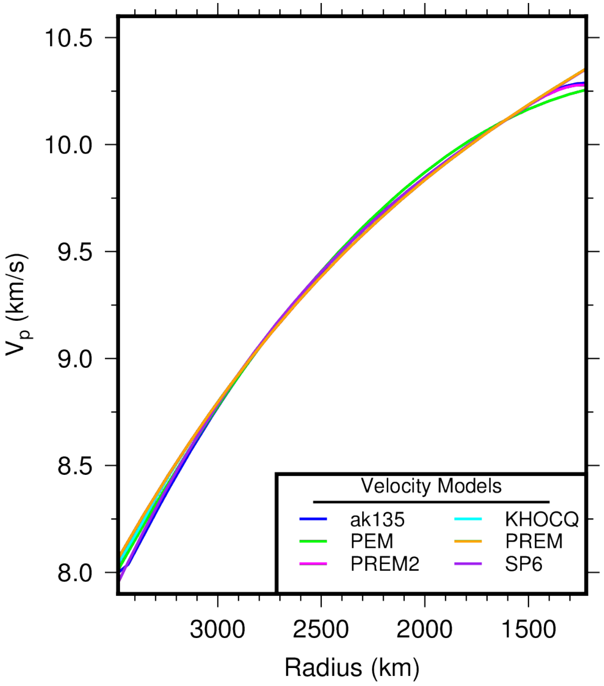
Behavior at the boundaries of our world: What can we learn about core and mantle dynamics from long and short period seismology?

Jessica C. E. Irving, Alex Burky & Frederik Simons, Princeton University
Sanne Cottaar, University of Cambridge; Vedran Lekić, University of Maryland
Wenbo Wu, Caltech; Sidao Ni, Chinese Academy of Sciences, Wuhan

JCEI acknowledges support from the NSF

Earth's outer core



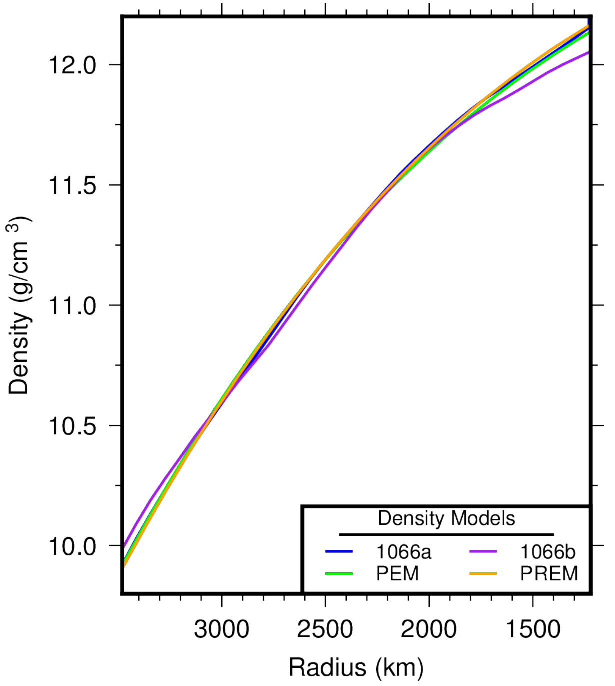
Velocity models published 1975–2010. Based on modes & body waves, or body waves alone.

Important role in Earth's dynamics:

- Generation of the geodynamo;
- Provides heat to the mantle – part of the power source for plate tectonics.
- Is there stratification at the top? If so, <u>why</u>, <u>when</u> and <u>how</u>?

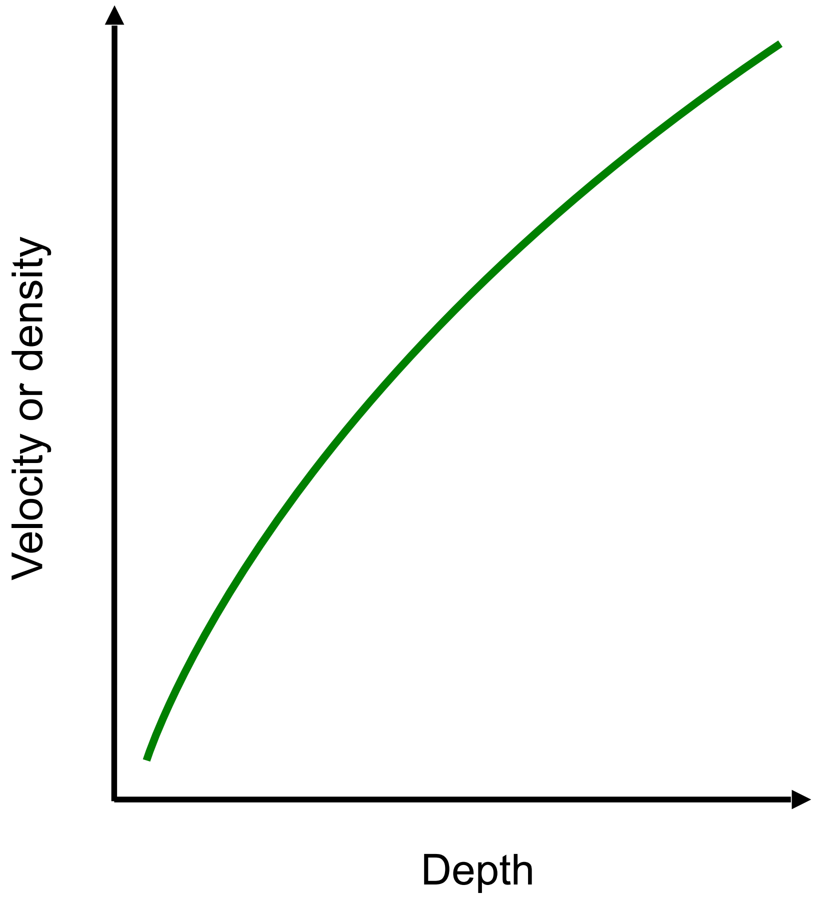
Existing seismological models of the outer core are not perfect. They are:

- Parameterized for simplicity, not grounded in physics;
- Based on older data;
- Show disagreement between body wave and normal mode based models;
- Therefore less useful for other scientists.



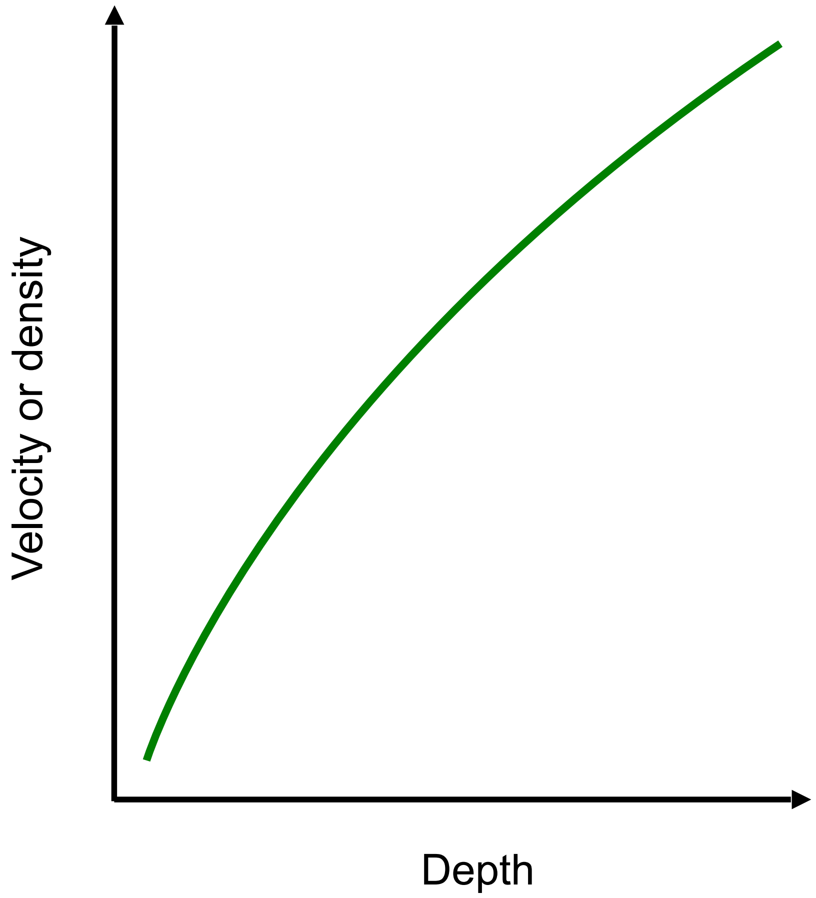
Density models published 1975–1981.

Earth's outer core – What can we do better?



Earth's outer core – What can we do better?

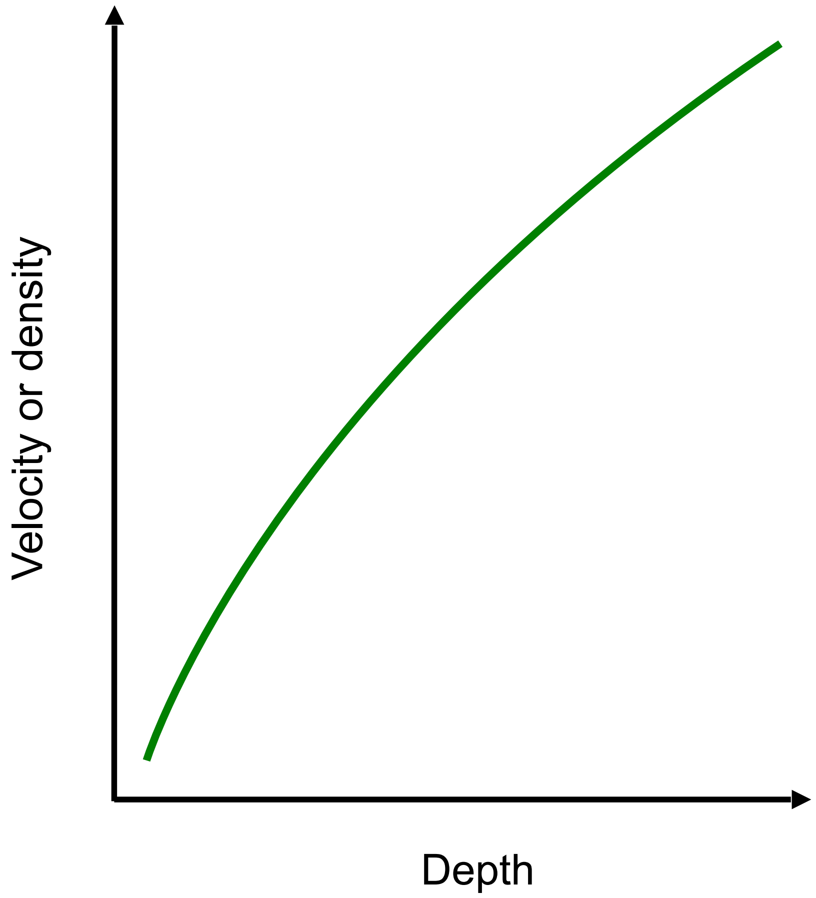
We made a new model of the outer core's seismic properties (v_p and ρ) and mineralogical properties.



Earth's outer core – What can we do better?

We made a new model of the outer core's seismic properties (v_p and ρ) and mineralogical properties.

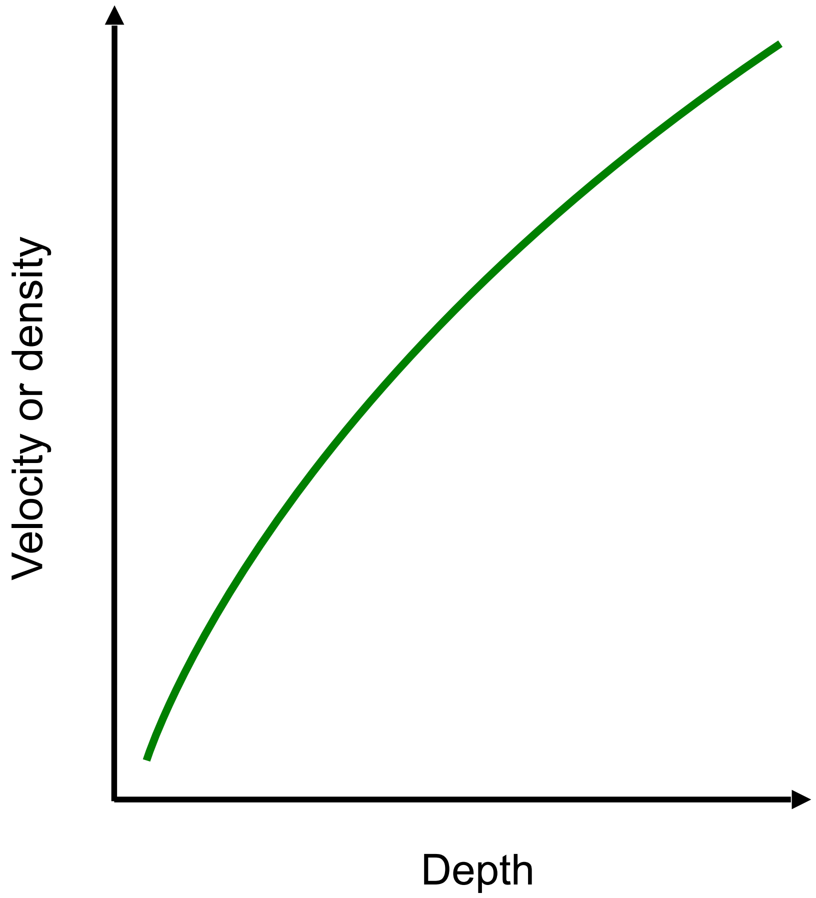
- We expect the outer core to (mostly) comprise a well-mixed liquid. Assume this is true everywhere. Assume PREM does a good job for the rest of the Earth.



Earth's outer core – What can we do better?

We made a new model of the outer core's seismic properties (v_p and ρ) and mineralogical properties.

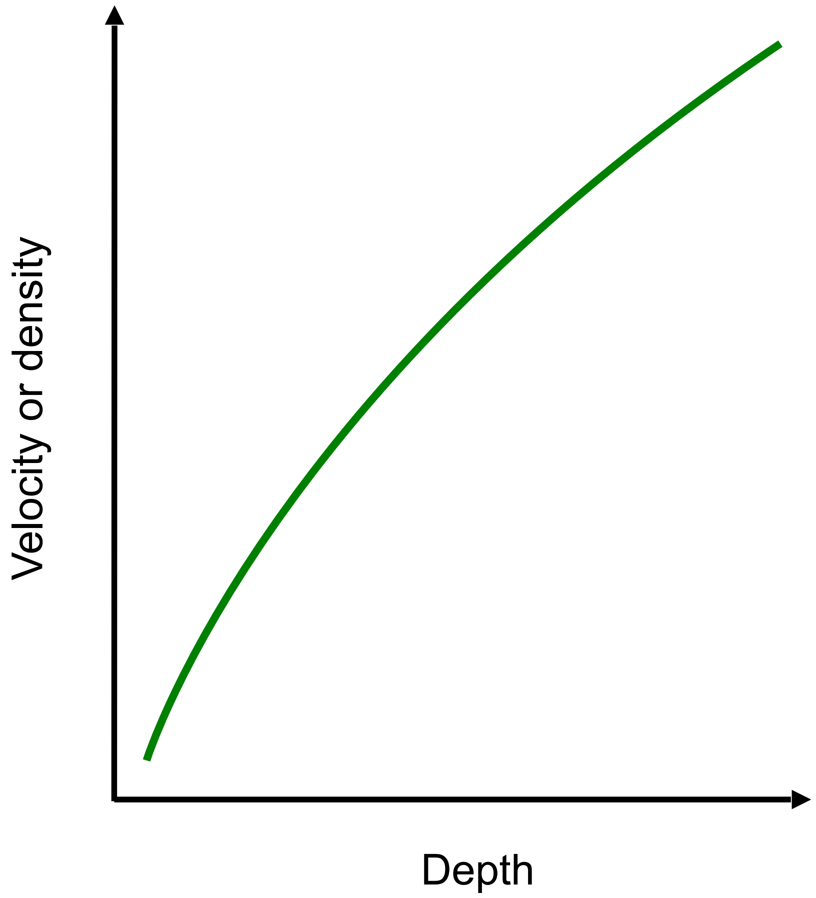
- We expect the outer core to (mostly) comprise a well-mixed liquid. Assume this is true everywhere. Assume PREM does a good job for the rest of the Earth.
- Look for the outer core's Equation of State, relating its bulk modulus and molar volume → we get velocity and density.



Earth's outer core – What can we do better?

We made a new model of the outer core's seismic properties (v_p and ρ) and mineralogical properties.

