Recent re-analyses of the Apollo lunar seismic data: Insight into the Moon's deep interior

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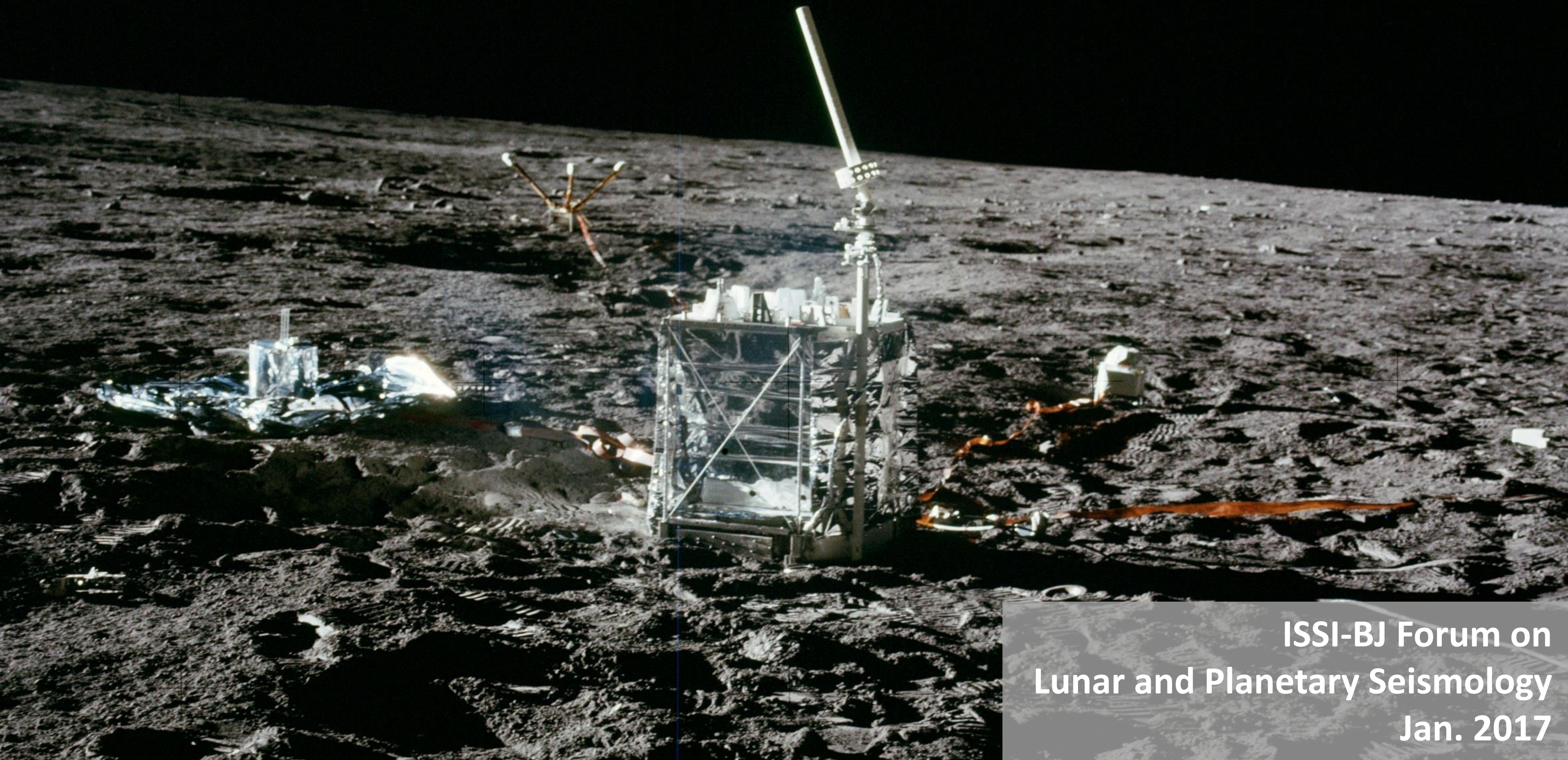

