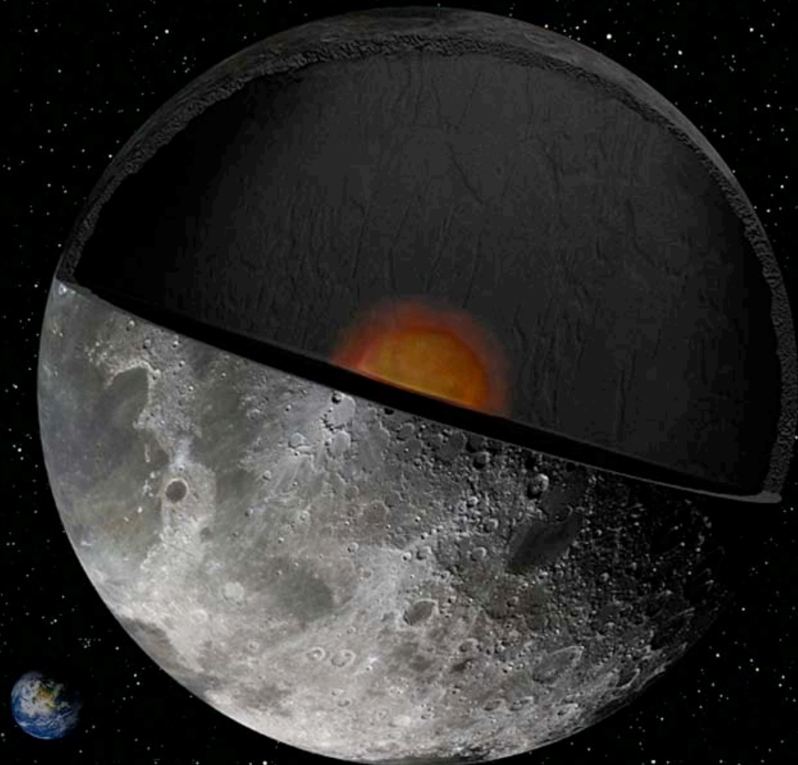


Lunar Geophysics Overview

Maria T. Zuber
Massachusetts Institute of Technology

NASA Lunar Science Forum
NASA Ames Research Center
July 21, 2010

Lunar geophysics – the big picture

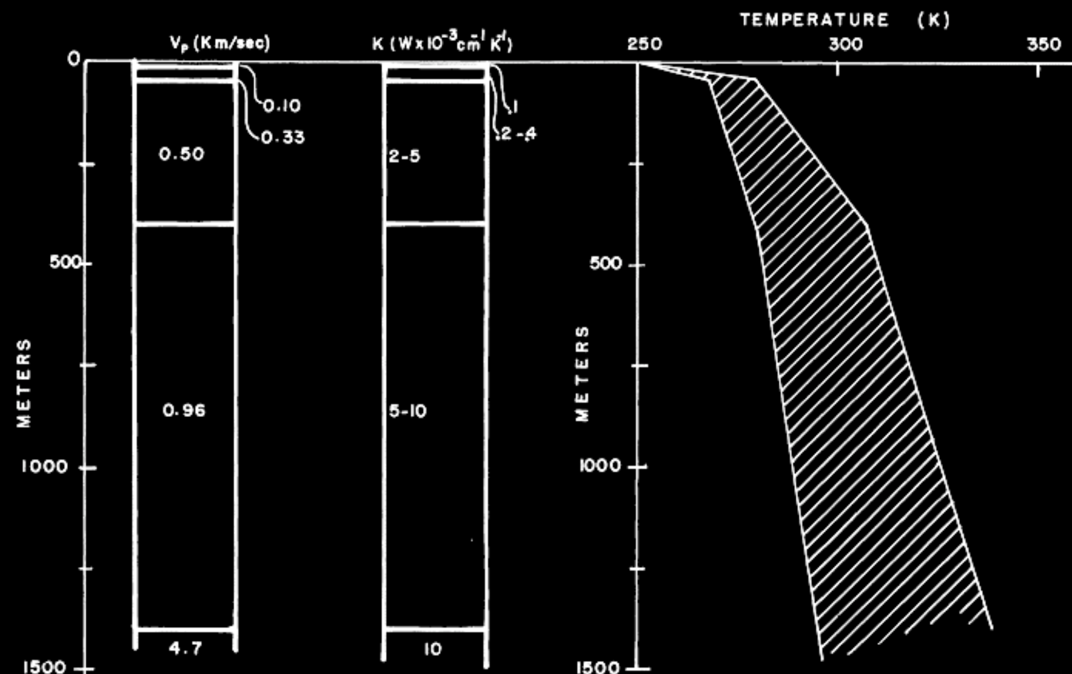
NASA/JPL/Galileo

The Moon is the most accessible example of a rocky, differentiated planetary body that preserves a primordial surface, and is therefore *the key to understanding the formation and evolution of terrestrial planets.*

Outstanding questions

- Why did the Moon apparently cool so early?
- Why does the Moon have an asymmetric structure (nearside/farside)?
- What is the thickness of the lunar crust?
- How much of crustal variability is due to variable melting vs. impact redistribution?
- What was the temporal evolution of magmatism and brecciation?
- How big are impact basins and how deep did they excavate and therrnally perturb the mantle?
- Did the mantle overturn subsequent to magma ocean solidification?
- How laterally heterogeneous is the lunar mantle?
- Does the Moon have a core?
- Does the Moon have a solid inner core?
- Did the Moon have a core dynamo?

Present-day boundary condition – heat flow

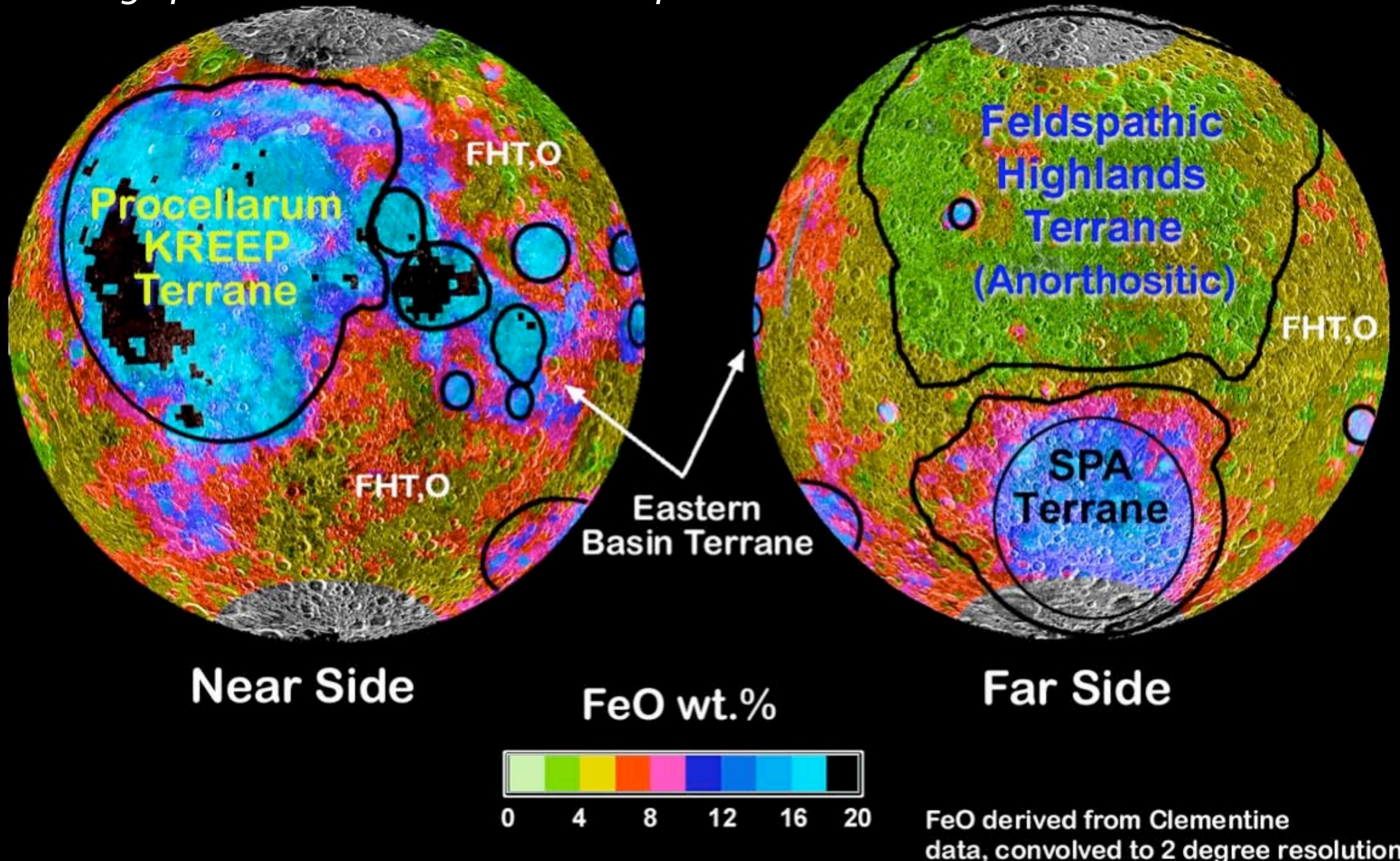


Langseth et al. [1976]

- Apollo heat flow experiments revealed:
  - regolith is extremely insulating.
  - surface thermal environment is readily disturbed by compaction and/or albedo changes.
  - lunar heat flow is spatially variable, necessitating distributed measurements to constrain local variations and distinguish among hypotheses.

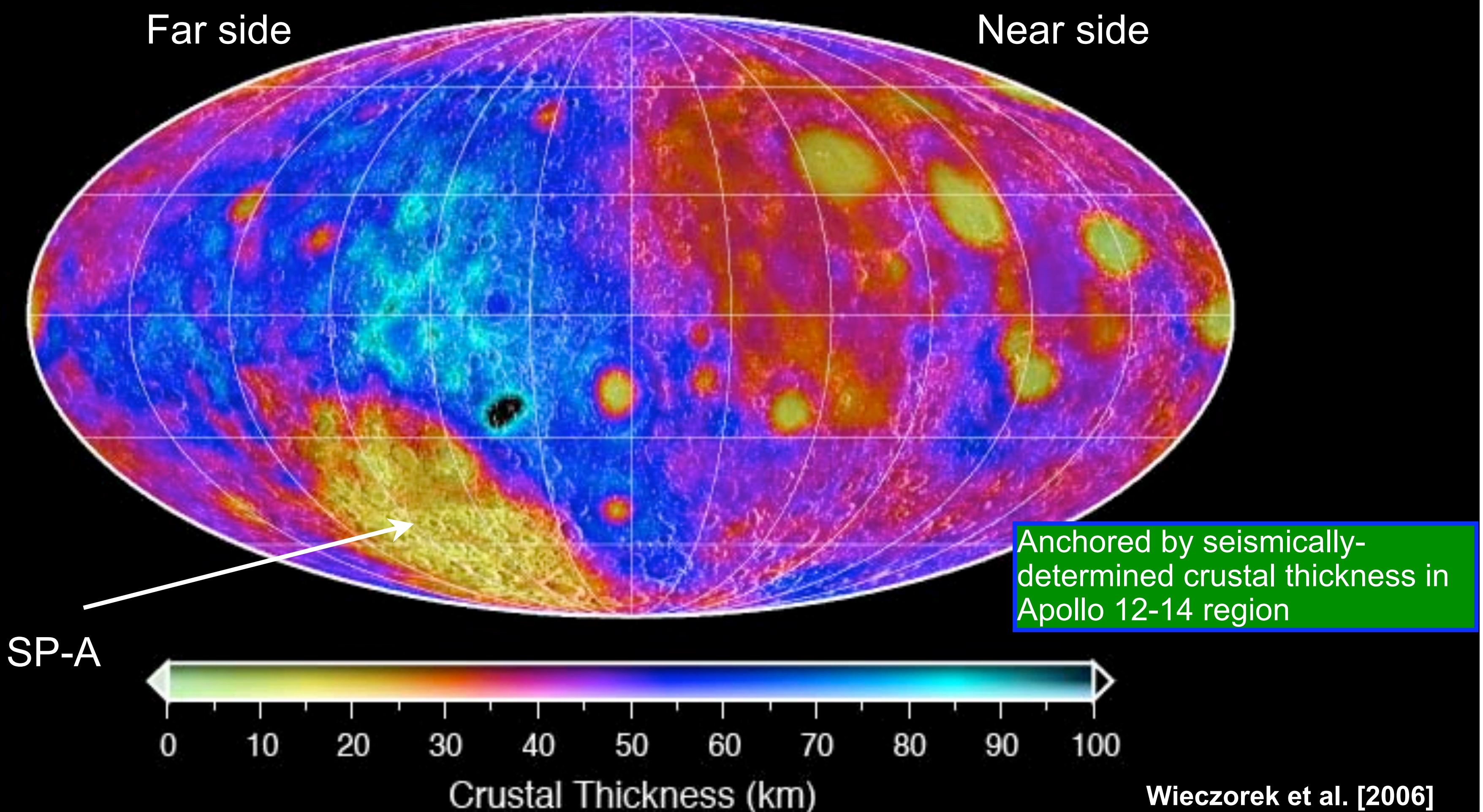
Evidence for lunar magma ocean

A large portion of lunar crust is composed of anorthositic materials.



Jolliff et al. [2000]

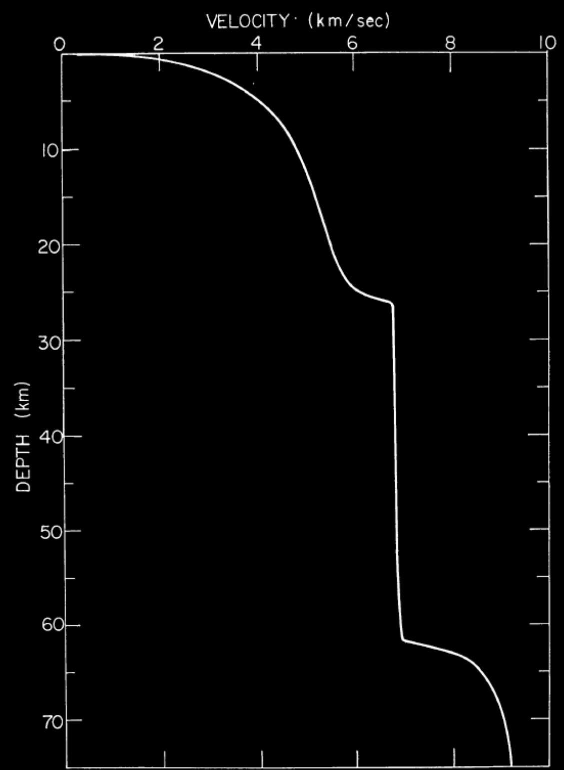
Crustal thickness modeling



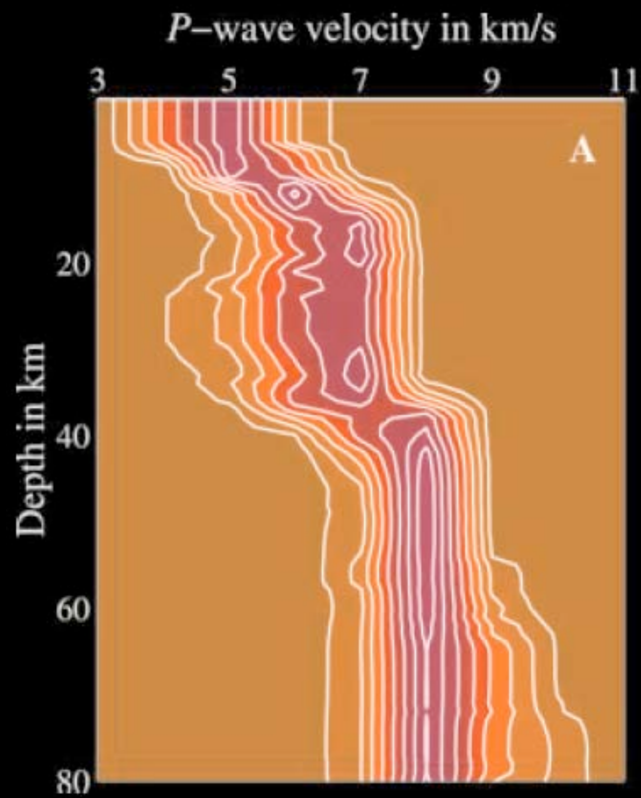
Wieczorek et al. [2006]

Gravity anomalies can be modeled in terms of crustal thickness variations, showing that large impact events excavated large quantities of crustal materials.