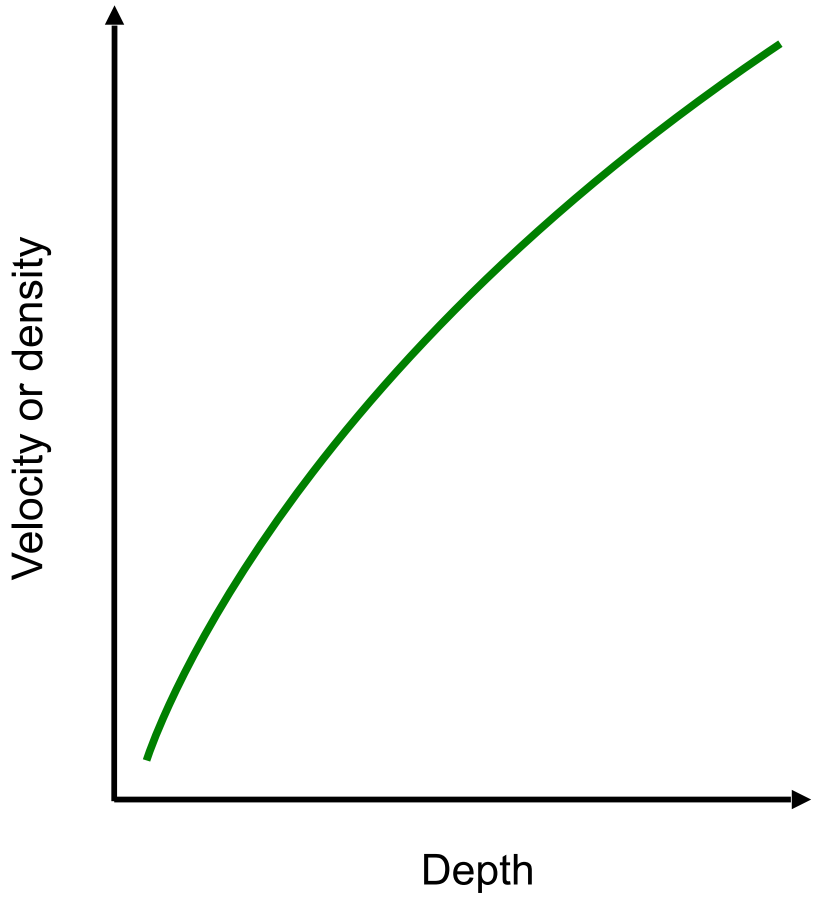
- We expect the outer core to (mostly) comprise a well-mixed liquid. Assume this is true everywhere. Assume PREM does a good job for the rest of the Earth.
- Look for the outer core's Equation of State, relating its bulk modulus and molar volume → we get velocity and density.
- We end up with a physics based parameterisation.



Earth's outer core – What can we do better?

We made a new model of the outer core's seismic properties (v_p and ρ) and mineralogical properties.

- We expect the outer core to (mostly) comprise a well-mixed liquid. Assume this is true everywhere. Assume PREM does a good job for the rest of the Earth.
- Look for the outer core's Equation of State, relating its bulk modulus and molar volume → we get velocity and density.
- We end up with a physics based parameterisation.
- We can also use new data!



Inversion for EoS & Seismic Parameters

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

(1) Choose values of K_{0S} K'_{0S} & V_0 using PyMc
(molar mass assumed to be 0.05kg)

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

(1) Choose values of K_{0S} K'_{0S} & V_0 using PyMc
(molar mass assumed to be 0.05kg)

(2) Using these EoS parameters, predict the outer core's v_p, ρ, using Burnman.

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

(1) Choose values of K_{0S} K'_{0S} & V_0 using PyMc (molar mass assumed to be 0.05kg)

(2) Using these EoS parameters, predict the outer core's v_p, ρ, using Burnman.

(3) Predict mode frequencies using MINEOS

Mode ${}_1S_3$
period ~ 18 minutes

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

Mode ${}_1S_3$
period ~ 18 minutes

(1) Choose values of K_{0S} K'_{0S} & V_0 using PyMc (molar mass assumed to be 0.05kg)

↓

(2) Using these EoS parameters, predict the outer core's v_p, ρ, using Burnman.

↓

(3) Predict mode frequencies using MINEOS

↓

(4) Compare with observations

Inversion for EoS & Seismic Parameters

Goal: isentropic Vinet EoS & seismic model which best describe the data.

Mode ${}_1S_3$
period ~ 18 minutes

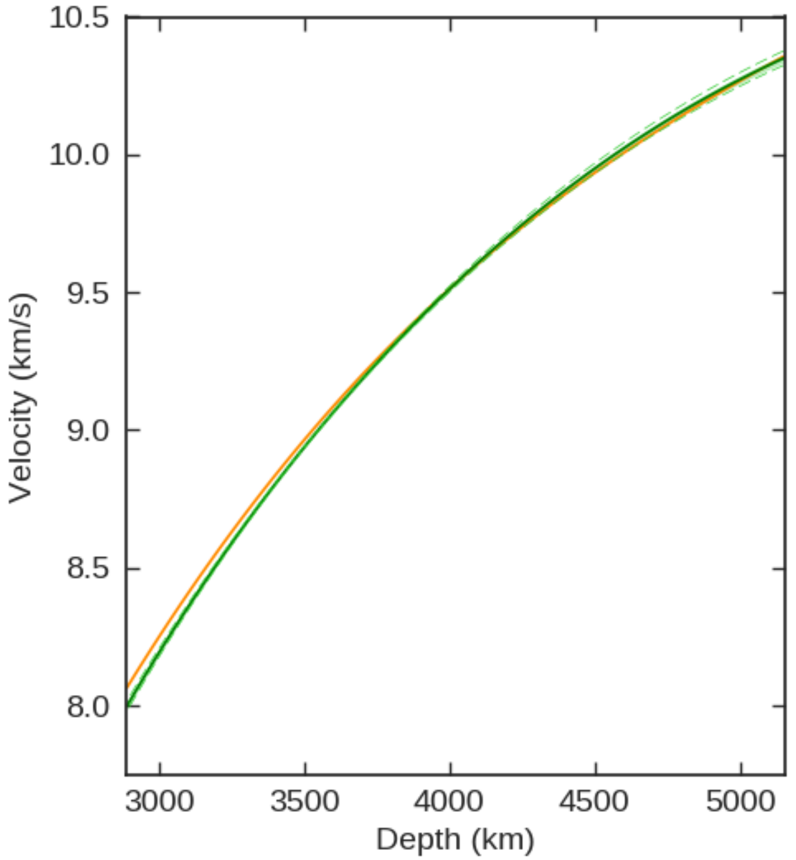
(1) Choose values of K_{0S} K'_{0S} & V_0 using PyMc (molar mass assumed to be 0.05kg)

(2) Using these EoS parameters, predict the outer core's v_p, ρ, using Burnman.

(3) Predict mode frequencies using MINEOS

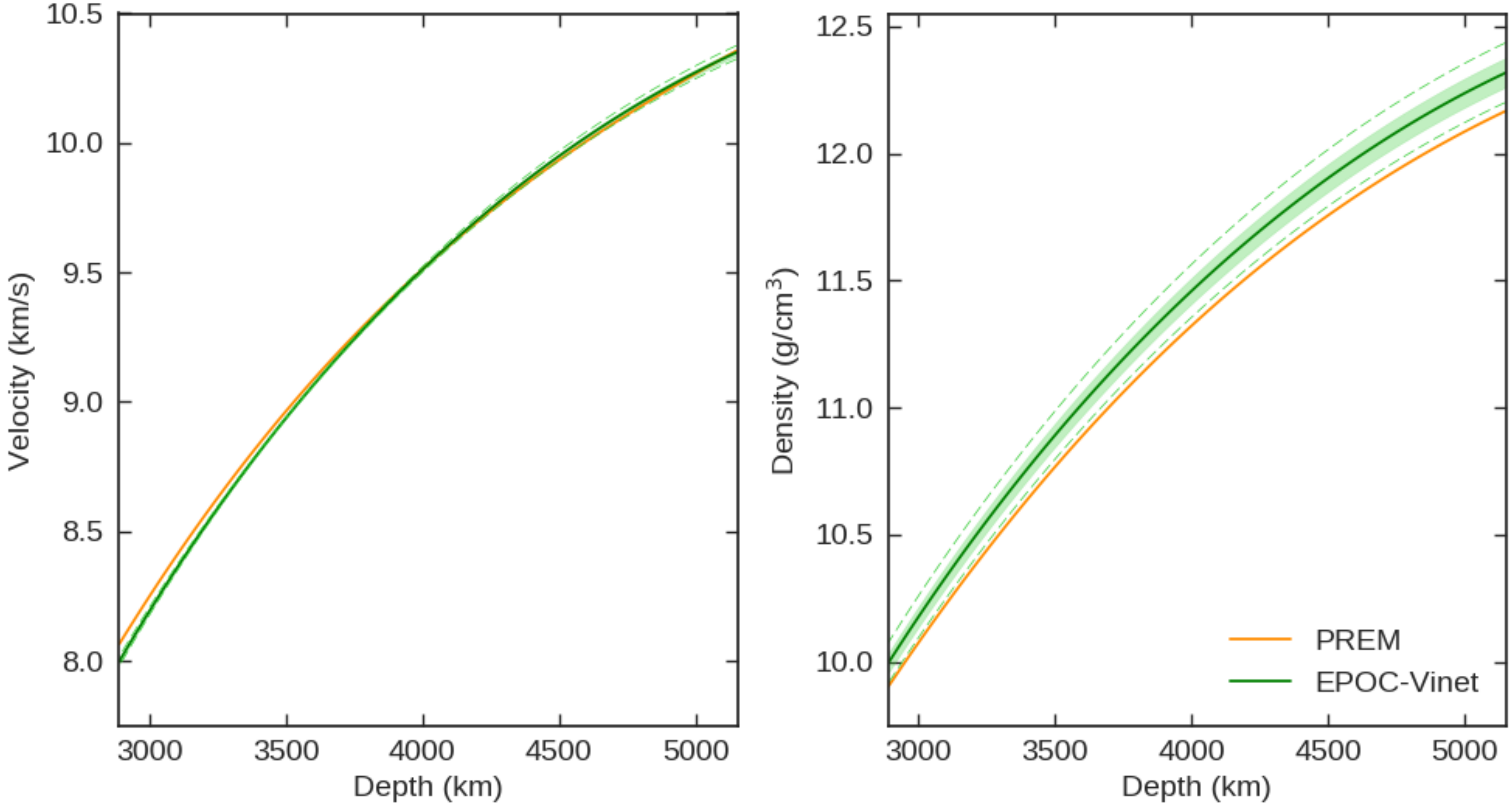
(4) Compare with observations

Elastic Parameters of the Outer Core: EPOC–Vinet



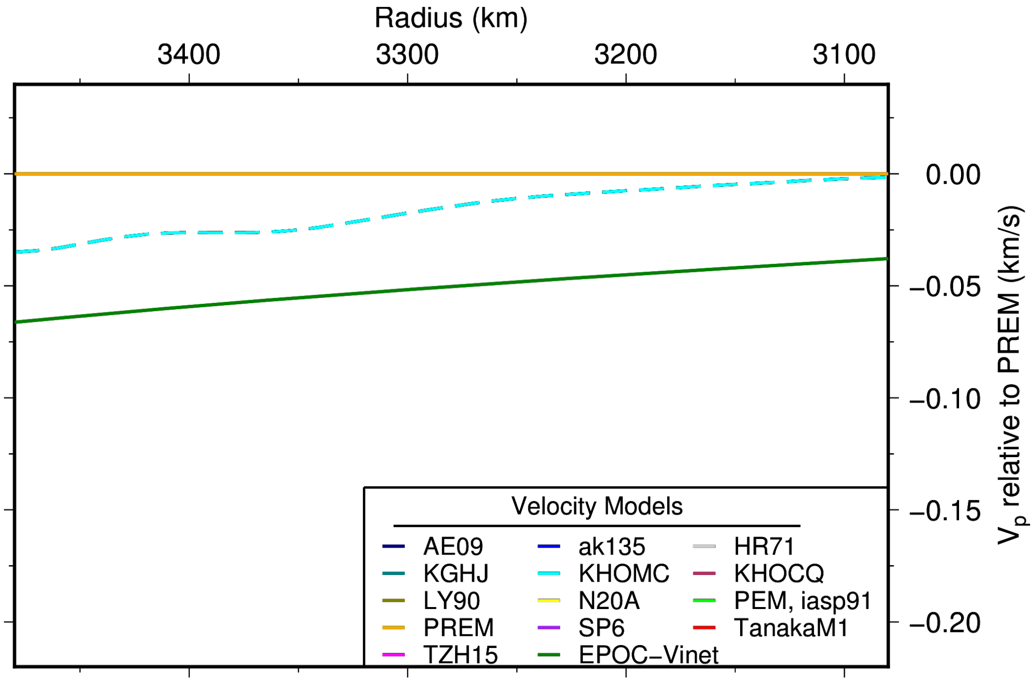
Irving, Cottaar & Lekic, Sci. Adv. 2018.

Elastic Parameters of the Outer Core: EPOC–Vinet



Irving, Cottaar & Lekic, Sci. Adv. 2018.

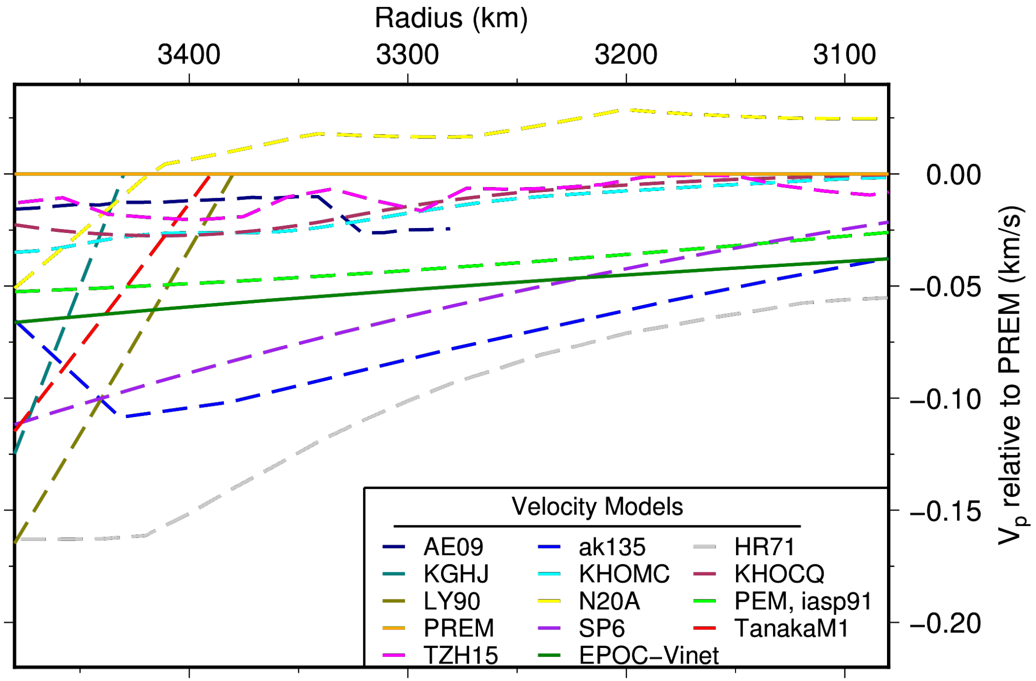
Uppermost outer core structure – an E' layer?



CMB

Towards the IC

Uppermost outer core structure – an E' layer?



CMB

Towards the IC

- A large number of E' velocity models exist, nearly all are slower than PREM.
- Some of these models suggest a seismically anomalous layer. Our model explains the mode data with a smooth curve. But a layer might still be present!

Uppermost outer core structure – an E' layer?

- The name E’ follows Bullen’s layer-naming convention
- Called the “Hidden Ocean of the Core” by Braginsky
- Buffett (2014, figure right) shows that estimates of flow at the surface of the outer core are predicted well by MAC waves; a 140 km thick layer works.
- May be the cause of signals in satellite observations of Earth’s magnetic field (Vidal and Schaeffer, 2015); and present in geomagnetic ‘jerk’ data (Chulliat et al., 2015).
- Other studies prefer no stratification, or cannot see its effect.

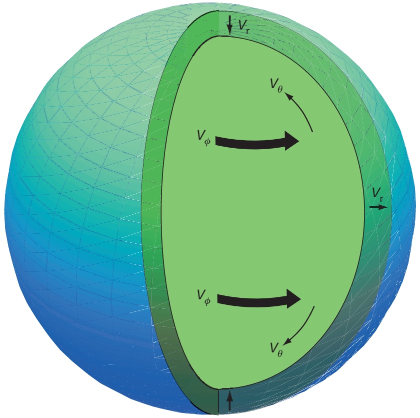
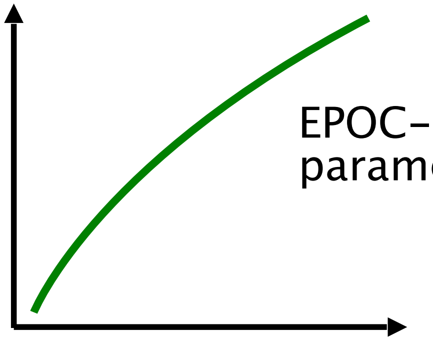


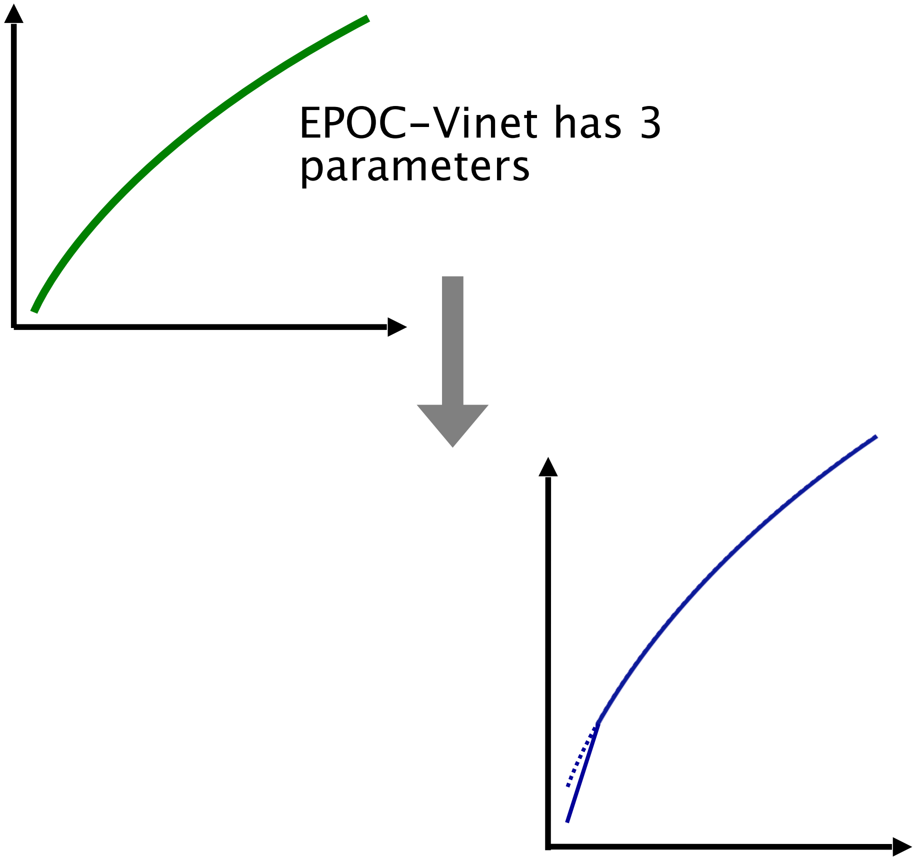
Figure 1 | Schematic illustration of the wave motion. Radial motion V_r causes a pressure perturbation, which drives an azimuthal flow V_w in the stratified layer. The presence of a radial magnetic field opposes V_w and induces a meridional flow V_h. The fluid velocities reverse direction over a full cycle of the wave.

