Seismic Tomography (Part IV, Key results)

Text-book image of the earth

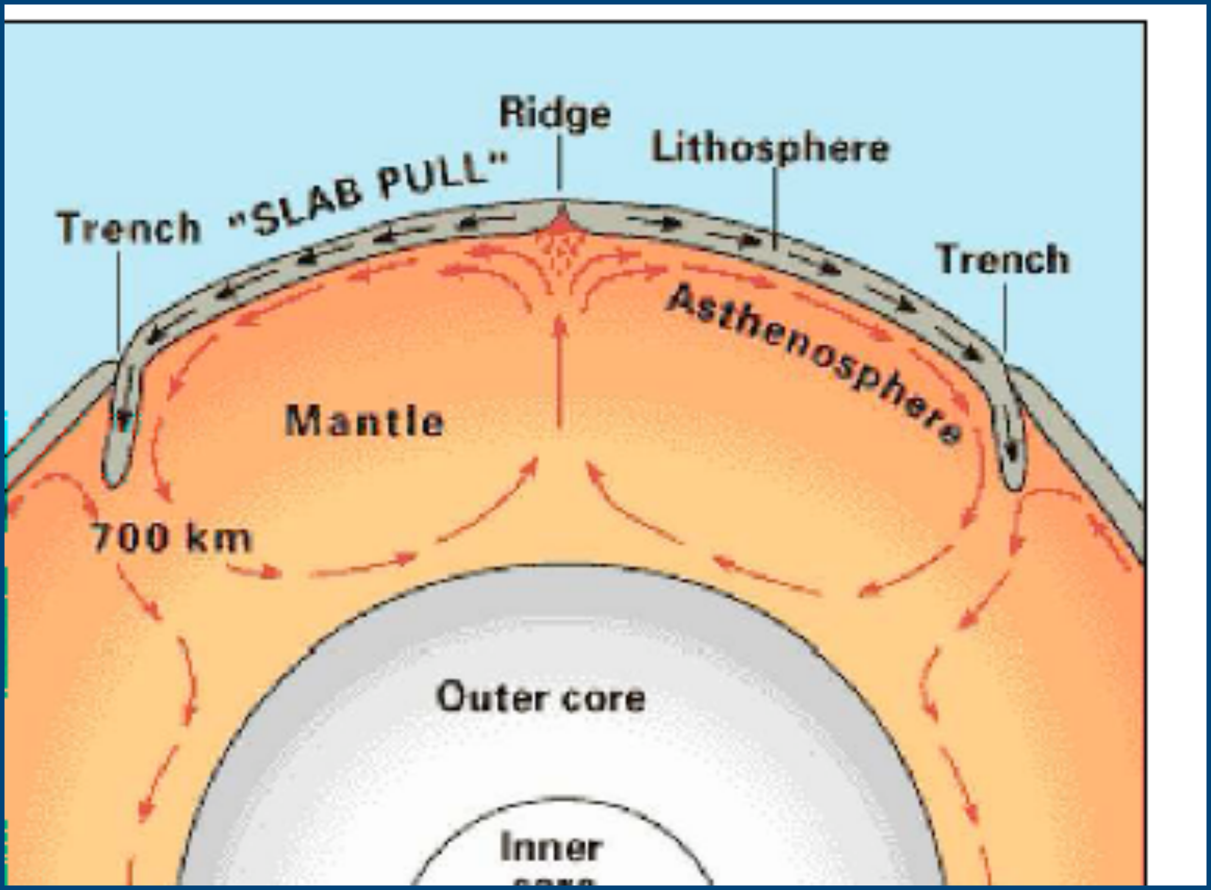
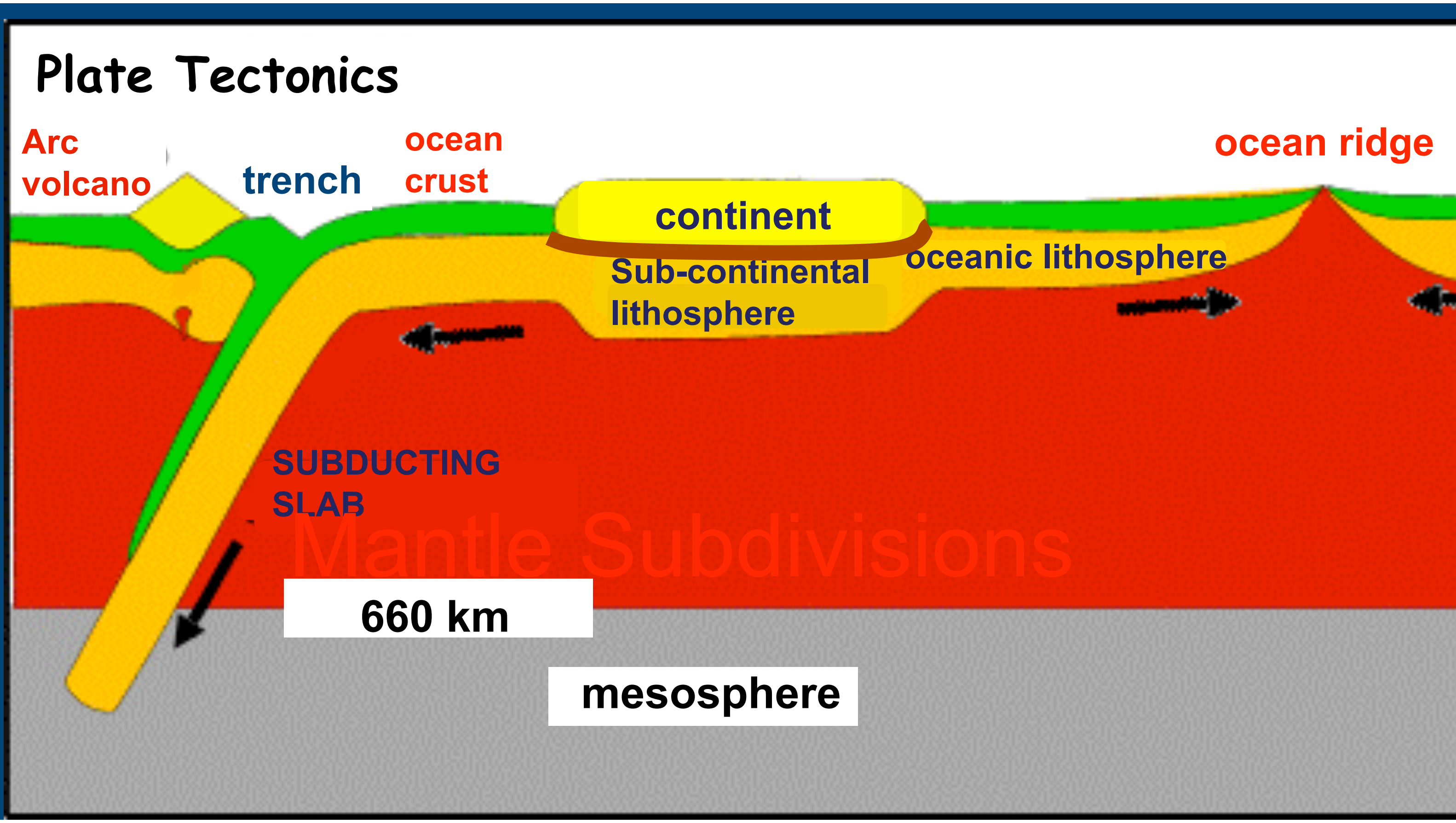
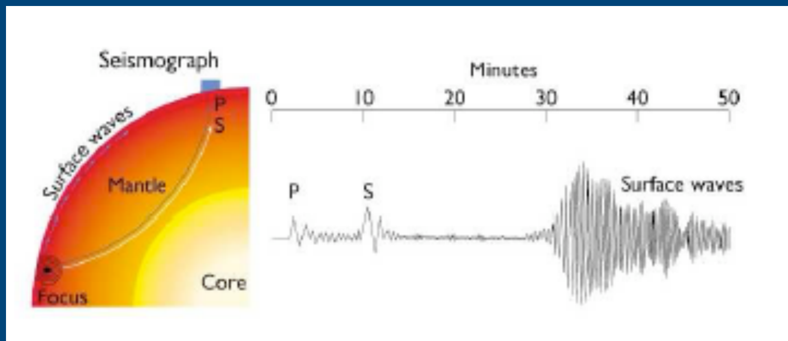


Table 6.1. Subdivisions of the earth. (Modified from Ringwood, 1975.)

Subdivision	Depth to boundaries (km)	Volume fraction of earth		Mass fraction of earth		Mass fraction of mantle
Crust	0–Moho	0.008		0.004		0.006
Upper mantle	Moho–400	0.16		0.10		0.15
Transition zone	400–1,000	0.22	0.82	0.17	0.68	0.24
Lower mantle	1,000–2,900	0.44		0.41		0.60
Outer core	2,900–5,100	0.154	0.162	—	0.32	—
Inner core	5,100–6,371	0.008		—		—

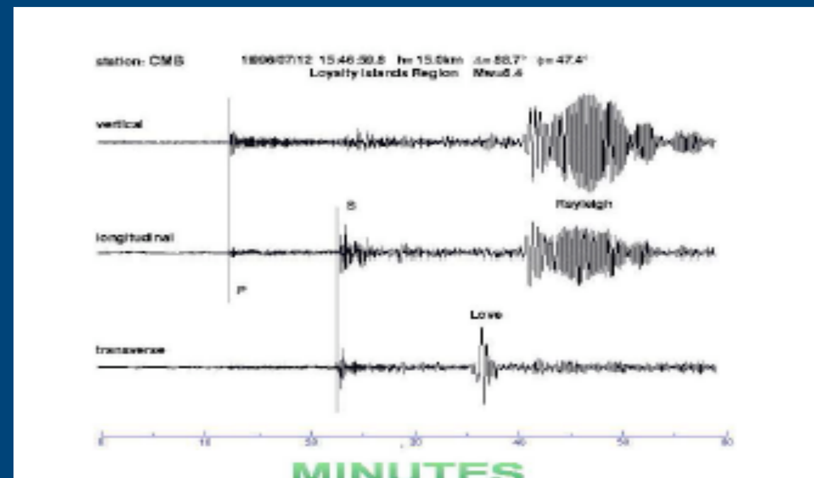


Common Data Types:

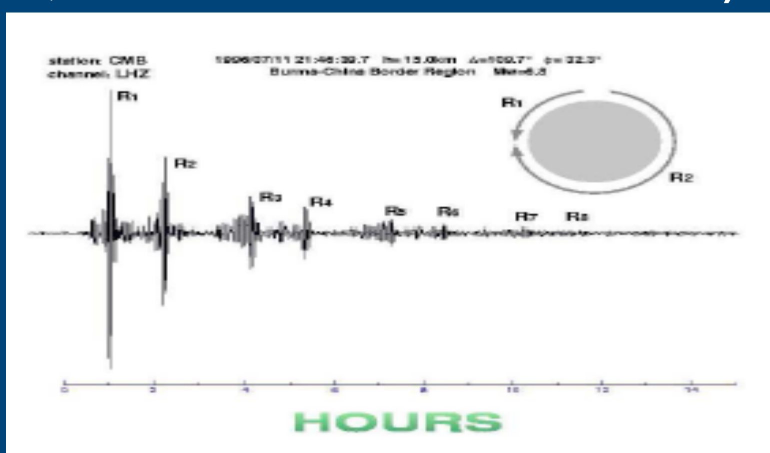


1. Travel time of body waves (especially differential times --- they are less sensitive to source-related errors)

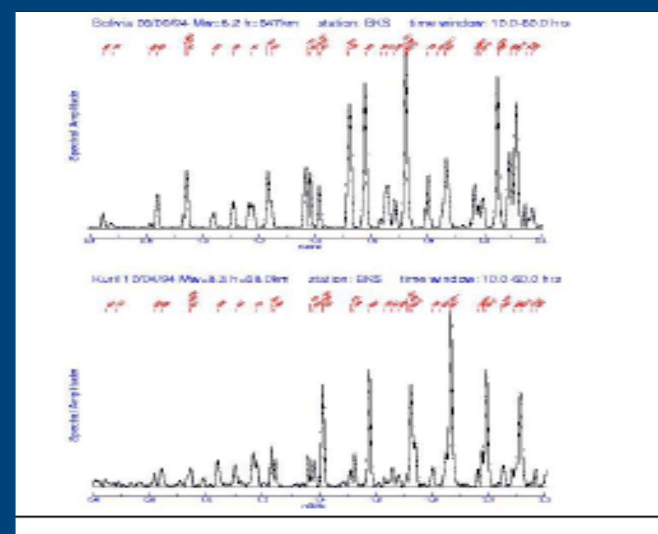
2. Fundamental Mode Surface Waves

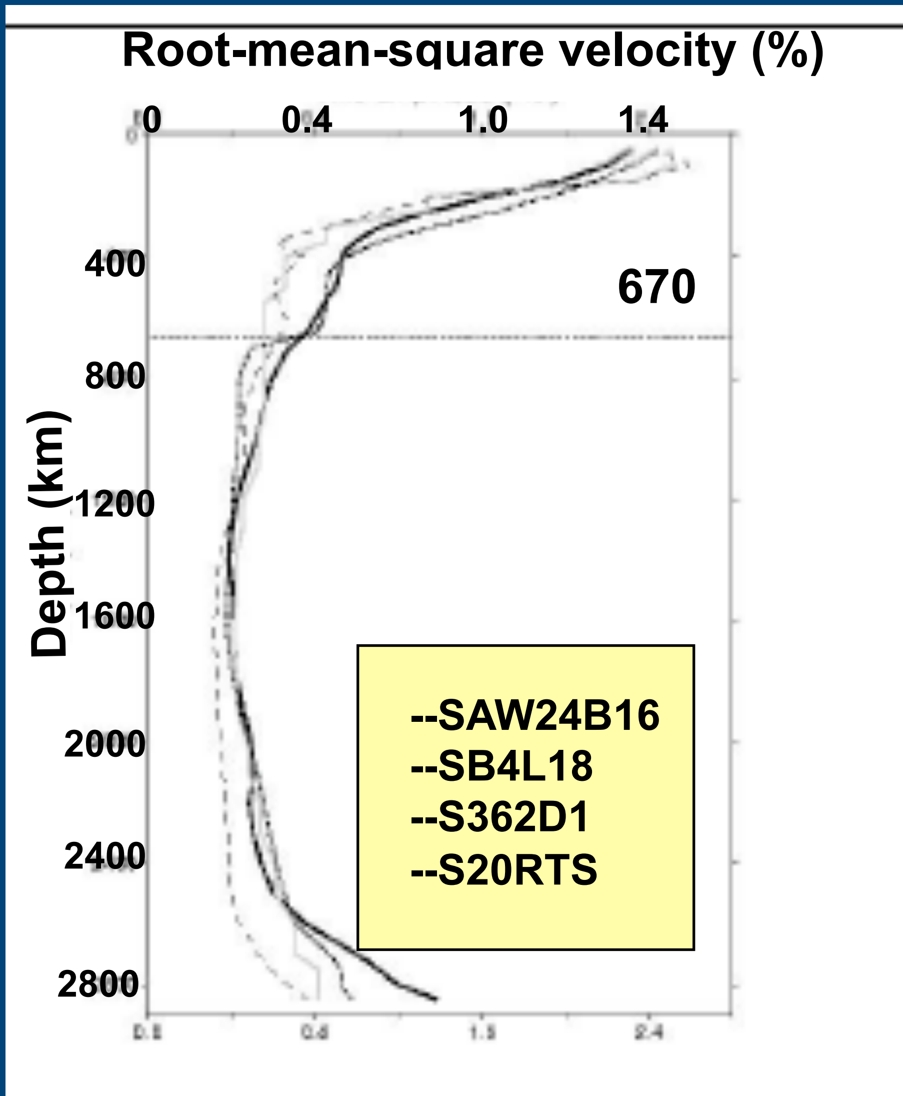


3. Longer Path Surface Waves (especially in resolving average variations across the earth, also odd-ordered harmonics)



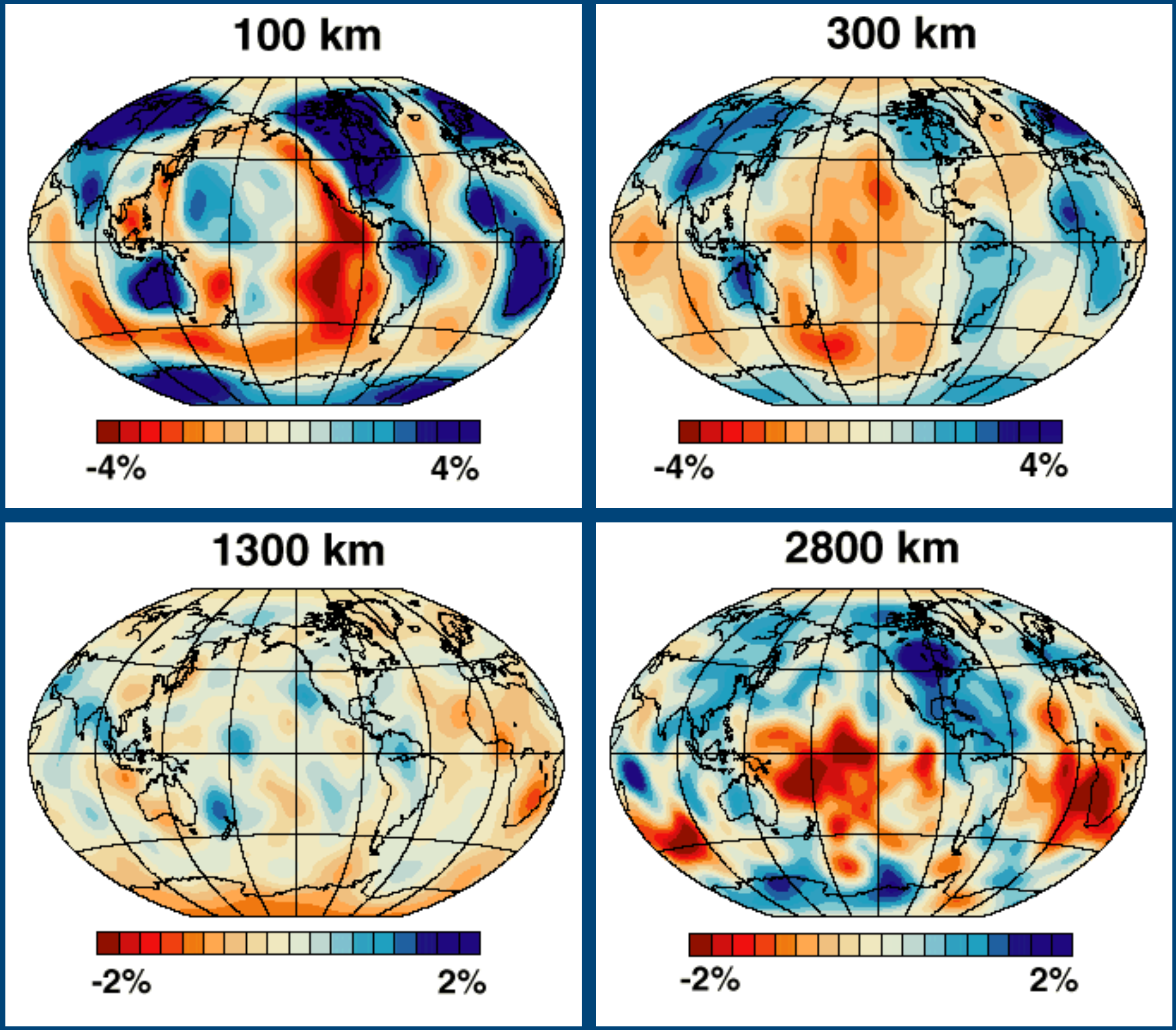
4. Normal Mode Frequencies (density sensitive)





Sum of the root-mean-squared velocity perturbations at a given depth of the earth. We can clearly see a highly heterogeneous upper mantle, a strange transition zone (400-700 km) and an increase in the level of average perturbations at the lower-most mantle.