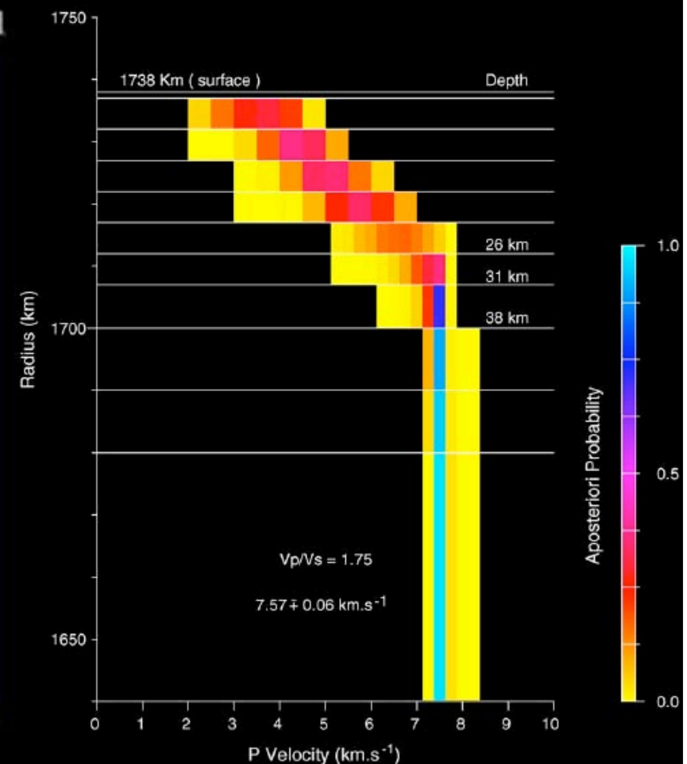
Constraints on crustal thickness from seismology



Toksöz et al. [1972]
~60 km



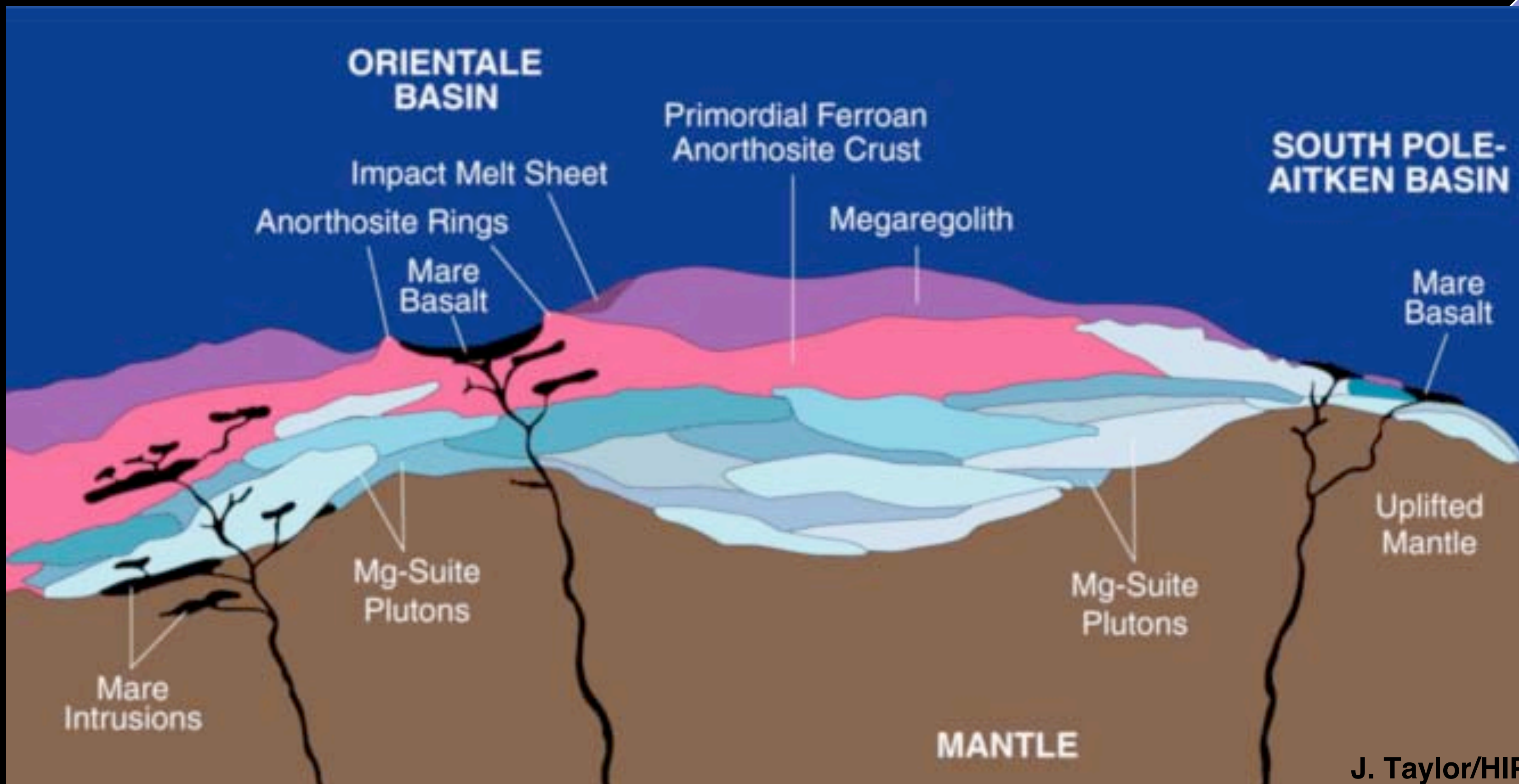
Khan and Mosegaard [2002]
38±3 km



Lognonné et al. [2003]
30±3 km

Each study used different seismic events, seismic arrival times and analysis techniques...

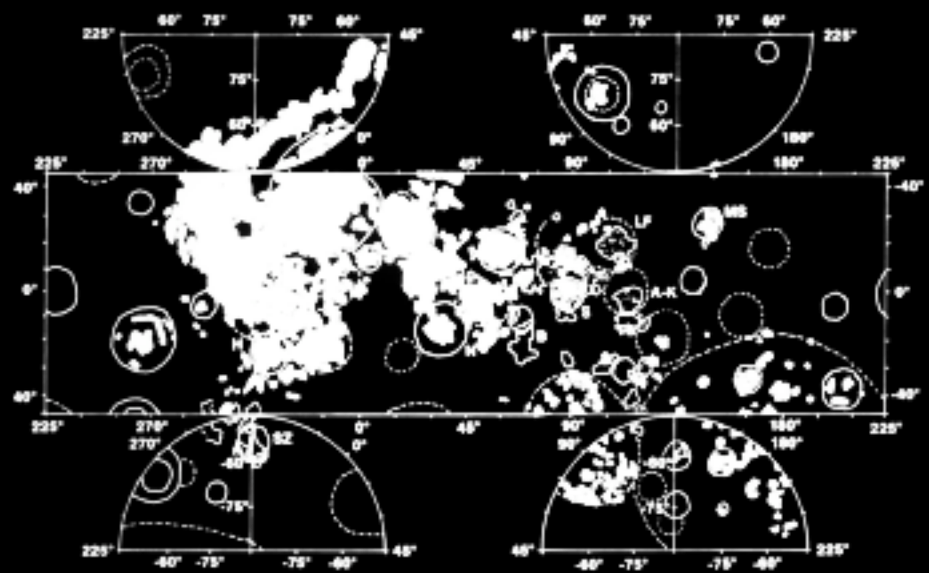
How complex is lunar crustal structure?



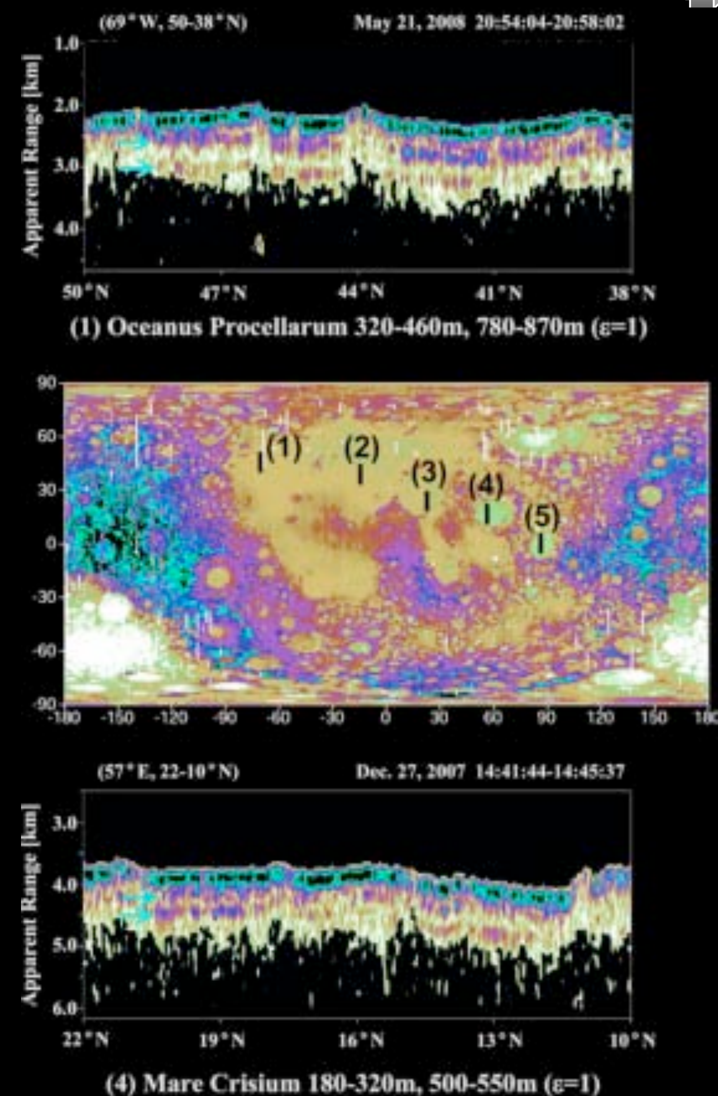
- What is the role of heterogeneous melting vs. impact redistribution in crustal thickness variations?
- How have impact-related brecciation and magmatic intrusion affected crustal structure?

What is the history of lunar magmatism?

- Distribution of maria (surface) and cryptomaria (intrusive volcanism) provides information on spatial and temporal distribution of melting.
- Surfical estimates based imaging & remote sensing; improved estimates of intrusive contributions require gravity, radar sounding, seismics.

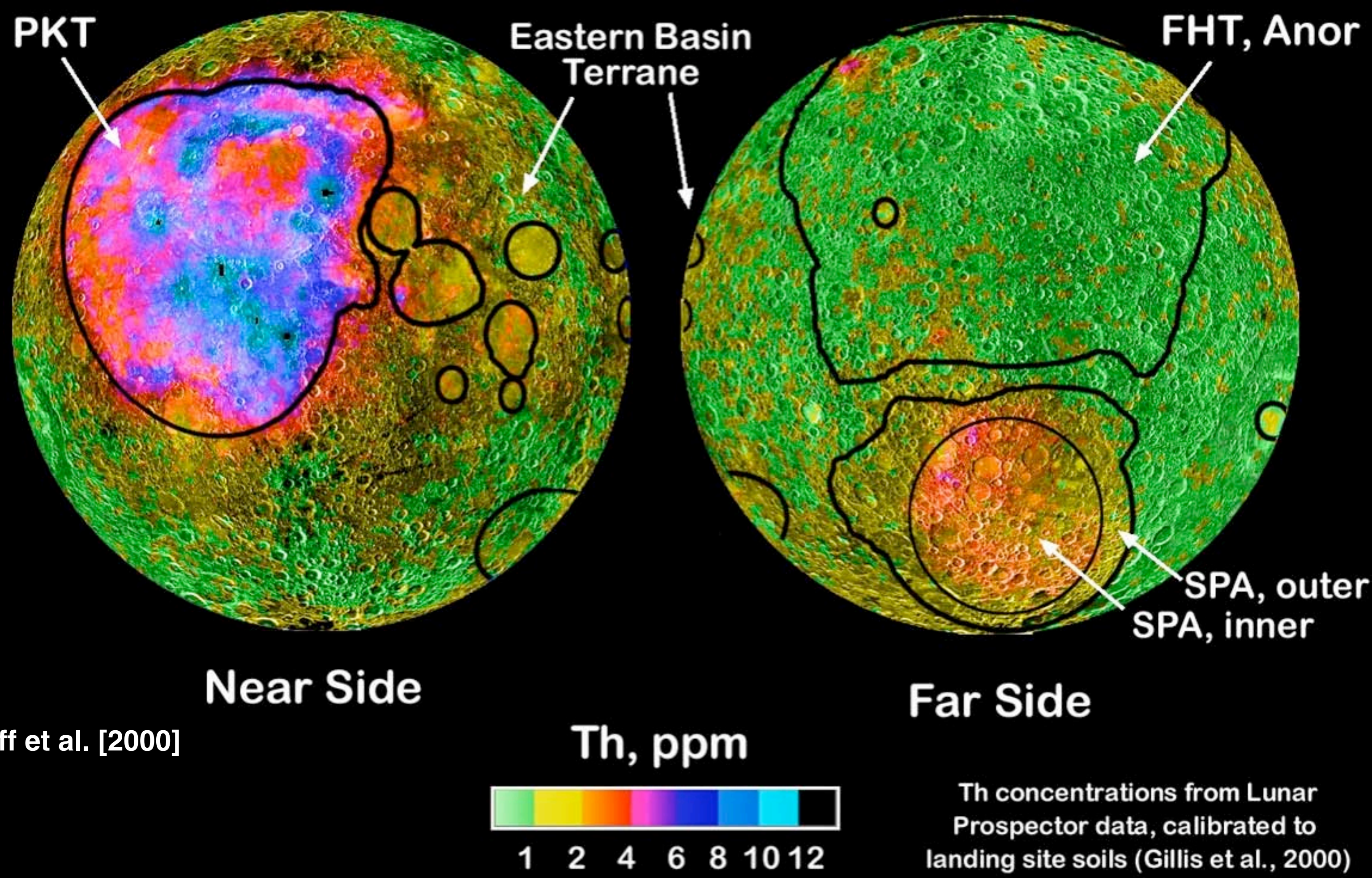


Head and Wilson [1992]



Ono et al. [2009]

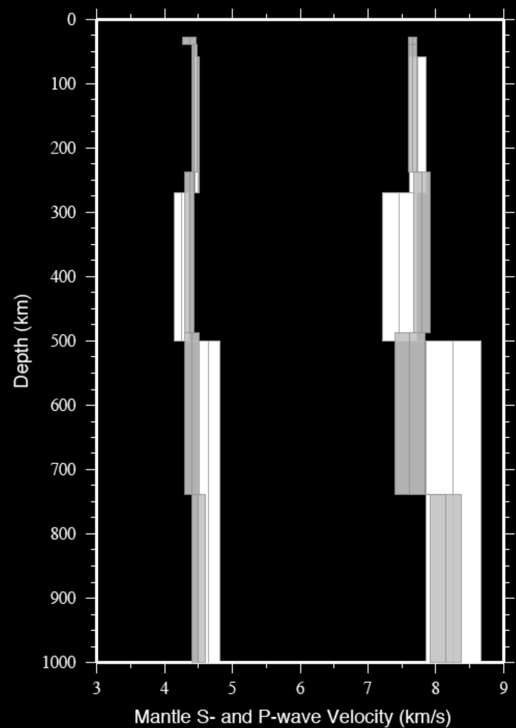
Evidence for enhanced near side melting



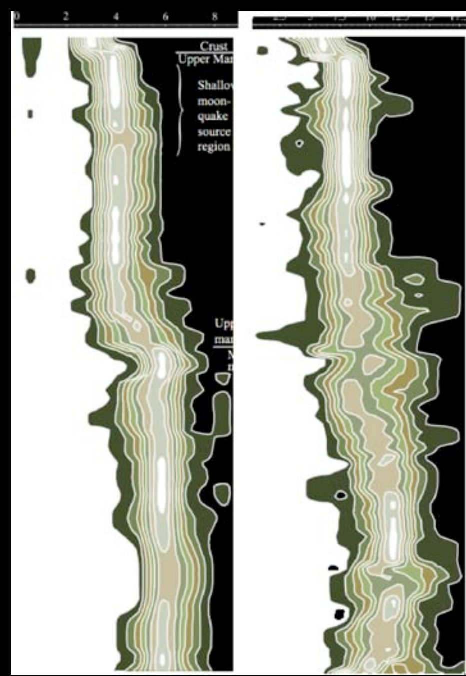
Jolliff et al. [2000]

Lunar Prospector γ-ray spectroscopy shows that Th, and by inference KREEP, is highly concentrated only in a near side crustal province: the <u>Procellarum KREEP Terrane</u> (PKT).