Permitting variation in D'' properties and an E' layer



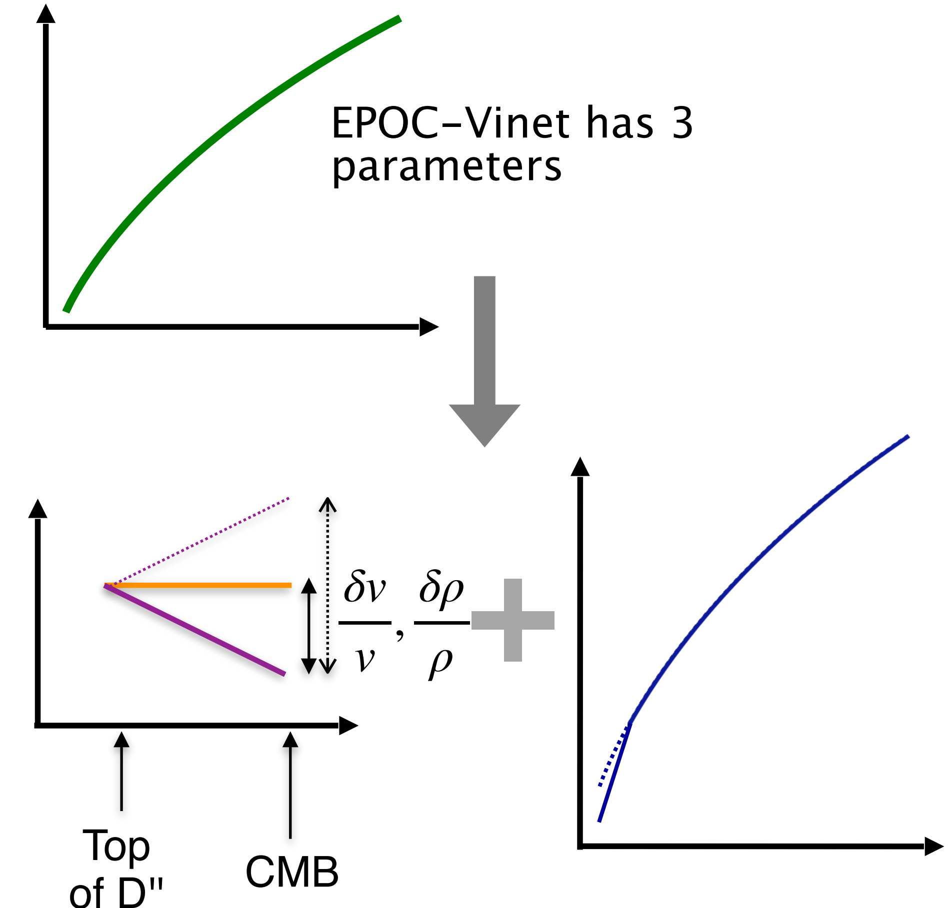
EPOC–Vinet has 3 parameters

Permitting variation in D'' properties and an E' layer



- Using the same methodology, we can:
  - allow a distinct E’ layer, where v_p and ρ diverge from those of the well mixed outer core

Permitting variation in D'' properties and an E' layer

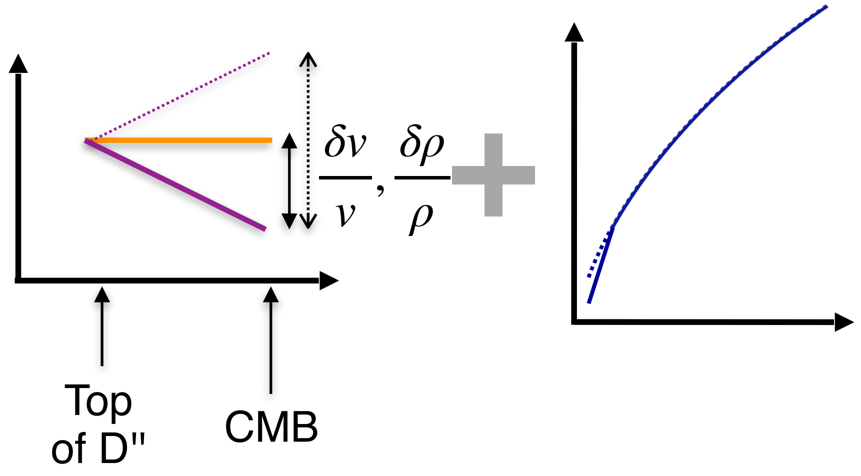


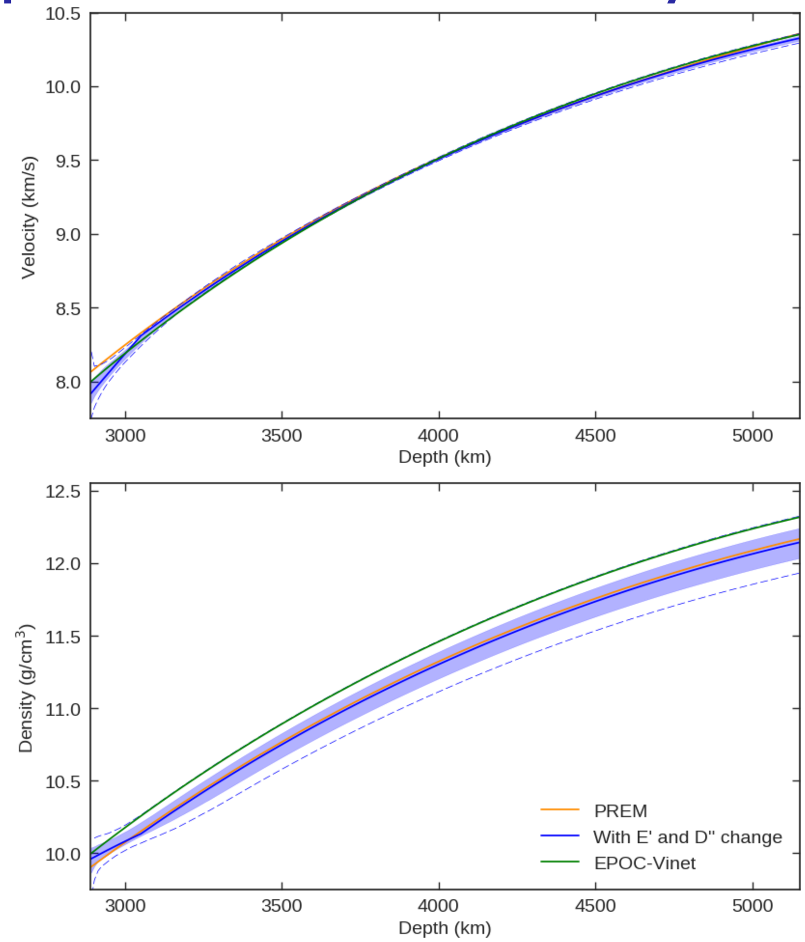
- Using the same methodology, we can:
  - allow a distinct E’ layer, where v_p and ρ diverge from those of the well mixed outer core

    and

  - let the seismic properties of the D'' (ρ, v_s and v_p) vary away from PREM towards the CMB.

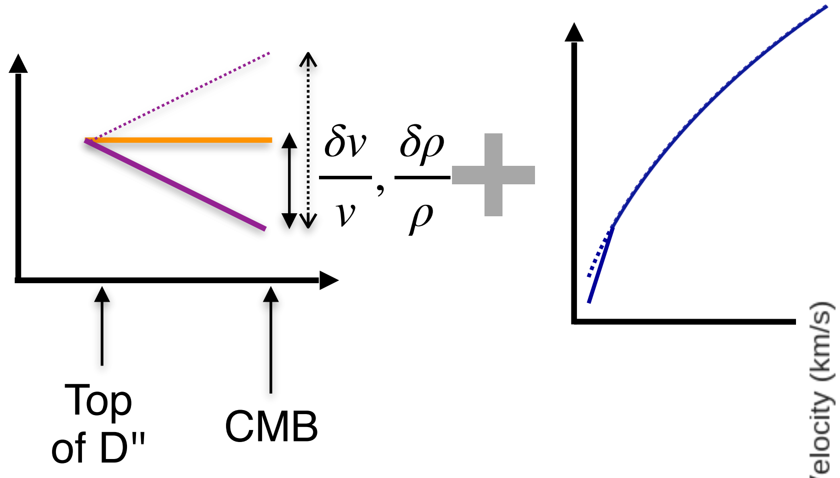
Permitting variation in D'' properties and an E' layer

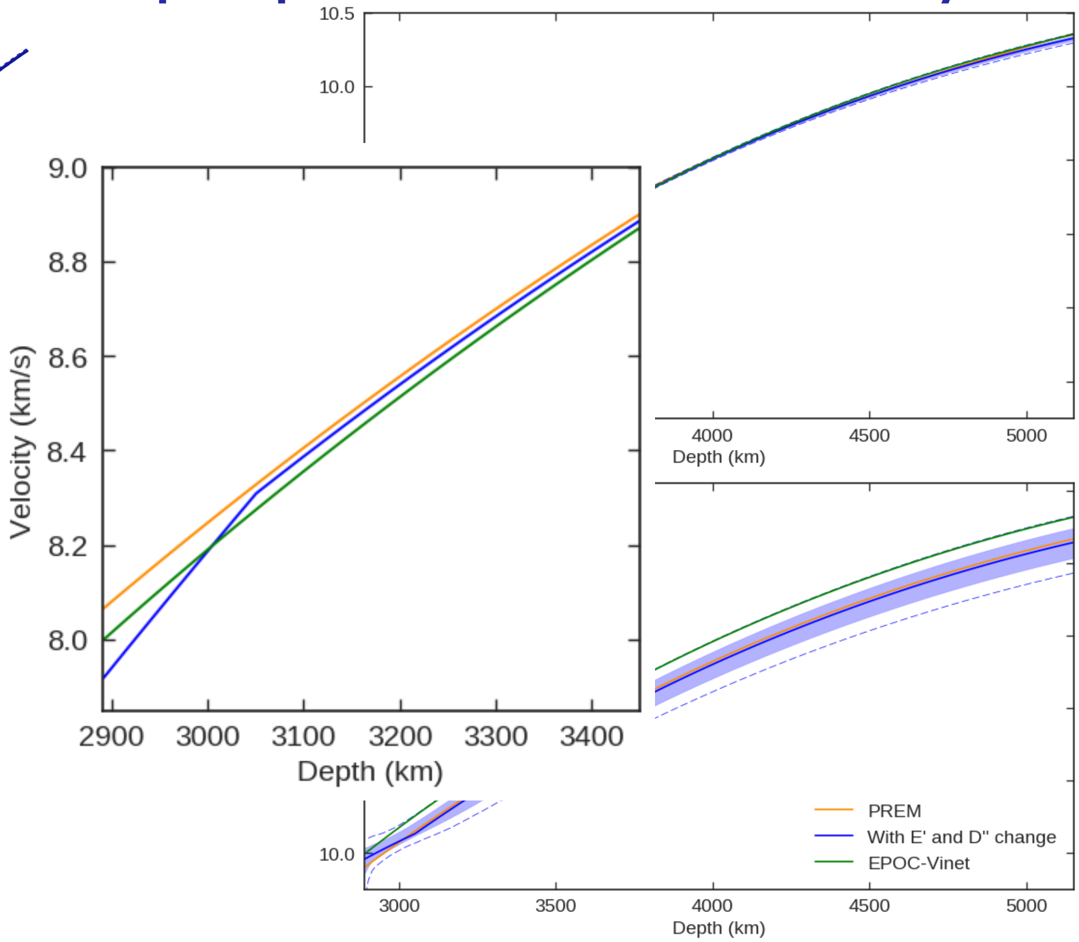




- v_s and v_p in the D'' decrease
- Need to see what body waves prefer

Permitting variation in D'' properties and an E' layer





- v_s and v_p in the D'' decrease
- Need to see what body waves prefer

Uppermost outer core structure – an E' layer?

Uppermost outer core structure – an E' layer?

Compositional convection and stratification of Earth's core

David R. Fearn* & David E. Loper

Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, Florida 32306

Nature Vol. 289 29 January 1981

Using parameter estimates relevant to the vicinity of the mantle–core boundary (with $D = 6 \times 10^{-9}\ m^2\ s^{-1}$) we find the depth of the stably stratified layer to be ~70 km.

What might generate an E' layer?

- Light elements concentrated by IC growth (eg Fearn & Loper, 1981, Gubbins & Davies 2013, Helffrich & Kaneshima 2013)

Uppermost outer core structure – an E' layer?

Compositional convection and stratification of Earth's core

David R. Fearn* & David E. Loper

Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, Florida 32306

Nature Vol. 289 29 January 1981

Using parameter estimates relevant to the vicinity of the mantle–core boundary (with $D = 6 \times 10^{-9}\ m^2\ s^{-1}$) we find the depth of the stably stratified layer to be ~70 km.

What might generate an E' layer?

- Light elements concentrated by IC growth (eg Fearn & Loper, 1981, Gubbins & Davies 2013, Helffrich & Kaneshima 2013)
- Mantle material dissolving into the OC (eg Buffett & Seagle, 2010, Nakagawa 2018)

Uppermost outer core structure – an E' layer?

Compositional convection and stratification of Earth's core

David R. Fearn* & David E. Loper

Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, Florida 32306

Nature Vol. 289 29 January 1981

Using parameter estimates relevant to the vicinity of the mantle–core boundary (with $D = 6 \times 10^{-9}\ \mathrm{m^2\ s^{-1}}$) we find the depth of the stably stratified layer to be ~70 km.

What might generate an E' layer?

- Light elements concentrated by IC growth (eg Fearn & Loper, 1981, Gubbins & Davies 2013, Helffrich & Kaneshima 2013)
- Mantle material dissolving into the OC (eg Buffett & Seagle, 2010, Nakagawa 2018)
- Planetary core formation – a primordial feature (see Helffrich & Kaneshima 2013), or remnants of the moon–forming impact (eg Landau et al, 2016)

Uppermost outer core structure – an E' layer?

Compositional convection and stratification of Earth's core

David R. Fearn* & David E. Loper

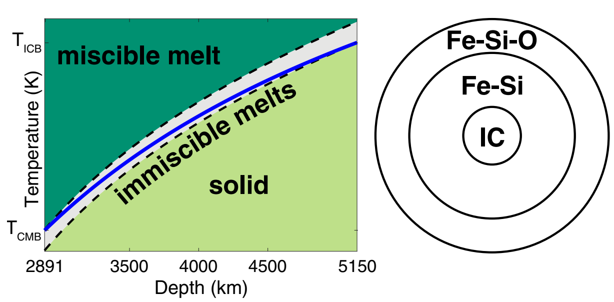
Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, Florida 32306

Nature *Vol. 289* *29 January 1981*

Using parameter estimates relevant to the vicinity of the mantle–core boundary (with $D = 6 \times 10^{-9}\ m^2\ s^{-1}$) we find the depth of the stably stratified layer to be ~70 km.

What might generate an E' layer?

- Light elements concentrated by IC growth (eg Fearn & Loper, 1981, Gubbins & Davies 2013, Helffrich & Kaneshima 2013)
- Mantle material dissolving into the OC (eg Buffett & Seagle, 2010, Nakagawa 2018)
- Planetary core formation – a primordial feature (see Helffrich & Kaneshima 2013), or remnants of the moon–forming impact (eg Landau et al, 2016)
- Immisible melts at OC conditions (eg Averson et al, 2019, figure right; but also Helffrich & Kaneshima 2004)



Uppermost outer core structure – an E' layer?

But what should it look like seismically?

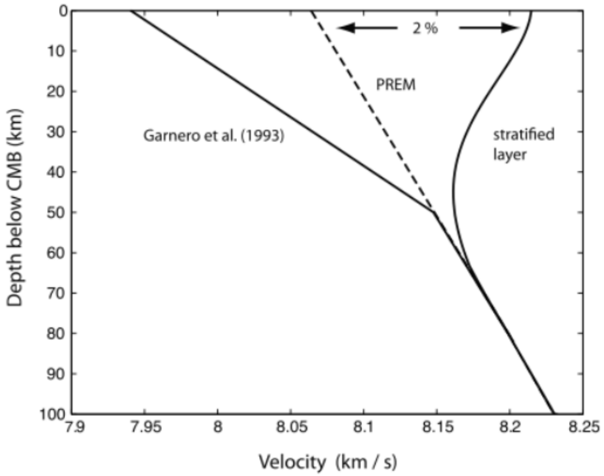


Figure from Buffett & Seagle, 2010

Uppermost outer core structure – an E' layer?

But what should it look like seismically?

