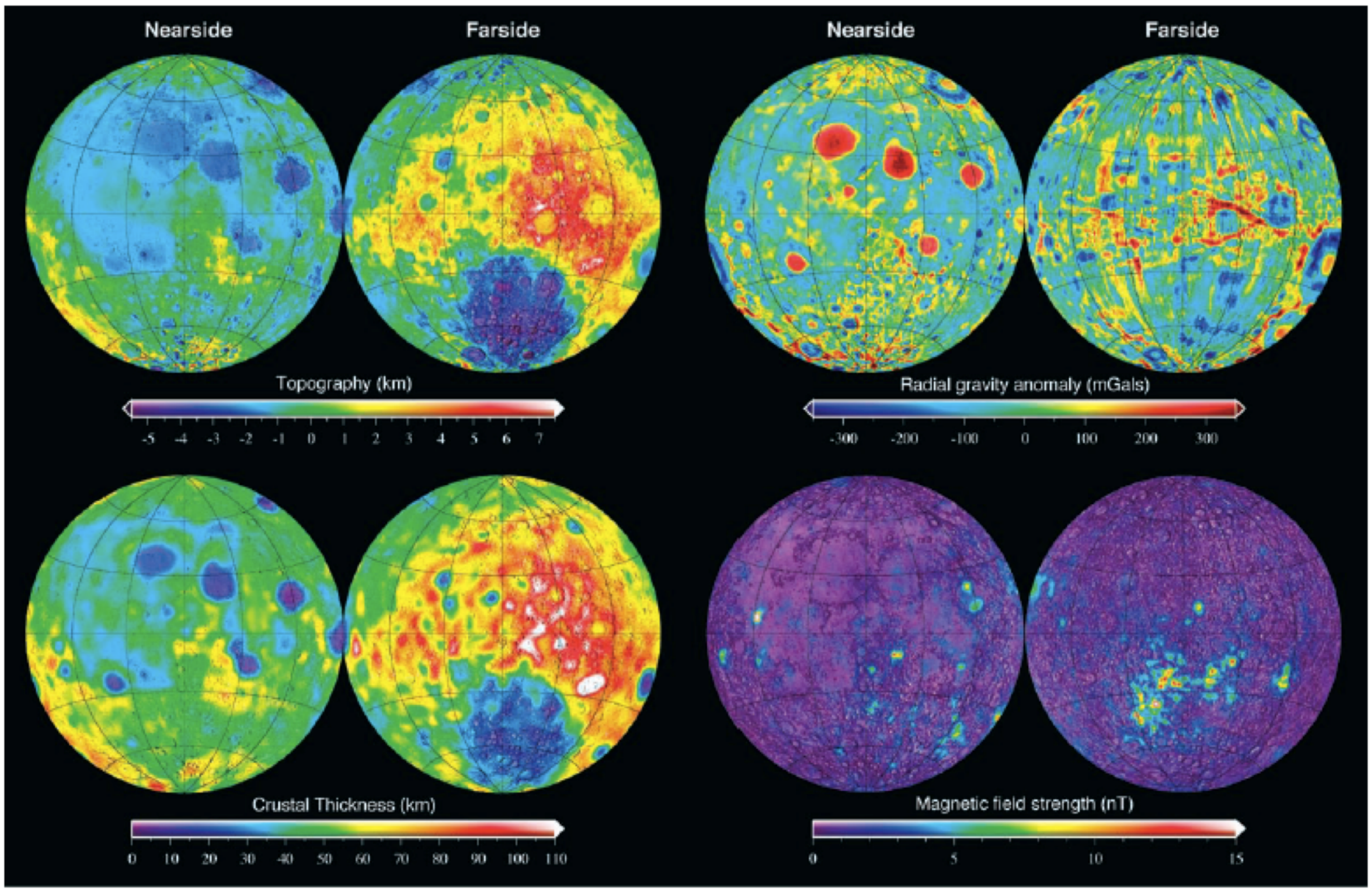
Crustal Thickness

- Calculated from gravity maps and topography
  - Assumptions about isostatic balance, Airy isostasy