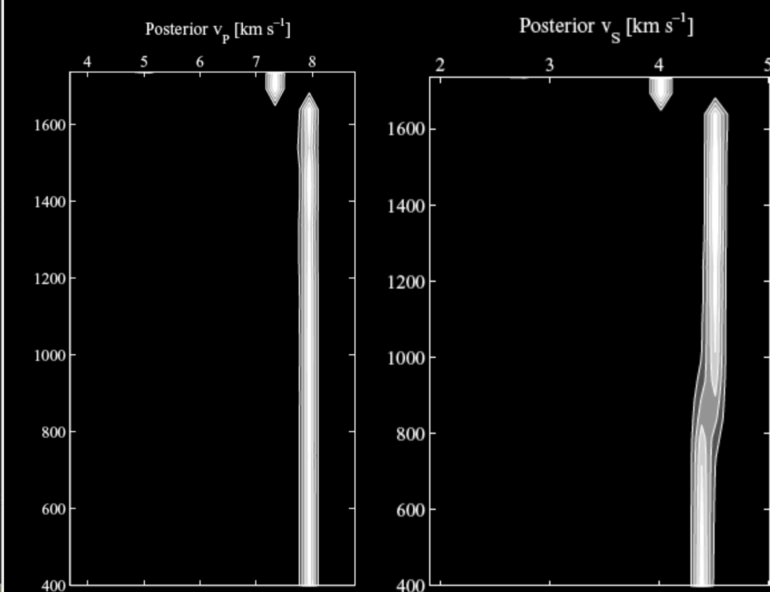
Is there a seismic discontinuity in the mantle?



Nakamura et al. [1982],
Lognonné et al. [2003]
Maybe: ~500 km



Khan and Mosegaard [2002]
Yes: 550 km depth

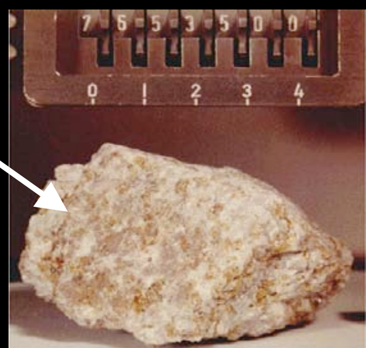


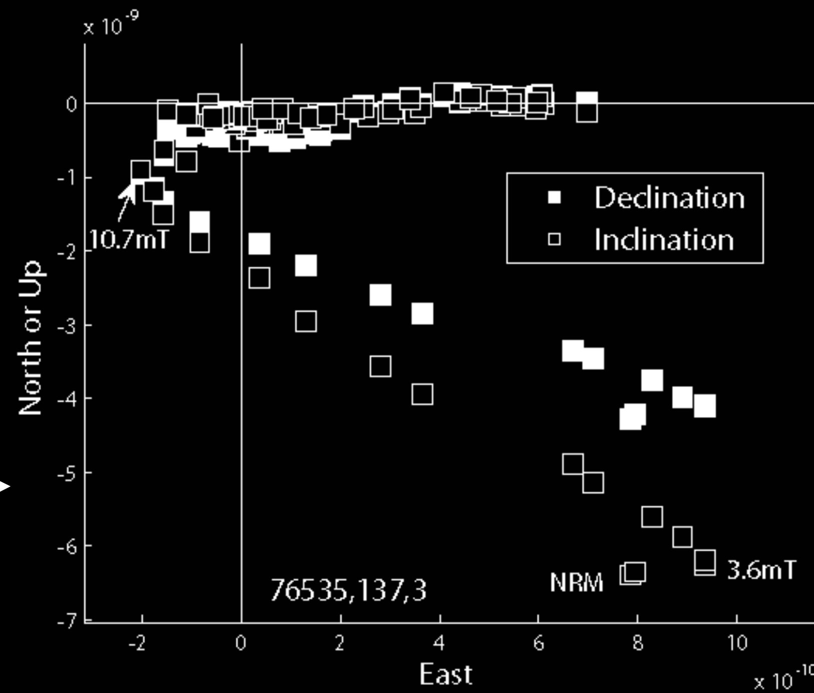
Khan et al. [2007)]
NO? or 850 km depth?

Each study used different seismic events, seismic arrival times and analysis techniques... *so don't know the answer, <u>but important for magma ocean depth</u>.*

Early lunar magnetism

Remanent Magnetization in 76535 (4.2 Ga)

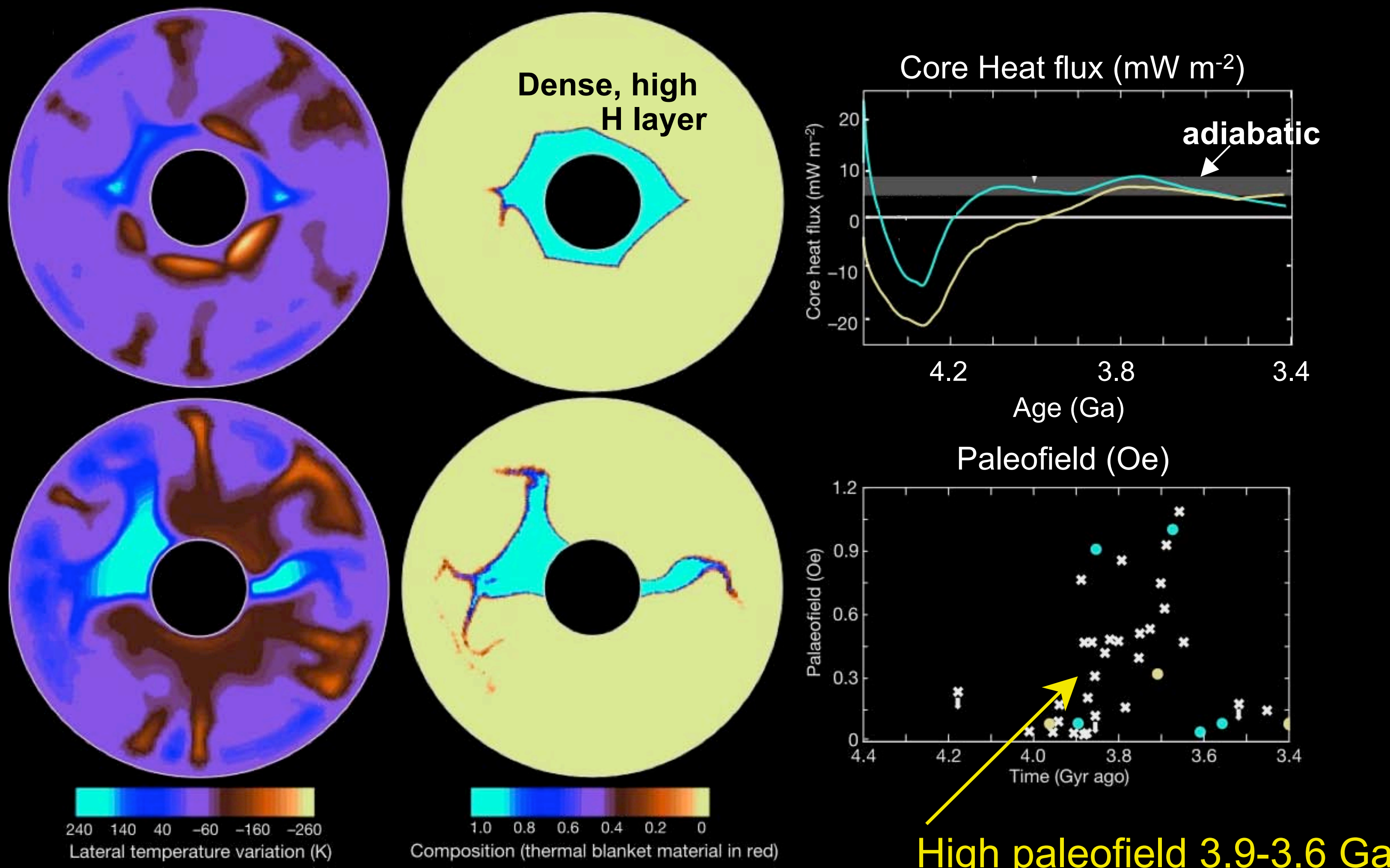




Garrick-Bethell et al. [2009]

- Magnetization in lunar rocks implies intense paleomagnetic fields (within an order of magnitude of Earth today).
- New analyses of ancient samples demonstrate that magnetic fields existed on the Moon as early as 4.2 Ga (before heavy bombardment).
- Ancient field cannot have come from Sun or Earth. May have come from an early core dynamo.

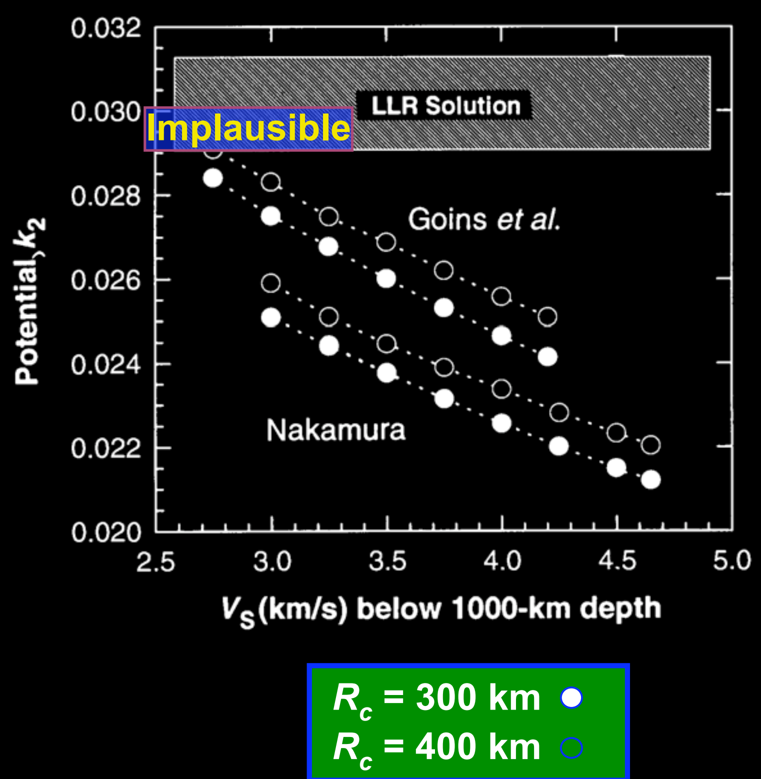
Was there a lunar core dynamo?



Stegman et al. [2003]

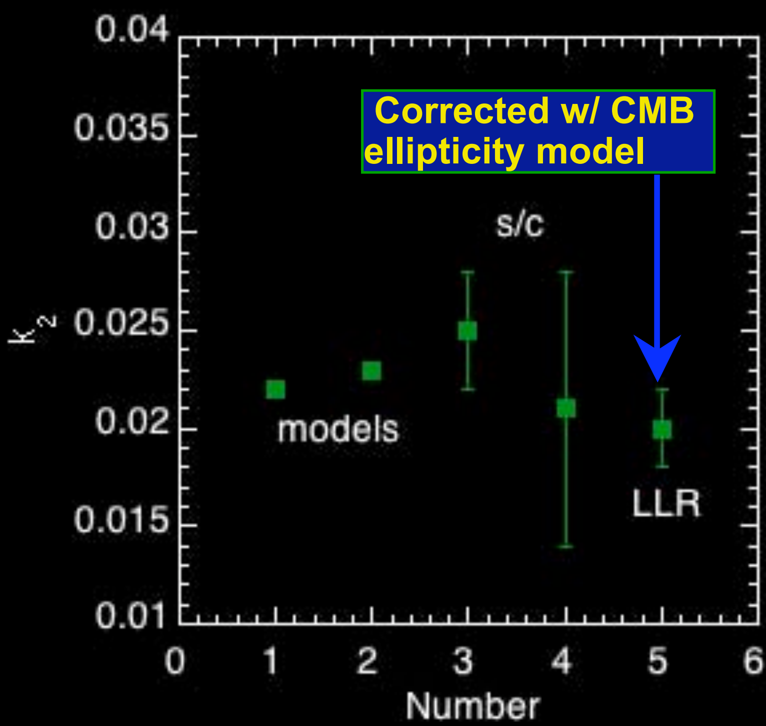
Deep interior: Evidence for core from k_2

Tidal Love Number



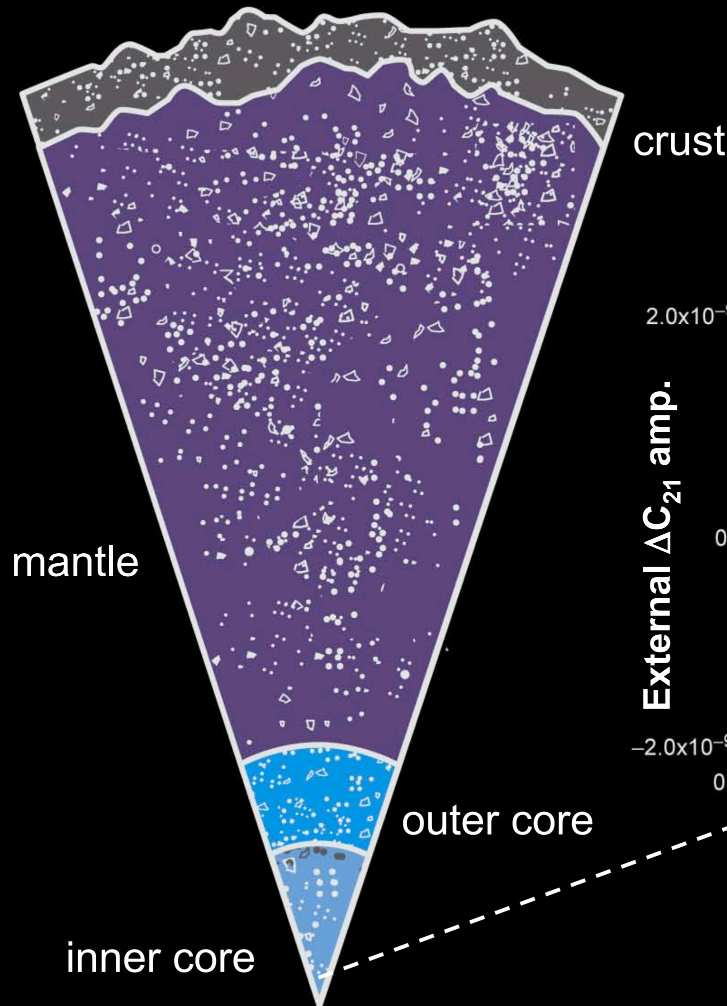
Dickey et al. [1994]

k_2 Model Values and Determinations

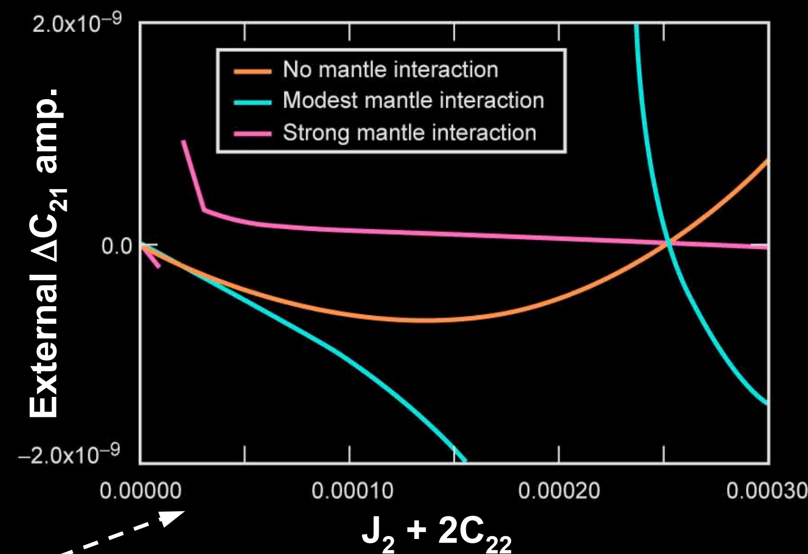


Konopliv et al. [1993]
Goosens and Matsumoto [2008]