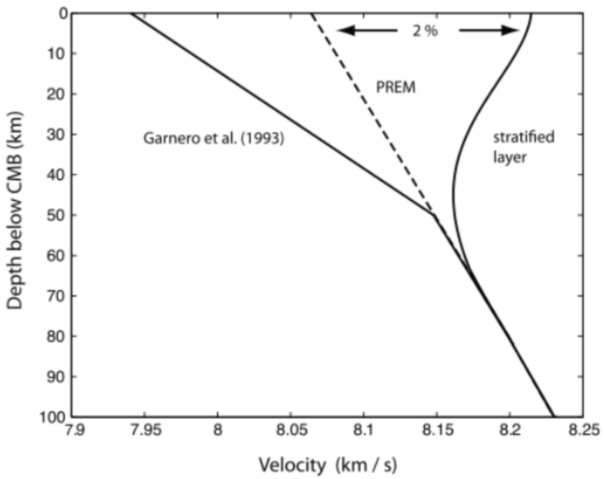


Figure from Buffett & Seagle, 2010

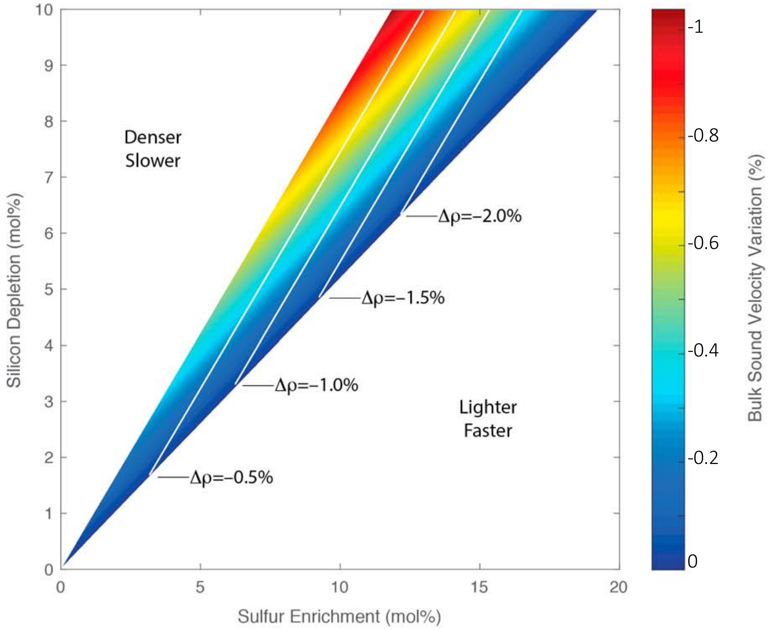


Figure from Brodholt & Badro, 2018

Maybe slow & light is possible?

Moving up to the MTZ

Figure from Kellogg, Hager & Van der Hilst, Science, 1999

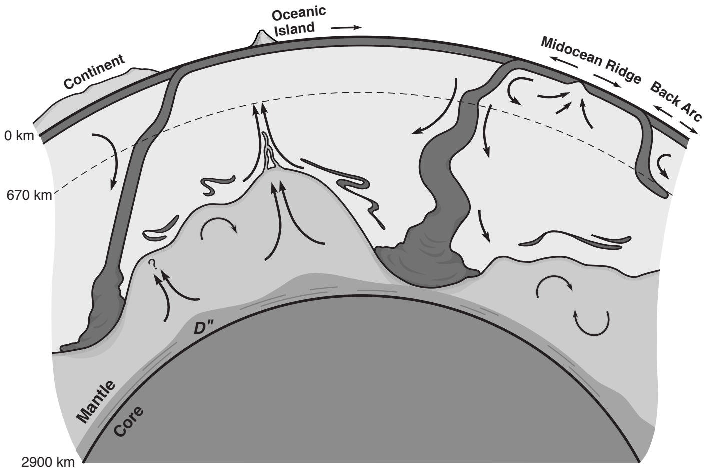


Figure from Fukao & Obayashi, 2013

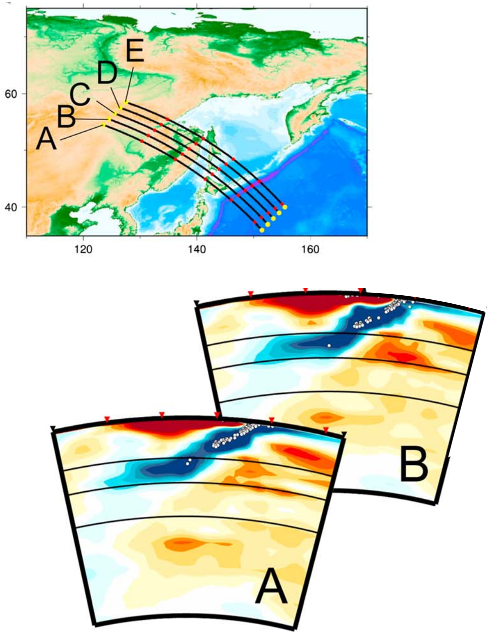
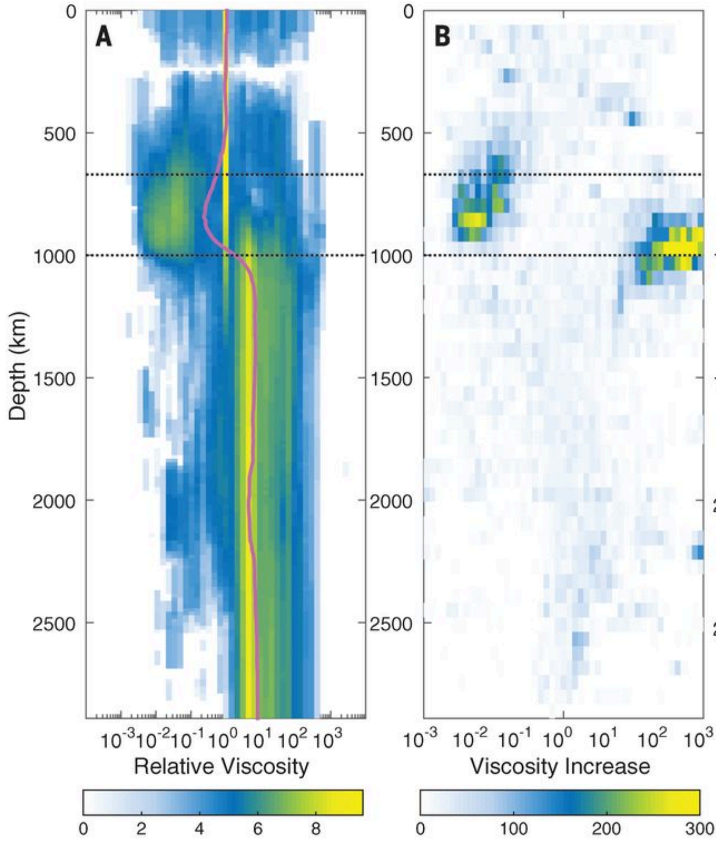
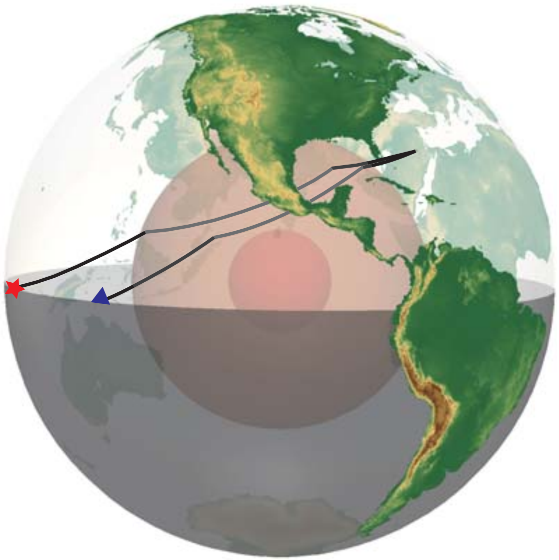


Figure from Rudolph, Lekic & Lithgow-Bertelloni, Science, 2015



- The question of how convection behaves in the mantle and whether layering is present has been tackled for decades – with insights from geochemistry, geodynamics and seismology.

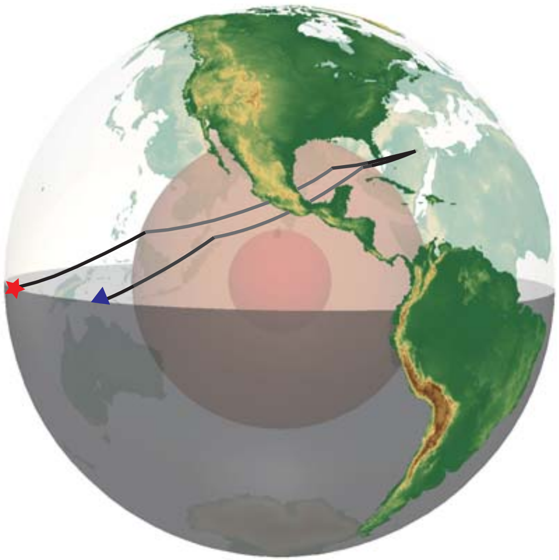
Moving up to the MTZ – P'•d•P'

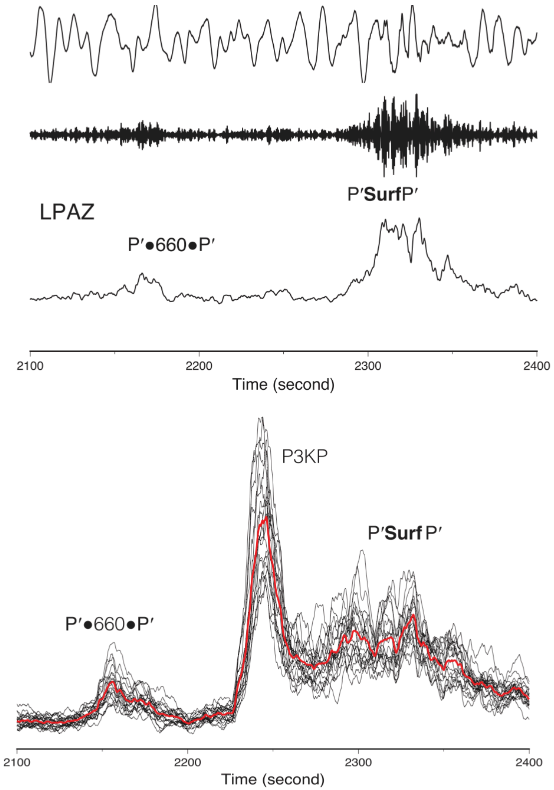


- Asymmetric P'•d•P' can be used to probe the mantle transition zone.

Wu, Ni & Irving, Science, 2019

Moving up to the MTZ – P'•d•P'

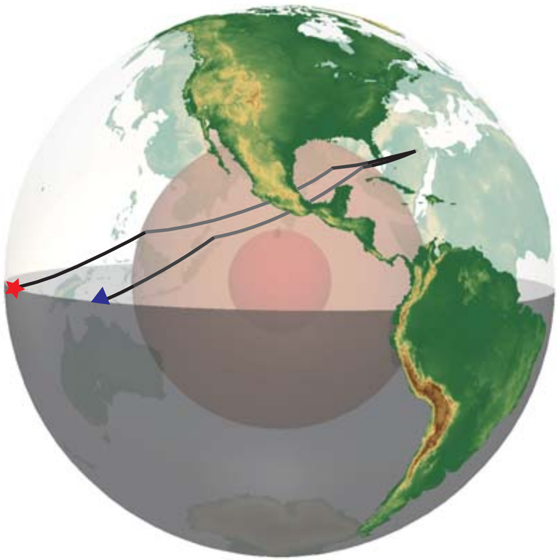


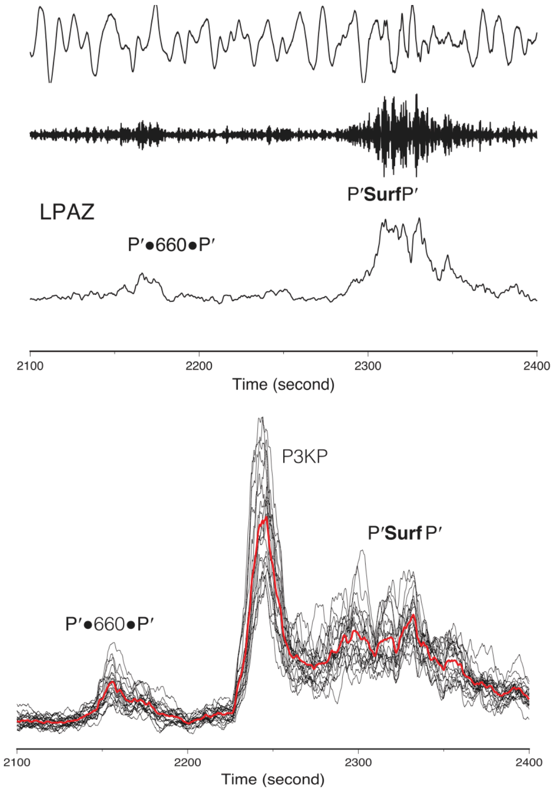


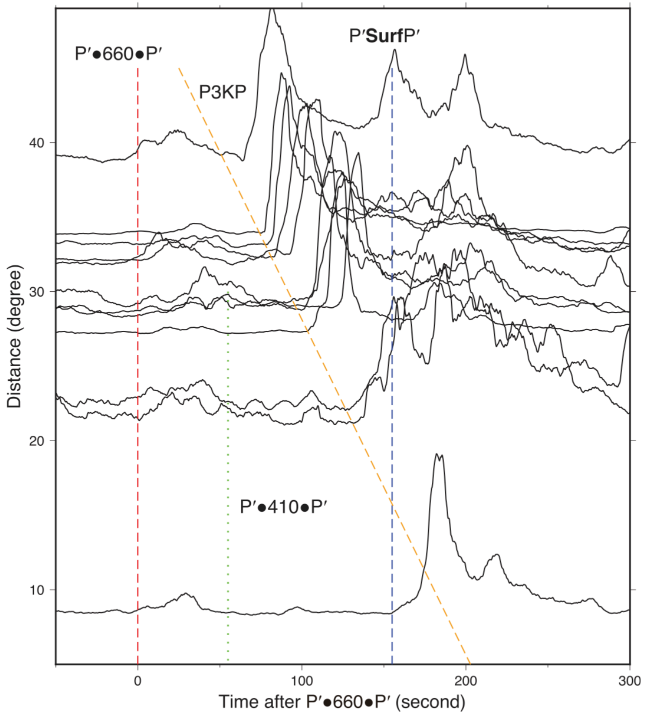
- Asymmetric P'•d•P' can be used to probe the mantle transition zone.

Wu, Ni & Irving, Science, 2019

Moving up to the MTZ – P'•d•P'



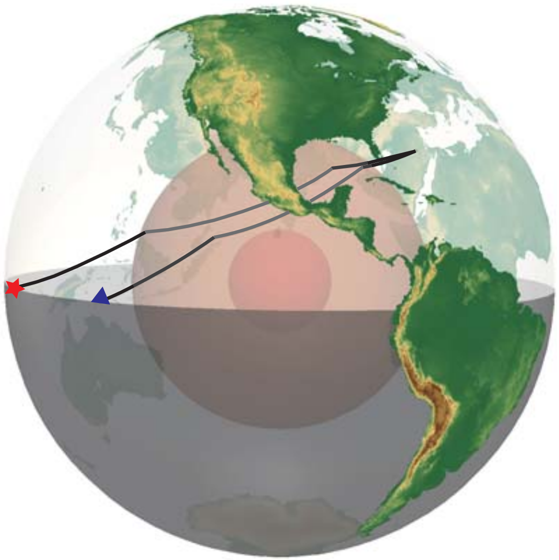


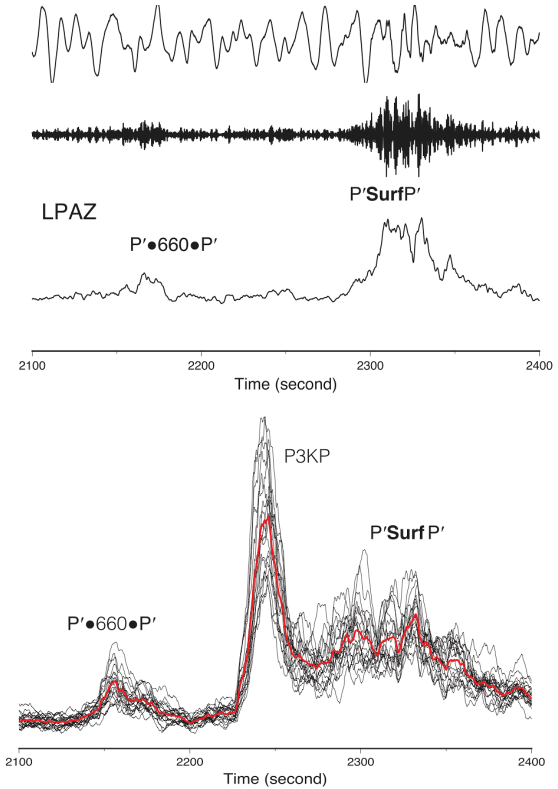


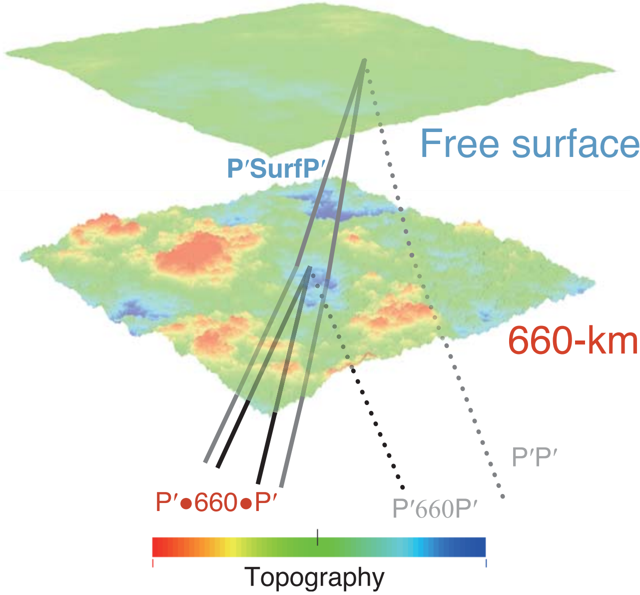
- Asymmetric P'•d•P' can be used to probe the mantle transition zone.