Crustal Thickness

- Byproduct of differentiation
  - Depth of magma ocean, Efficiency of plagioclase



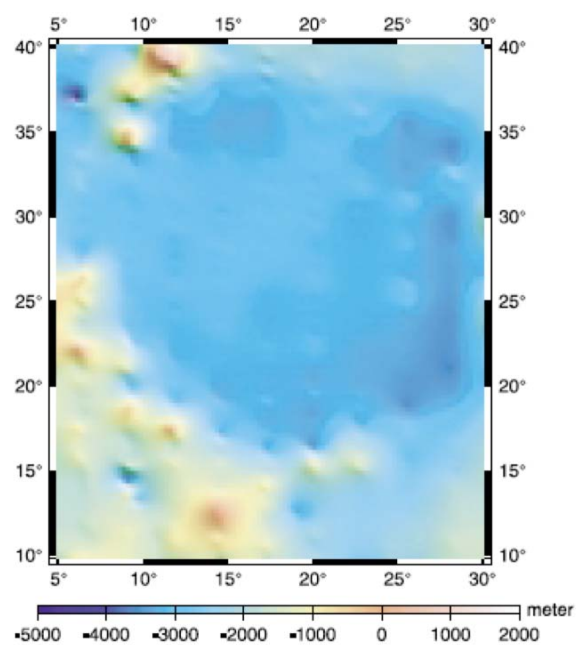
Dichotomy in Crustal Thickness

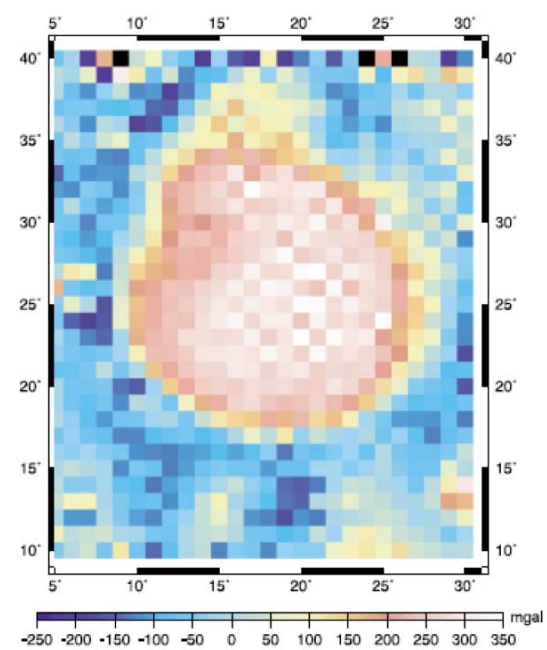
- Globally averaged depth, 40-45 km
- Apollo zone, 30-38 km
- Artifact from assuming crustal and mantle density homogeneity
  - Largest impact requires lower density crustal material to coat it
- Variations in composition both laterally (KREEP) and vertically (increasingly mafic with depth)
- Grail in 2011 combined with LRO topography will make things better

Mascons

- Large positive gravity anomalies
  - Center of large craters, but not all large craters
- Dense mare basaltic lava flow
- Structural uplift of dense mantle materials