Deep interior: Inner core detection



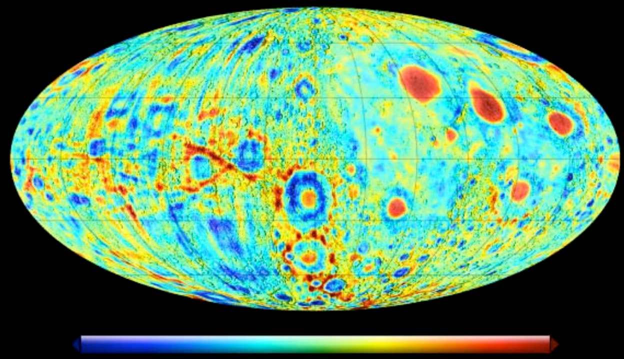
J_2 = gravitational oblateness
C_{22} = gravitational shape of equator
C_{21} = measures how gravity field is aligned with respect to polar axis of coordinate system



Williams [2007]

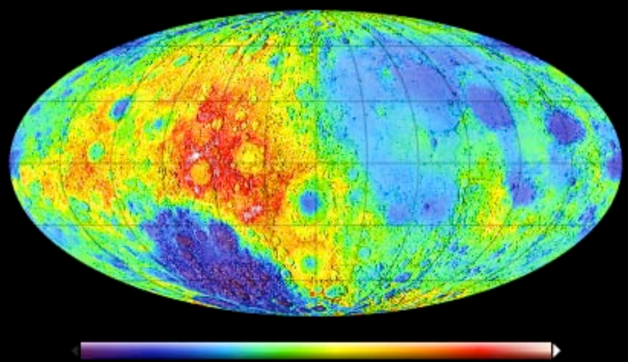
Differing tilts of mantle & solid inner core; equatorial planes precess about ecliptic plane & lead to 27.2-day periodic variations in C_{21} (also k_2 dependent).

Gravity and topography



gravity

geophysical model



topography

crustal density

crustal thickness

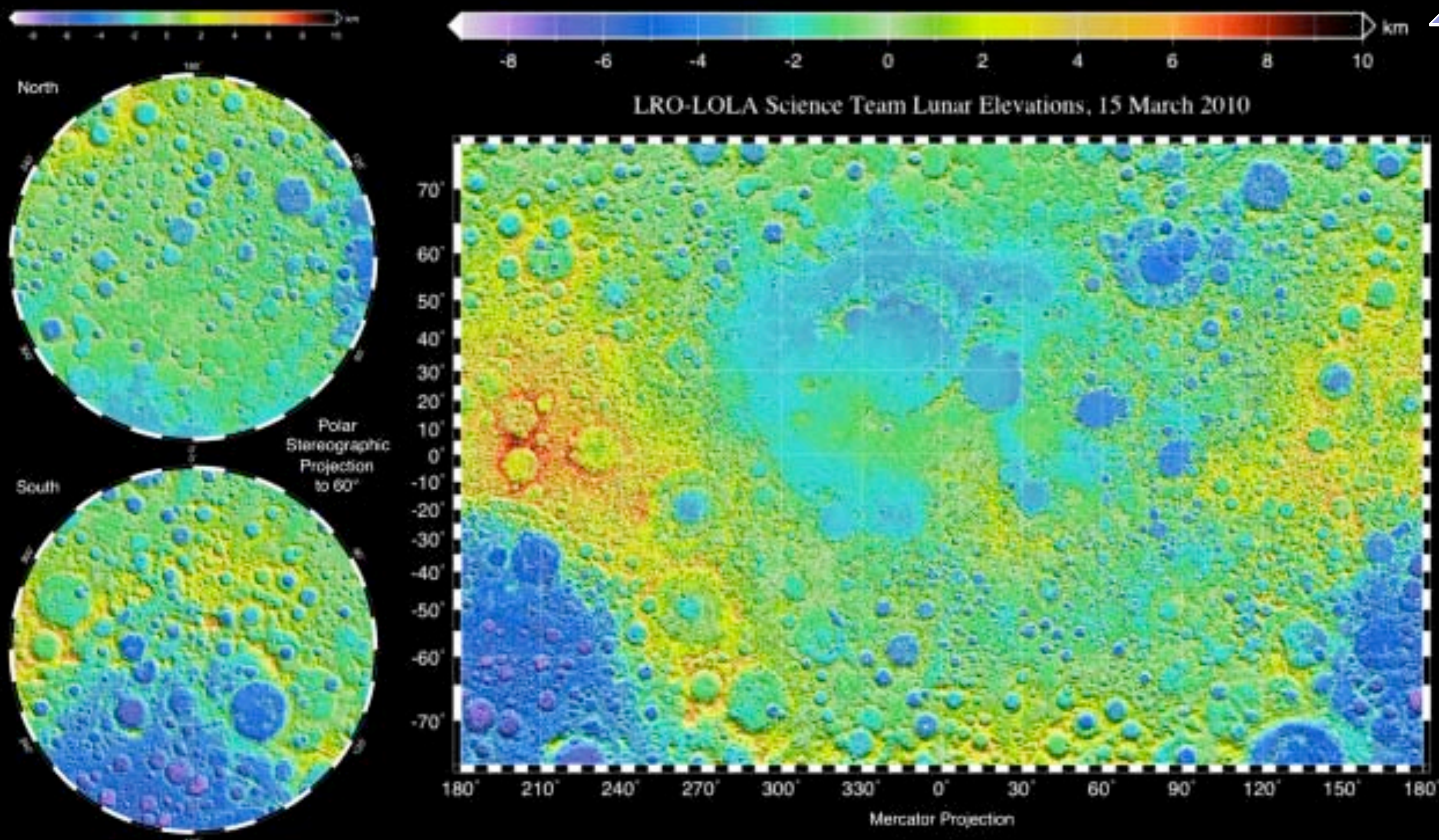
elastic thickness

load density

surface-subsurface loading ratio

phase relationship of loads

LOLA global topography – June 19, 2010



- 2 billion valid measurements, 800 M laser shots (compare to Mars: MOLA = 670 M measurements)
- 20-m along-track resolution; 1.25-km average orbit track spacing @ equator.

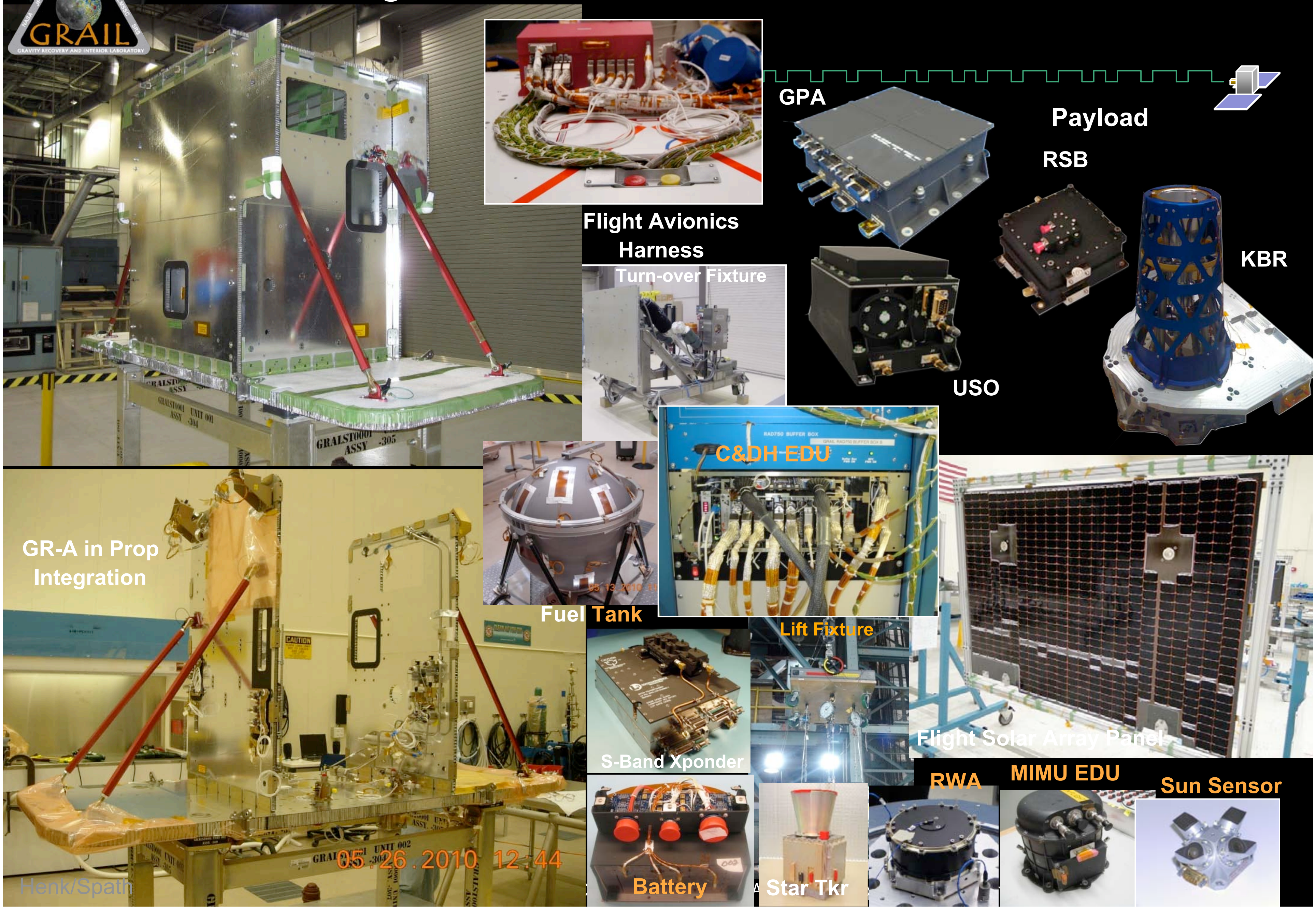
Smith et al. [2010]

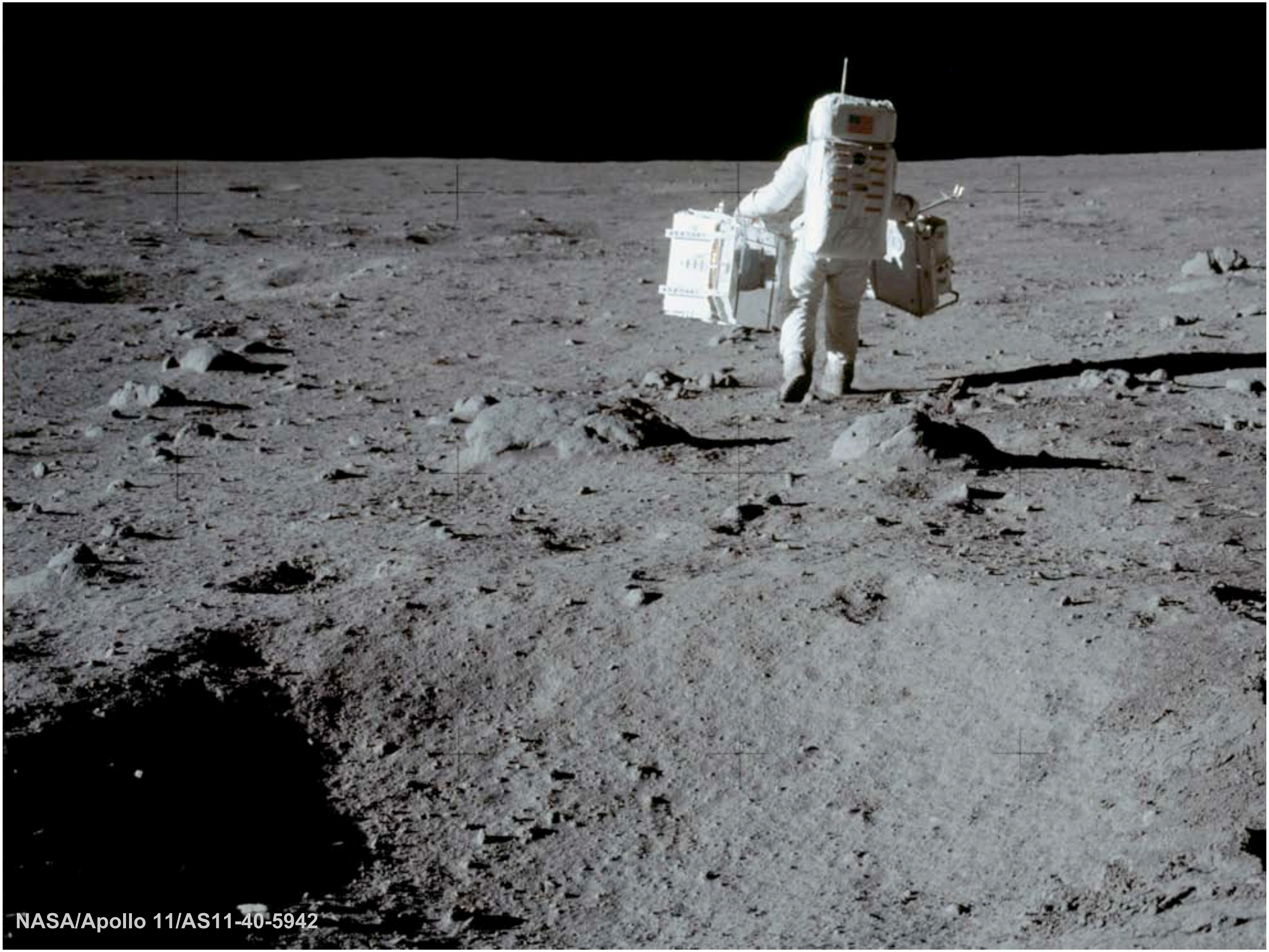
GRAIL mission – on track for September 2011 launch

Mariner 10

- Primary mission objectives:
  - Determine the structure of the lunar interior, from crust to core
  - Advance understanding of the thermal evolution of the Moon
- Secondary mission objective:
  - Extend knowledge gained from the Moon to other terrestrial planets

GRAIL flight hardware




NASA/Apollo 11/AS11-40-5942

Major questions in thermal modeling

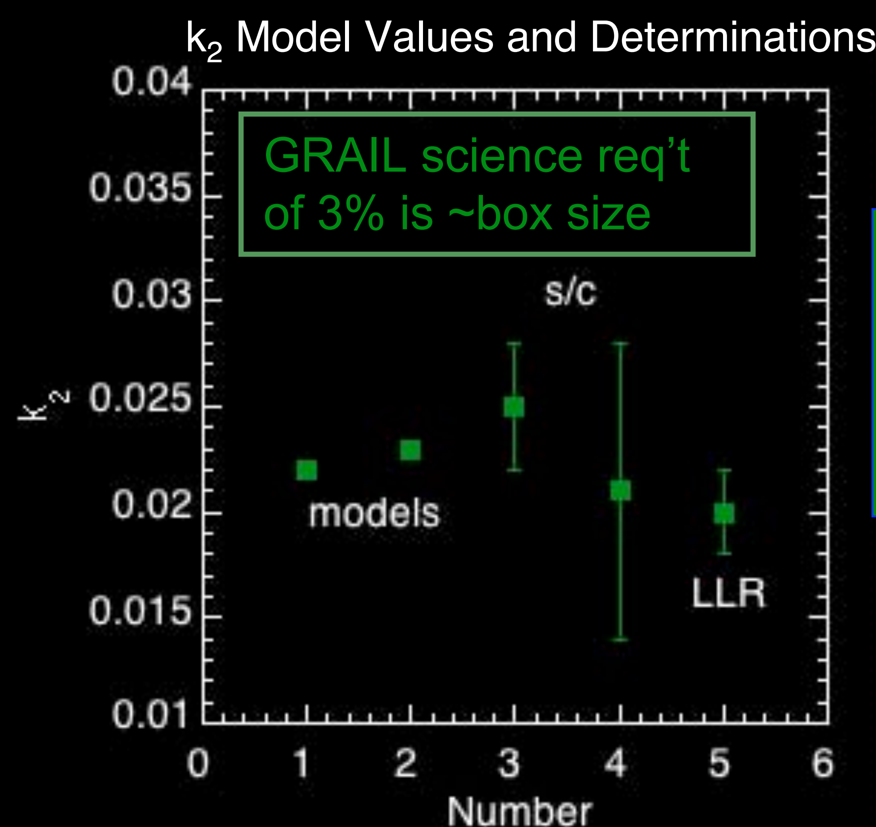
- What was the temperature distribution in the Moon immediately following accretion?
- What was the chemical and density stratification and was there an overturn?
- If so, what was the temperature distribution immediately after the overturn?
- Did dense layers rich in heat sources sink to form a thermal/ compositional boundary layer (BL) at the CMB?
- If so, did the BL eventually generate plumes?
- What was the effect of impacts on the heat budget?
- How has the Moon apparently maintained a partially (at least) molten core to the present?