Wu, Ni & Irving, Science, 2019

Moving up to the MTZ – P'•d•P'



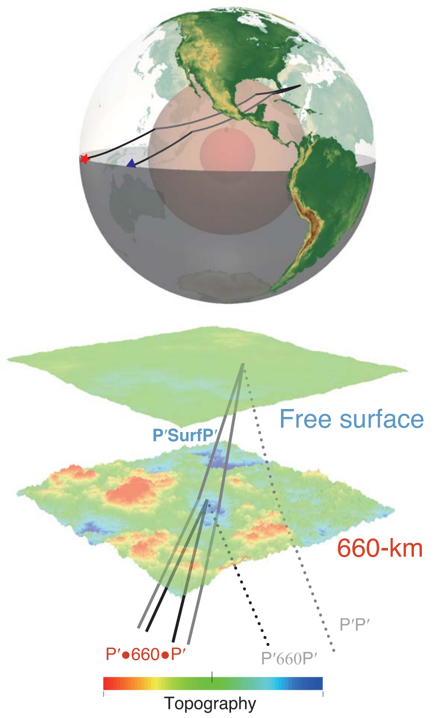


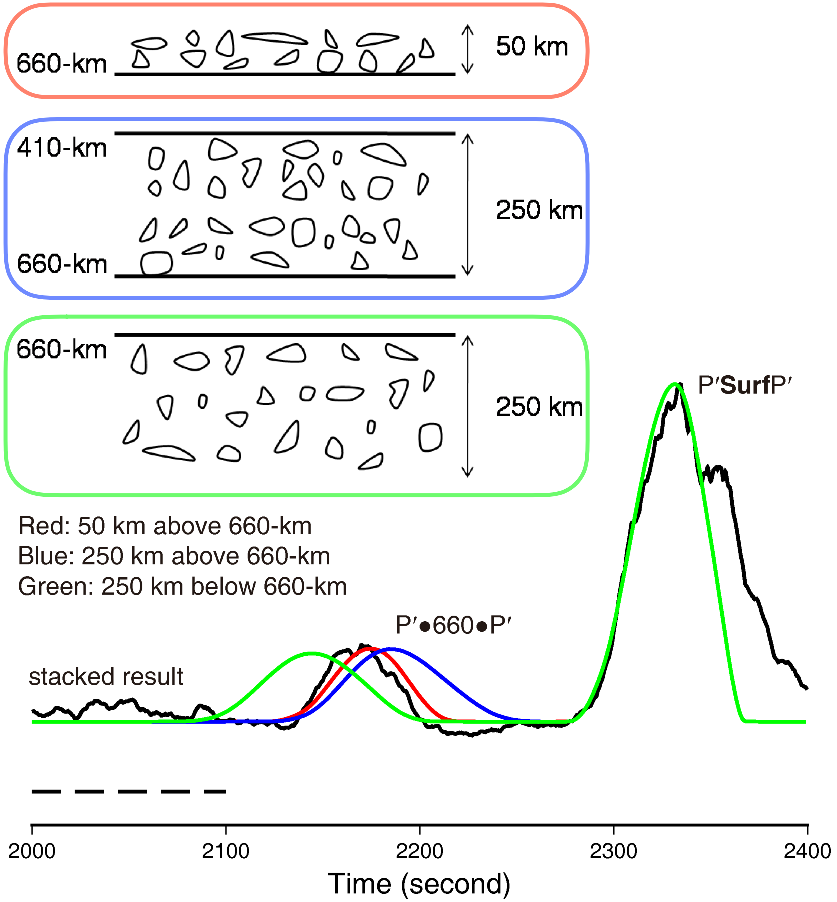


- We found very significant scattering from the '660 km' discontinuity — it is much rougher than the free surface.

Wu, Ni & Irving, Science, 2019

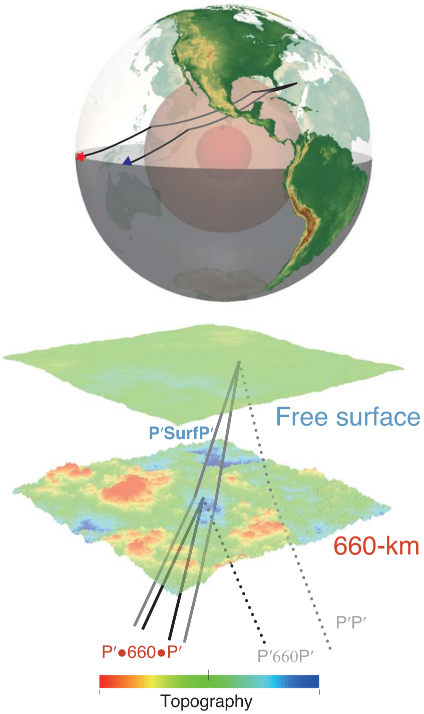
P'•d•P' from scattering?

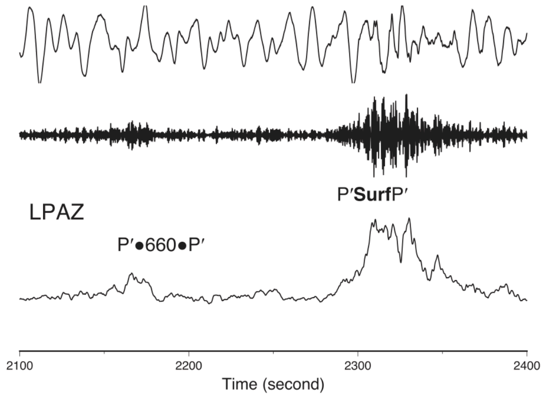


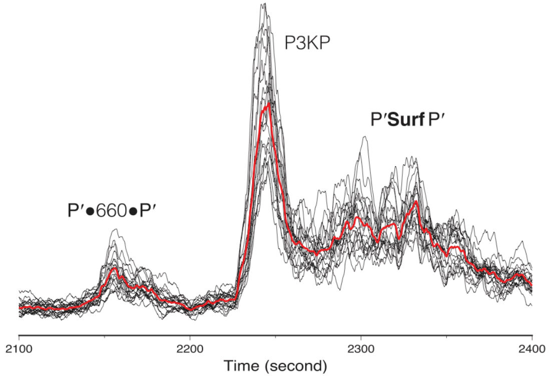


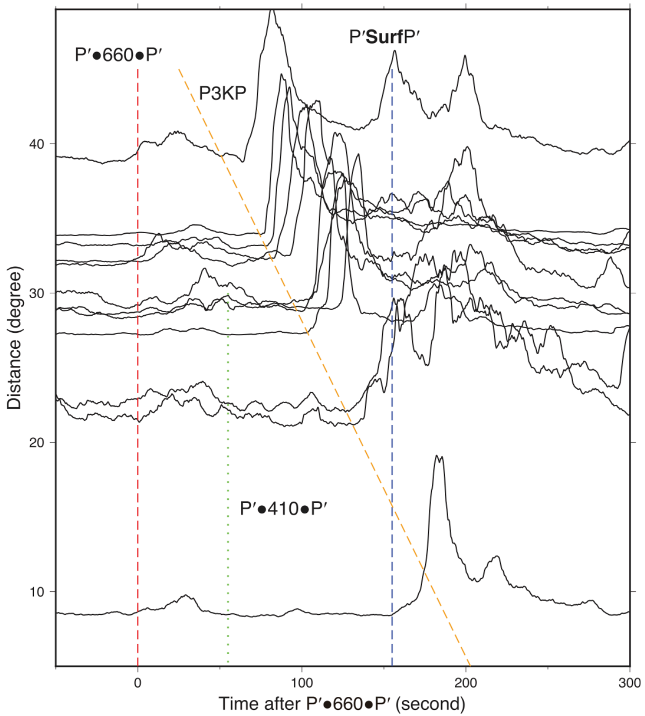
- We model the signal as coming from a 660 with substantial topography, but a thin layer of strong scatterers could produce a similar signal.

P'•d•P' and mantle convection



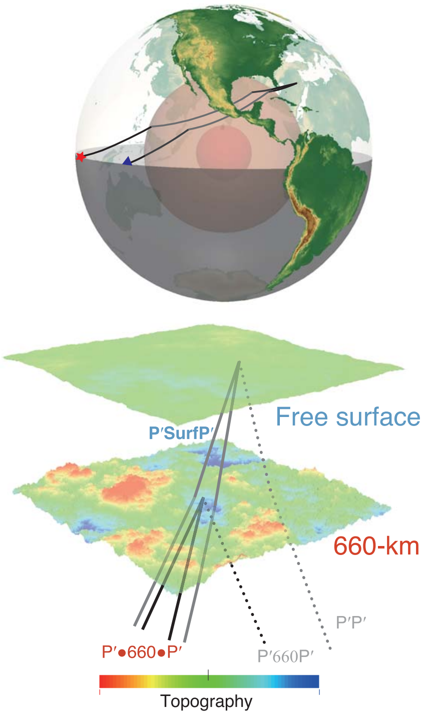


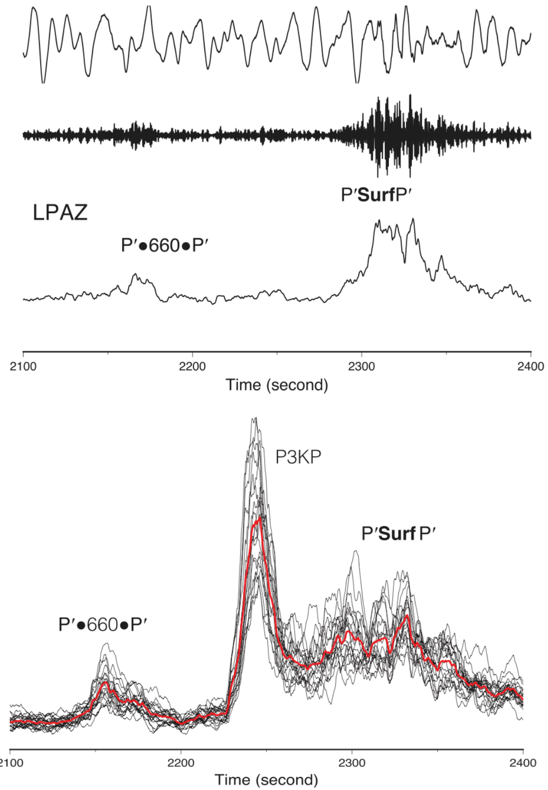


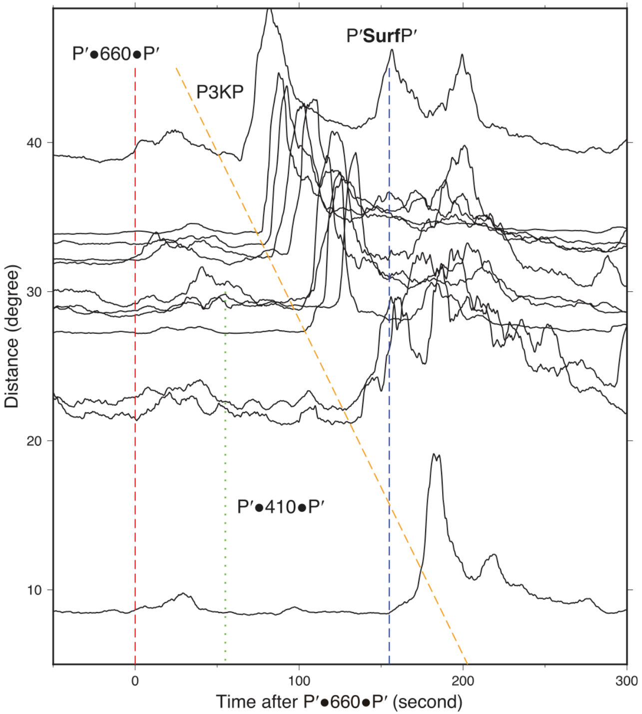


Wu, Ni & Irving, Science, 2019

P'•d•P' and mantle convection



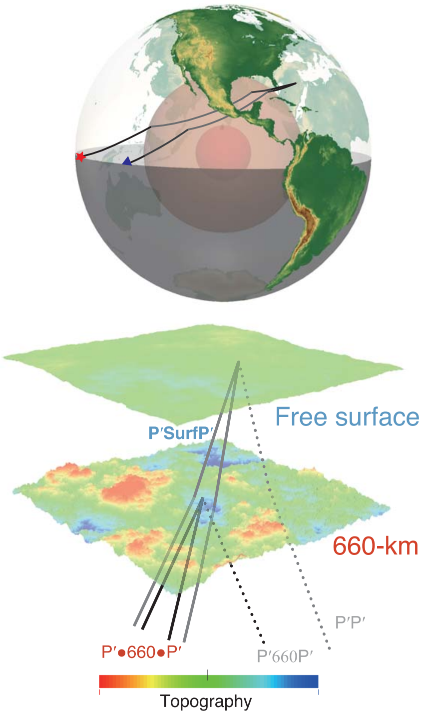


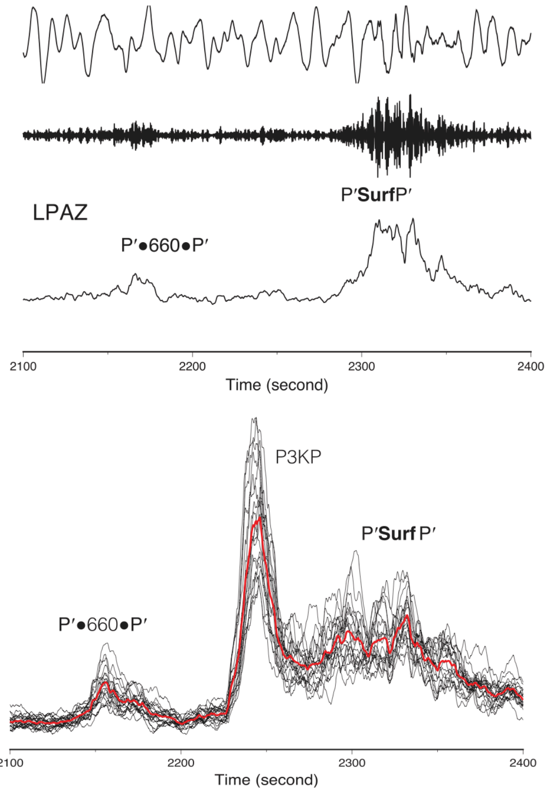


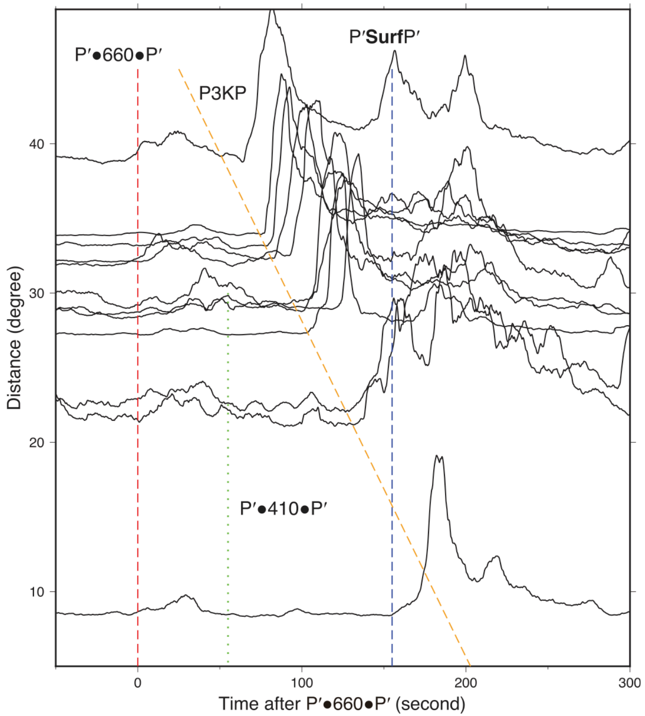
- Substantial scattering from the ‘660 km’ discontinuity — it is much rougher than the free surface.

Wu, Ni & Irving, Science, 2019

P'•d•P' and mantle convection



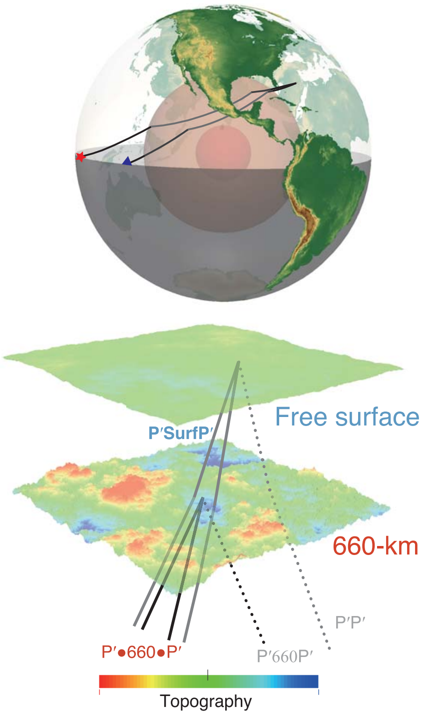




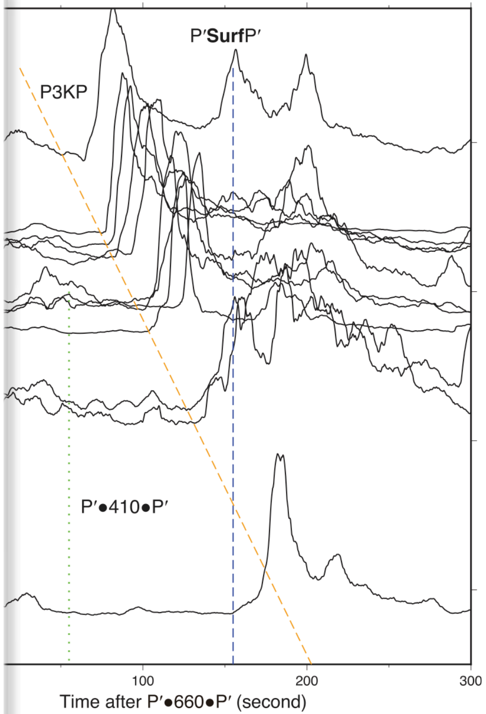
- Substantial scattering from the ‘660 km’ discontinuity — it is much rougher than the free surface.
- Symptomatic of chemical heterogeneity & impaired convection between the upper and lower mantle.