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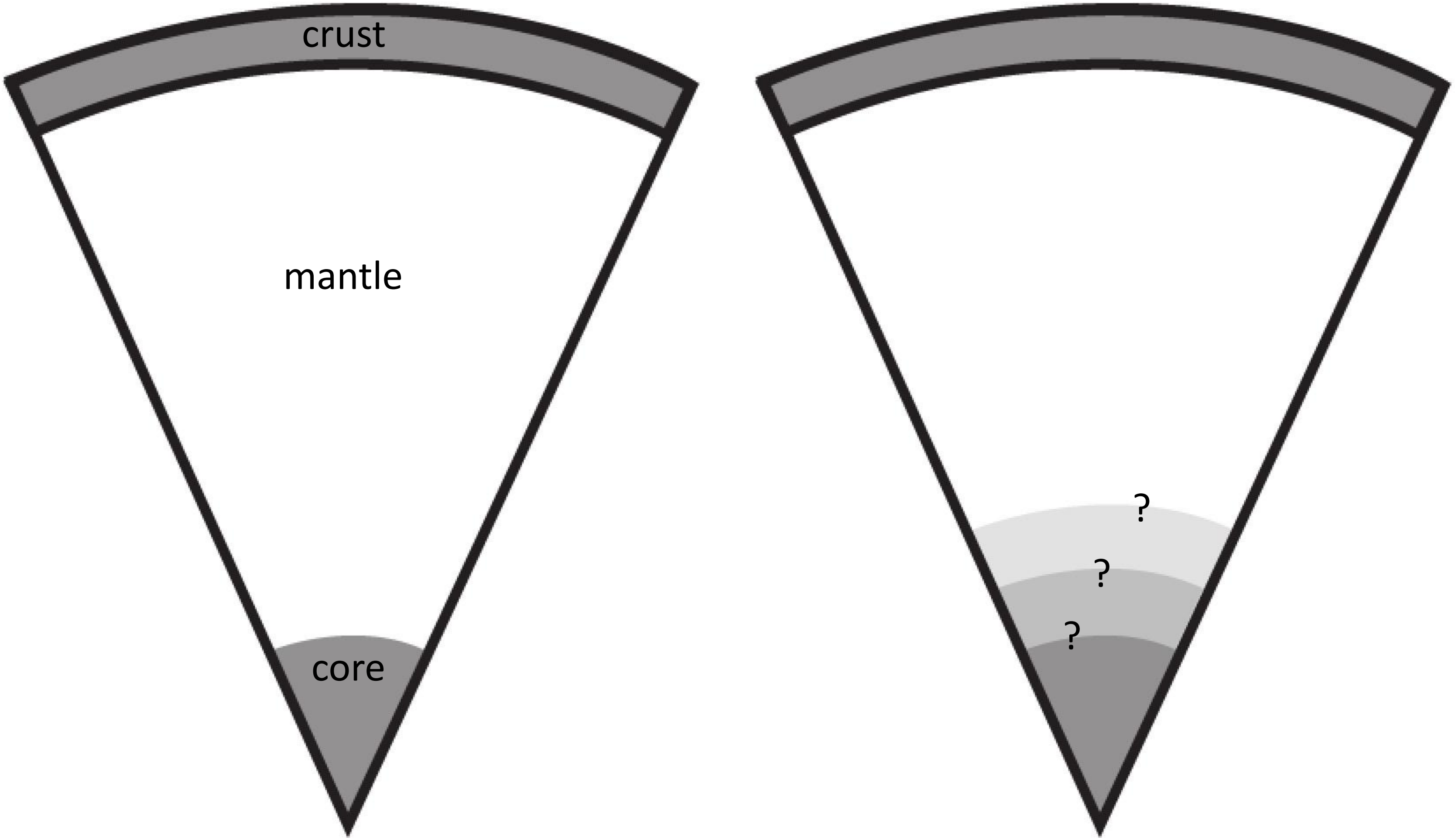
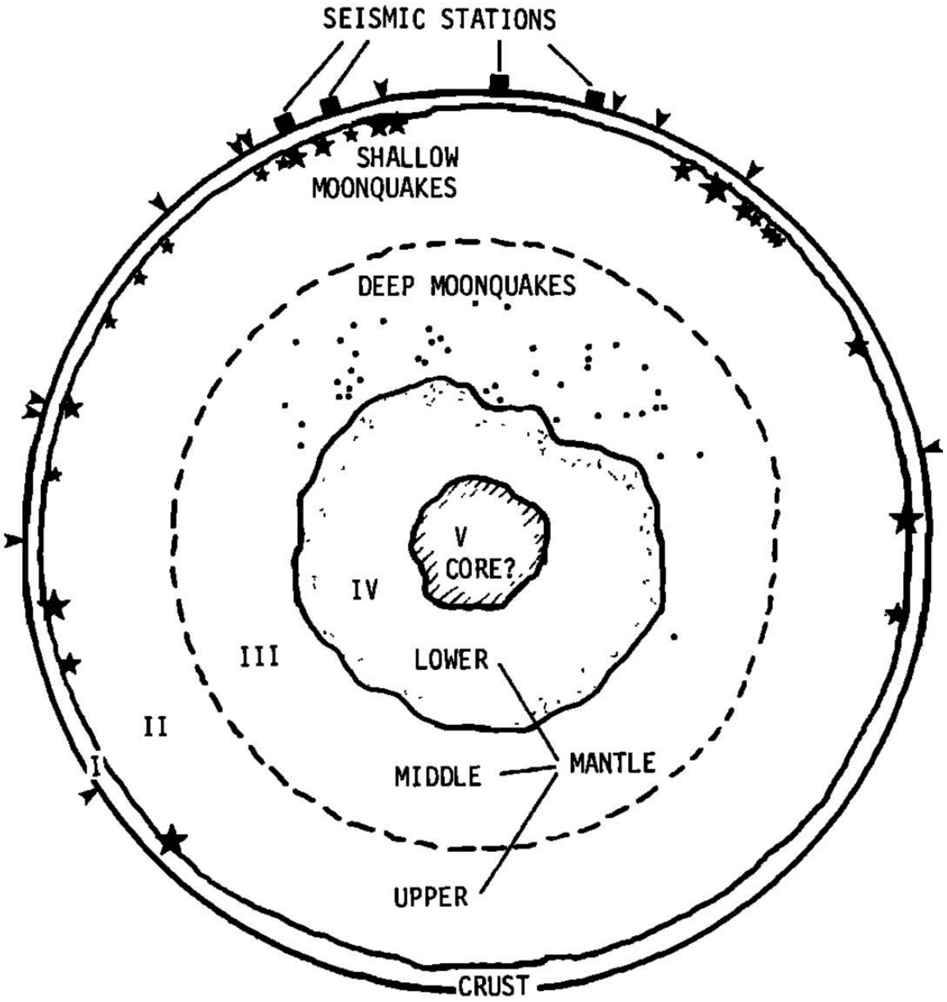
Understanding prior to re-analysis of Apollo data and the GRAIL lunar gravity mission

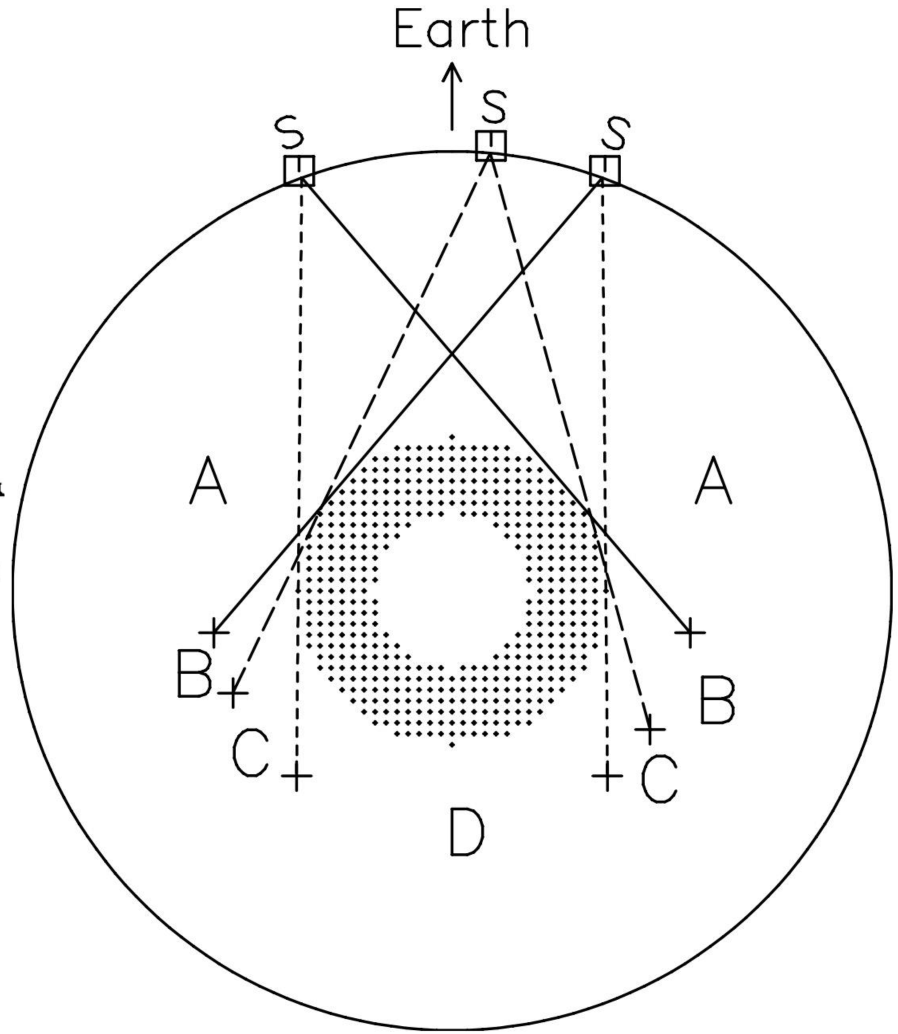
- Moon's moment of inertia roughly approximated by homogeneous sphere ($I_{solid}/MR^2 = 0.3930 \pm 0.0003$), so if a core is present, it must be small