What are useful constraints on the thermal history?

- Confirming the existence of a dynamo and its duration.
- Establishing effective elastic thickness in space and time to infer heat flow and interior temperatures.
- Estimating interior temperature in space and time using thermobarometry
- Estimating the distribution of crustal magmas in space and time

Deep interior and core

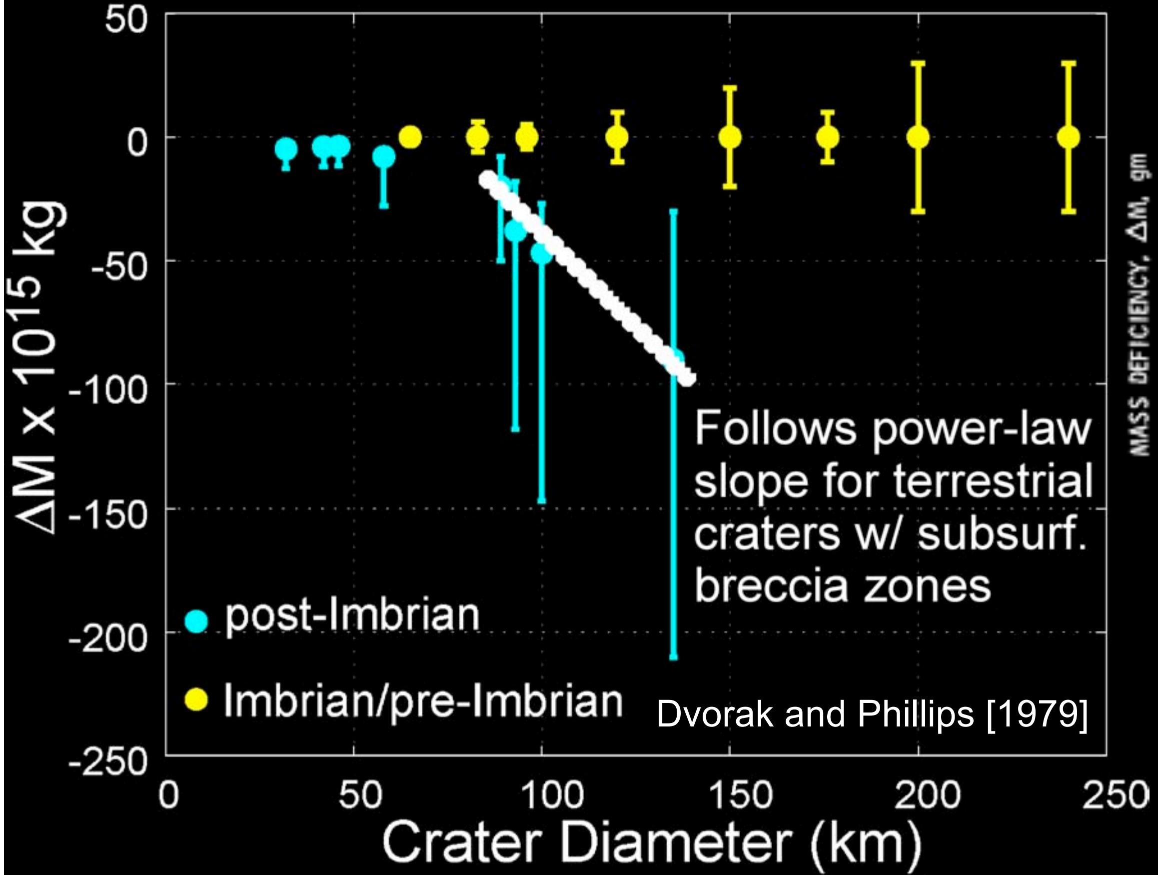
	Requirement	Baseline (CBE)
Deep interior	$k_2 \pm 6\text{x}10^{-4}$ (3%)	± 0.5 **(0.3) x10^{-4}**
Inner core detection	$k_2 \pm 2\text{x}10^{-4}$ (1%)	± 0.5 **(0.3)x10^{-4}**
	C_{21} ±1x10^{-10}	± 0.5 **(0.3) x10^{-10}**

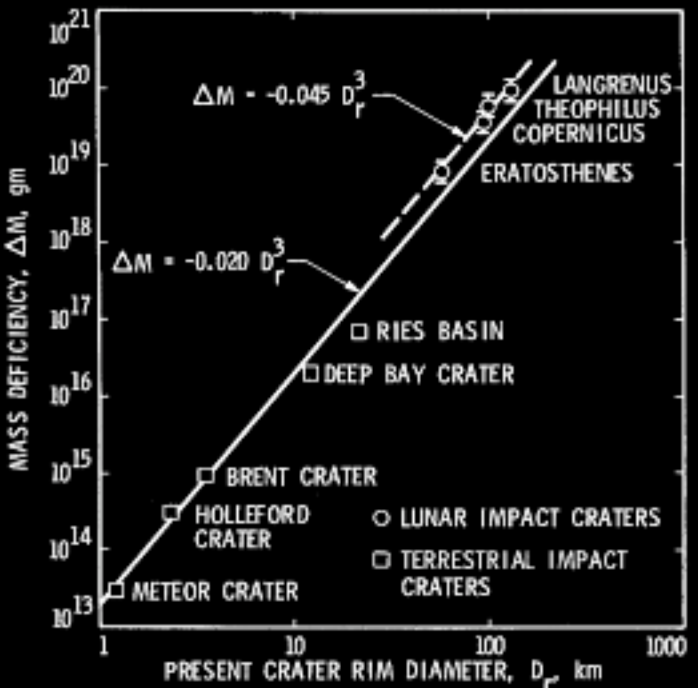


S/C k_2 and LLR data separate CMB oblateness from shear modulus in deep interior, e.g., is there partial melt in lower mantle?

Konopliv et al. [1993]
Goosens and Matsumoto [2008]

Craters as drills for crustal magmatism

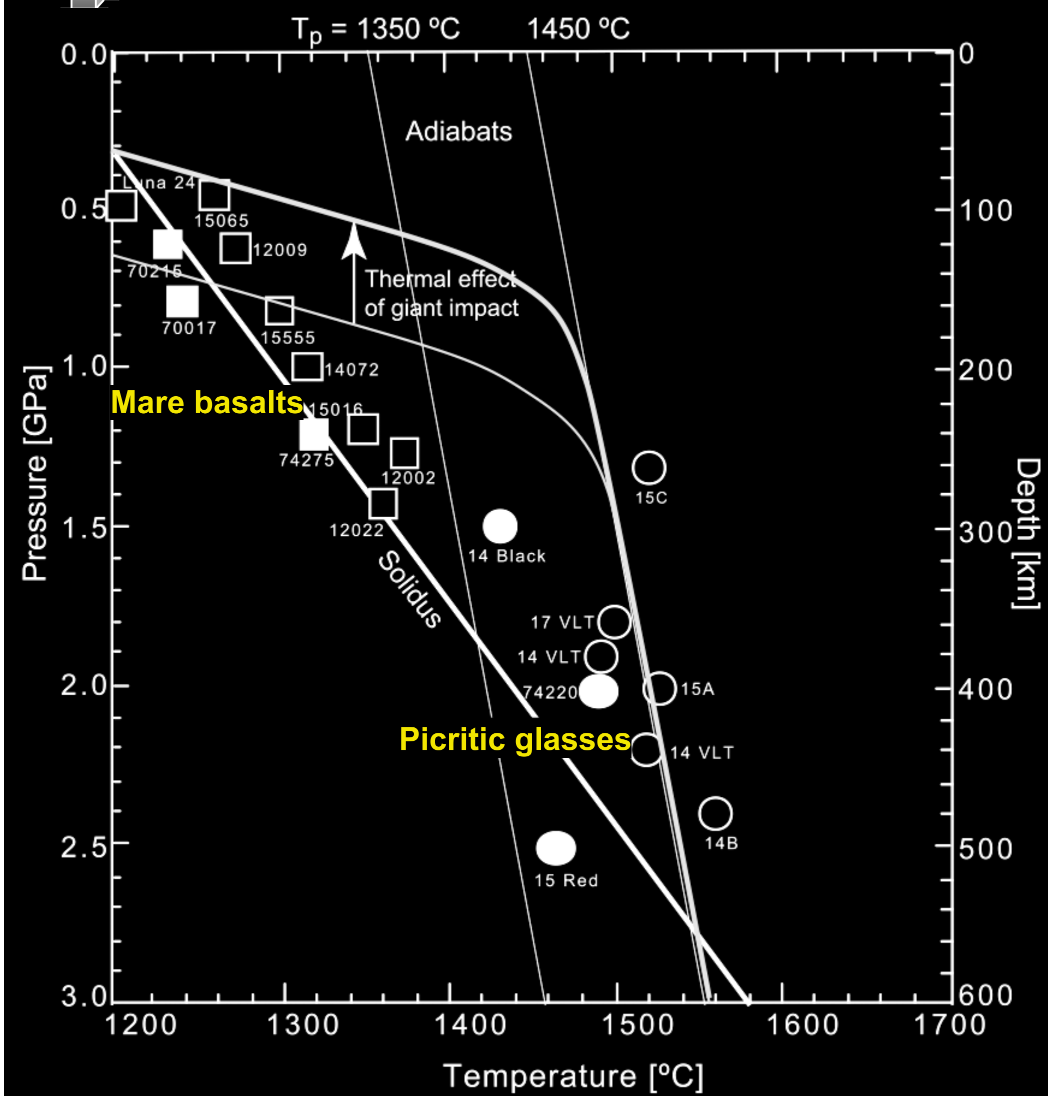




Best GRAIL analogy is Kepler (*D* = 32 km) from Apollo 16 ss @ 18-20 km alt.; |Δg| (max) ~15-20 mGal. GRAIL CBE for 30-km block = **0.007 mGal**.

GRAIL can produce a global set of crater mass deficiencies down to craters ~30 km in size and potentially map out the magmatic history of the lunar crust in space and time.

Using petrology to infer mantle temperatures



Elkins-Tanton *et al*. [2004]

- Mantle @ ~3.5 Ga
- Inferred from multiple saturation points of picritic glasses and mare basalts
- Thermal effect of giant impact shown
- Need to do thermo-barometry on KREEP basalts, Mg-suite, and KREEP-poor magnesian magmas in FHT
- Potentially a strong constraint on *T*(space, time)

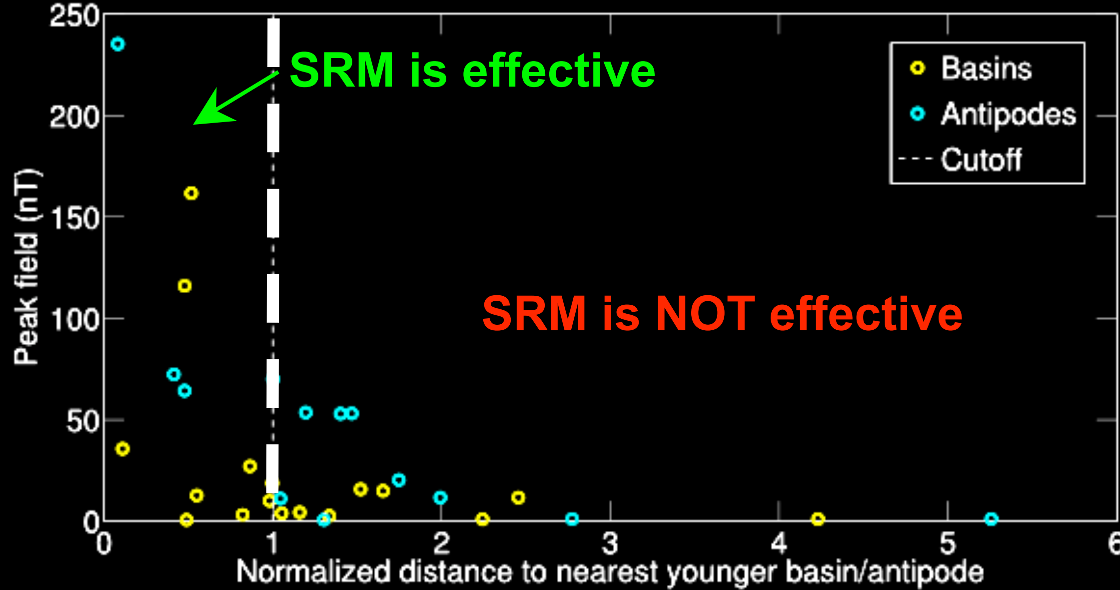
Is there a lunar core?

Probably, with outer portion likely liquid.

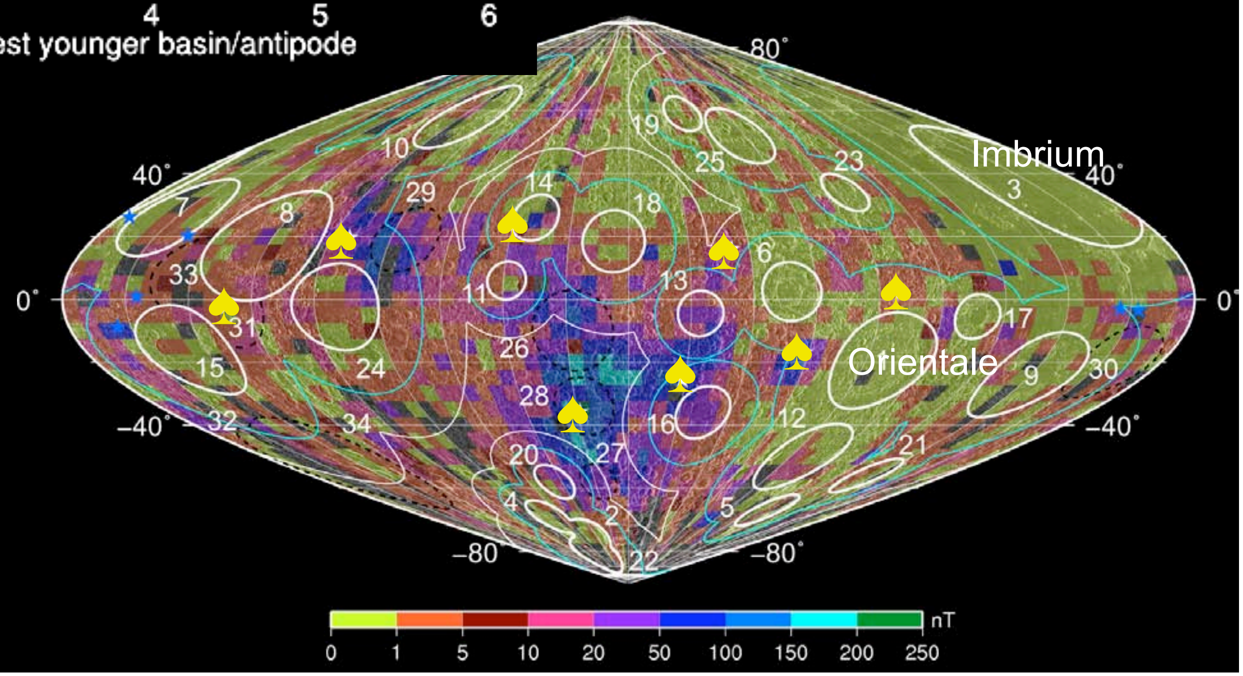
- Consistent with moment of inertia.
- Likely required by induced magnetic dipole (Hood).
- Likely required by LLR estimate of <u>apparent</u> potential Love number, k_2 – appears to require oblateness of CMB [Dickey et al., 1994].
- Dissipation parameters (from LLR) indicate a fluid core and strong tidal dissipation [Williams, 2007].