Wu, Ni & Irving, Science, 2019

P'•d•P' and mantle convection



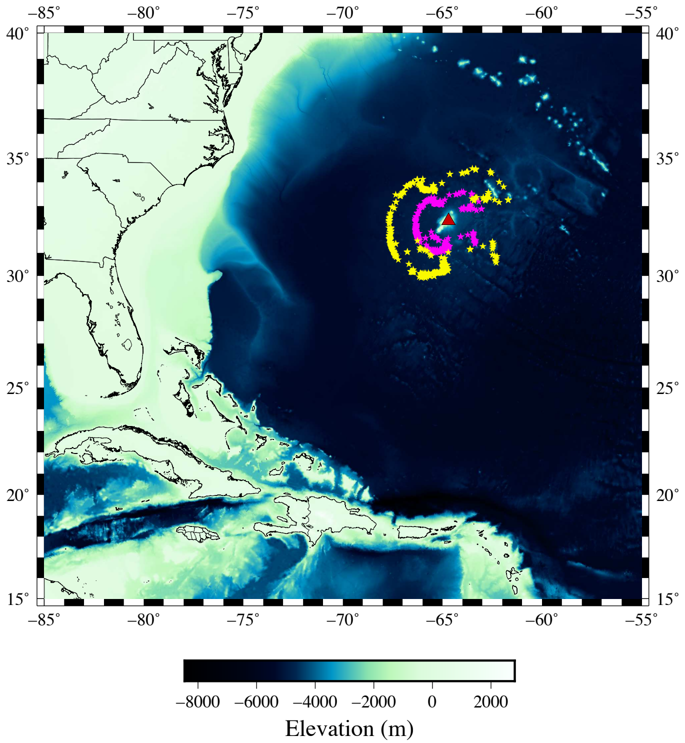
See Wenbo Wu's AGU presentation for more details!

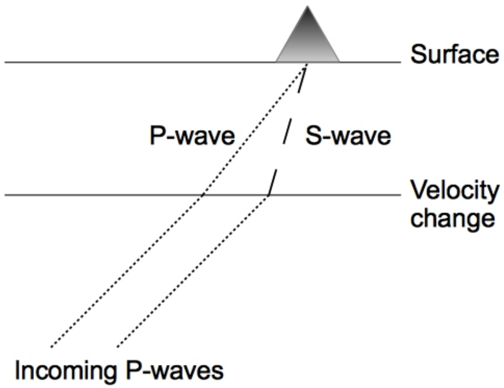


- Substantial scattering from the '660 km' discontinuity — it is much rougher than the free surface.
- Symptomatic of chemical heterogeneity & impaired convection between the upper and lower mantle.

Wu, Ni & Irving, Science, 2019

Flow at the 660?

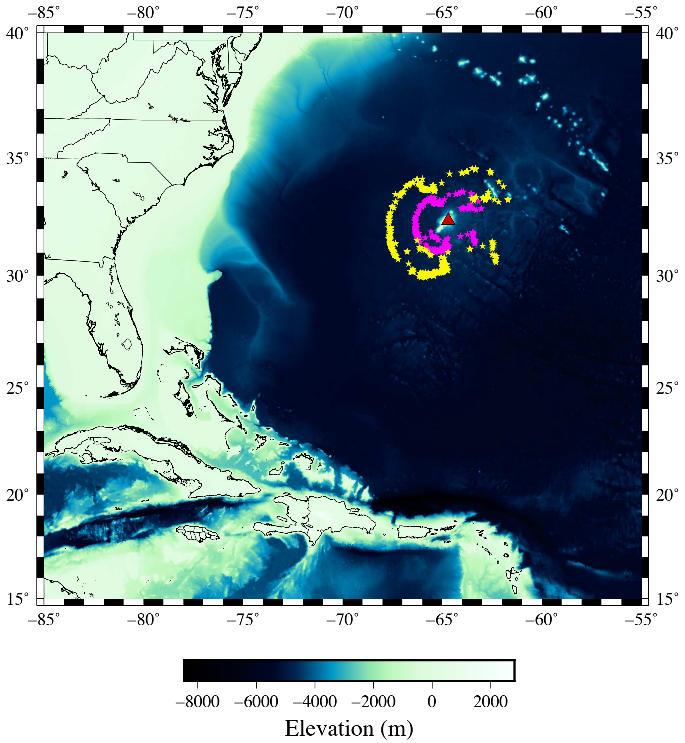


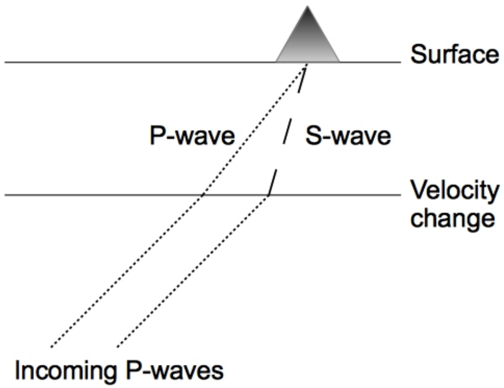


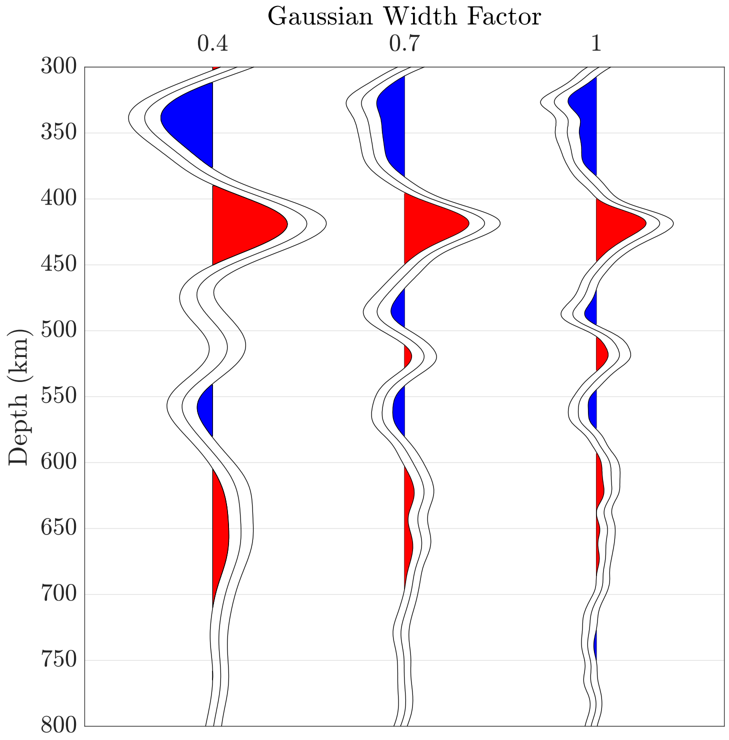
- Previous studies disagree about the genesis of the Bermudian Islands. We are looking under Bermuda using receiver functions.
- We're also developing a new receiver function metric to help assess receiver function quality.

Burky, Irving & Simons, in prep

Flow at the 660?



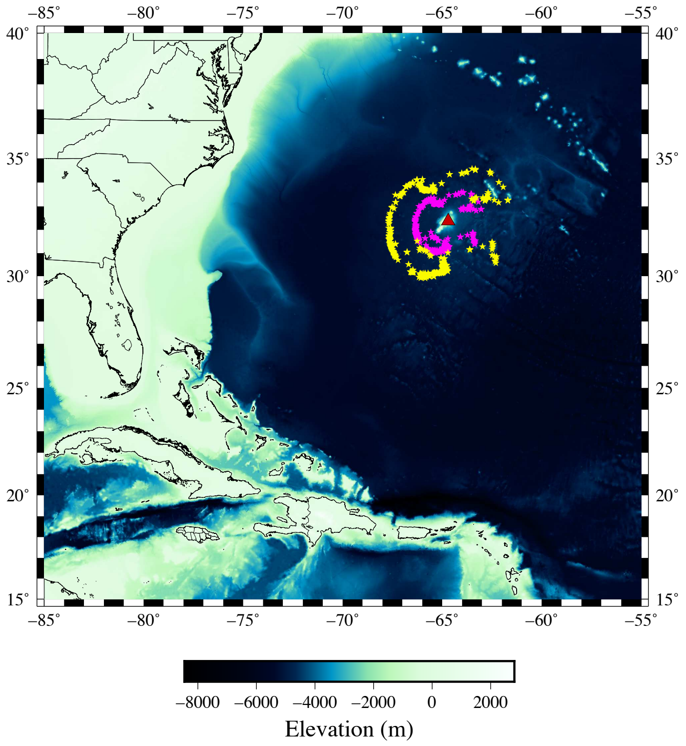


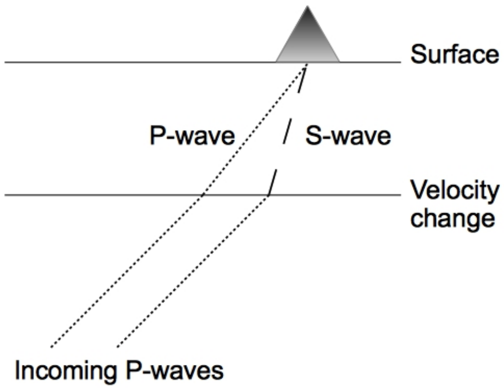


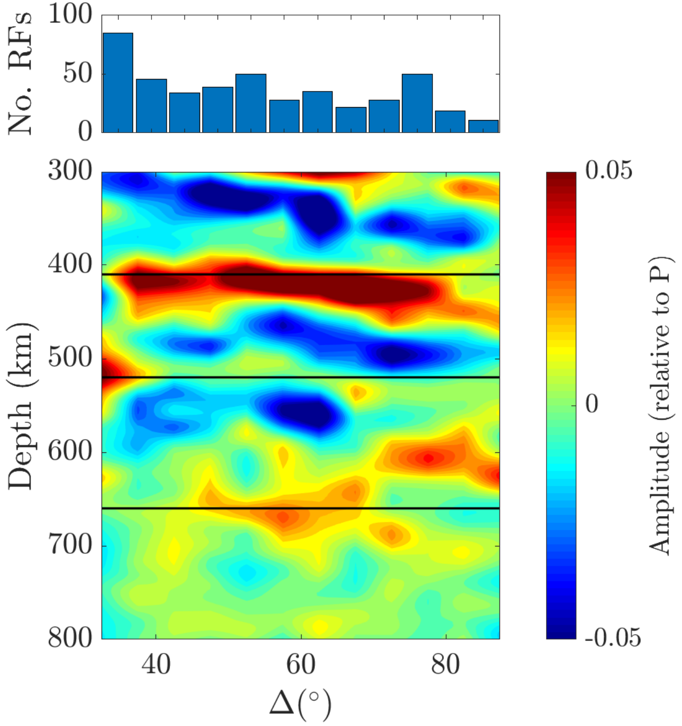
- Previous studies disagree about the genesis of the Bermudian Islands. We are looking under Bermuda using receiver functions.
- We're also developing a new receiver function metric to help assess receiver function quality.

Burky, Irving & Simons, in prep

Flow at the 660?



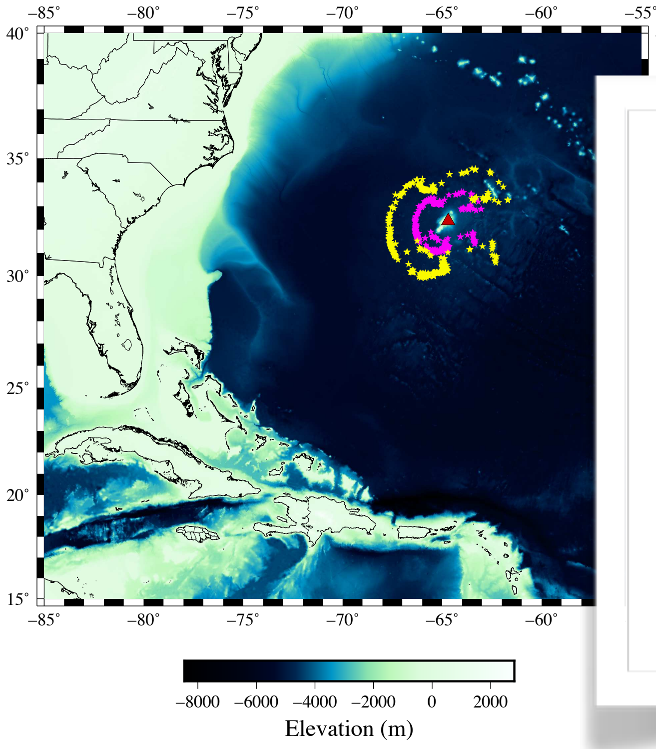




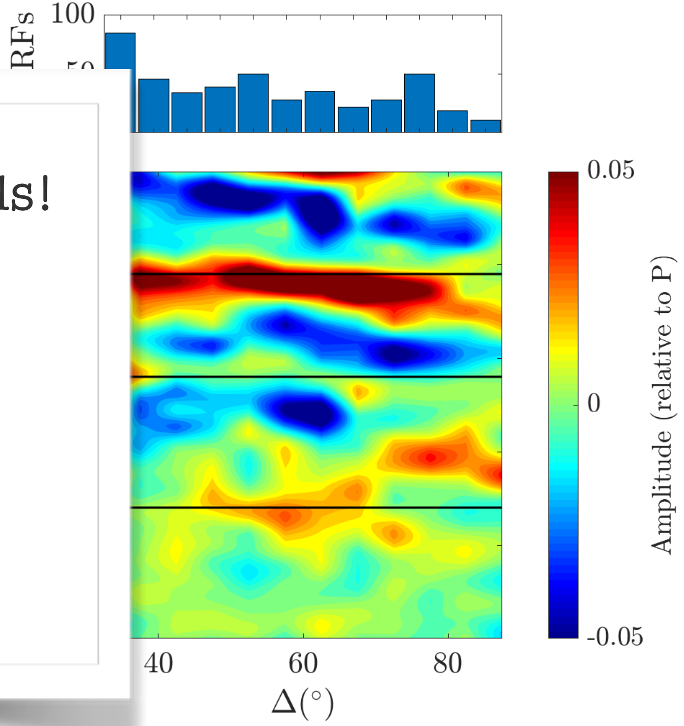
- We're developing a new receiver function metric to help assess receiver function quality.
- We find that Bermuda is underlain by a deeper than average '410' km discontinuity, and a complex '660' km.

Burky, Irving & Simons, in prep

Flow at the 660?



See Alex Burky's AGU presentation for more details!



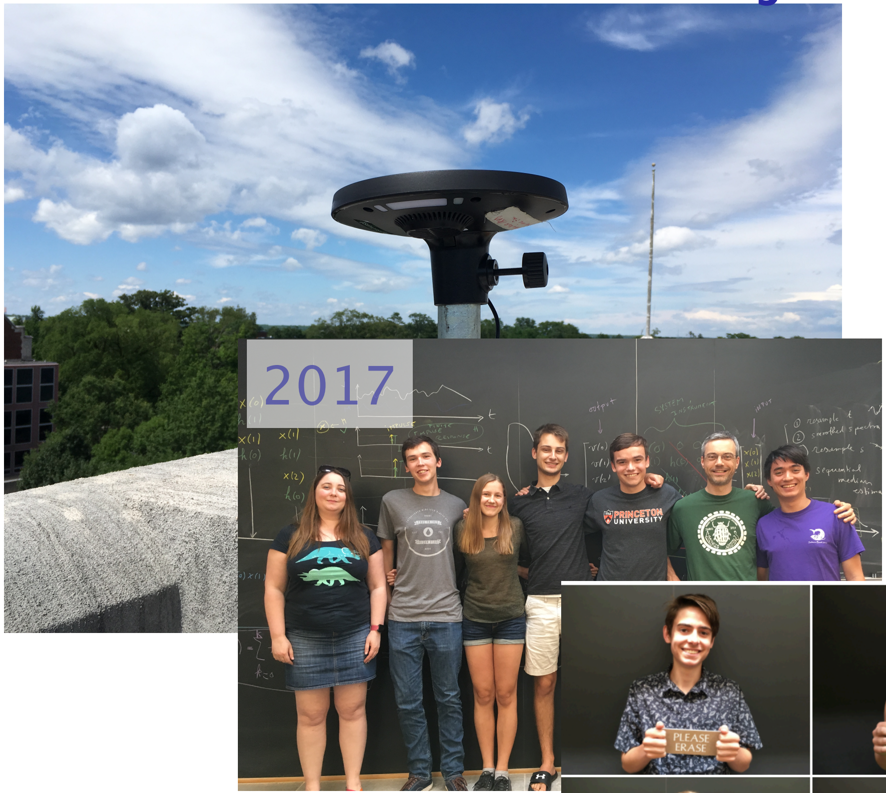
- We're developing a new receiver function metric to help assess receiver function quality.
- We find that Bermuda is underlain by a deeper than average '410' km discontinuity, and a complex '660' km.