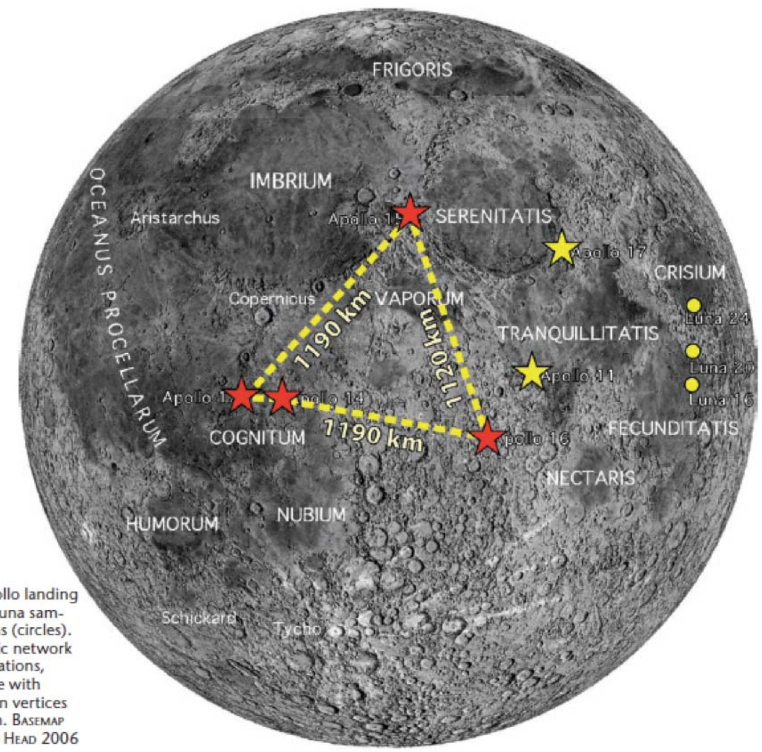
Mare Serenitatis





Apollo Seismic Network

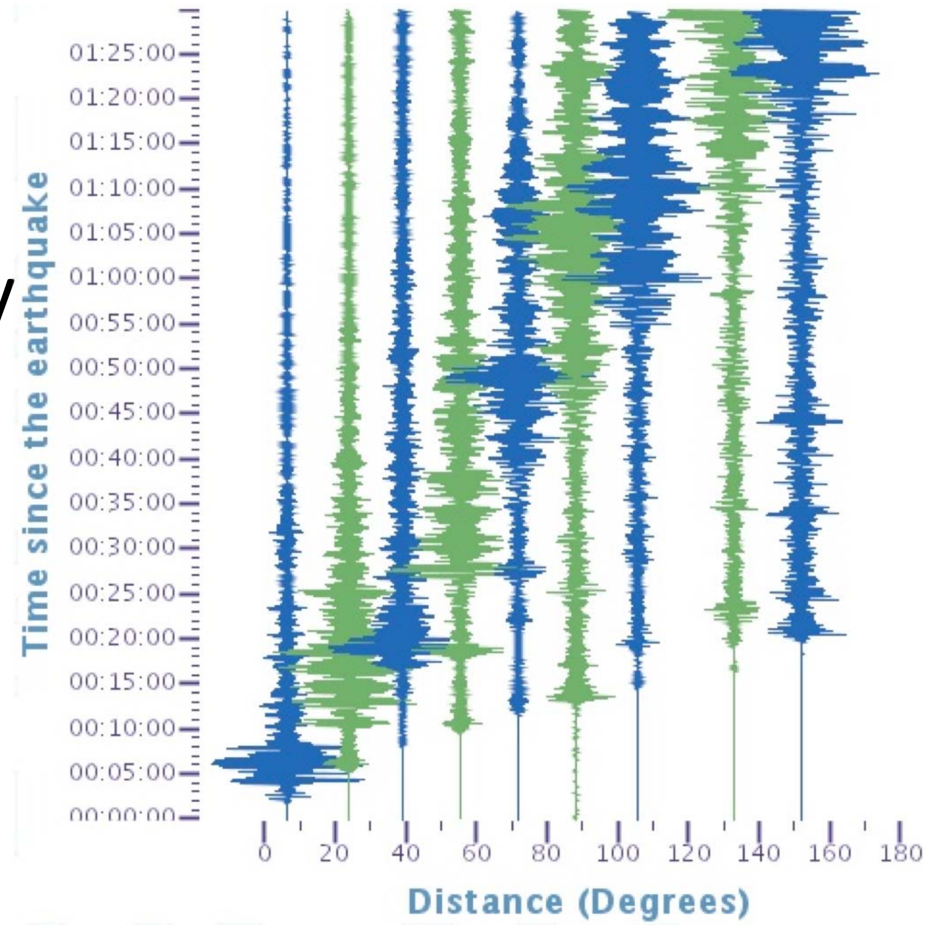
- Seismometers laid as part of the ALSEP on Apollo 12, 14, 15, 16
- Operated for 8 years
- 1800 meteroid impacts
- 28 energetic, shallow moonquakes
- 7000 weak, deep moonquakes