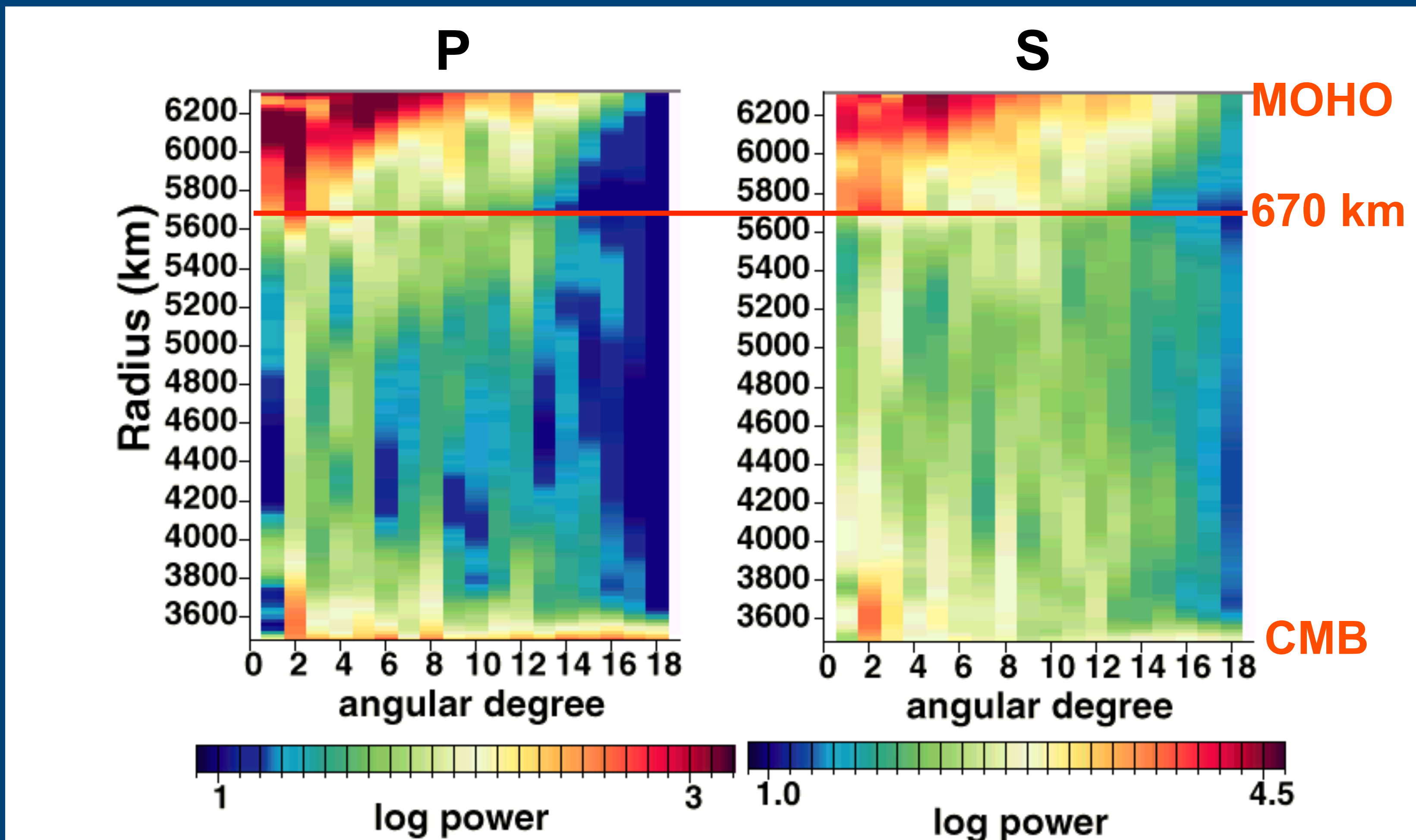
Shear Velocity



Fact 1: Lithosphere and Lowermost Mantle are highly heterogeneous

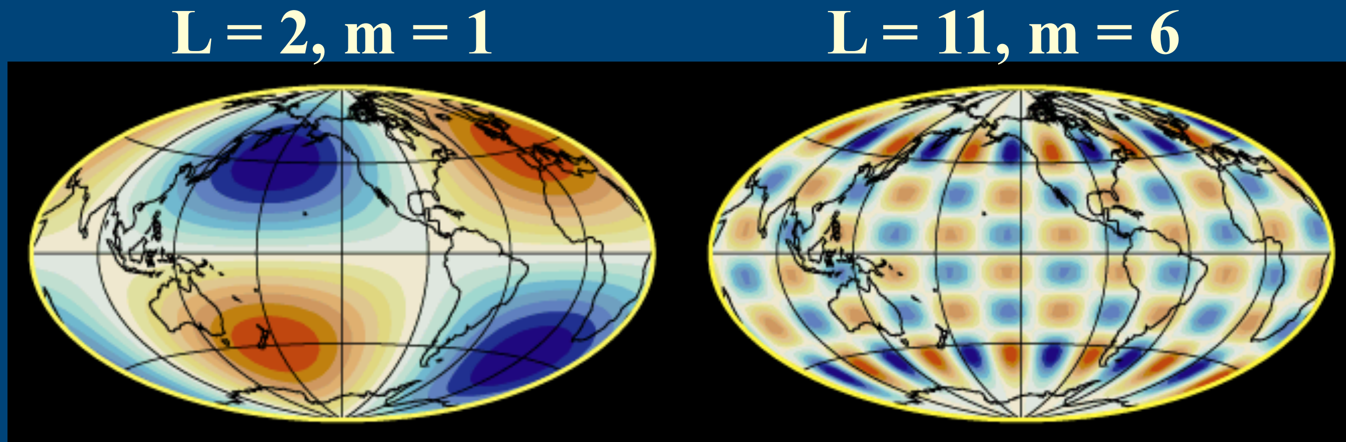
(TOPO362, *Gu et al., 03*)

Fact II: The mantle is dominated by long wavelengths, from top to the bottom

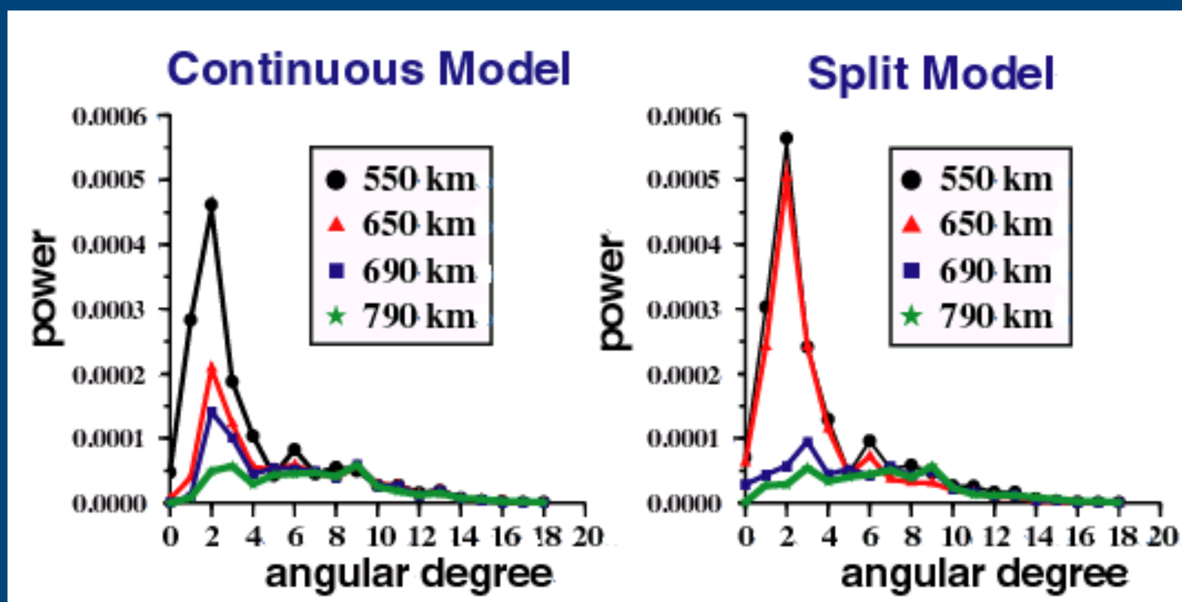


What is shown: Each vertical strip represents the power (spherical harm power of deg L = sum (coef_of_each_m squared) (2l+1 terms)

Spherical Harmonics



Power Spectra

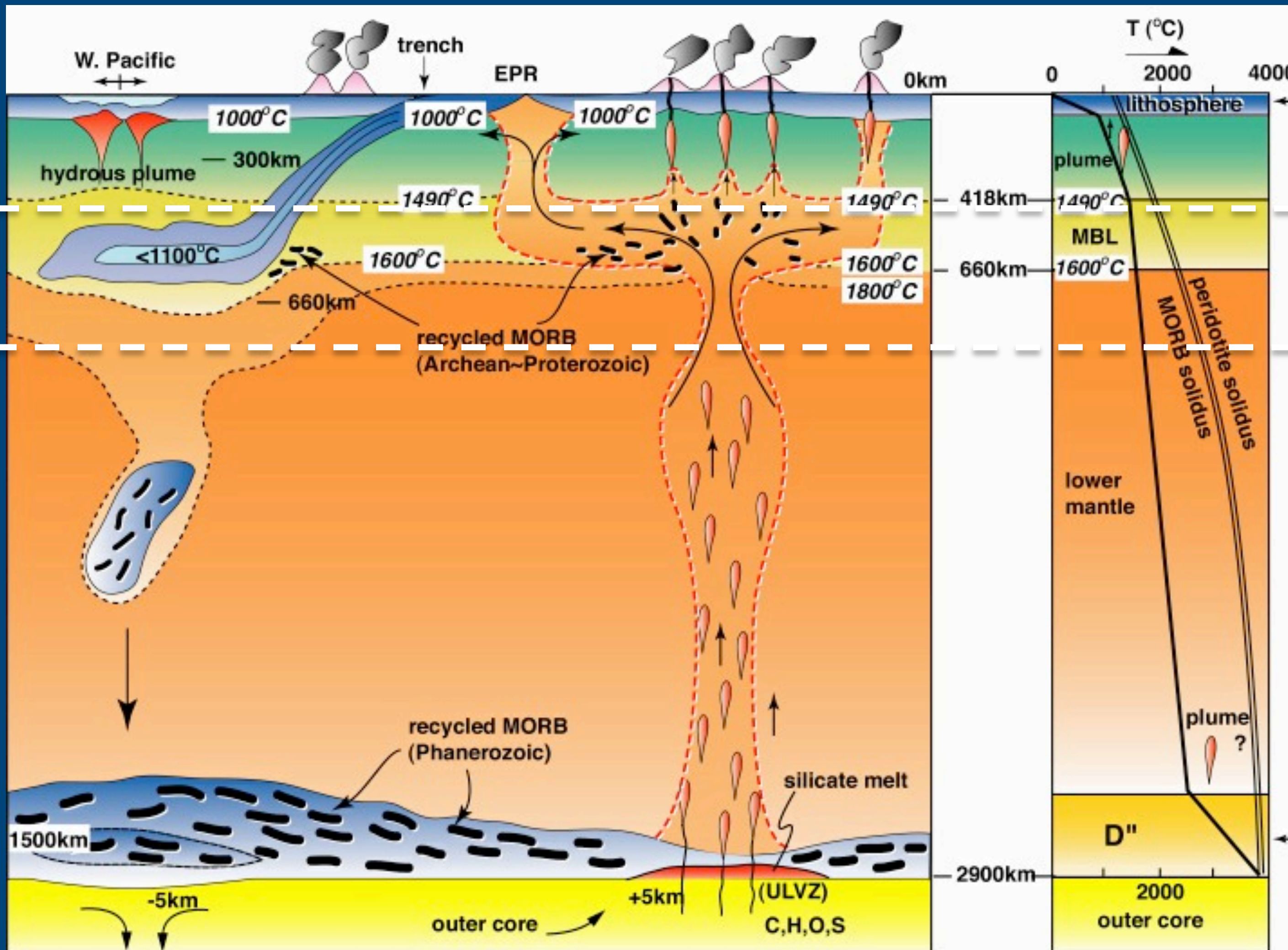


Key features: sharp dropoff

It is not that simple!

Continuous Plumes and Slabs ??

Boundary zone?



Main obstacle:: limited data sensitivity and resolution

The Battle of the MIDDLE EARTH:

End-member Global Convection Models

'Layered-mantle'

Flow Barrier?

'Whole-mantle'

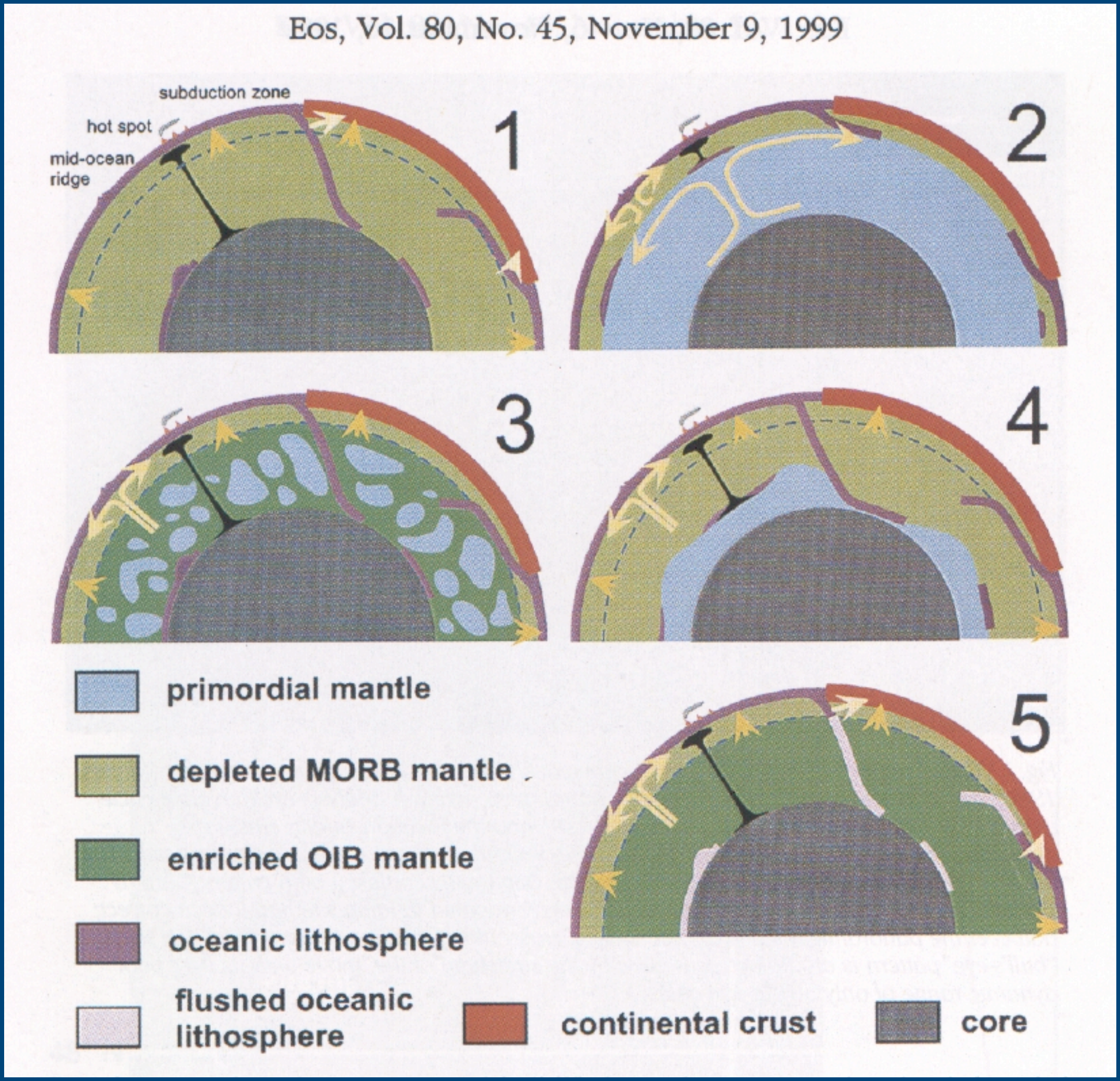
There is no shortage of Models

Possible, Geochem?