LLR = Lunar Laser Ranging; CMB = Core-Mantle Boundary

SRM* can't explain everything



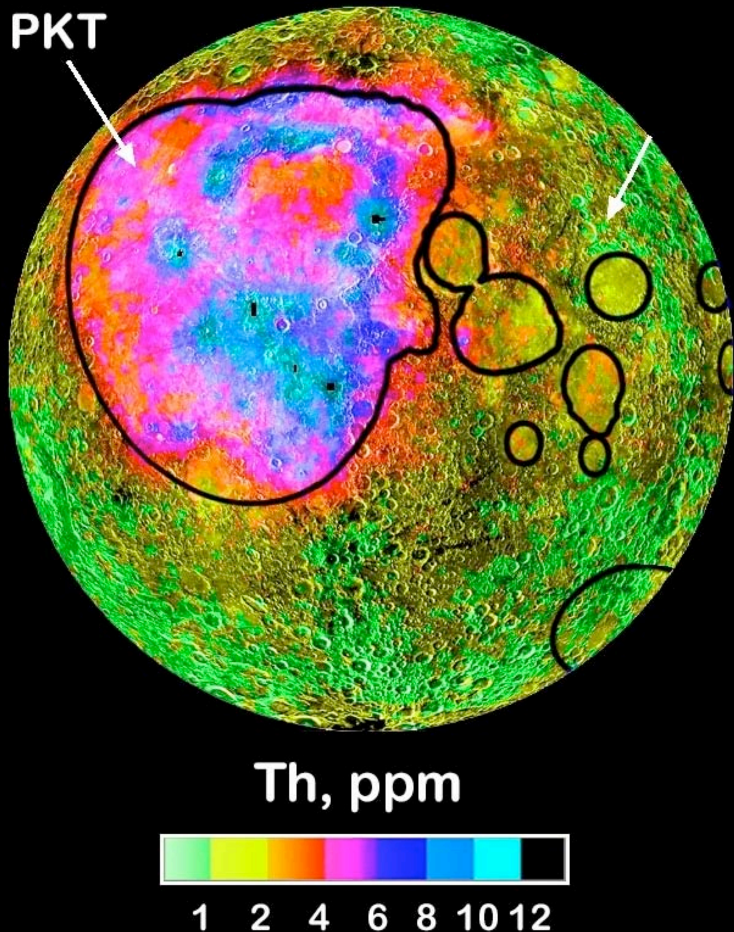
*SRM = shock remanent magnetization; *doesn't require dynamo*

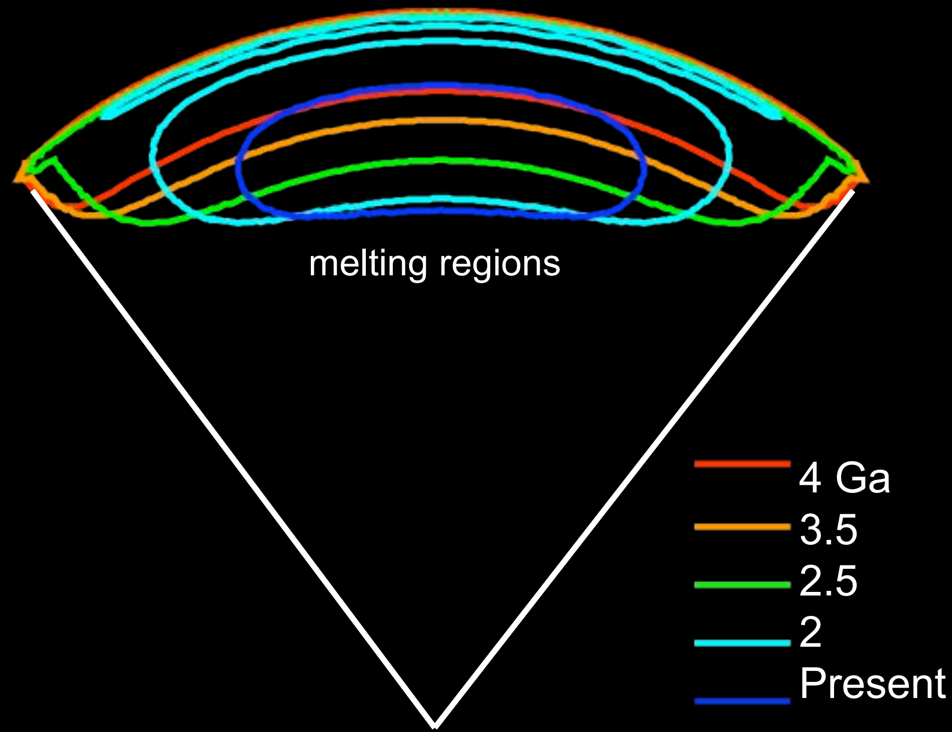


Mohit *et al.* [2008]
ER data from
Mitchell *et al.*, [2008]

♠ = Major antipode location

Asymmetry may arise from the shallow KREEP layer itself





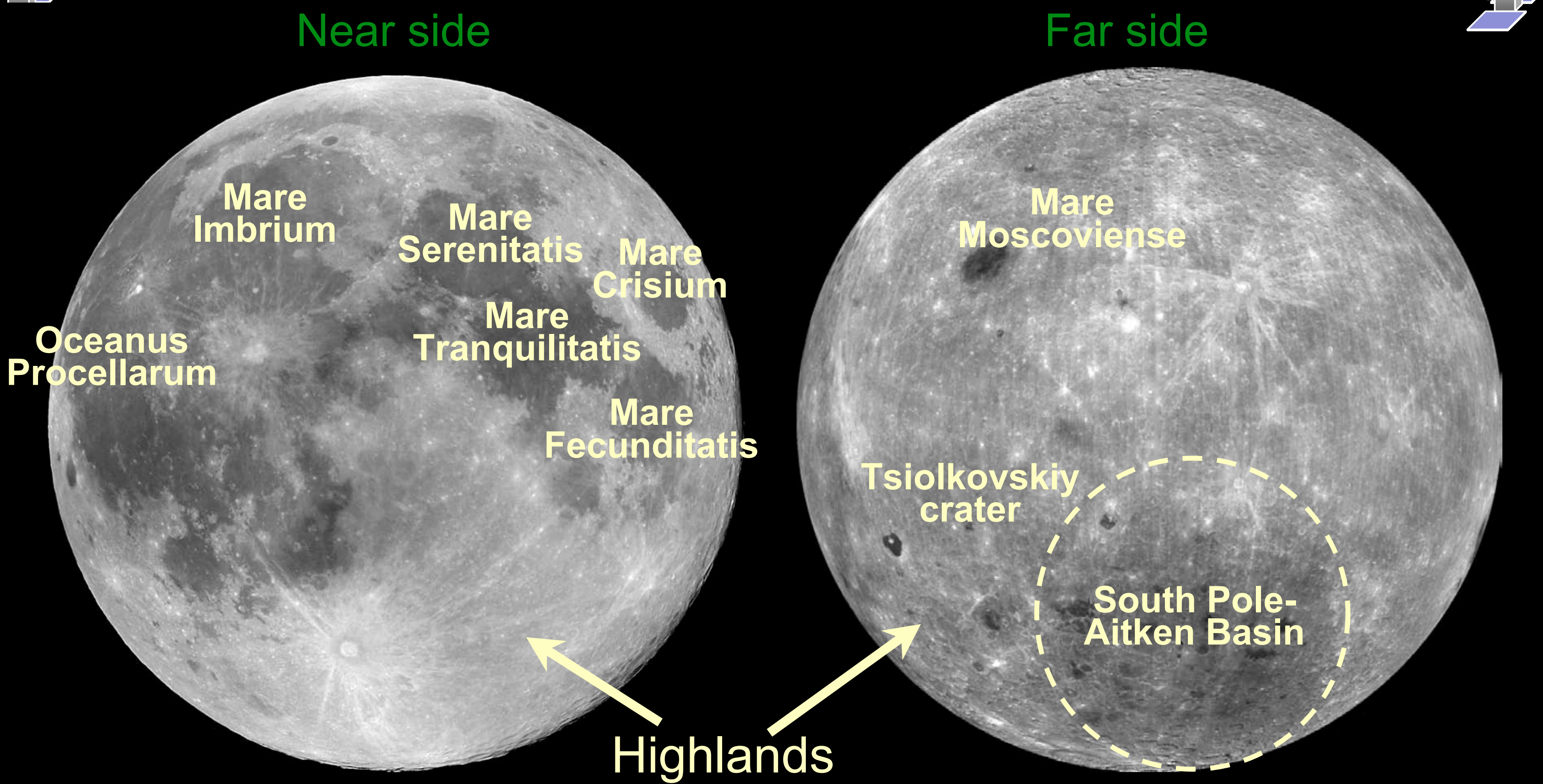
Wieczorek and Phillips [2000]

A thick KREEP layer in the PKT could heat and melt the underlying mantle to depths of about 500 km over several billion years.

Magnetic paleointensity: New view

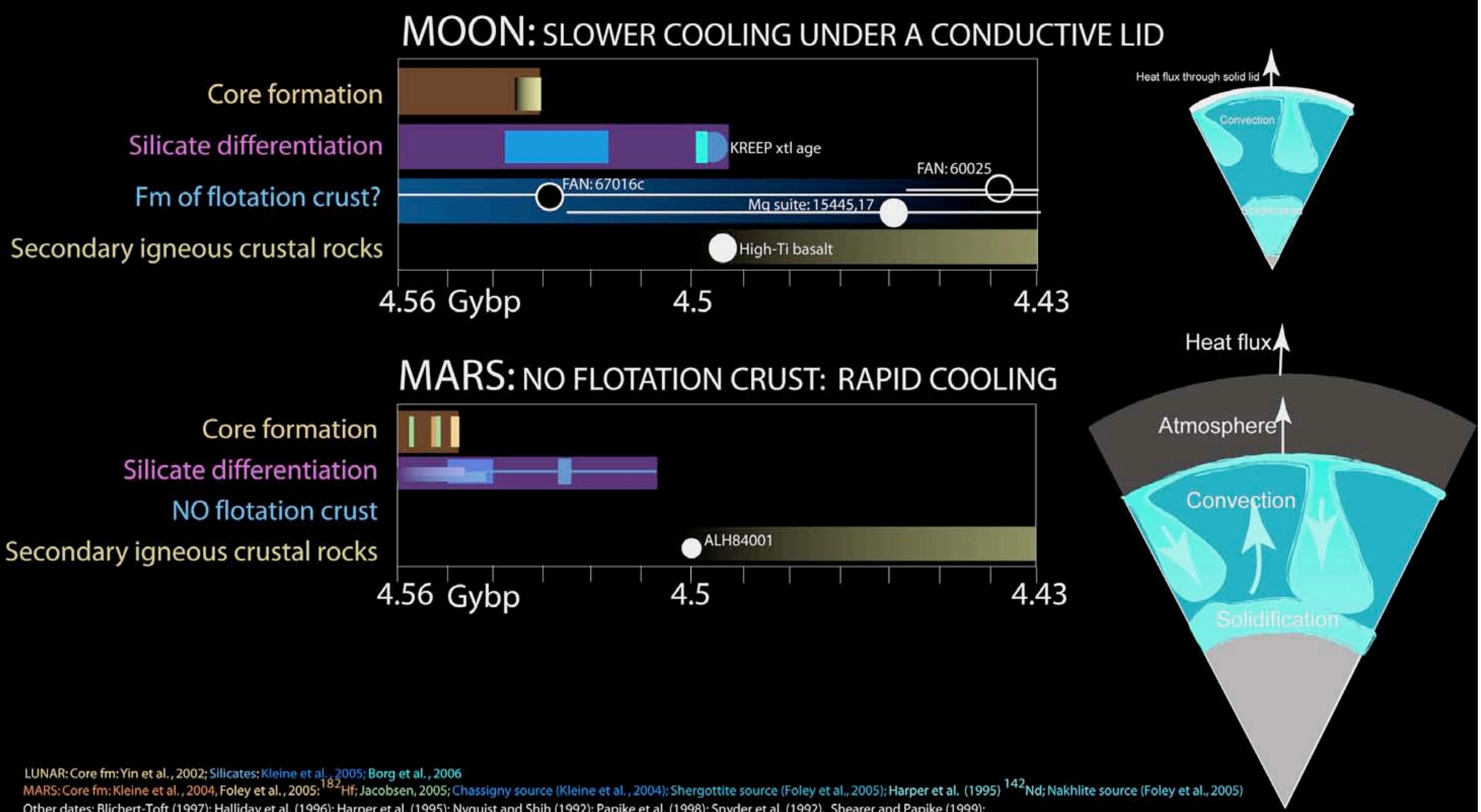
- Paleointensity measurements don't support a dynamo exclusive to 3.9-3.6 Ga. Hindrance by:
  - Limited number of samples
  - Variety and quality of paleointensity experiments
  - Ambiguous interpretation of complex paleointensity results
  - New measurements from pre-Late Heavy Bombardment (LHB)
  - Pre-LHB magnetic fields measured from orbit
- "There is not a single lunar paleointensity result (in this study or in the published literature) that passes the criteria of a successful and robust paleointensity experiment (relative or absolute) as applied to terrestrial samples." [*Lawrence et al*., 2008]
- Paleointensity magnitudes should be questioned, but not the existence of lunar remanent magnetization itself.

Distribution of mare basalts



Most mare basalts erupted on the nearside in Procellarum KREEP terrane.