Seismic measurements found…

- 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

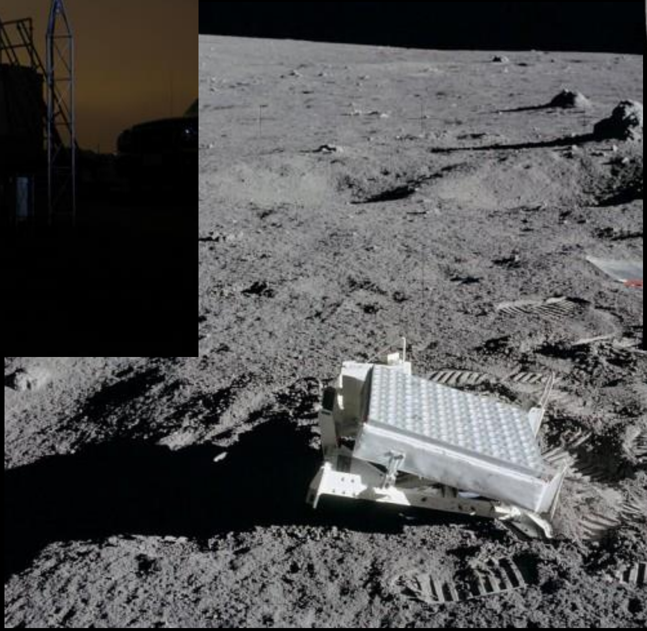


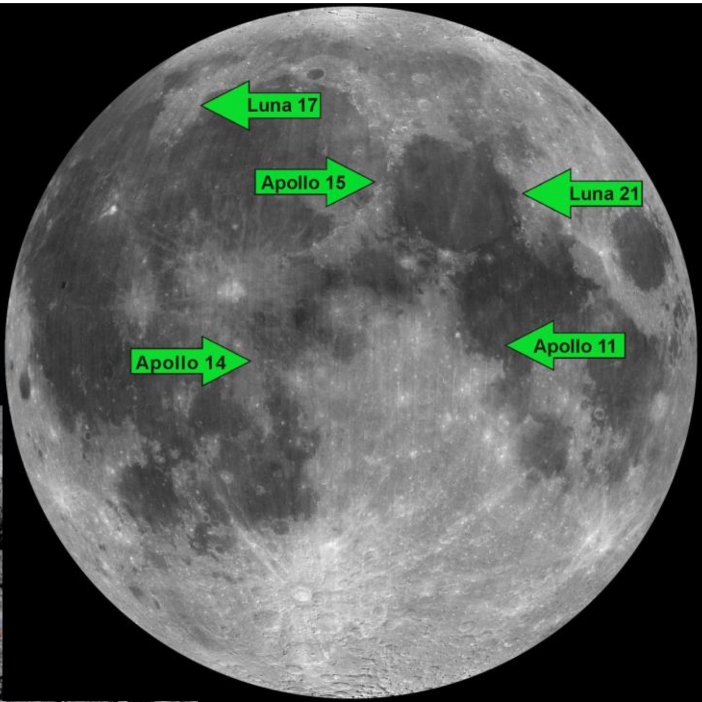


Indirect measurements found…

Lunar Laser Ranging (LLR):

- LLR began precise monitoring of the Moon’s geodetic parameters in 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

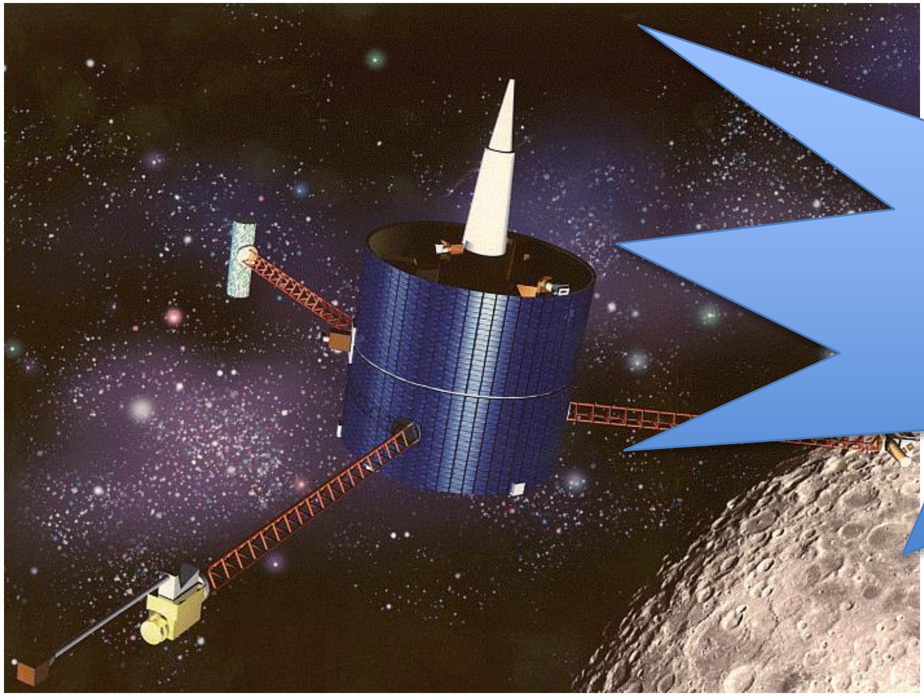


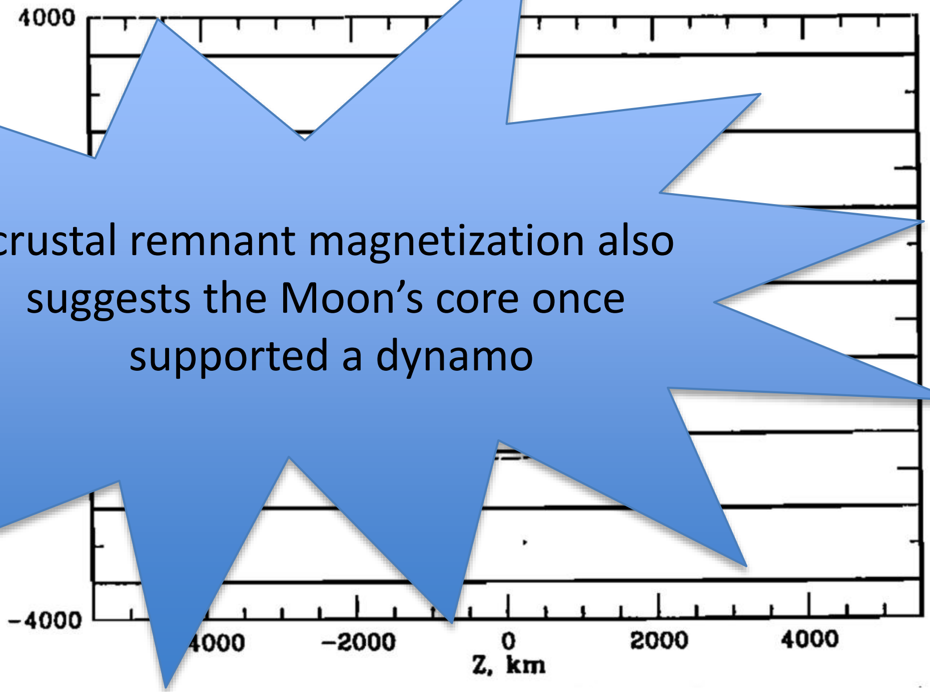


Indirect measurements found…

Magnetic Induction

- In April of 1998, the Lunar Prospector orbit plane was nearly parallel to the Sun-Moon line, optimally oriented for using the magnetometer to detect an induced moment in the Earth's geomagnetic tail
- Assuming that the induced field is caused entirely by electrical currents near the surface of a highly electrically conducting metallic core, the preferred core radius = 340+90 km.
- For an iron-rich composition such a core would represent 1 to 3% of the lunar mass