No penetrating slabs

Too exotic, too rough

Invisible?



Modified from Albarede & van der Hilst, 1999

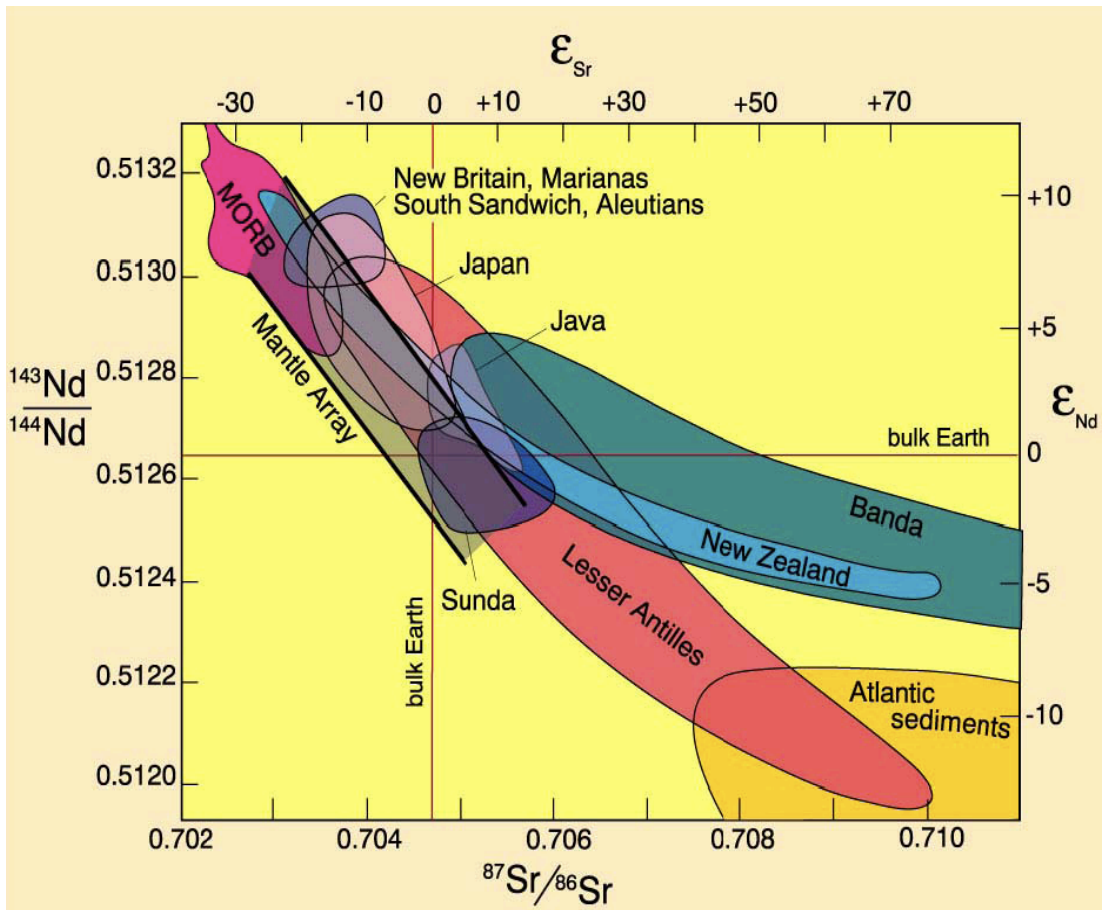
1. New Britain, Marianas, Aleutians, and South Sandwich show restricted range close to MORB (*mid-ocean ridge basalt*)

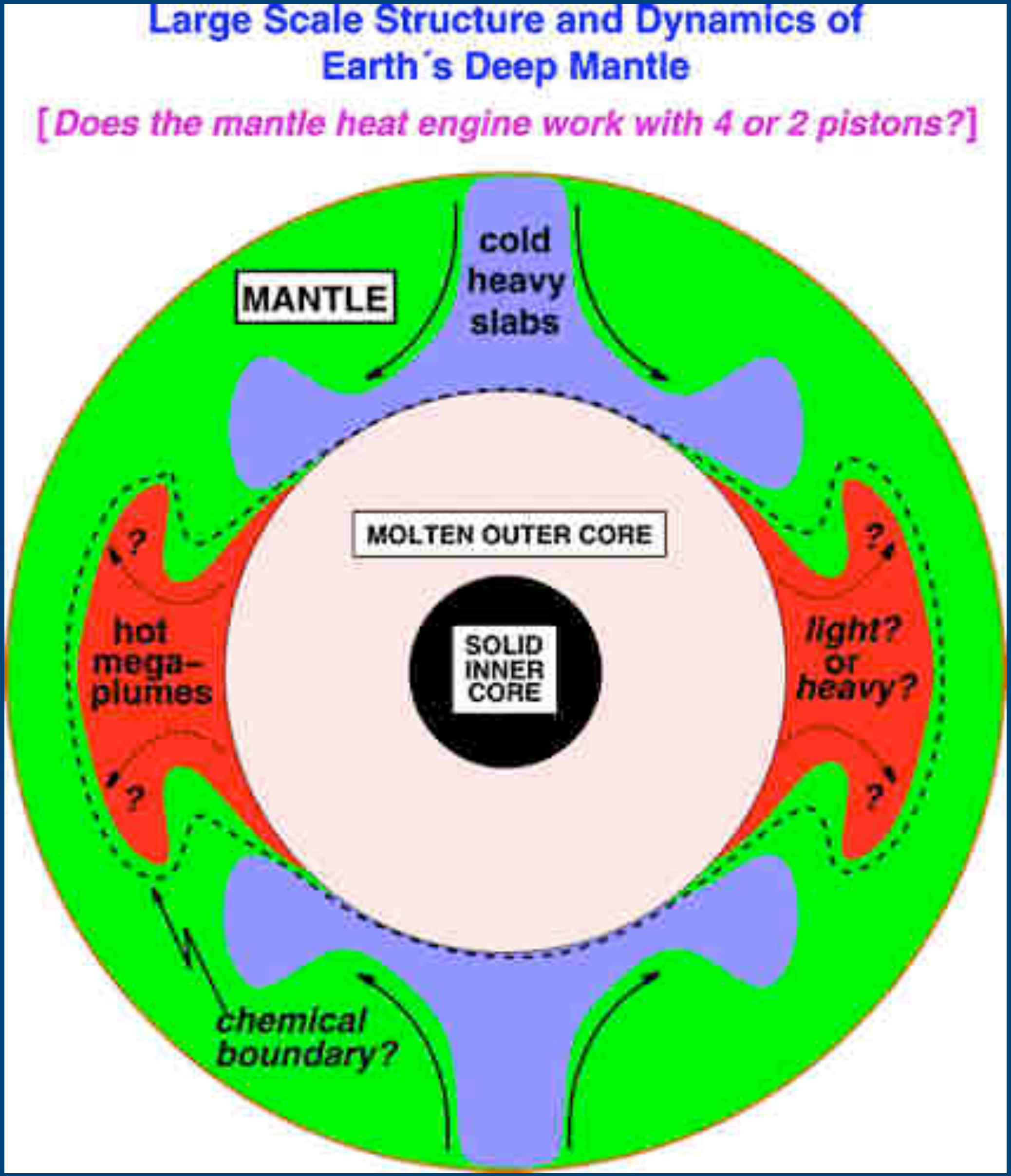
2. Other arcs show the effect of addition of different continental components to source, most likely Atlantic sediment (Antilles) or Pacific sediment (Banda, New Zealand). The basaltic lavas are more enriched in radioactive elements (more "original" or "*primordial*") and more gassed. These are often referenced as "*Ocean Island Basalt*" ***(or OIB)***

Indication:

Perhaps there is a deeper Reservoir such that Mid-ocean ridges are only sensing the upper mantle (which is de-gassed and less radioactive, as in MORB), where as there is a lower mantle reservoir that is only sampled by the ocean islands in the form of OIB.

***Heat flow paradox*: total expected heat flow budget= 45 Terawatt, observed 31-34 Terawatt, something hidden??**





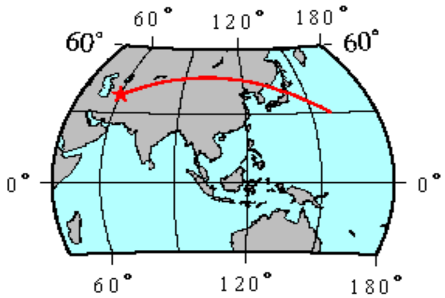
Taken from Forte and Mitrovica's work

Question:

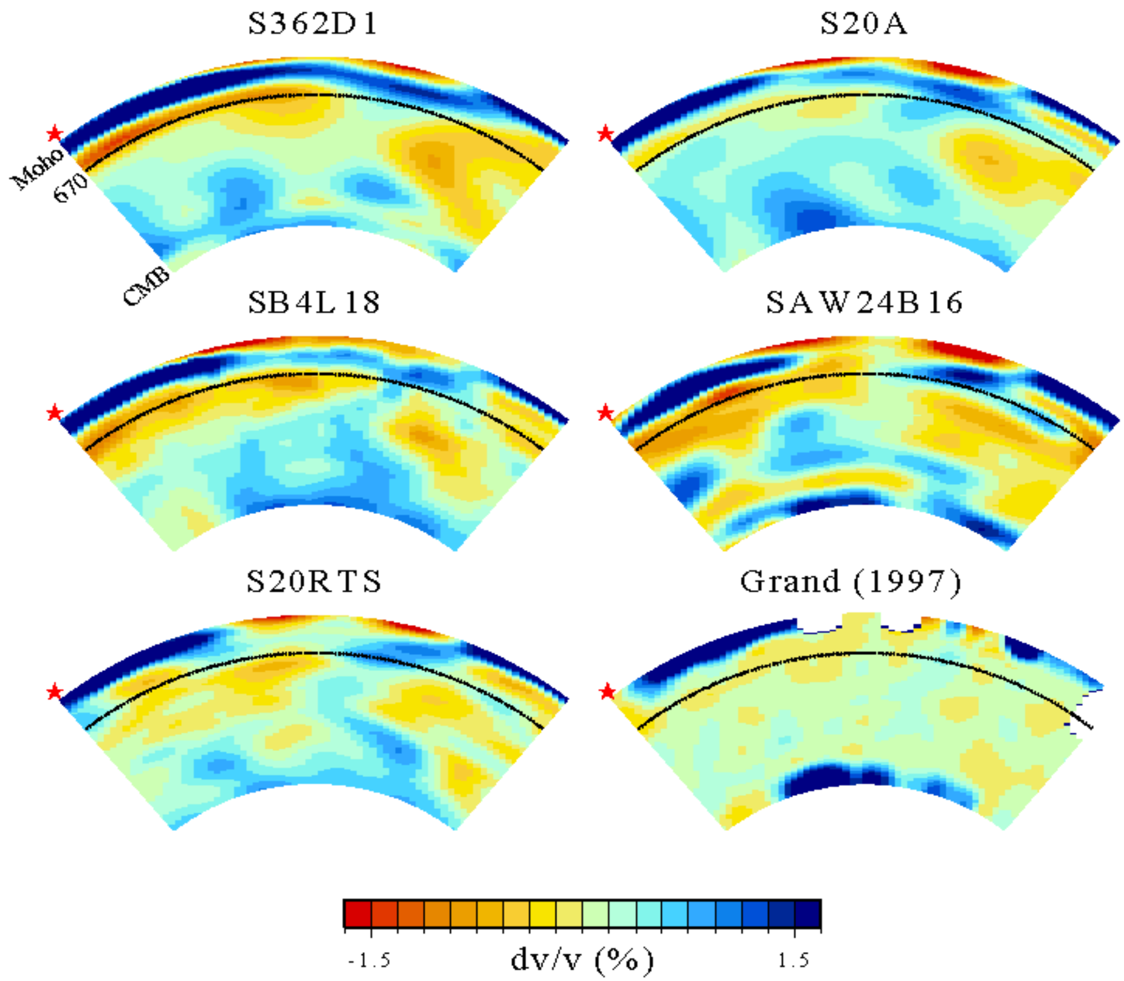
Is mantle "top-down" or "bottom-up", or perhaps both?

Focus:

1. Velocity
2. Mantle interfaces
3. Anisotropy



Isotropic Shear Velocity



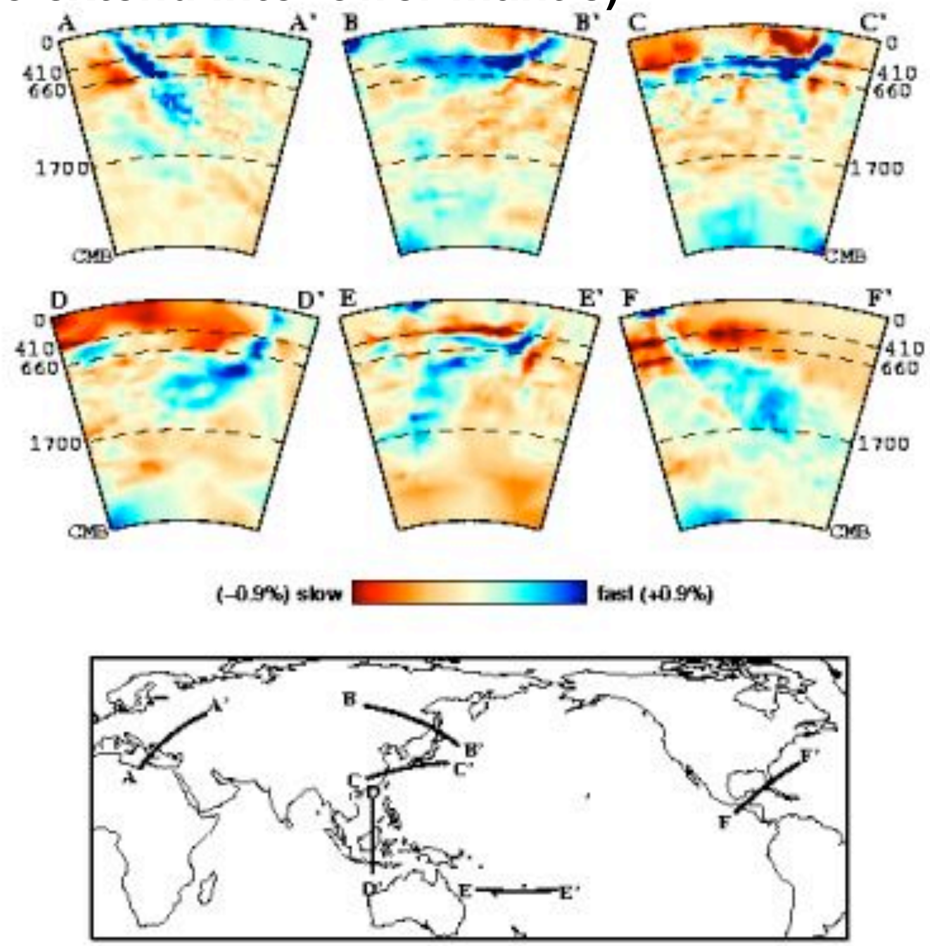
Gu et al. 01

Top-down view

Indications of slab-like high velocities can potentially be found in the Lower Mantle beneath the Tonga, North/Central America (Farallon).

The origins, depths and strengths are all different.

High resolution model of the Earth (showing different slab geometries, some seem to flatten in the upper mantle, some seem to extend into lower mantle)

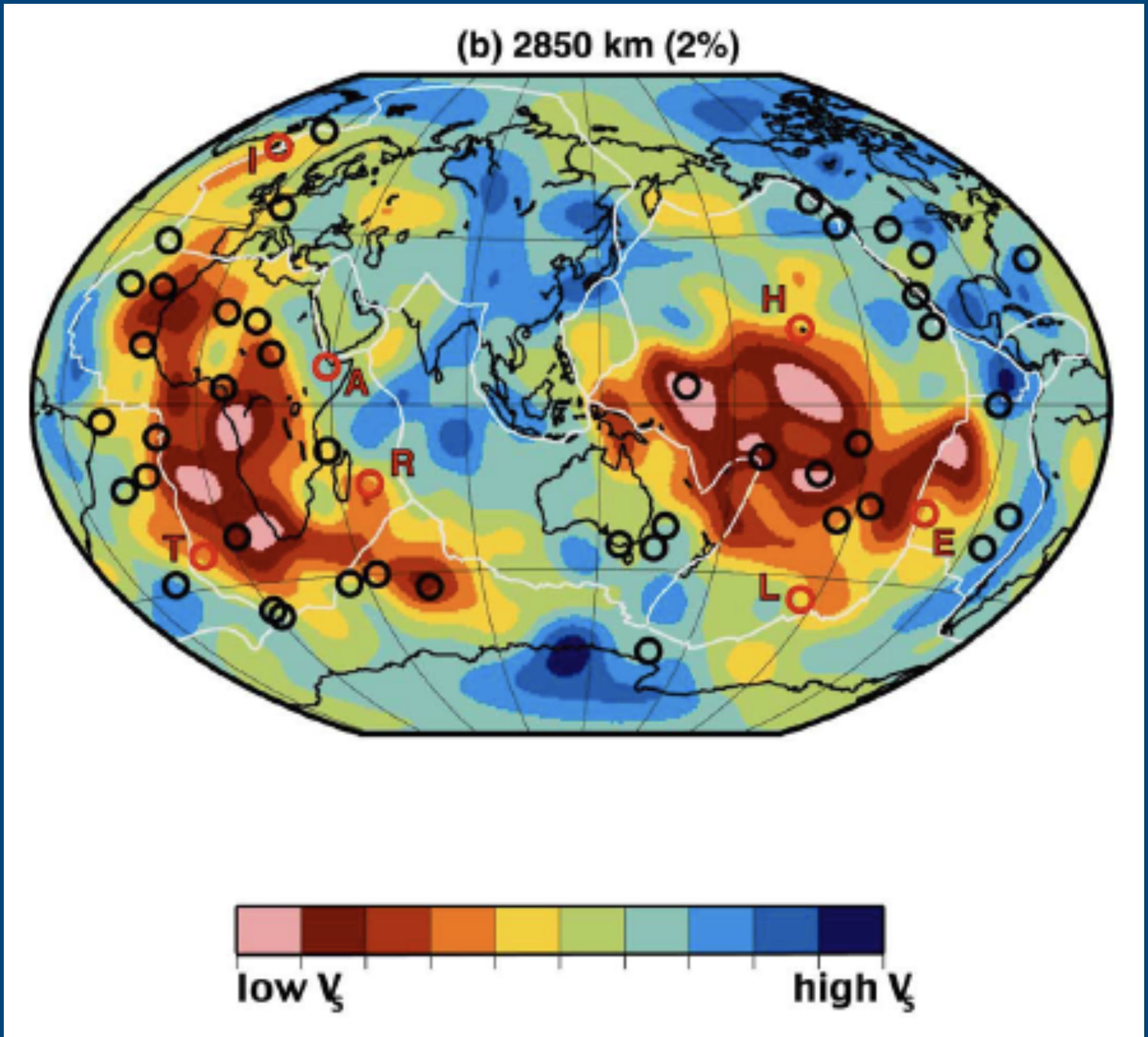


Van der Hilst et al., 1998

Spatial Correlation: Hotspots and CMB Structure

Observations:

1. Existence of hot thermal or compositional anomalies at CMB
2. Correlation of hotspots with deep mantle anomalies
3. Presence of cold-anomalies, splashing onto the CMB.