Burky, Irving & Simons, in prep

Project GuyotPhysics

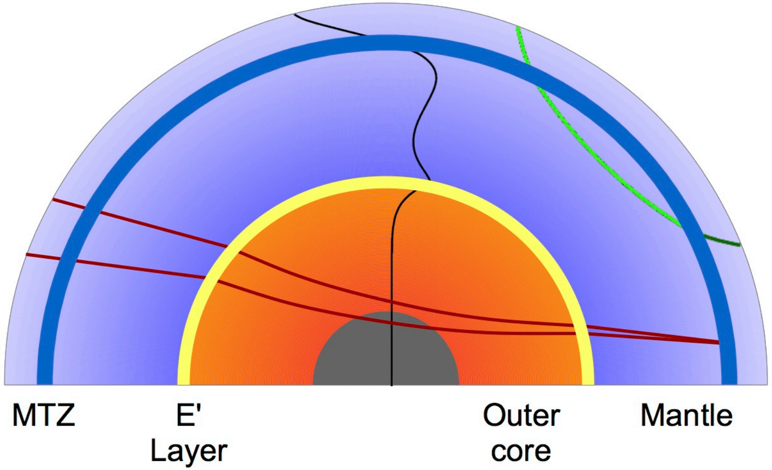
Project GuyotPhysics

Project GuyotPhysics



With Profs
Frederik Simons, Princeton &
Alain Plattner, U Alabama

Conclusions

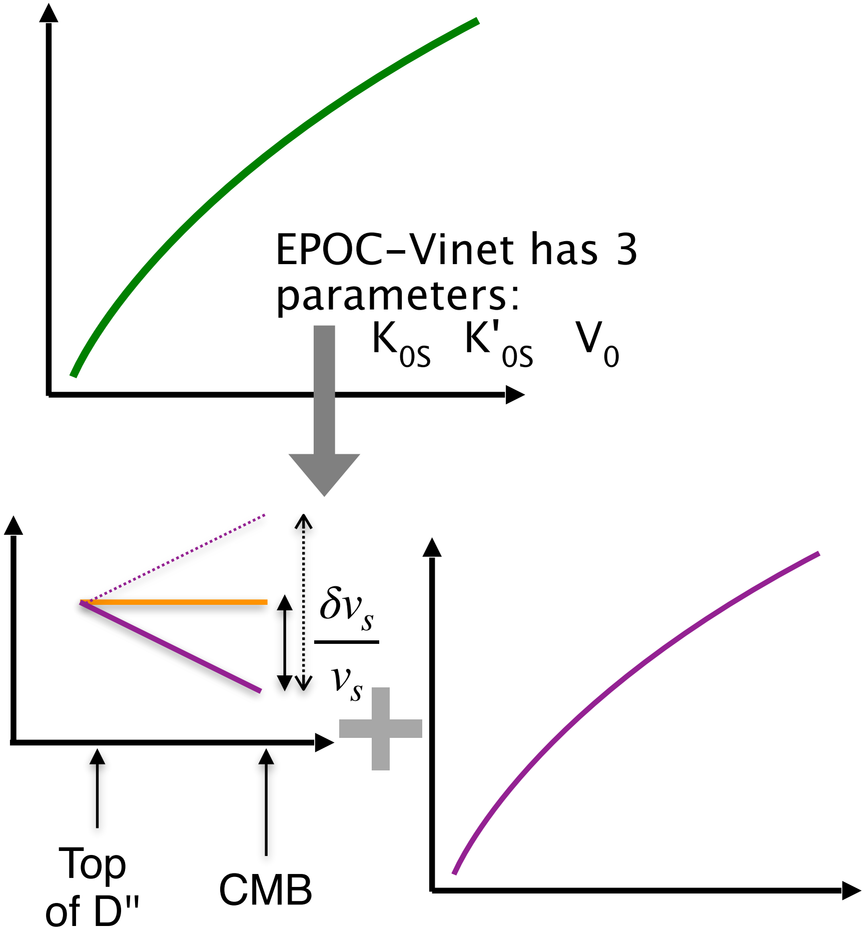


Long and short period seismology can be applied to look at the physical properties of the Earth at geodynamically important boundaries.

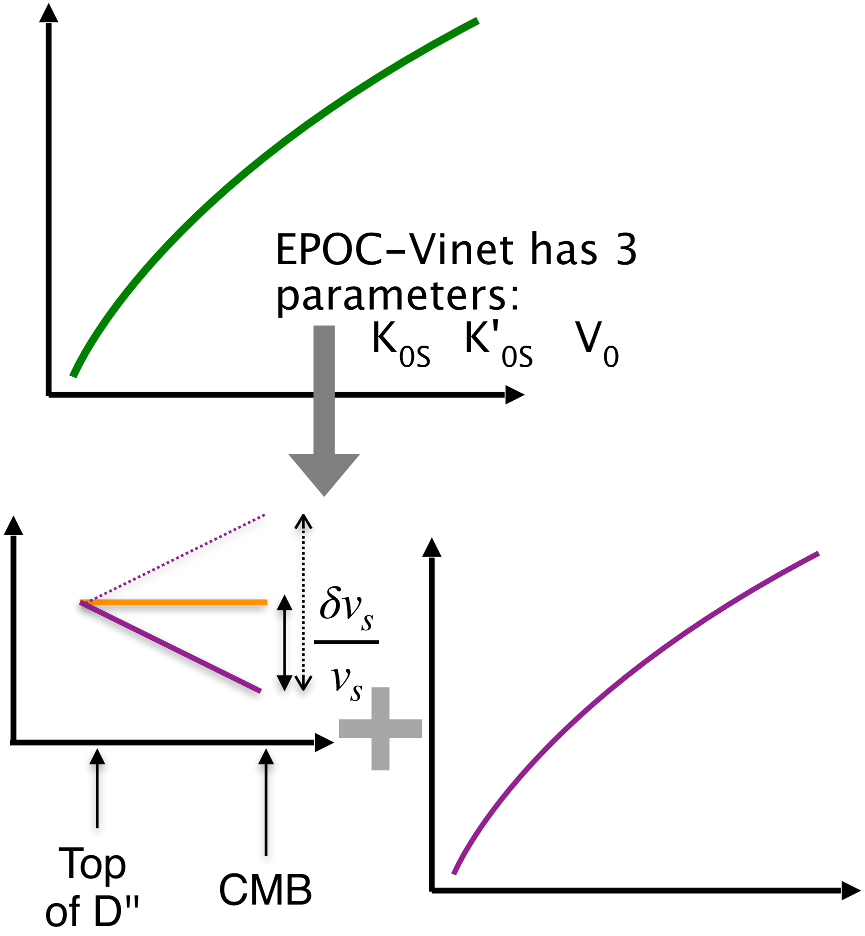
At the ‘660’, we see evidence of roughness, indicating imperfect mixing. This does not mean that material flow through the ‘660’ is absent, but it may be imperfect.

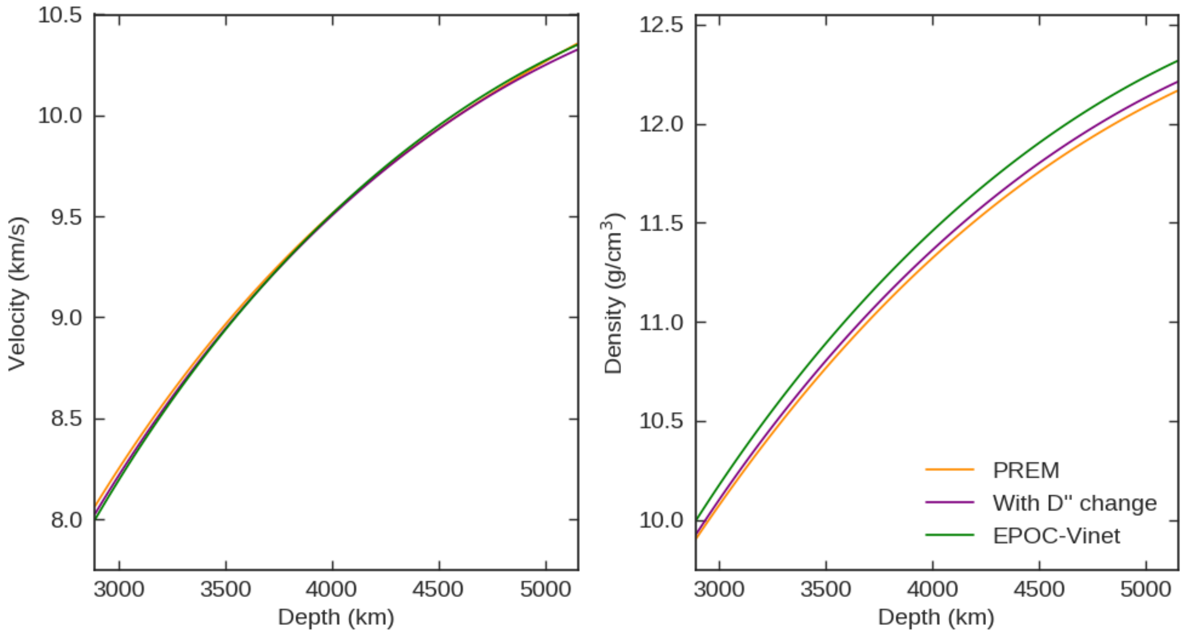
At the uppermost outer core, our EPOC outer core model reduces the need to have a slow E’, but when one is permitted it is favored. This suggests that there may be a compositionally distinct reservoir at the top of the outer core. The genesis mechanism for such a layer is still open.

Trade-offs with D'' properties



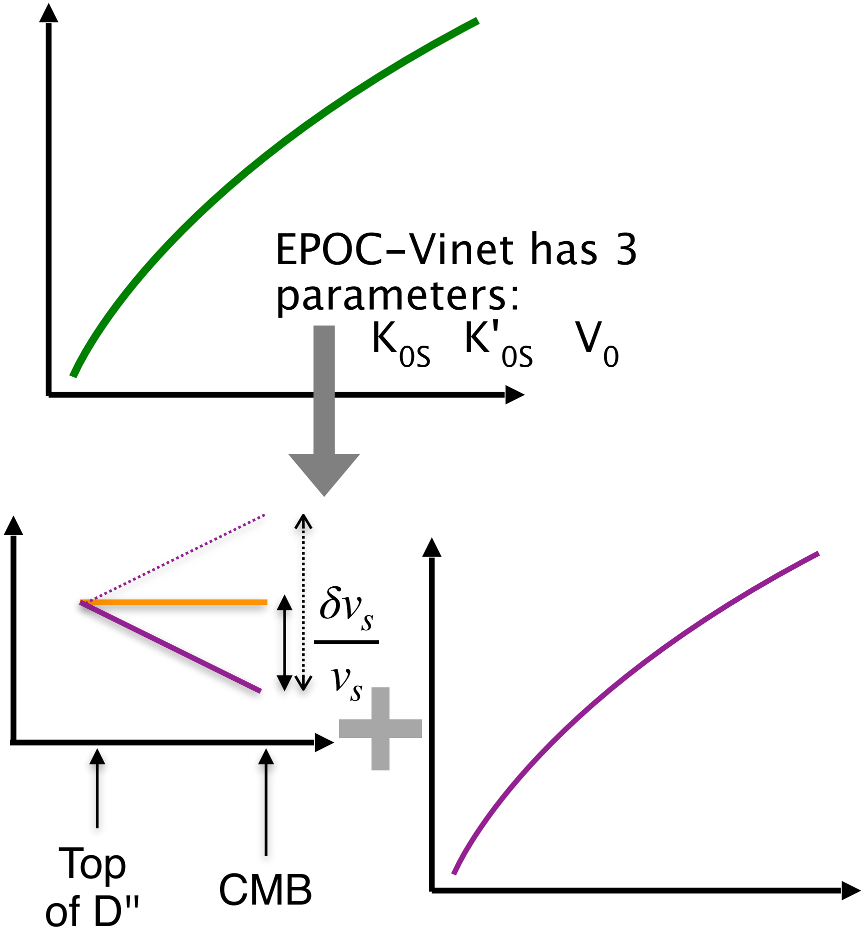
Trade-offs with D" properties

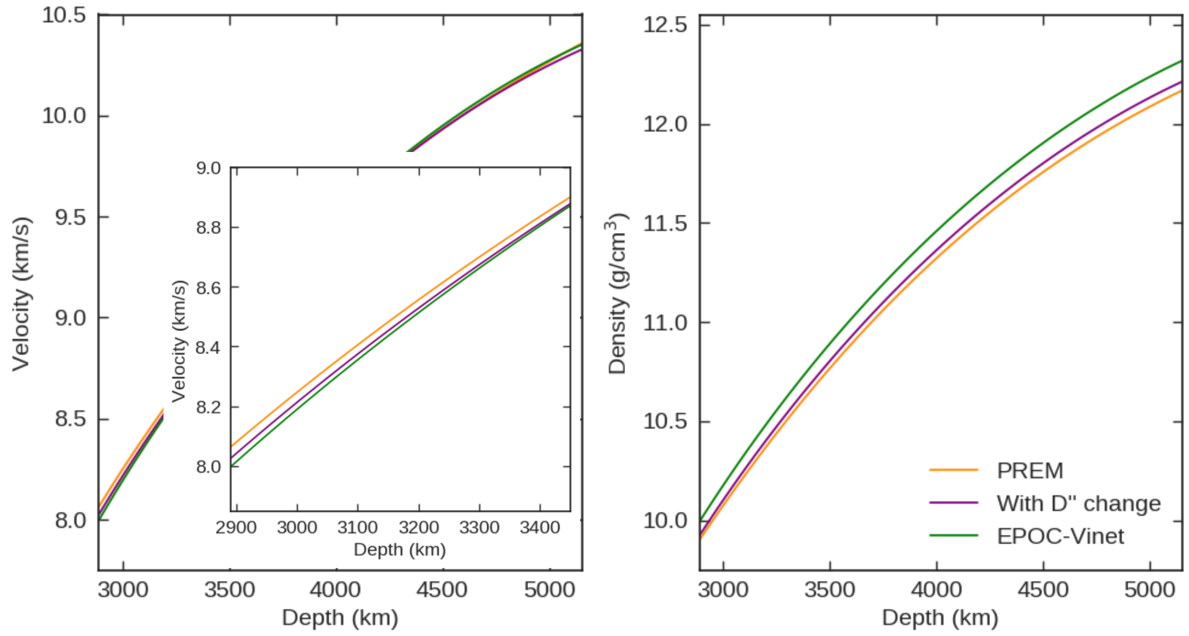




- Using the same methodology, we can let the seismic properties of the D" vary away from PREM towards the CMB. In this example we fix how v_p and ρ vary as v_s changes.
- In this case the velocity changes a little but ρ changes more.

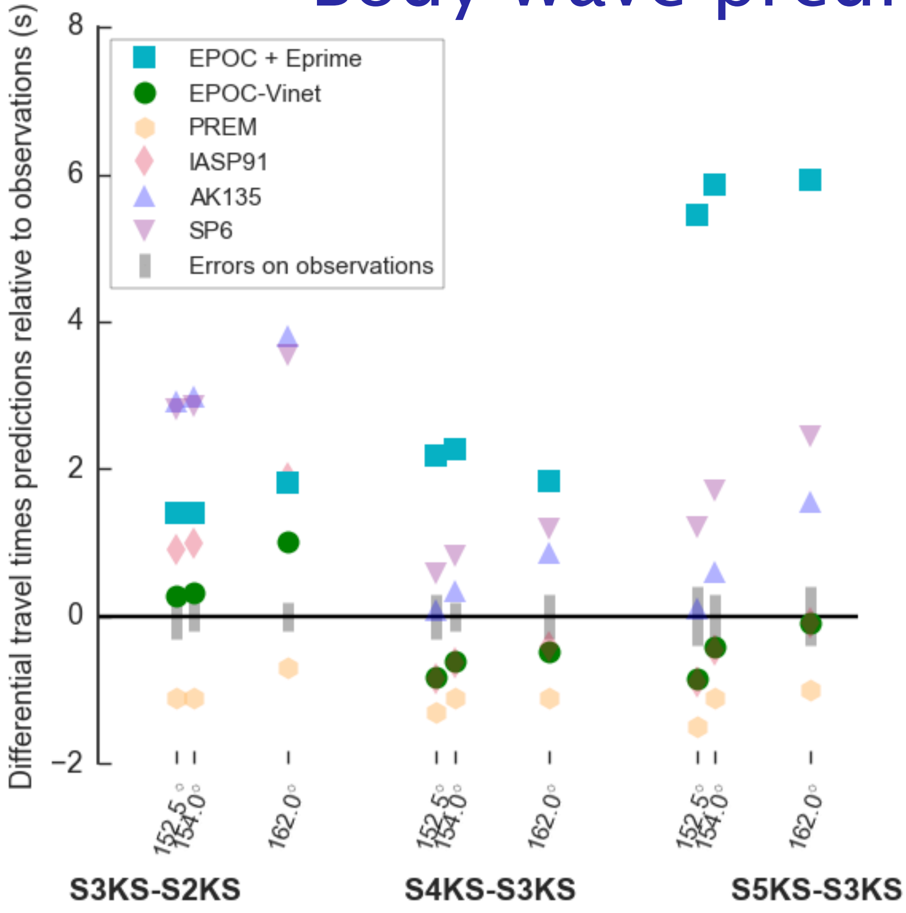
Trade-offs with D'' properties

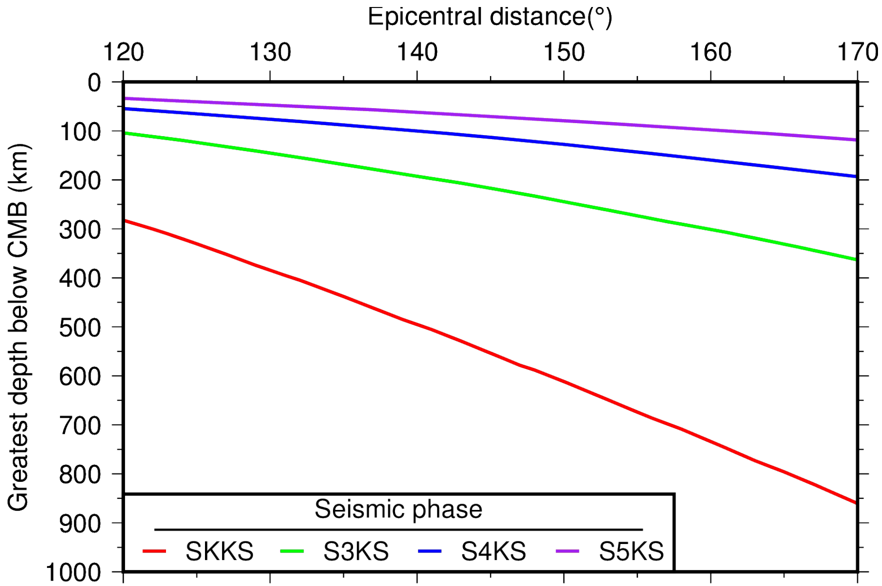




- Using the same methodology, we can let the seismic properties of the D'' vary away from PREM towards the CMB. In this example we fix how v_p and ρ vary as v_s changes.
- In this case the velocity changes a little but ρ changes more.