crustal remnant magnetization also suggests the Moon’s core once supported a dynamo

Indirect measurements found…

Compositional constraints:

- Over the past 30 years, estimates of siderophile (“metal-seeking”) elements in the lunar mantle have been used to argue for the presence of a small metallic core (0.1–5.5 lunar wt%)

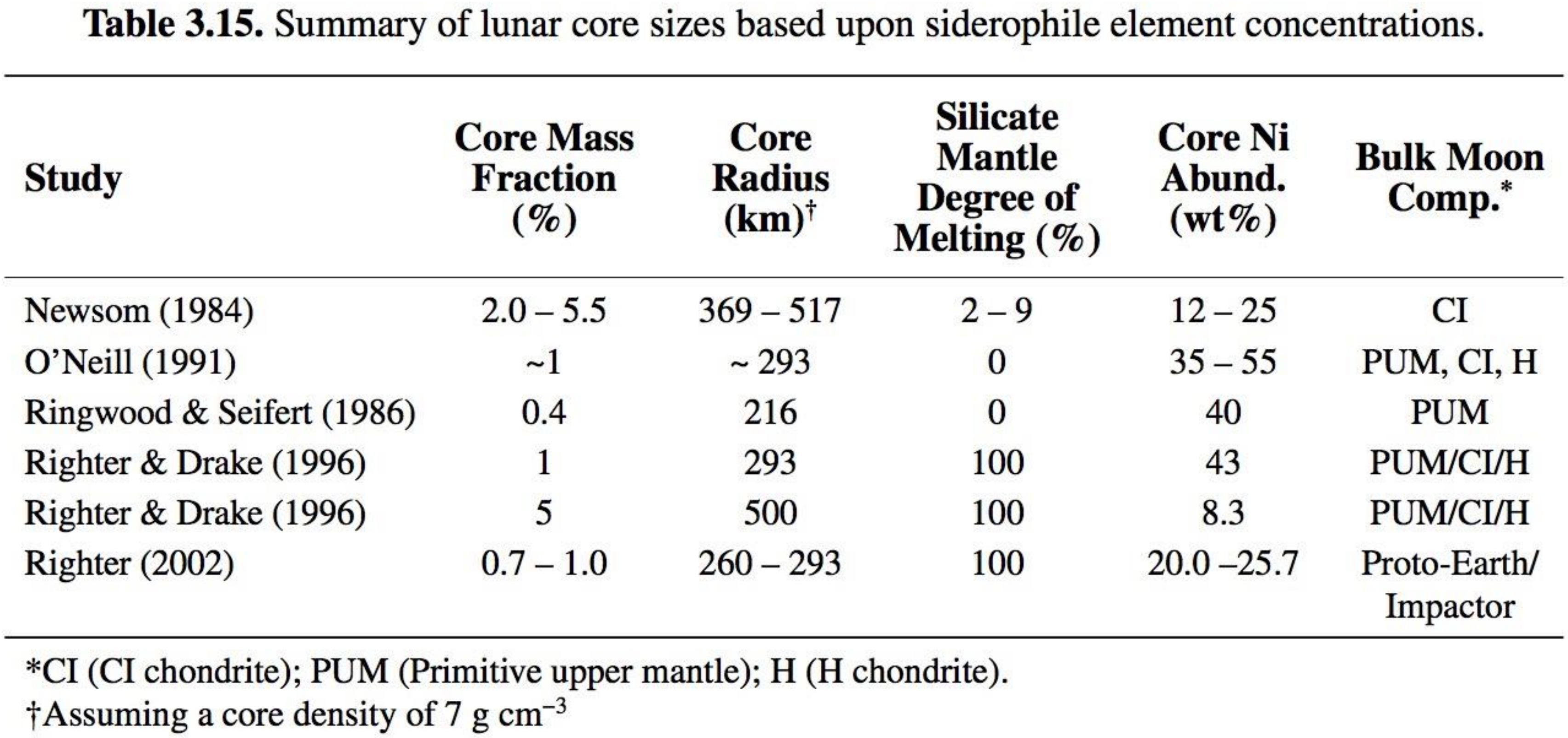


Table 3.15. Summary of lunar core sizes based upon siderophile element concentrations.

Study	Core Mass Fraction (%)	Core Radius (km)†	Silicate Mantle Degree of Melting (%)	Core Ni Abund. (wt%)	Bulk Moon Comp.*
Newsom (1984)	2.0 – 5.5	369 – 517	2 – 9	12 – 25	CI
O’Neill (1991)	~1	~ 293	0	35 – 55	PUM, CI, H
Ringwood & Seifert (1986)	0.4	216	0	40	PUM
Righter & Drake (1996)	1	293	100	43	PUM/CI/H
Righter & Drake (1996)	5	500	100	8.3	PUM/CI/H
Righter (2002)	0.7 – 1.0	260 – 293	100	20.0 –25.7	Proto-Earth/ Impactor