Apollo landing
and Luna sam-
stations (circles).
seismic network
four stations,
triangle with
etween vertices
200 km. Basemap
ER AND Head 2006

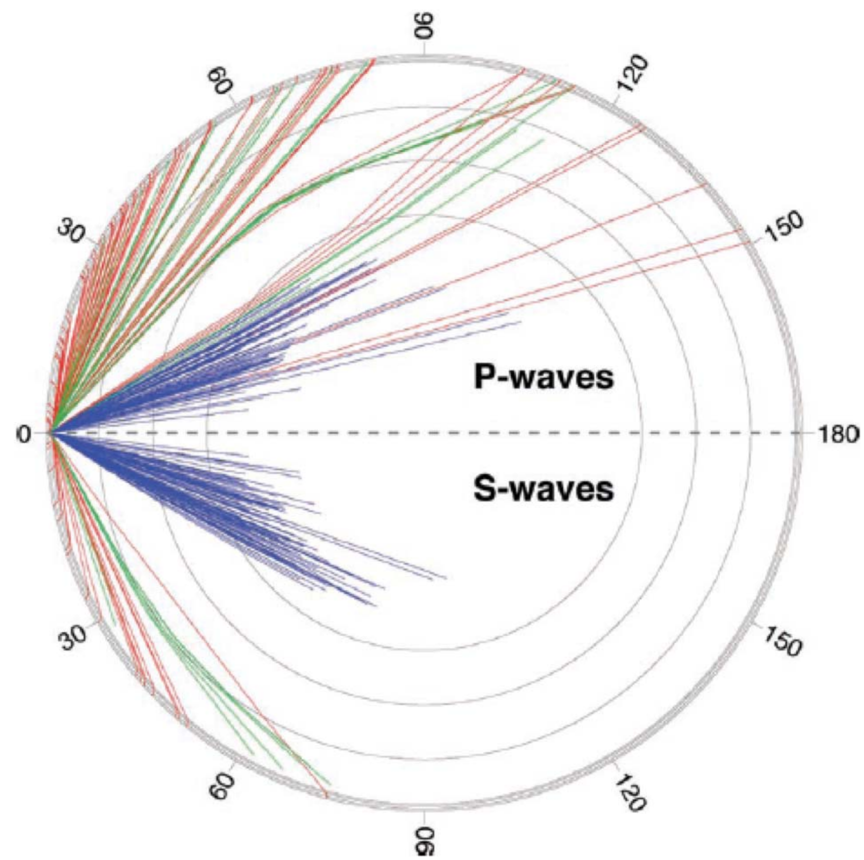
Velocity Profiles

- Waves take different amounts of time to travel through different material
- Crust and Mantle are distinctions in composition, so they show up



Velocity Profiles

- Uncertainty in arrival times can exceed 10 secs
  - Regolith disperses seismic wave fronts
- Two independent arrival-time datasets
- Network only lasted 8 of 18.6 year period
- Most recent work shows no velocity discontinuities in the mantle