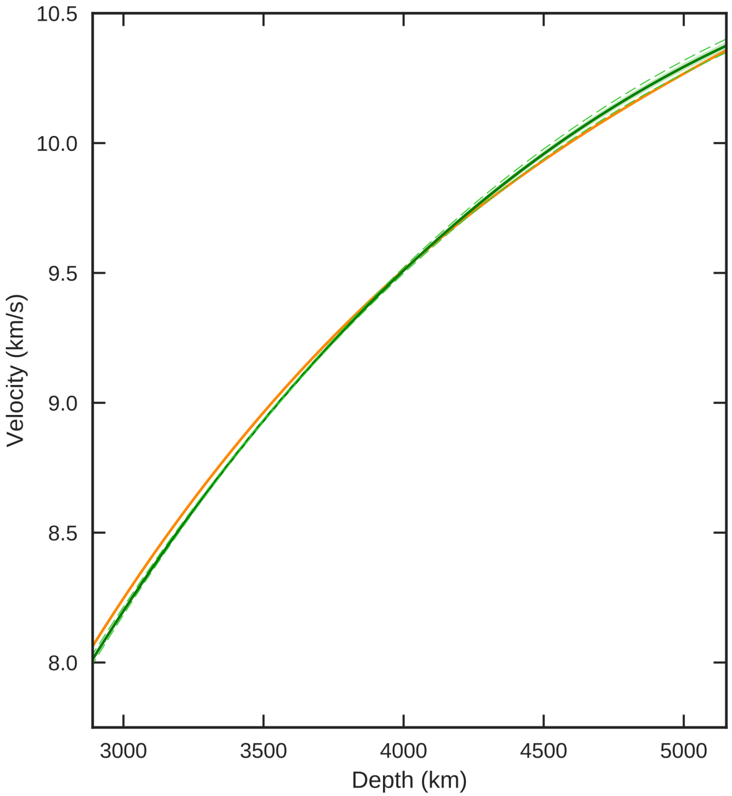
Body wave predictions for an E' layer

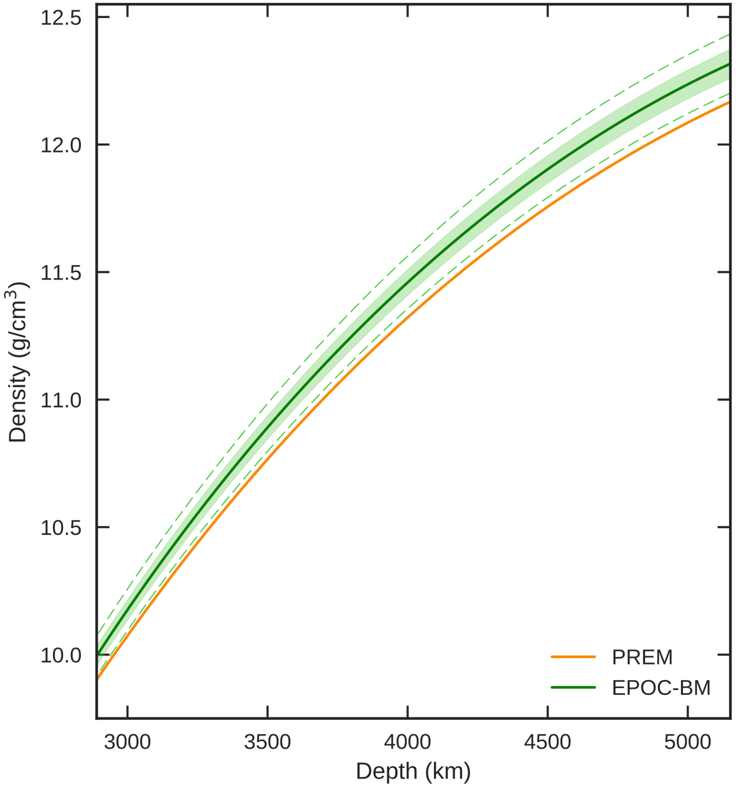




- Travel time anomalies are too extreme for rays which spend most of their time very close to the CMB → these model predictions may be too slow at the CMB when an E' layer is included.

What if we had used a Birch Murnaghan formulation?





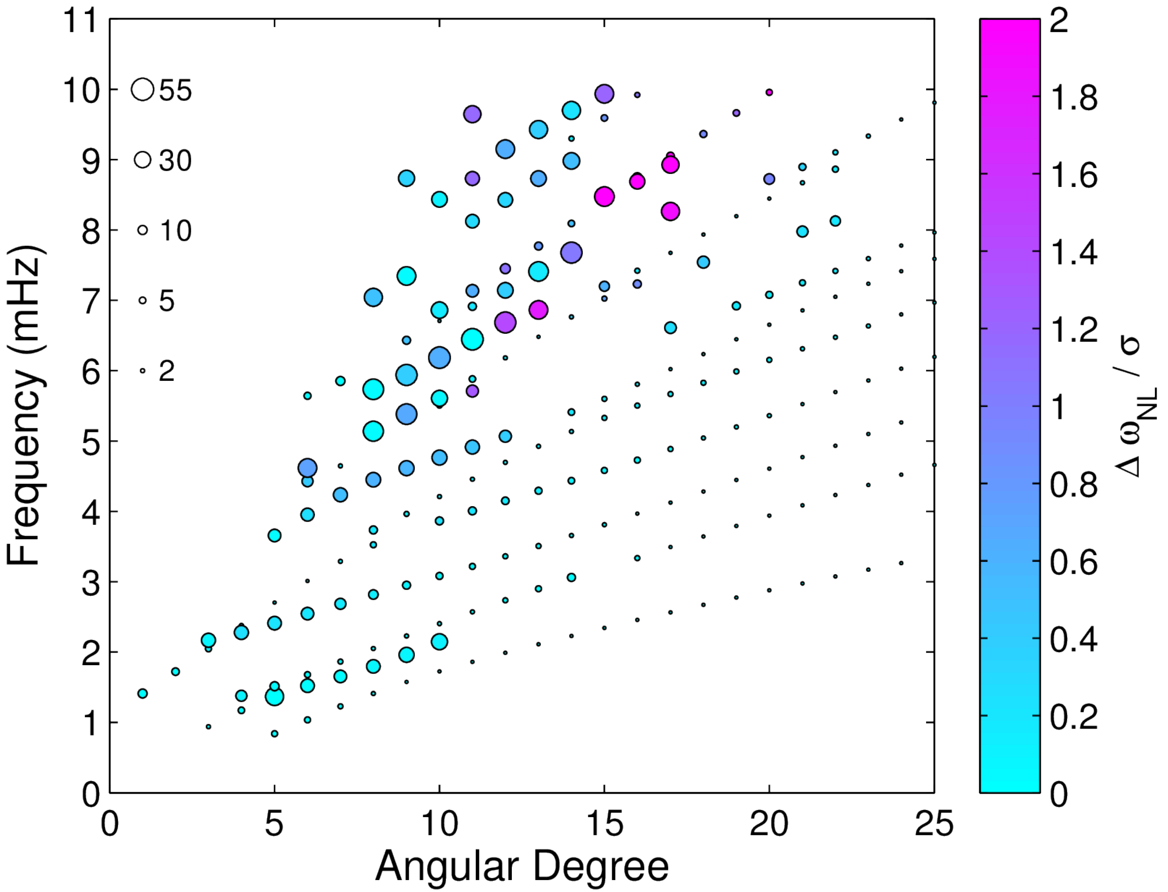
- Velocity & density models obtained from the ensemble of Birch–Murnaghan EoS parameters are very close to those of EPOC–Vinet:

$|\Delta Vp| \leq 0.02$km/s &
$|\Delta\rho| \leq 0.001$ g/cm^3.

- Different formulations give different extrapolations from core to ambient conditions result in different values for the EoS parameters

Irving, Cottaar & Lekić, *Science Advances,* 2018

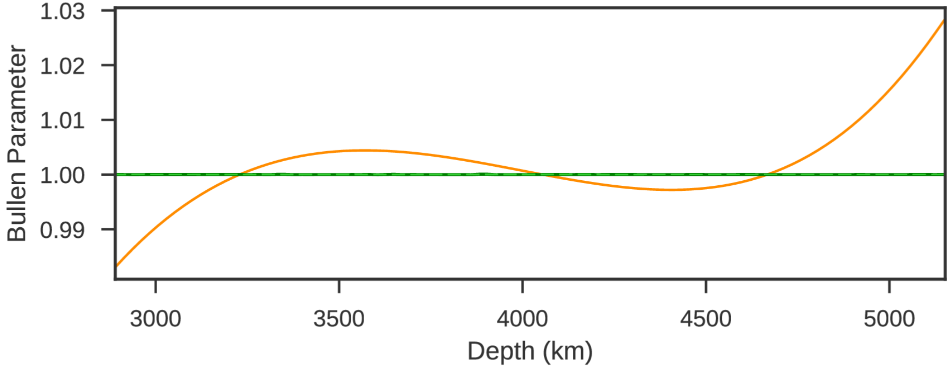
Why a linearized inversion might be problematic

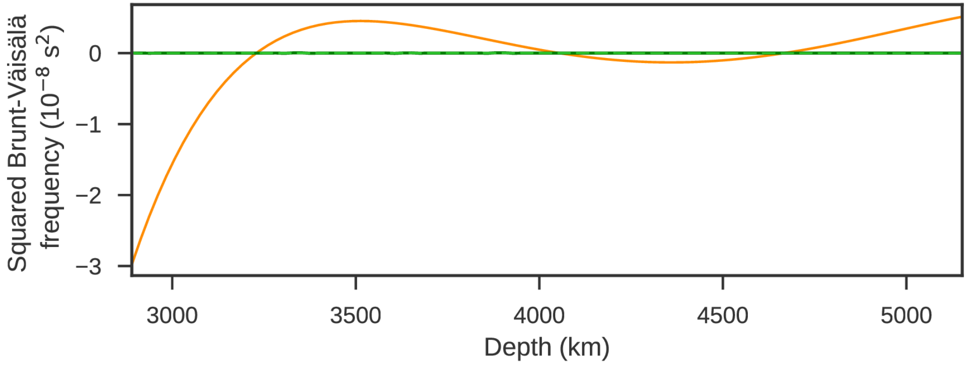


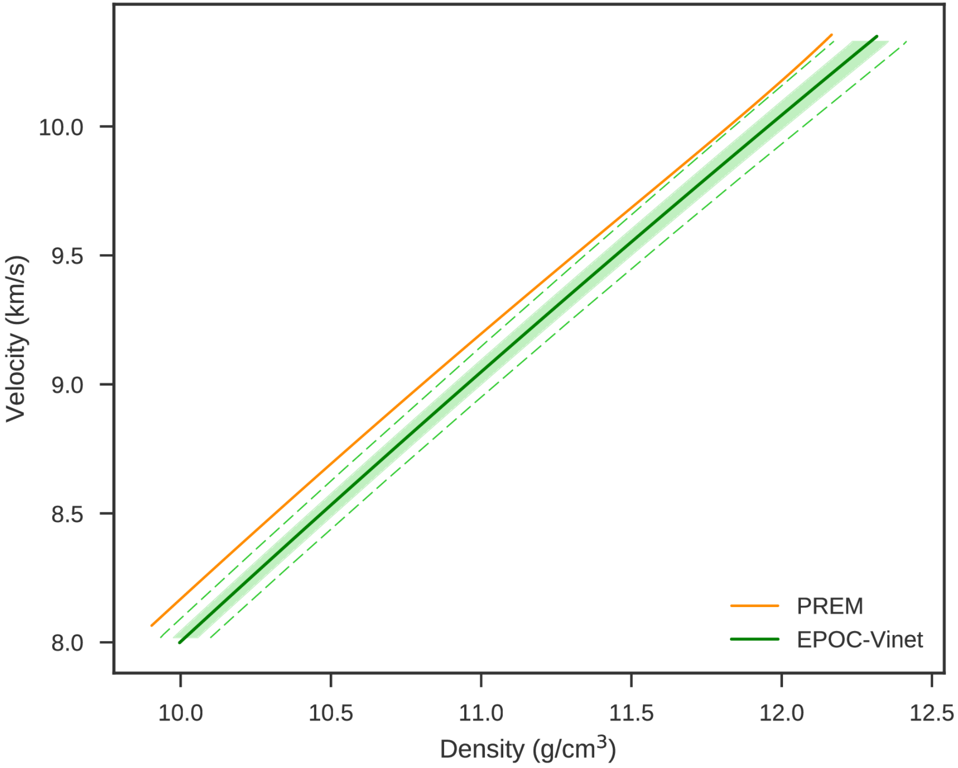
- Non-linearity of the relationship between mode center frequency and elastic parameters of the core.
- Each symbol corresponds to a different mode used, and its size is proportional to the mode's sensitivity to outer core structure (%).
- Symbol color represents the magnitude of the non-linearity of mode frequency shift due to a 1% perturbation to outer core v_p, compared to uncertainty on the measurement due to mantle structure (which is nearly always greater than measurement error).

Irving, Cottaar & Lekić, *Science Advances*, 2018

EPOC–Vinet is homogeneous and stable







Irving, Cottaar & Lekić, *Science Advances,* 2018

Selected References

- AK135: B. L. N. Kennett, E. R. Engdahl, and R. Buland. Constraints on seismic velocities in the Earth from travel times. Geophys. J. Int., 122(1):108-124, 1995.
- Burnman: S. Cottaar, T. Heister, I. Rose, C. Unterborn. BurnMan: A lower mantle mineral physics toolkit. Geochem. Geophys. Geosyst. 15:1164-1179, 2014.
- IASP91: B. L. N. Kennett and E. R. Engdahl. Traveltimes for global earthquake location and phase identification. Geophys. J. Int., 105(2):429-465, 1991.
- MINEOS: G. Masters, M. Barmine, and S. Kientz. Mineos. California Institute of Technology, Pasadena, CA, 2011 and J. H. Woodhouse, The calculation of eigenfrequencies and eigenfunctions of the free oscillations of the Earth and the Sun, in Seismological algorithms: Computational Methods and Computer Programs, 1988
- PEM: A. M. Dziewonski, A. L. Hales, and E. R. Lapwood. Parametrically simple Earth models consistent with geophysical data. Phys. Earth Planet. Inter., 10(1):12-48, 1975.
- PREM: A. M. Dziewonski and D. Anderson. Preliminary Reference Earth Model. Phys. Earth Planet. Inter., 25(4):297-356, 1981.
- PREM2: X. Song and D.V. Helmberger. A P wave velocity model of Earth's core. Journal of Geophysical Research: Solid Earth. 100(B6):9817-30, 1995.
- SP6: A. Morelli and A. M. Dziewonski. Body wave traveltimes and a spherically symmetric P-and S-wave velocity model. Geophys. J. Int., 112(2):178-194, 1993.
- Mode data:

  A. Deuss, J. Ritsema, and H. van Heijst. A new catalogue of normal-mode splitting function measurements up to 10 mHz. Geophys. J. Int., 193(2):920-937, 2013.
  P. Koelemeijer, A. Deuss, and J. Ritsema. Observations of core-mantle boundary Stoneley modes. Geophys. Res. Lett., 40(11):2557-2561, 2013.
  T . G. Masters and R. Widmer. Free Oscillations: frequencies and attenuations, Volume 1, pages 104-125. American Geophysical Union, 1995.
  REM. Reference Earth Model website. http://igppweb.ucsd.edu/~gabi/rem.html
  J. S. Resovsky and M. H. Ritzwoller. New and refined constraints on three-dimensional Earth structure from normal modes below 3 mHz. J. Geophys. Res., 103(B1):783-810, 1998.

- Other outer core models:

C. Alexandrakis and D. W Eaton. Precise seismic-wave velocity atop Earth’s core: No evidence for outer-core stratification. Phys. Earth Planet. Inter., 180(1):59-65, 2010.
A. L. Hales and J. L. Roberts. The velocities in the outer core. Bull. Seismol. Soc. Am., 61(4): 1051-1059, 1971.
E. J. Garnero, D. V. Helmberger, and S. P. Grand. Constraining outermost core velocity with SmKS waves. Geophys. Res. Lett., 20(22):2463-2466, 1993.
G. Helffrich and S. Kaneshima. Outer-core compositional stratification from observed core wave speed profiles. Nature, 468(7325):807-810, 2010.
S. Kaneshima and G. Helffrich. Vp structure of the outermost core derived from analysing large-scale array data of SmKS waves. Geophys. J. Int., 193(3):1537-1555, 2013.
T. Lay and C. J. Young. The stably-stratified outermost core revisited. Geophys. Res. Lett., 17 (11):2001-2004, 1990.
R. Kind and G. Müller. The structure of the outer core from SKS amplitudes and travel times. Bull. Seismol. Soc. Am., 67(6):1541-1554, 1977.
S. Tanaka. Possibility of a low P-wave velocity layer in the outermost core from global SmKS waveforms. Earth Planet. Sci. Lett, 259(3):486-499, 2007.
V. Tang, L. Zhao, and S.-H. Hung. Seismological evidence for a non-monotonic velocity gradient in the topmost outer core. Sci. Rep., 5:8613, 2015.