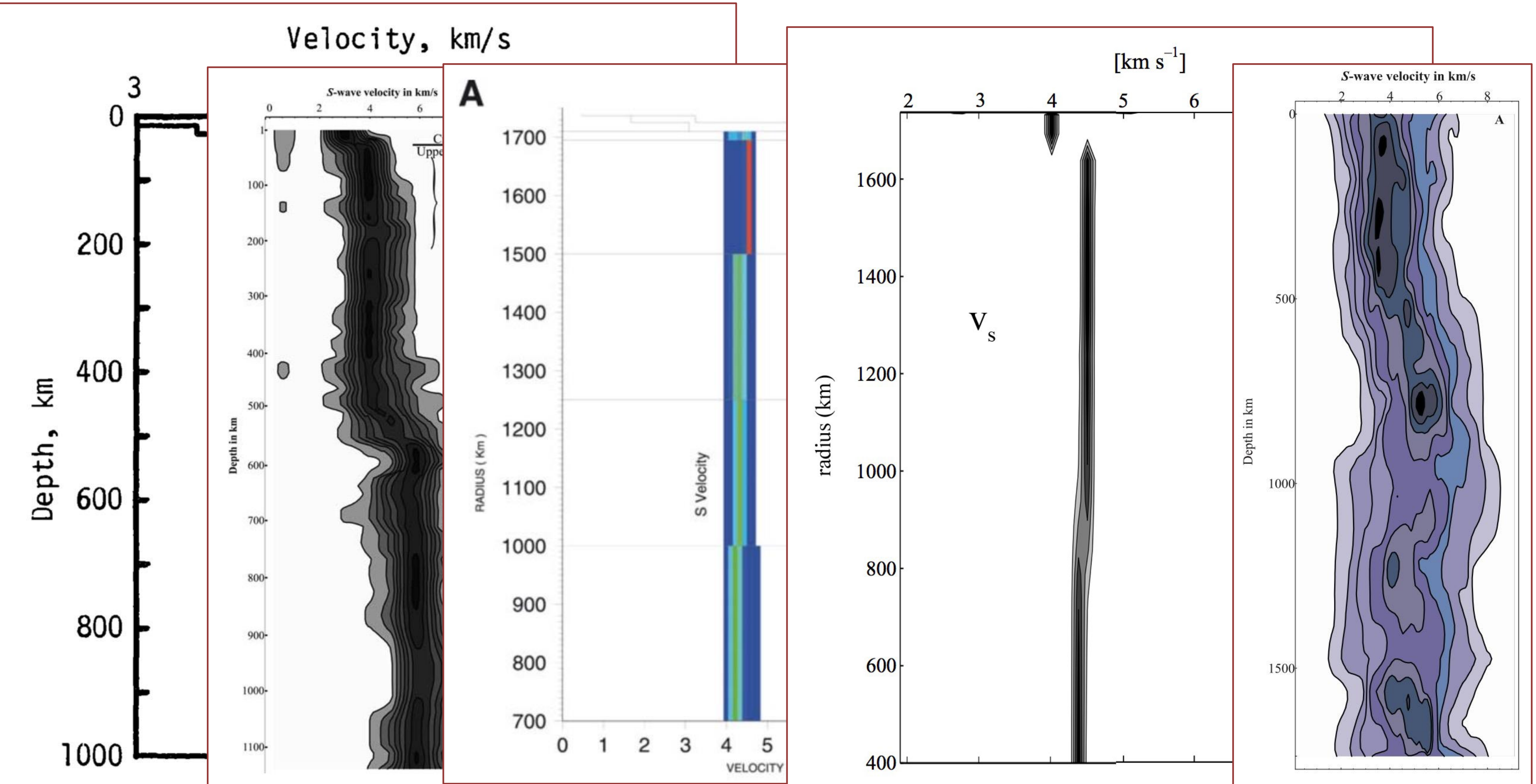
*CI (CI chondrite); PUM (Primitive upper mantle); H (H chondrite).
†Assuming a core density of 7 g cm^{-3}

Uncertainties are also evident in seismic velocity models

<u>seismic only:</u>
Nakamura 1983
Khan 2000, 2002
Lognonne 2003
Gagnepain-Beynix 2006

<u>joint seismic & gravity:</u>
Khan 2007

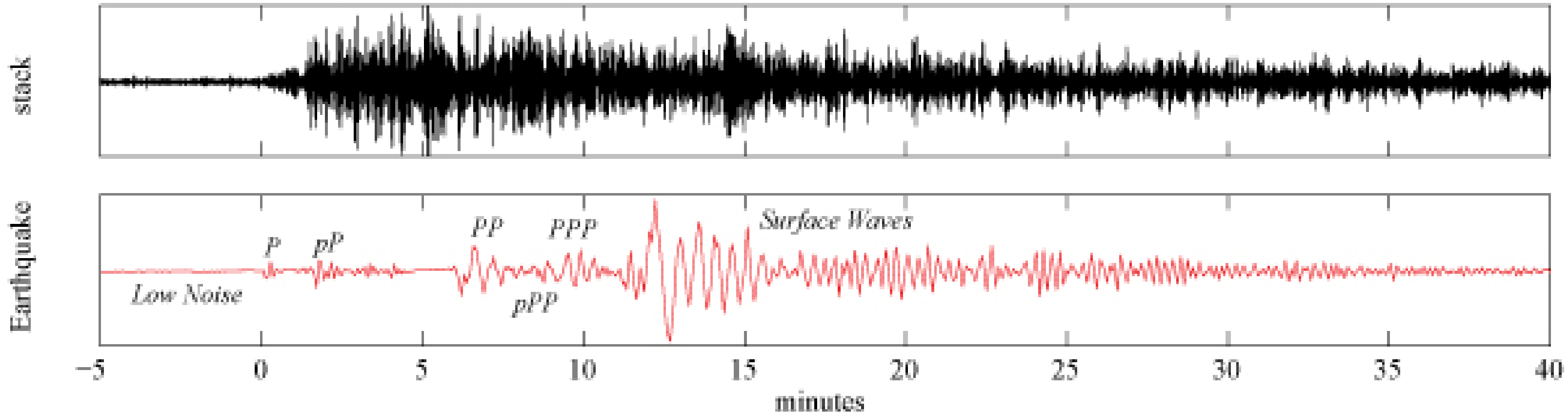
<u>free oscillations:</u>
Khan 2001



Uncertainties are also evident in seismic velocity models

sources of velocity uncertainty include:

- P and S pick error
  - Long-duration codas caused by the scattering and reverberations of seismic energy in the highly fractured lunar regolith, which leads to emergent, rather than impulsive arrivals.
  - Limited bandwidth of the Apollo instruments meant that many events occurred at or near the detection threshold of the instruments



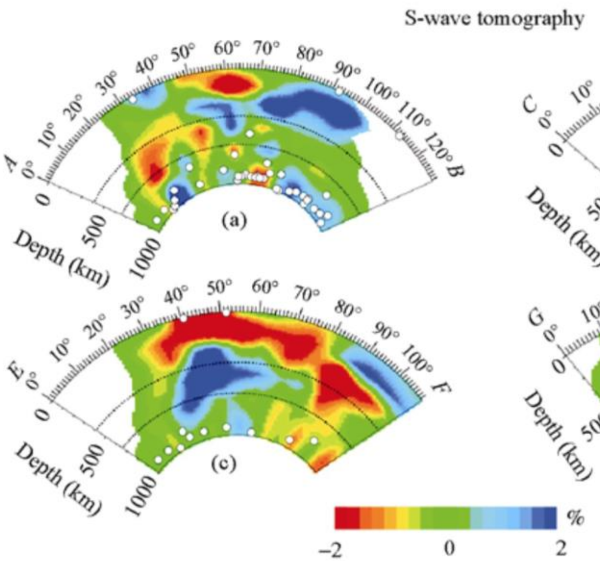
- Small number and limited geographical extent of seismic stations
- Depth and location uncertainty of moonquakes
- Assumed velocities in overlying layers