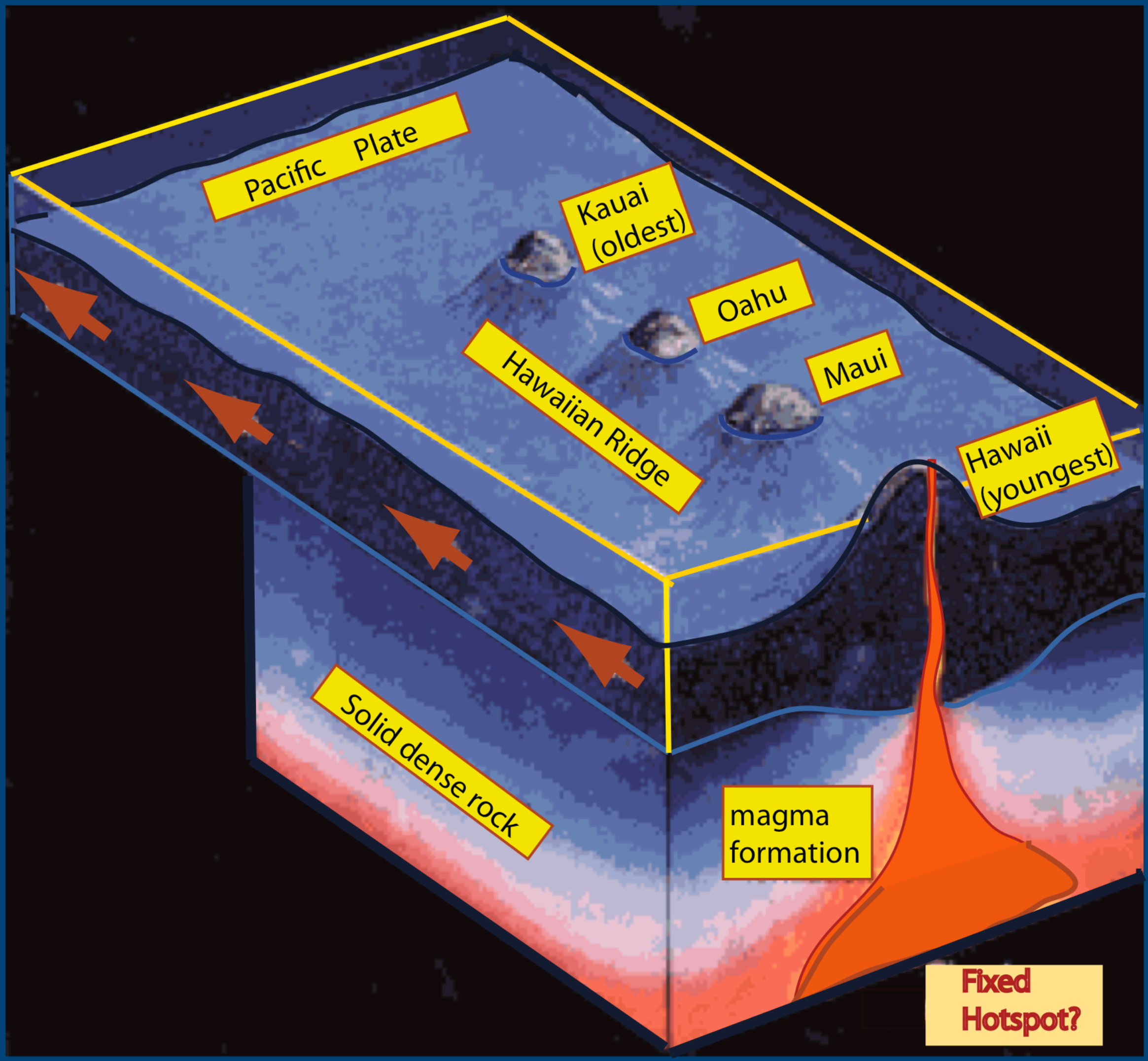
Courtillot et al., EPSL, 2003

Hot Thermal Upwelling: ***BOTTOM-UP VIEW***

Hot plumes (“*Bottom-Up*”)

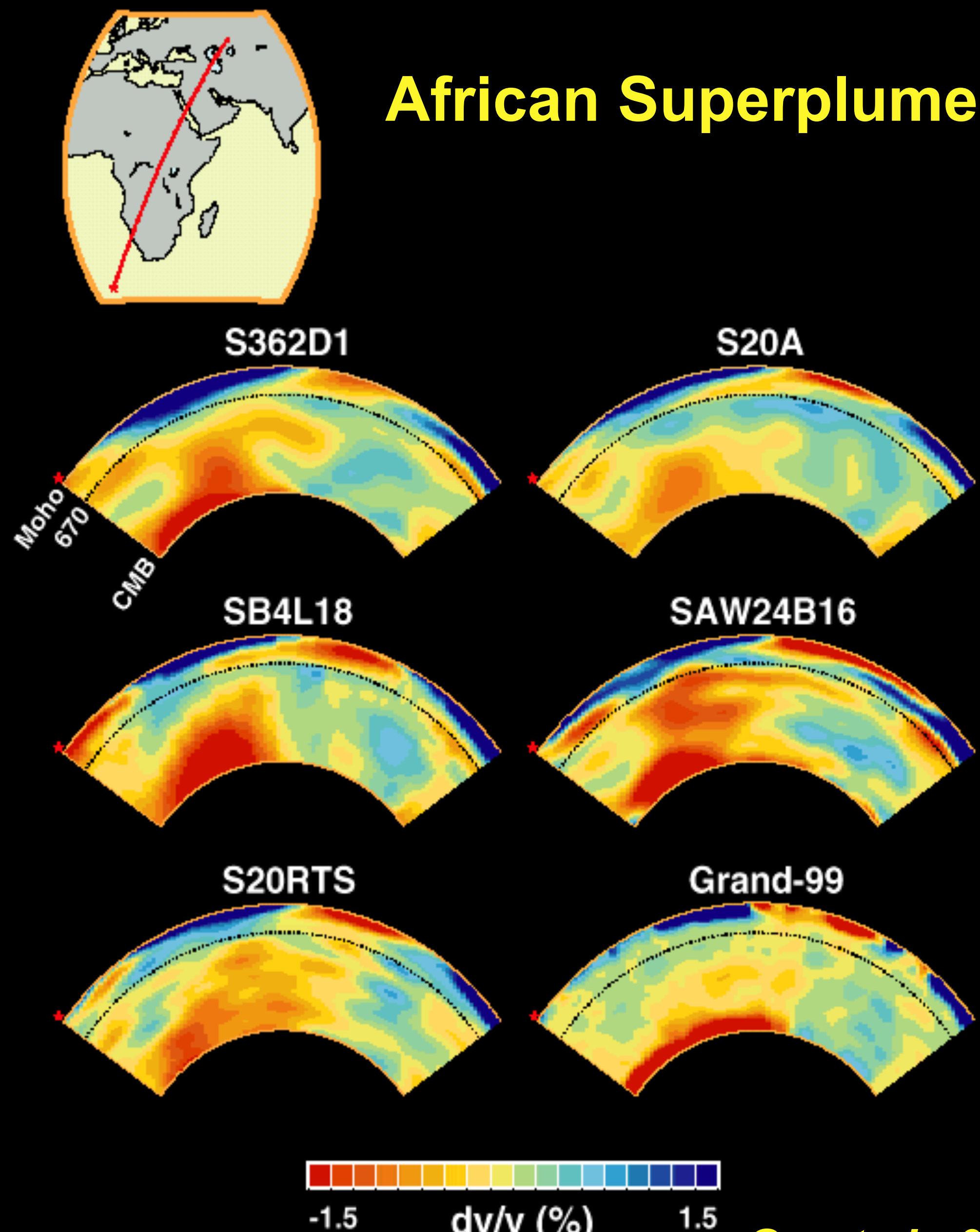
Often assumed for ‘Deep-rooted’ hotspots:

Vertical continuity and stationary conduit, effectively scarring over a moving plate. So the geometry of the volcano chain suggests past plate movements.

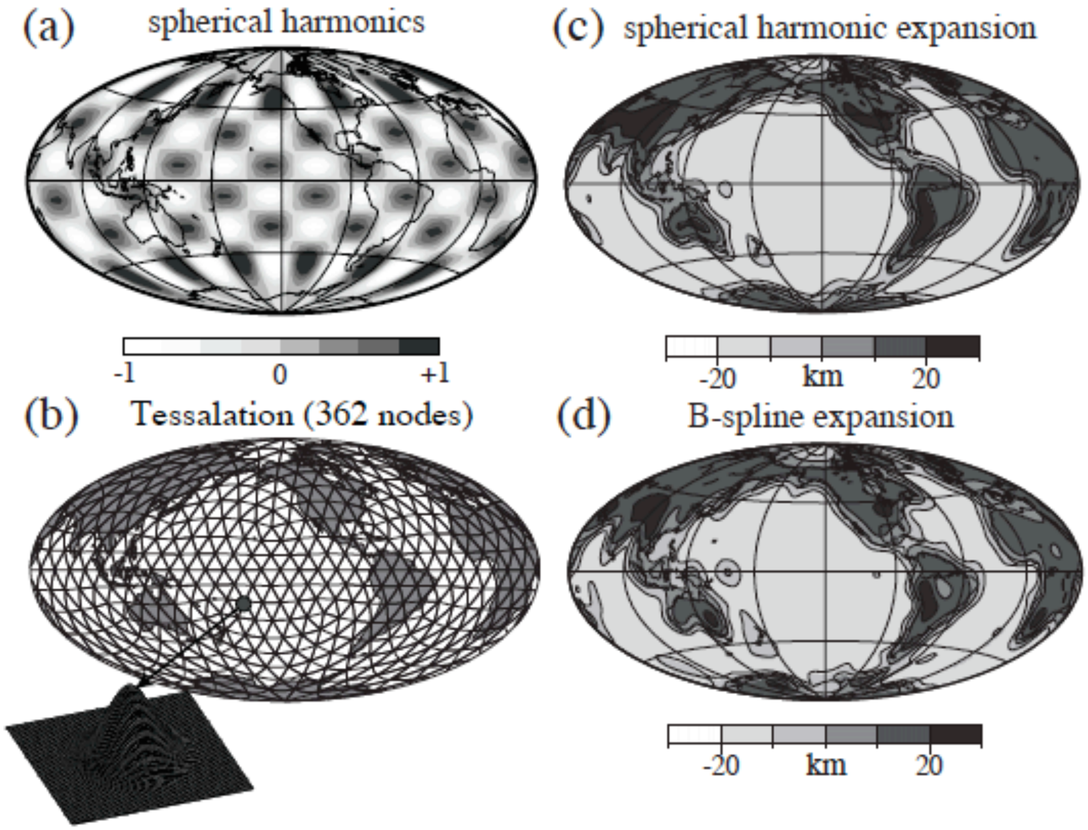


Bottom-Up

African Superplume



Gu et al., 03



Fact I: Inversion parameters (i.e., choices of basis functions) can affect inversion results. But they should resemble. After all, there is one earth!

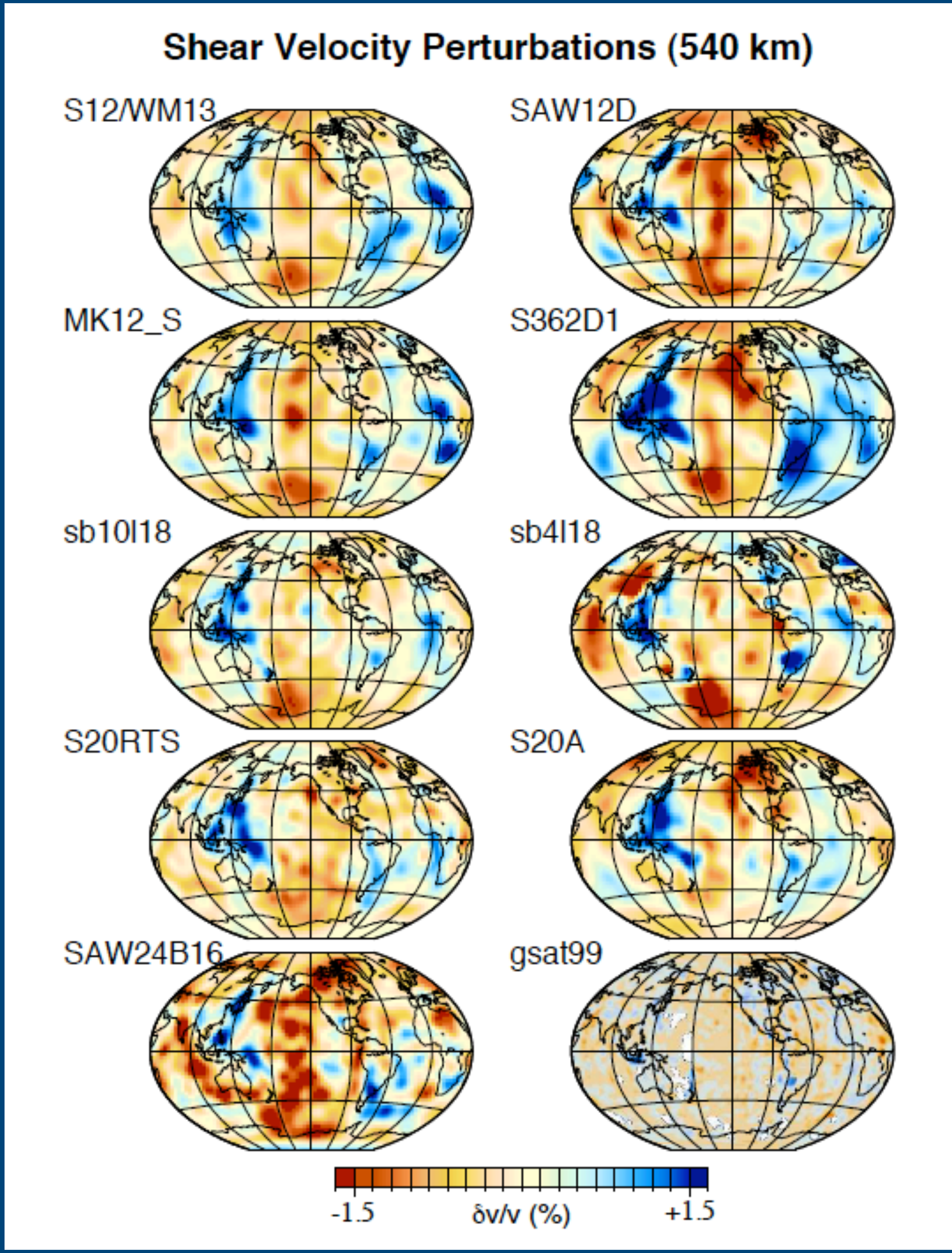
Figure 3: (a) Normalized spherical harmonic function (Press et al., 2007) with angular order $l = 18$ and azimuthal order $m = 6$. The total number of model coefficient (i.e., *sin* and *cos* terms) is 361. (b) Equal-area tessellation of the Earth's surface. The total number of vertices is 362. (c) Expansion of crustal thickness (Crust 2.0, Bassin et al., 2000) using spherical harmonics up to degree 12. (d) Expansion of crustal thickness using spherical B-splines (Gu et al., 2001) centered at each vertex in panel (b). With similar model coefficients, the results of the inversion-based expansions are highly consistent between the two parameterizations.