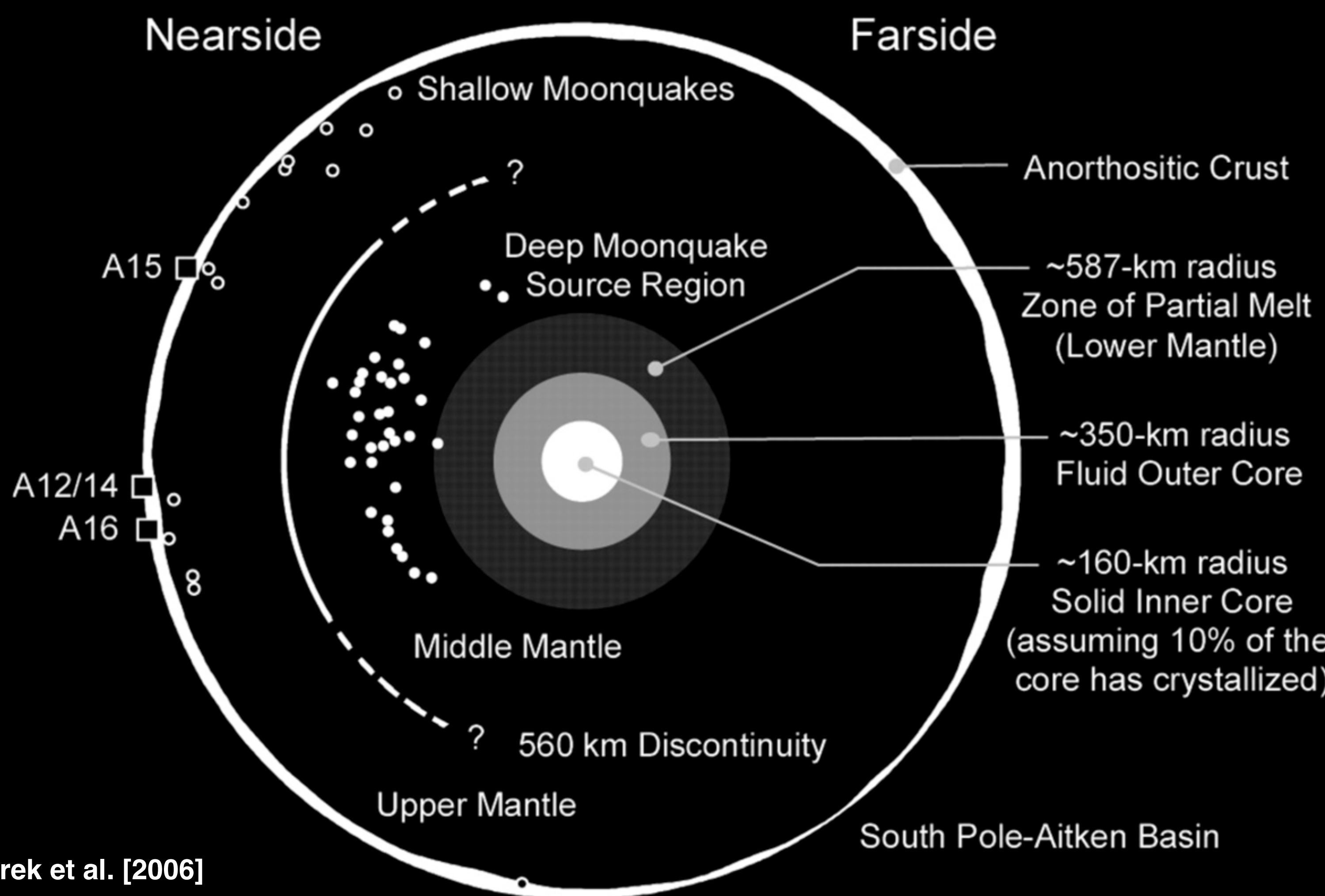
Comparative magma oceanography



LUNAR: Core fm: Yin et al., 2002; Silicates: Kleine et al., 2005; Borg et al., 2006
MARS: Core fm: Kleine et al., 2004, Foley et al., 2005: ^{182}Hf; Jacobsen, 2005; Chassigny source (Kleine et al., 2004); Shergottite source (Foley et al., 2005); Harper et al. (1995) ^{142}Nd; Nakhlite source (Foley et al., 2005)
Other dates: Blichert-Toft (1997); Halliday et al. (1996); Harper et al. (1995); Nyquist and Shih (1992); Papike et al. (1998); Snyder et al. (1992), Shearer and Papike (1999);

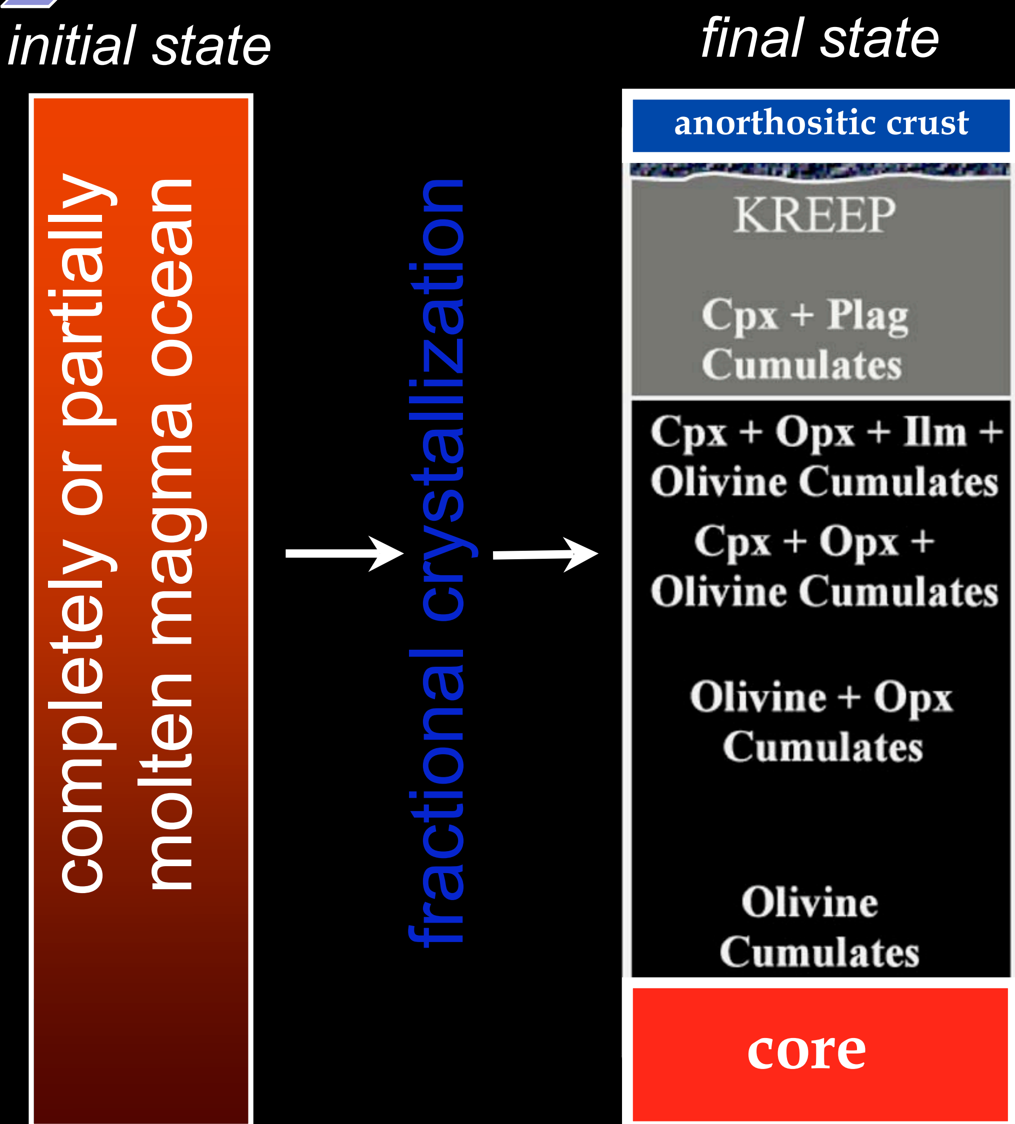
Elkins-Tanton [2008]

Notional view of lunar interior



Wieczorek et al. [2006]

Magma ocean crystallization: Nominal view

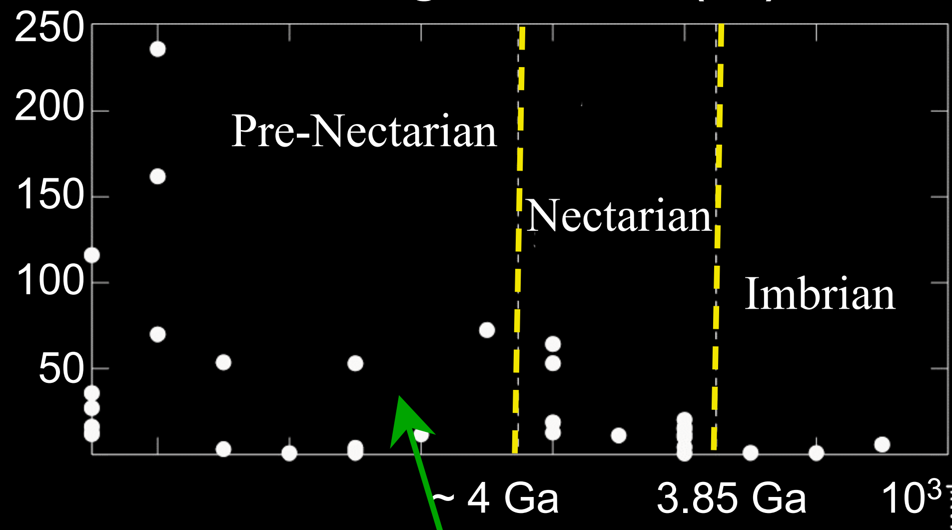


- First minerals to crystallize are Mg-rich olivines, which sink.
- As crystallization proceeds, cumulates become more iron rich, and dense.
- After ~75% crystallization, anorthite (plagioclase) begins to crystallize, and floats.
- Last liquids to crystallize are enriched in heat producing and incompatible elements (*i.e.*, KREEP), concentrated in western nearside.

Shearer et al. [2006]

Compare mapped field to paleointensity

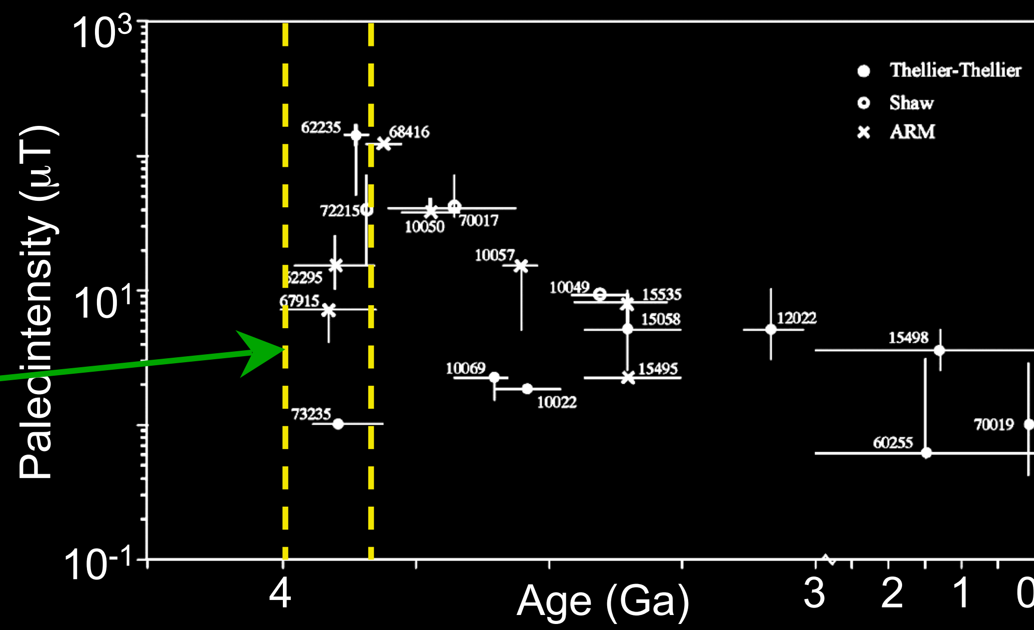
Peak magnetic Field (nT)



Mohit *et al.* [2008]
ER data from
Mitchell *et al*., [2008]

Reconciling remotely mapped field behavior within basins and paleointensities

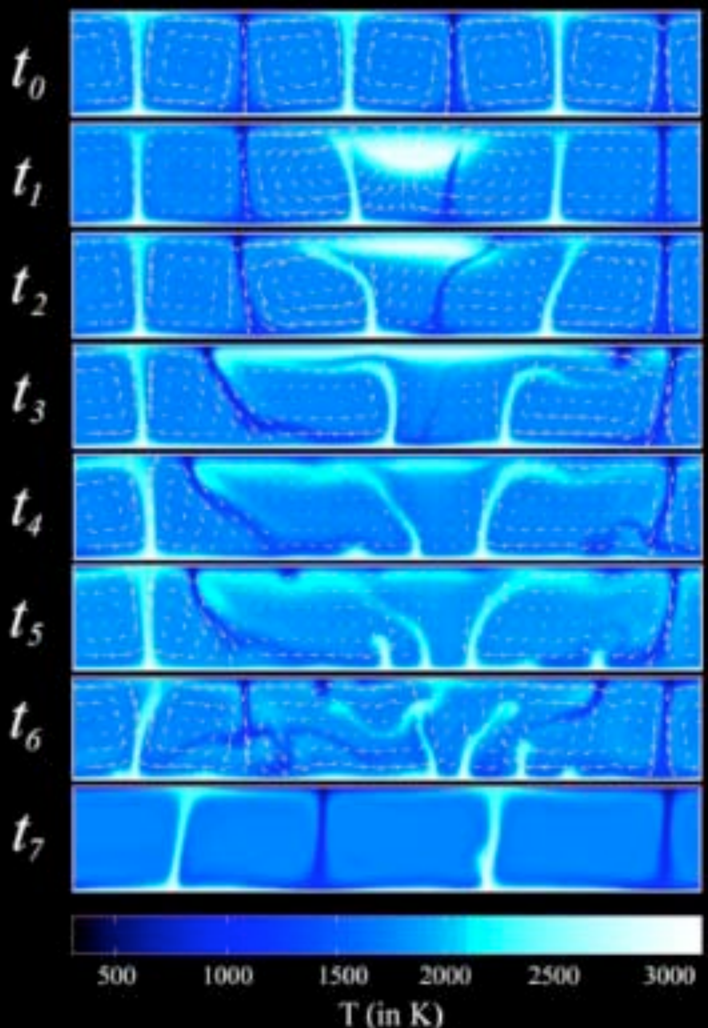
Paleointensity (µT)



New lab evidence for remanence before LHB [Garrick-Bethell et al., 2009]

Cisowski *et al.* [1983]

How did large impacts thermally perturb the mantle?

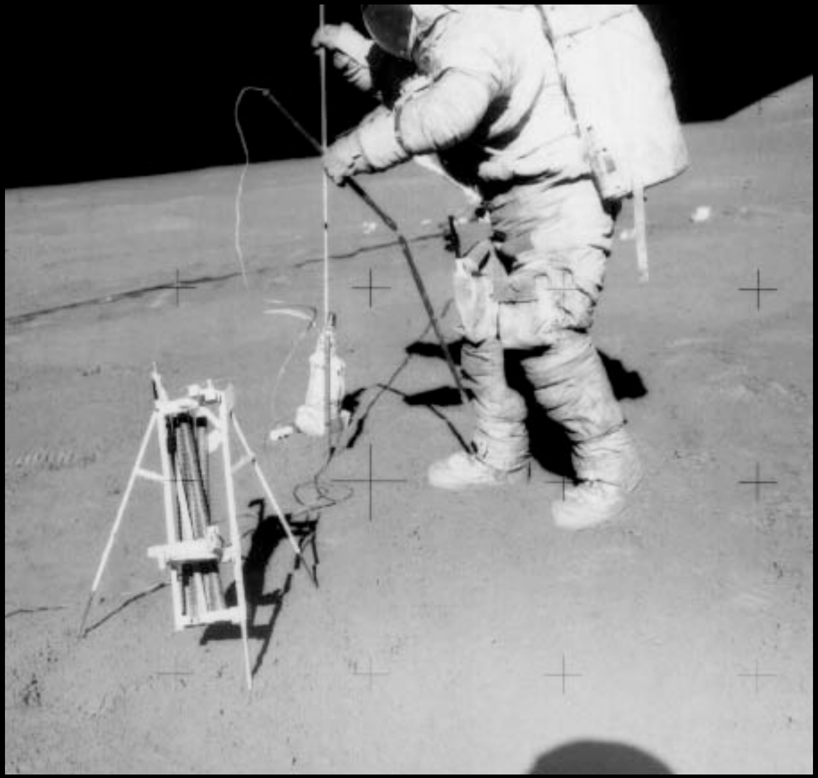


Watters, Zuber & Hager [2009]

- Major impacts heat crust & mantle and transmit heat into core.
- Plume formation favored beneath thermal anomaly.
- Chaotic convective period ensues.
- Enhanced surface volcanism throughout

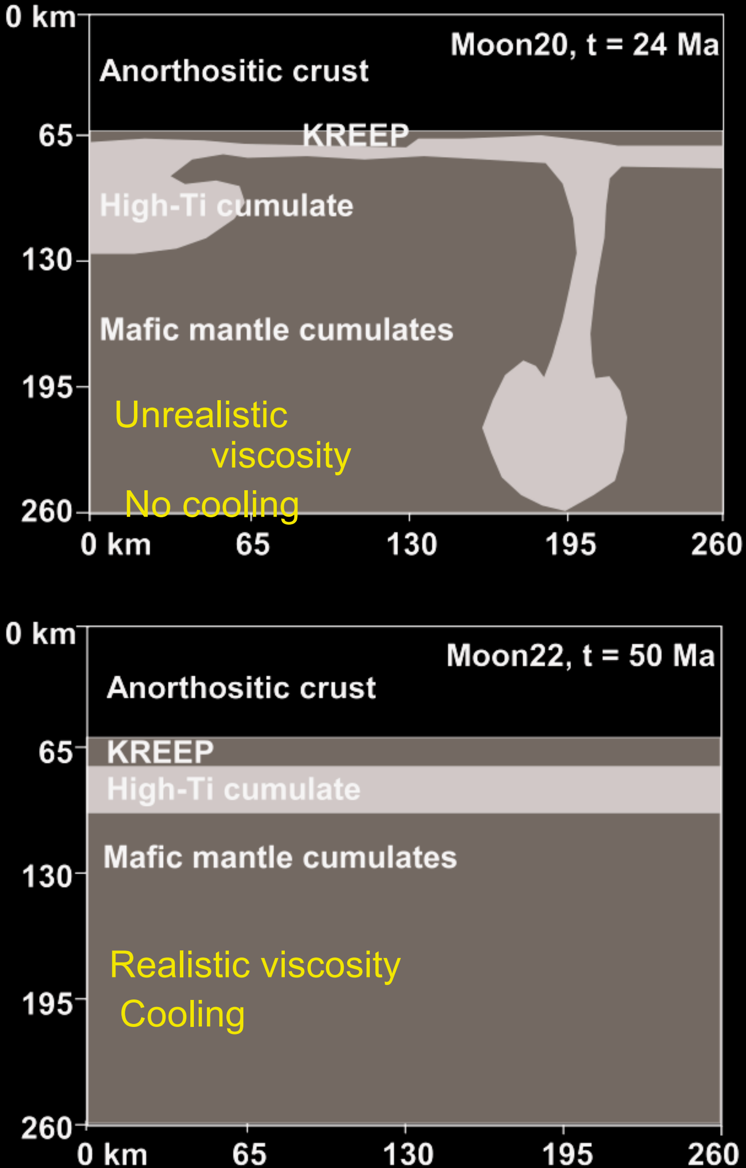
Lunar heat flow

- Interior heat flow provides key information on abundance of radiogenic elements and lunar thermal evolution.
- Astronauts made measurements at Apollo 15 and 17 sites.
- Using conductivity measurements based on the propagation of annual wave rather than from a heat pulse [Langseth et al., 1976] estimated heat flow values are 21 and 16 mWm^2 at Apollo 15 and 17, respectively.
- But heat flow measurements are affected by topography and subsurface heterogeneity; local effects about and many measurements in a locality are necessary to get a reliable estimate.