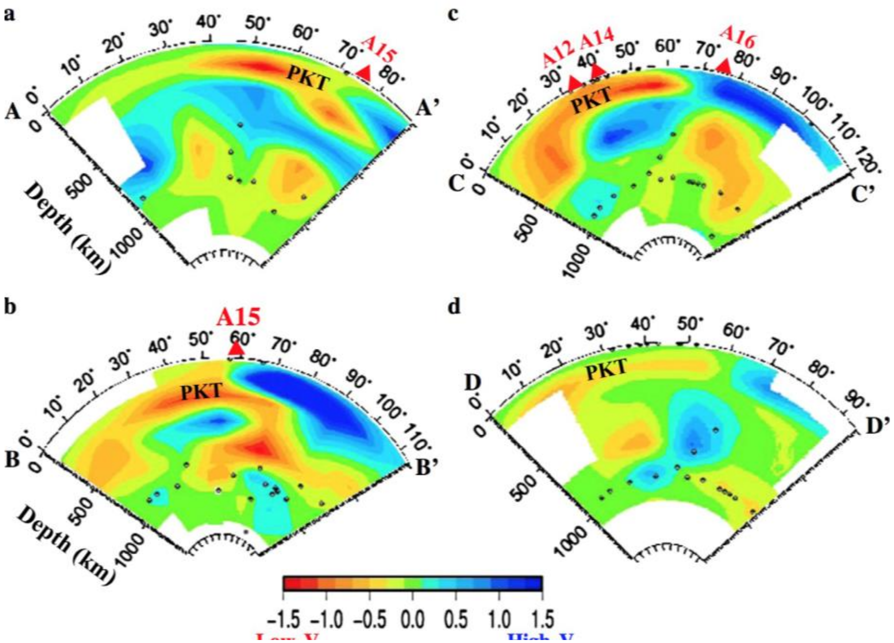
Error level:

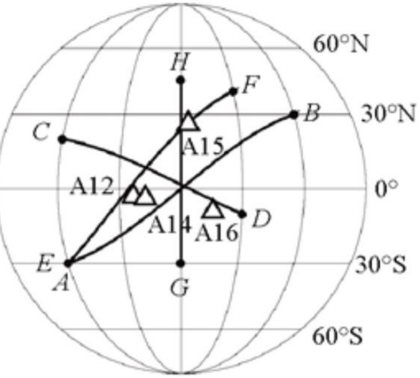
➢ Anywhere from 100 to several hundred m/s uncertainty in seismic velocities, the lower bound of which is on the threshold for mineralogical interpretations

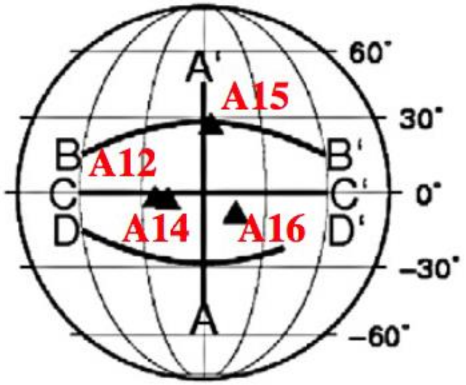
Some attempts at seismic tomography

- P- and S-wave arrivals from a variety of seismic signals are fit on a 3-D grid via velocity perturbations in the mantle and crust (Zhao et al., 2008 & 2012)