Deep Moonquakes

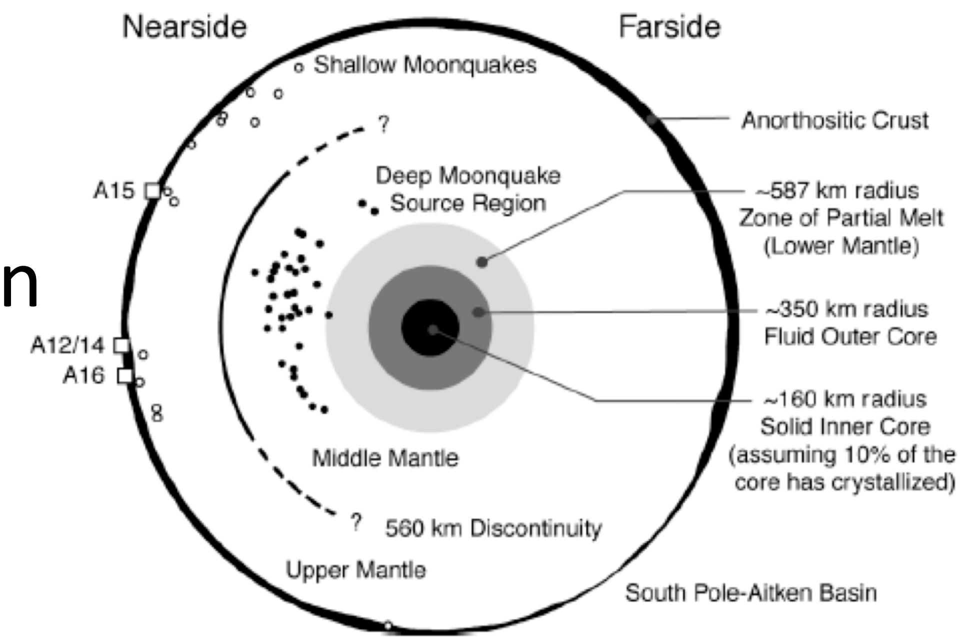
- Very low stress drops, very weak
- Correlated with tides raised by the Earth
- Originate from 300 “nests”, repeatedly activated
- Nests appear to be located on Moon’s nearside
  - Hypothesis: Nearside more seismically active, correlates with mare basalts (huh?)
  - Hypothesis: Signal Attenuation (cont. next slide)

Deep Seismic Signal Attenuation

- Shear waves appear to be absent for those ray paths that probe the deepest portions of the mantle
- Consistent with laser ranging data suggesting a quality factor of 30 for the moon, good damper
- Scenario: Magma-filled fractures located in the deep mantle are relieving small stresses induced by Earth-raised tides

Core

- Core is smaller than other terrestrial/icy planets and satellites, 460 km
  - Density, radius, moment of inertia
  - Consistent with measurements of an induced magnetic field
- Rotational data indicates energy dissipation between a molten core and a solid mantle



Historical Magnetic Field

- Lunar samples have strong magnetizations
- Magnetization detected in orbit, but from what depth?
- Hypothesis: Moon had internal dipole
  - Difficult for such a small core
  - Age constraints indicate a field that turned on late, 3.9 Gya
- Hypothesis: Large impacts are responsible

Large impacts are responsible

- Generate a plasma that propagates strong transient magnetic fields
- High crustal fields appear to be correlated with basin ejecta
- Correlation between some strong crustal fields and the antipodes of some of the youngest and largest impact basins
  - Plasma cloud encircles moon and amplifies field diametrically opposite the impact

Both Hypotheses

- Early dynamo exits
- Iron poor regolith, does not retain signal
- Impact basins create by iron-rich impactors do retain field
- Antipodal fields are still created via plasma
- Still questions remain on how a field could be maintained with such a small core

Future Experiments Needed

- Seismic Network with lateral and temporal expanse
  - Characterize the core, measure waves that pass through it
  - Understand “nests”, tidal?
  - Crustal thickness, dichotomy?
- Samples
  - SPA, understand difference in morphology
  - How deep is magnetization?

References

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