NASA/Apollo 15

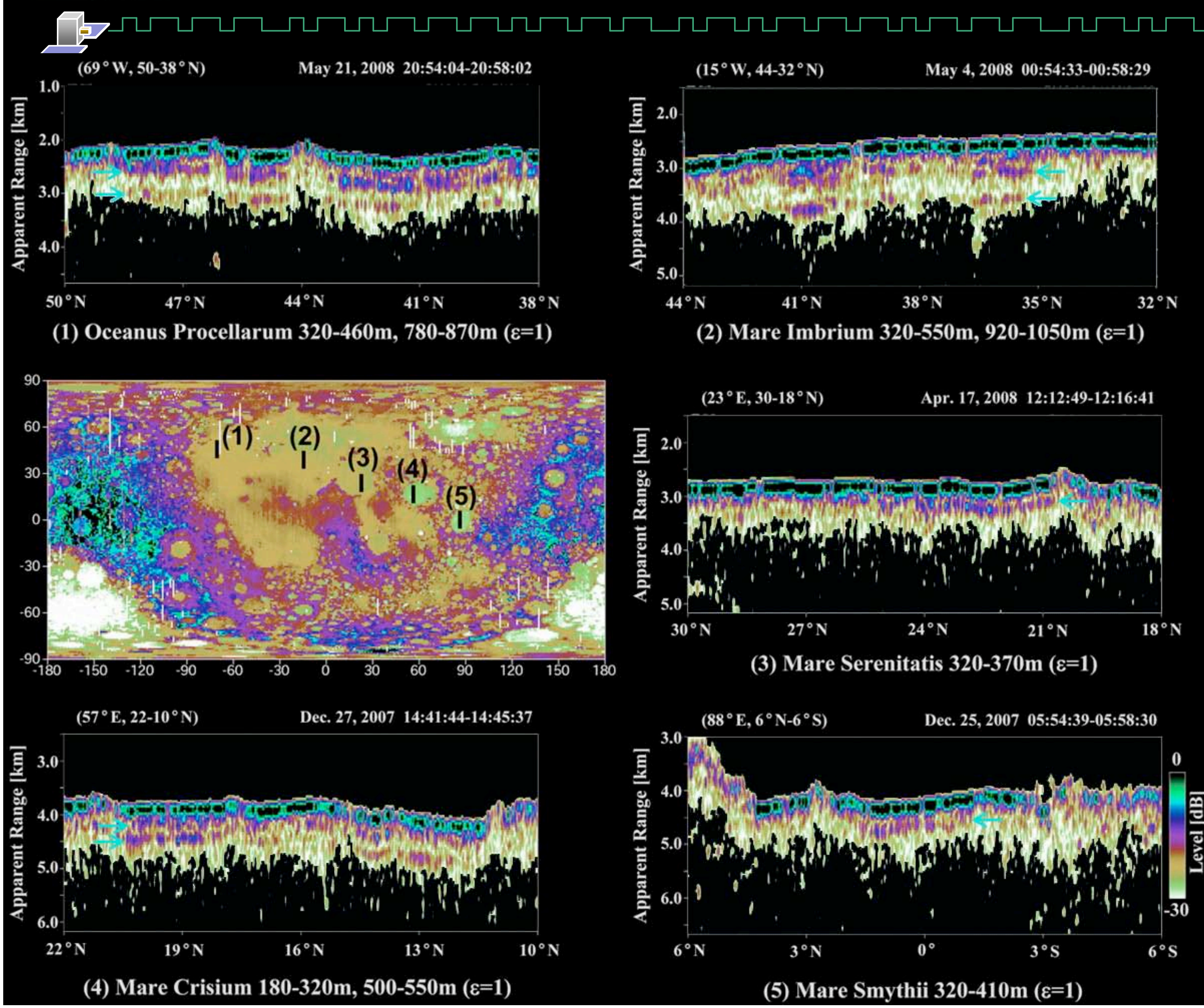
Sinking Hi-Ti cumulates is hard to do



- Under realistic thermals conditions and rheology, sinking of high-Ti cumulate layer is implausible.
- High-Ti material is required at shallower depths by ~3.5 Ga to create high-Ti mare basalts and picritic glasses.
- Sinking is possible if mixed w/ olivine to lower the viscosity.
- Remelting may led to negative buoyancy and shallow sinking, creating heterogeneous mantle.

Elkins-Tanton *et al*. [2002]

What is the distribution of regolith?

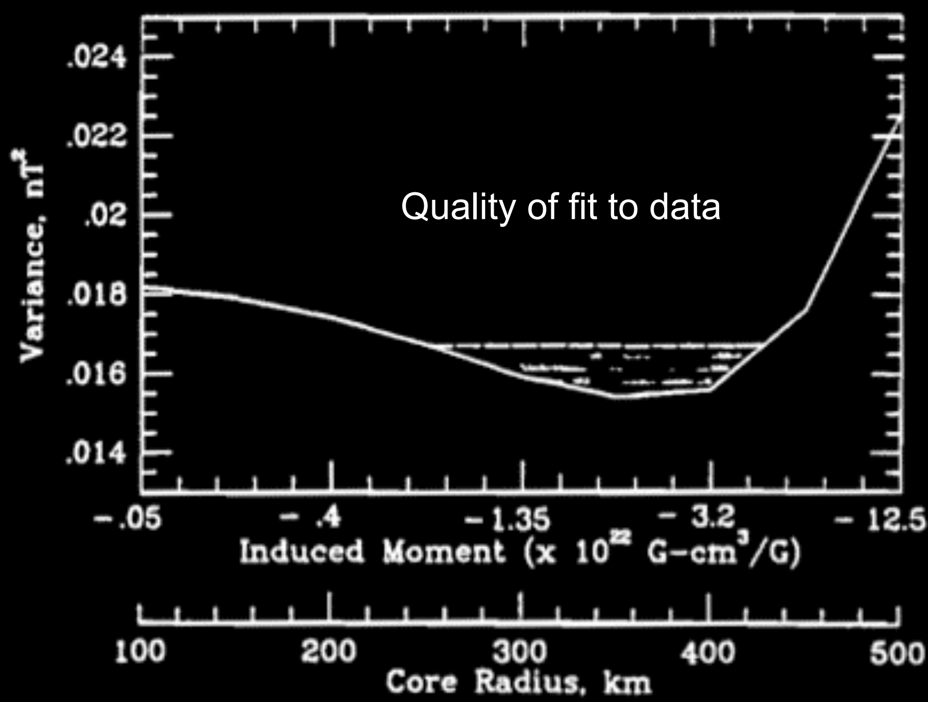


Elucidates interplay between bombardment & volcanism.

Ono et al. [2009]

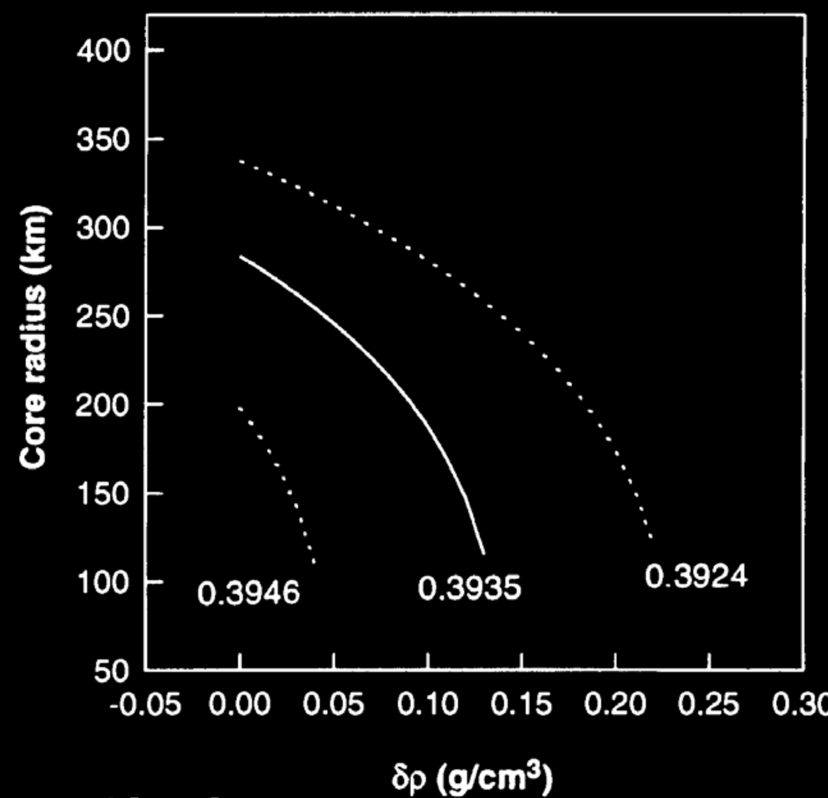
Deep interior: Evidence for core

Induced magnetic dipole moment



Hood *et al.* [1999]

Core radius vs. C/MR²



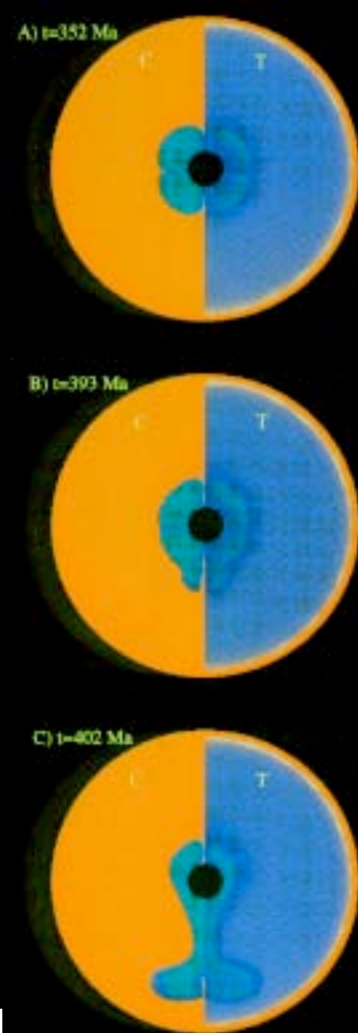
Dickey *et al.* [1994]

$C/MR^2 = 0.3940 \pm 0.0019$

$220 < R_{Max\_core} < 350$ km

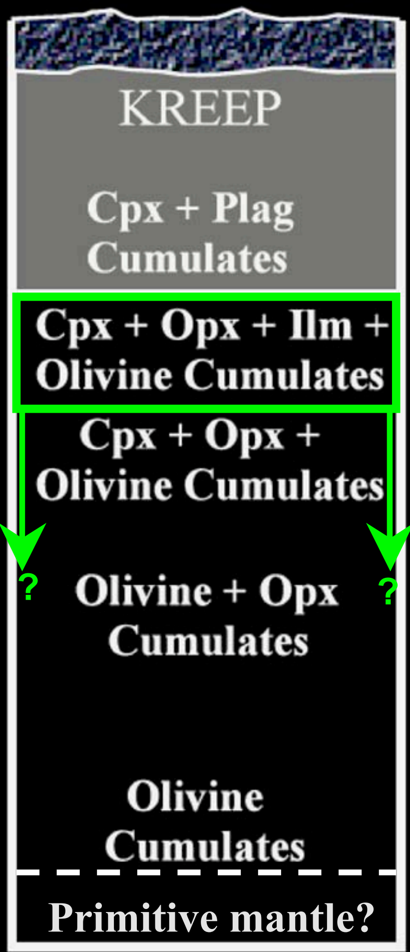
Possible explanations for asymmetry

- Nearside Procellarum Basin [Whitaker, 1981].
- Nearside concentration of KREEP basalt at end of magma ocean crystallization [*Wieczorek and Phillips*, 2000].
- First-degree pattern dominated instability of basal ilmenite-olivine-pyroxene cumulate layer [*Zhong et al*., 2000].

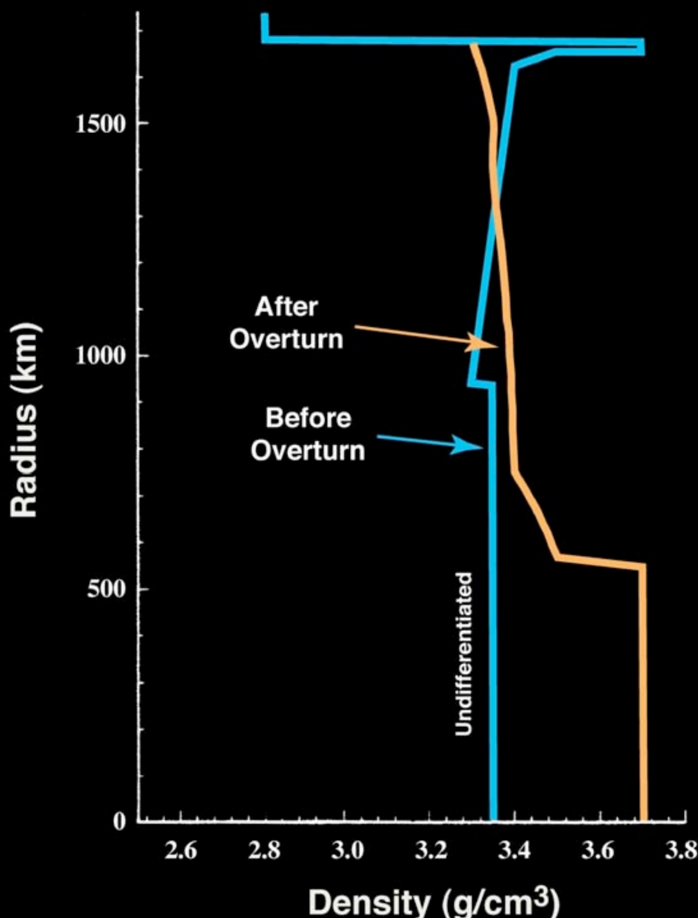


Zhong, Parmentier and Zuber [2000]

Did the mantle overturn?



Shearer *et al.* [2006]



Hess & Parmentier [1995]

- After magma-ocean crystallization, mantle is gravitationally unstable, with dense Fe/Ti-rich cumulates overlying Mg-rich cumulates.
- Mantle could have overturned bringing deep Mg-rich cumulates to upper mantle and sending Ti- and Fe-rich cumulates to the deep interior.