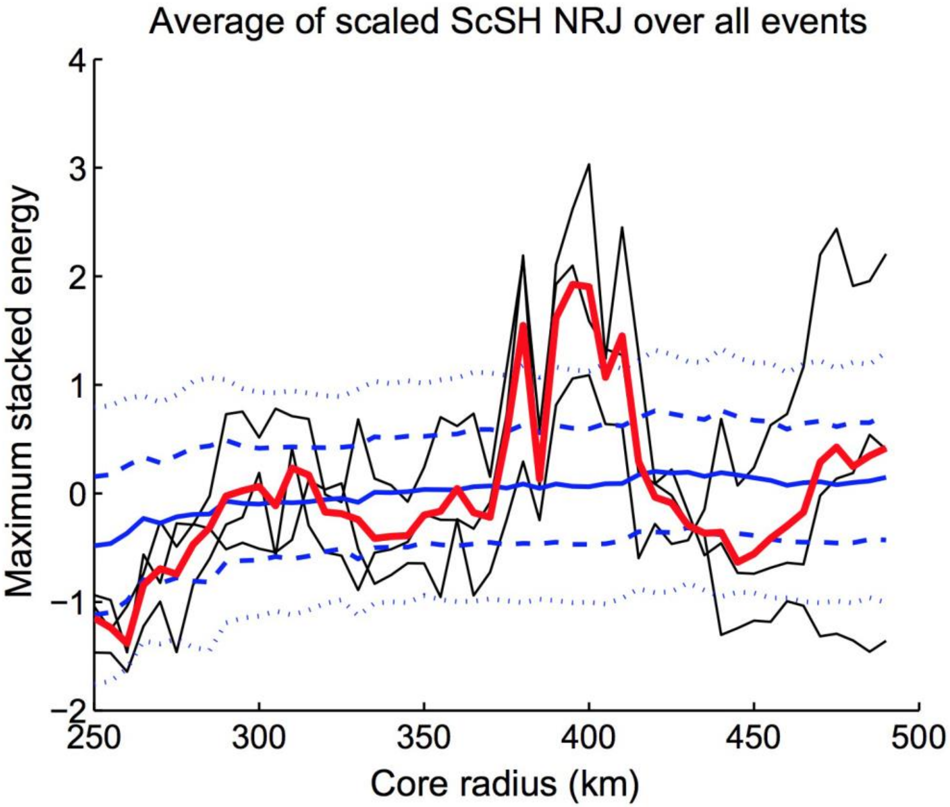


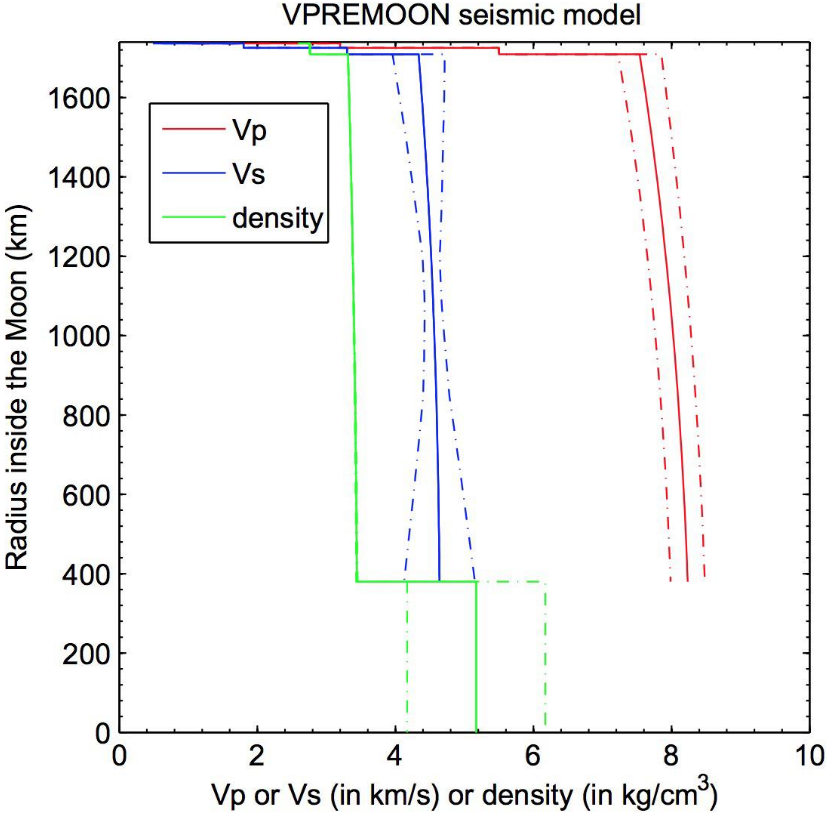




seismic models of the core based on recent re-analyses

Garcia et al., 2011

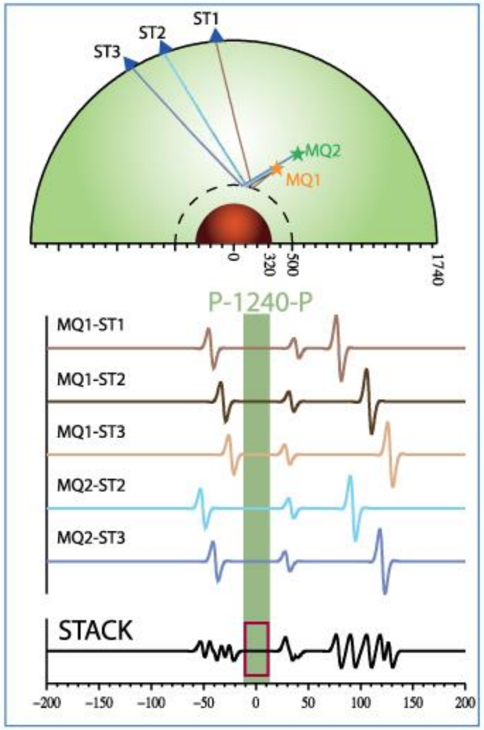


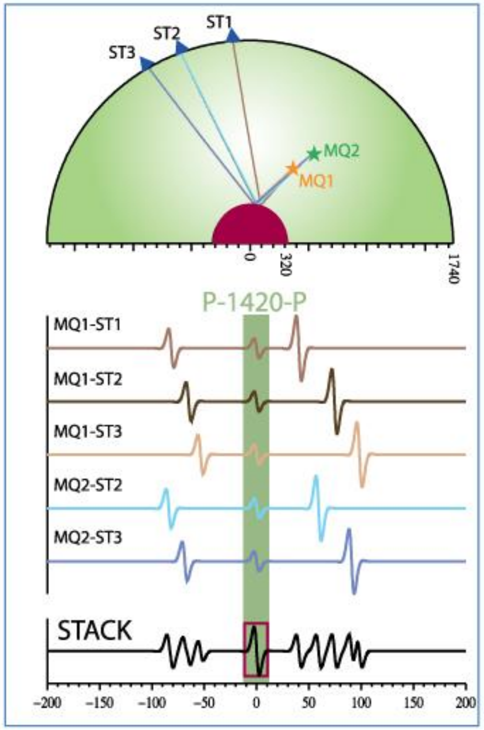


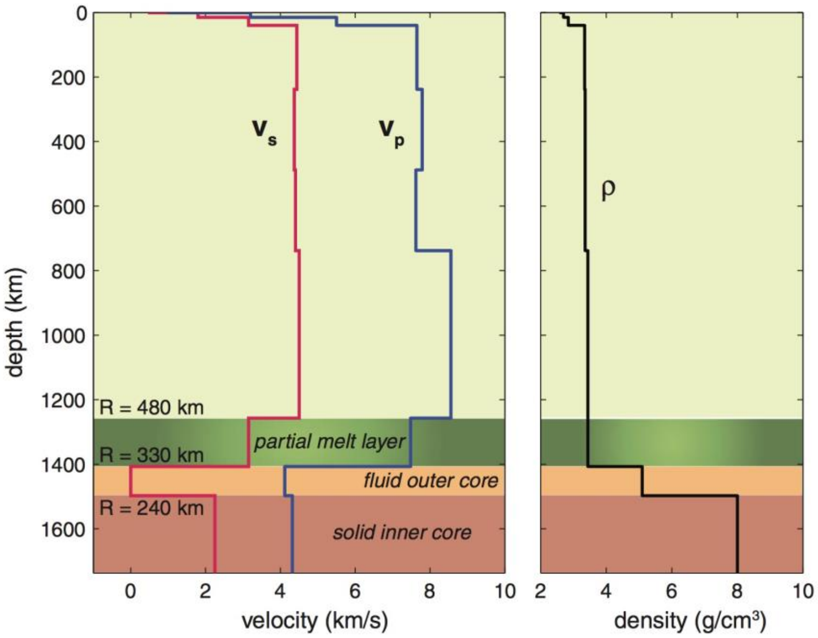
core radius = 380 ± 40 km

seismic models of the core based on recent re-analyses

Weber et al., 2011







core radius = 330 ± 20 km

GRAIL found…

Williams et al., 2014 family of core models consistent with geodetic parameters

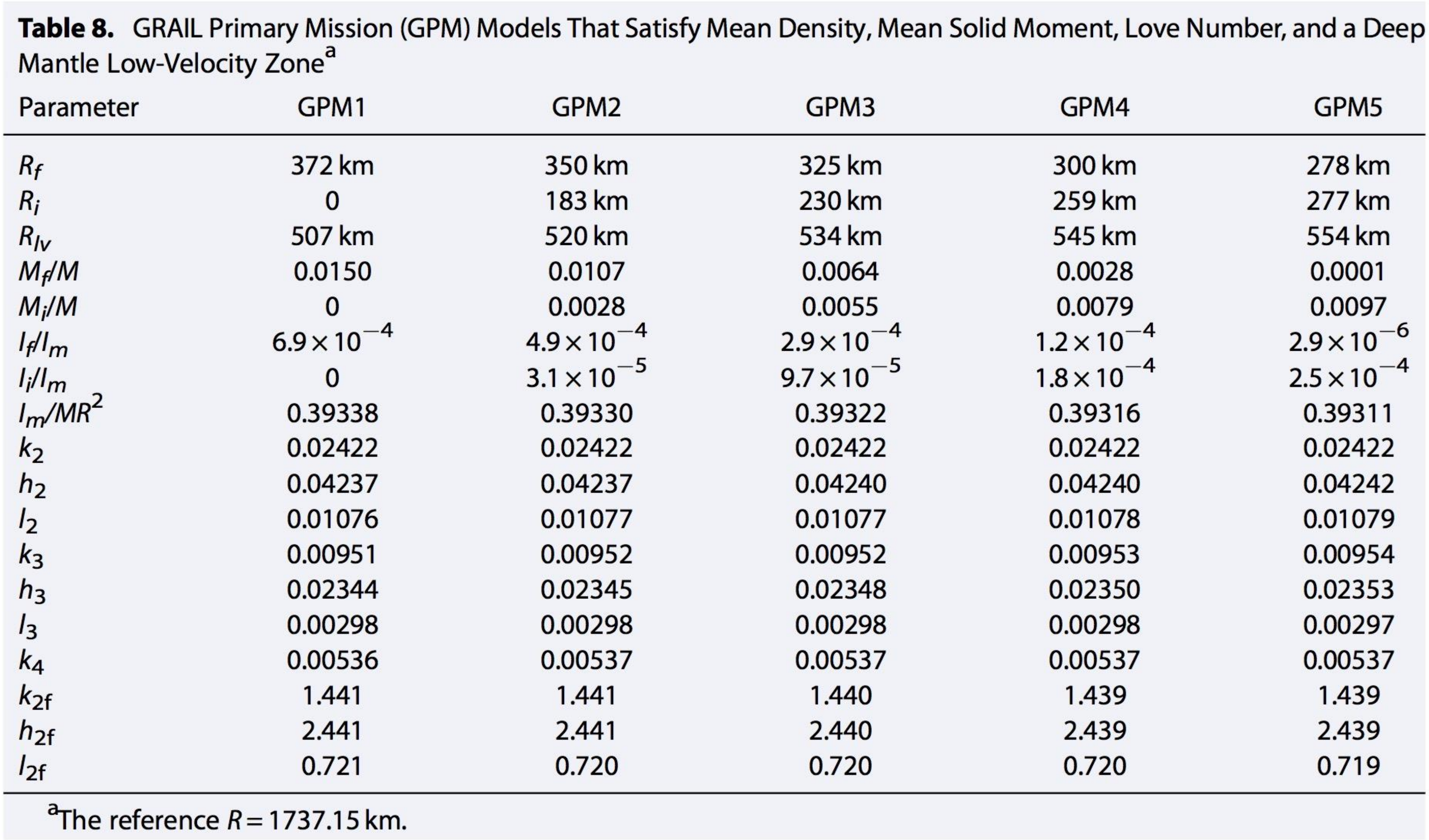


Table 8. GRAIL Primary Mission (GPM) Models That Satisfy Mean Density, Mean Solid Moment, Love Number, and a Deep Mantle Low-Velocity Zone[a]

Parameter	GPM1	GPM2	GPM3	GPM4	GPM5
R_f	372 km	350 km	325 km	300 km	278 km
R_i	0	183 km	230 km	259 km	277 km
R_{lv}	507 km	520 km	534 km	545 km	554 km
M_f/M	0.0150	0.0107	0.0064	0.0028	0.0001
M_i/M	0	0.0028	0.0055	0.0079	0.0097
I_f/I_m	6.9×10^{-4}	4.9×10^{-4}	2.9×10^{-4}	1.2×10^{-4}	2.9×10^{-6}
I_i/I_m	0	3.1×10^{-5}	9.7×10^{-5}	1.8×10^{-4}	2.5×10^{-4}
I_m/MR^2	0.39338	0.39330	0.39322	0.39316	0.39311
k_2	0.02422	0.02422	0.02422	0.02422	0.02422
h_2	0.04237	0.04237	0.04240	0.04240	0.04242
l_2	0.01076	0.01077	0.01077	0.01078	0.01079
k_3	0.00951	0.00952	0.00952	0.00953	0.00954
h_3	0.02344	0.02345	0.02348	0.02350	0.02353
l_3	0.00298	0.00298	0.00298	0.00298	0.00297
k_4	0.00536	0.00537	0.00537	0.00537	0.00537
$k_{2\mathrm{f}}$	1.441	1.441	1.440	1.439	1.439
$h_{2\mathrm{f}}$	2.441	2.441	2.440	2.439	2.439
$l_{2\mathrm{f}}$	0.721	0.720	0.720	0.720	0.719

[a] The reference $R = 1737.15$ km.

Is a partial melt layer required?

yes:

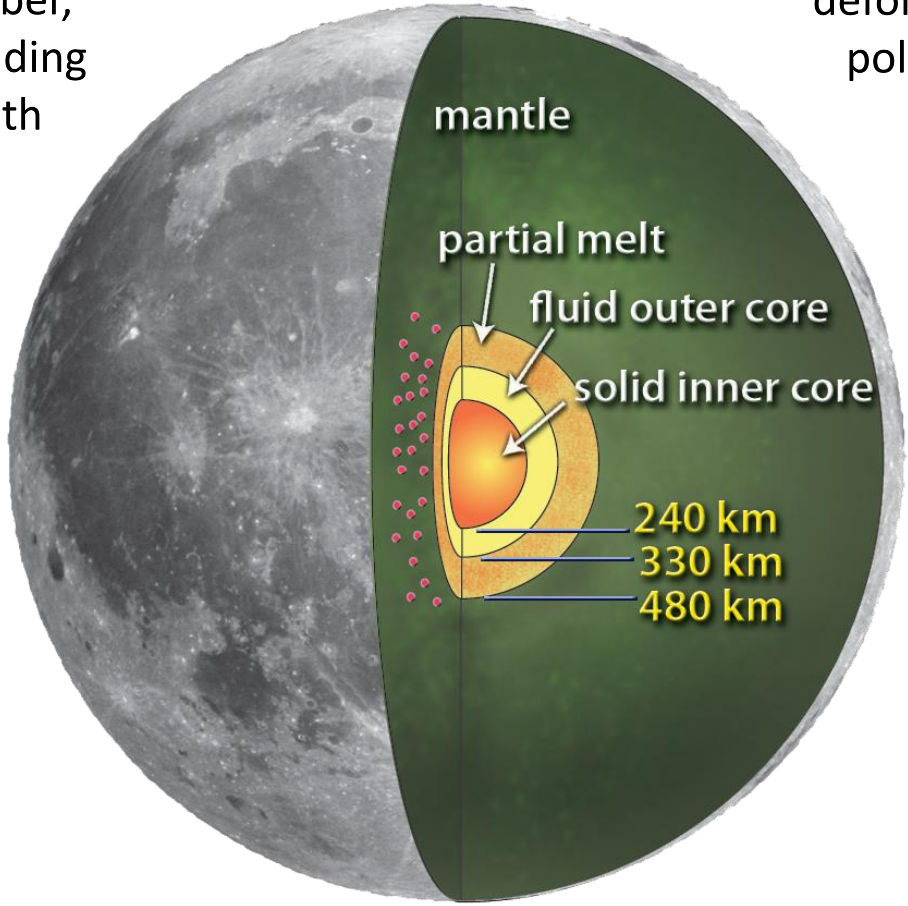
Khan et al., 2014

Inversion of lunar geophysical data (mean mass and moment of inertia, tidal Love number, and electromagnetic sounding data) in combination with phase-equilibrium computations

no:

Nimmo et al., 2012

viscoelastic dissipation model based on laboratory deformation of melt-free polycrystalline olivine



how to reduce uncertainty?

topic of presentation by R. Garcia