Main characteristic

Subduction zones near Japan and South America are fast.

Reason: Ponding of slabs

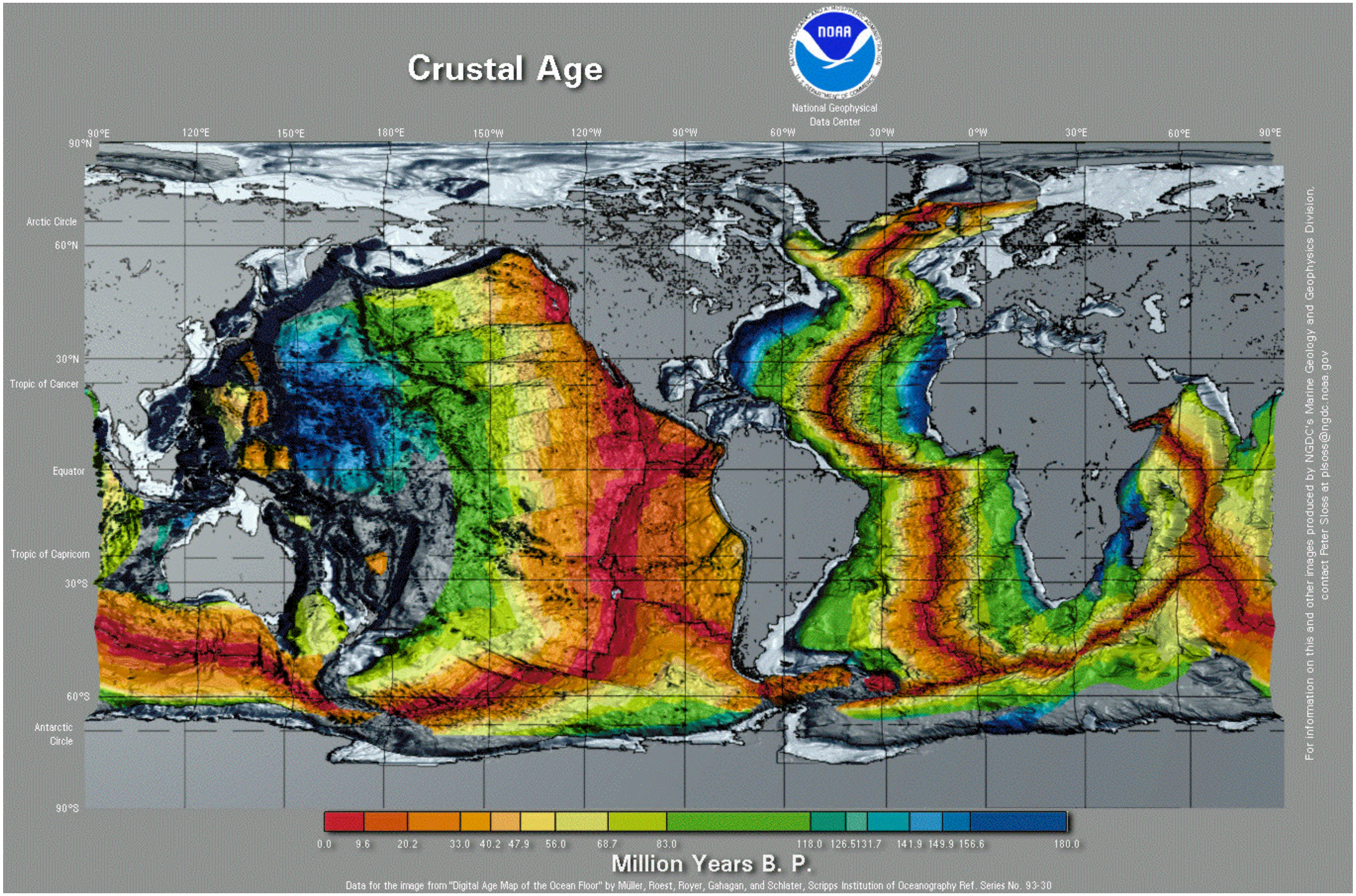
This also shows the consistencies between models, despite differences.



Oceanic Crust

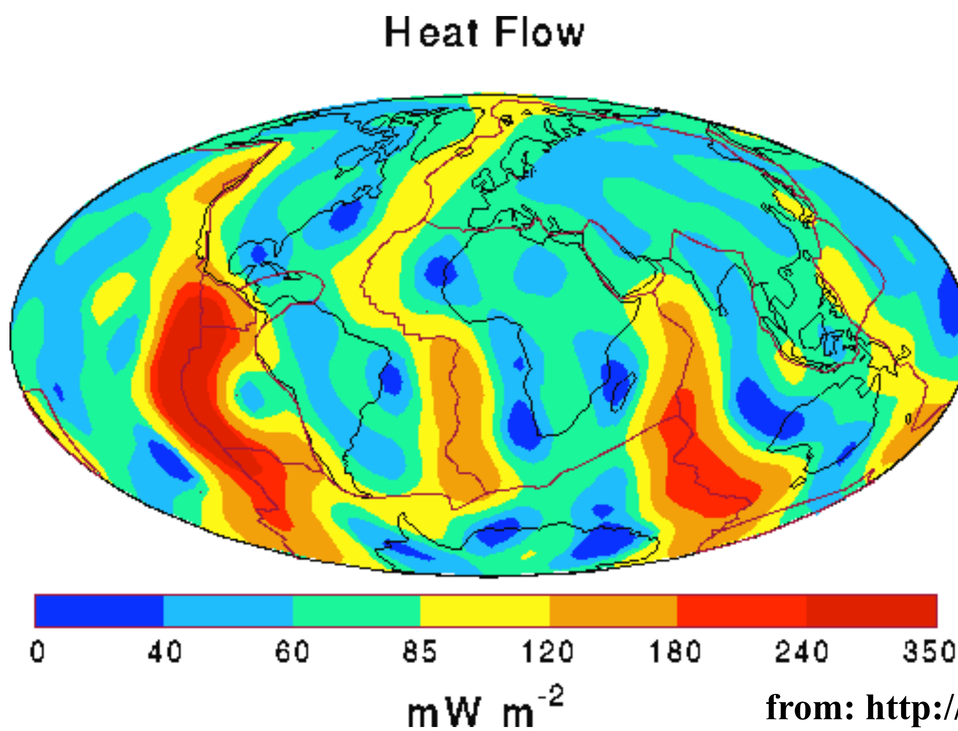
as a consequence of seafloor spreading (and subduction),

oceanic crust is < 200 Ma old (with exception of ophiolites)



note pattern of increasing age away from ridges

Heatflow & Tomography

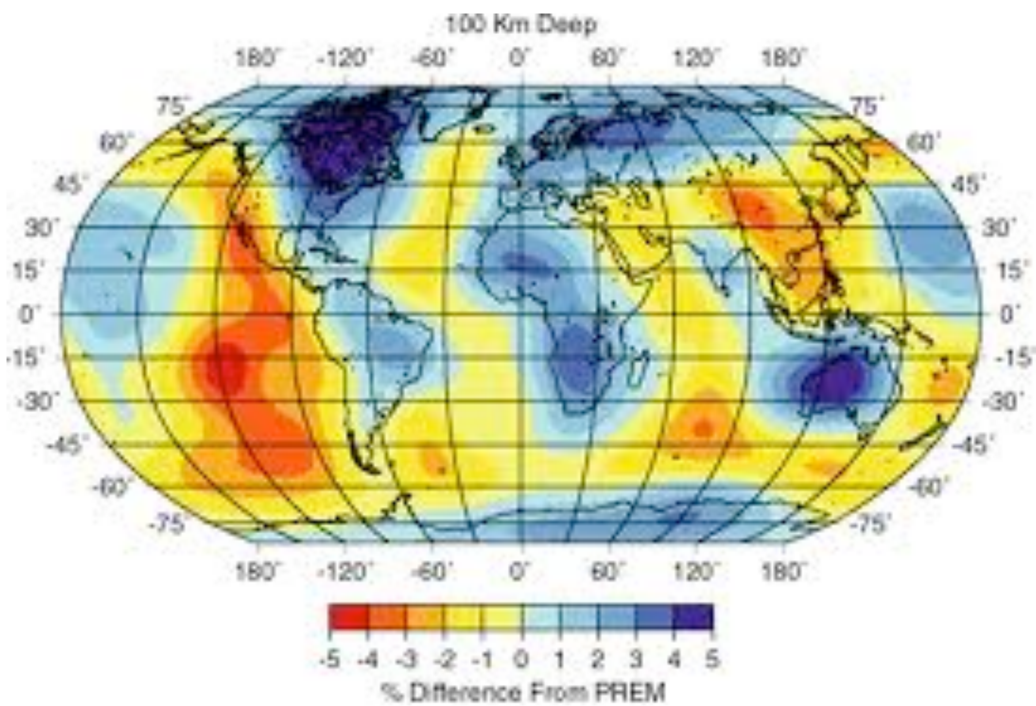


Observed heat flow:

warm: near ridges

cold: over continents

from: http://www-personal.umich.edu/~vdpluijm/gs205.html



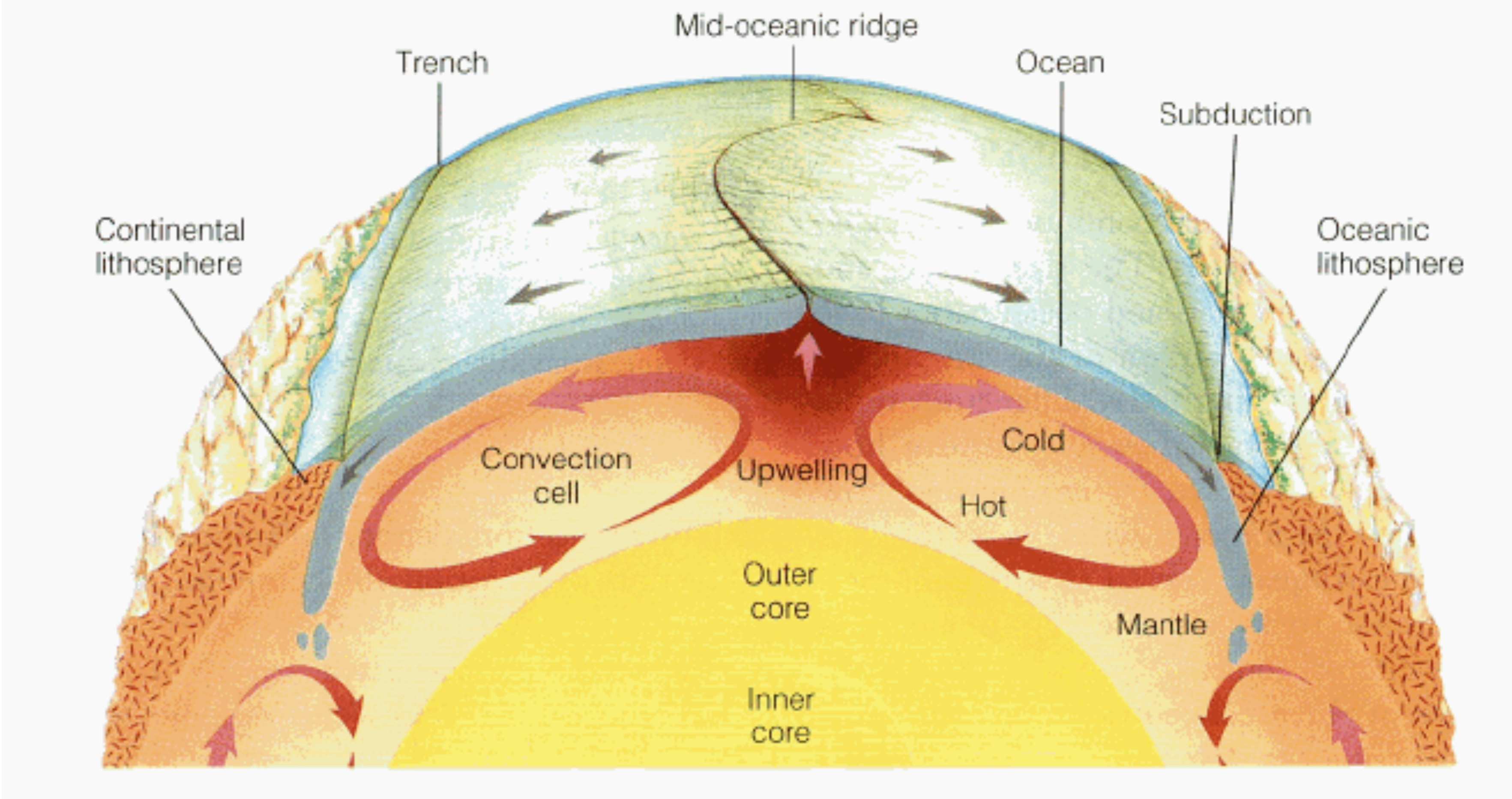
Inverted Shear Velocity:

slow: near ridges

fast: over continents

Formation of Ocean Crust: Texbook image, great graphics, very cool illustration

Only Problem: WRONG! Ridges & mantle plumes are normally NOT CONNECTED!



Ridge opens

↓

Pressure drops on top

↓

Mantle material expands + rises

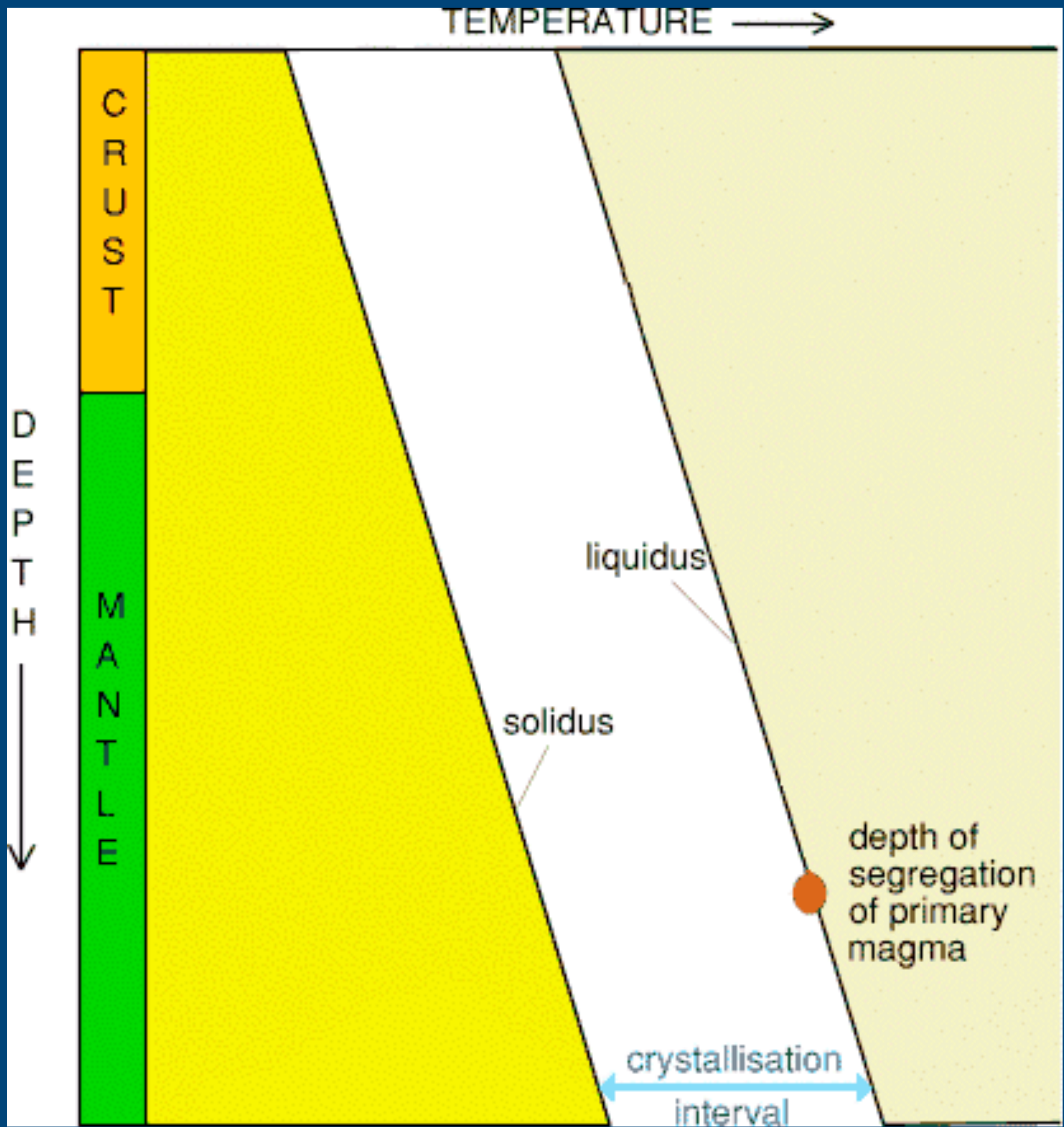
↓

Rise too fast to give up heat, melting temperature drops as pressure decrease, MELTS!

↓

Get close to top, heat loss increases, melt becomes denser, partial melt

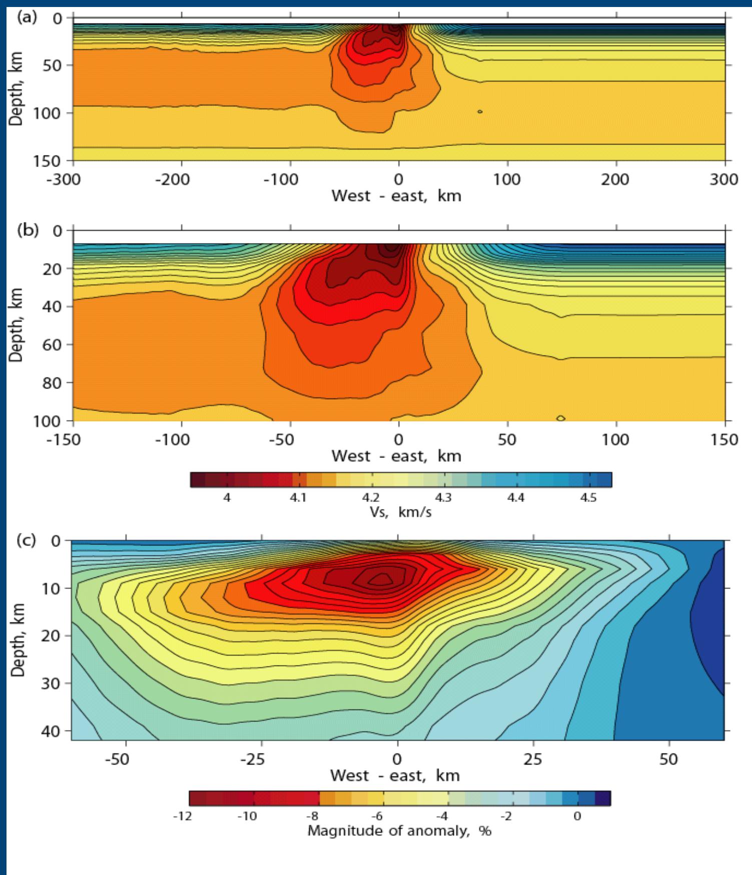
Geotherm: Geothermal gradient, rate at which the Earth's temperature increases with depth, indicating outward heat flows from a hot interior. ..



Regional study of LVZ under EPR

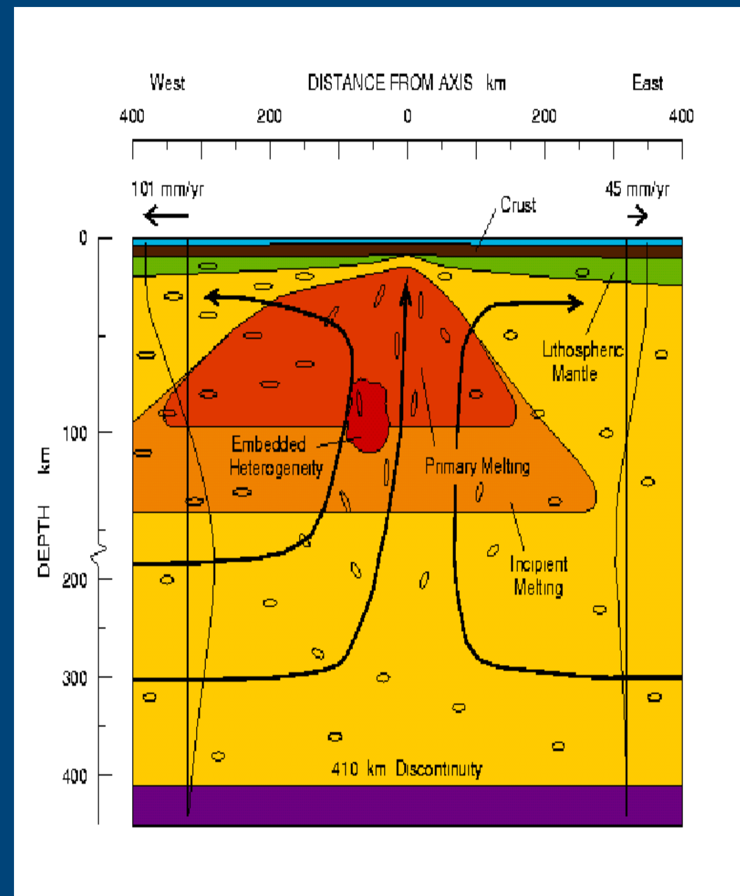
Mantle and Crustal Velocity Study from MELT (20 degree south)

Dunn & Forsyth (2002)



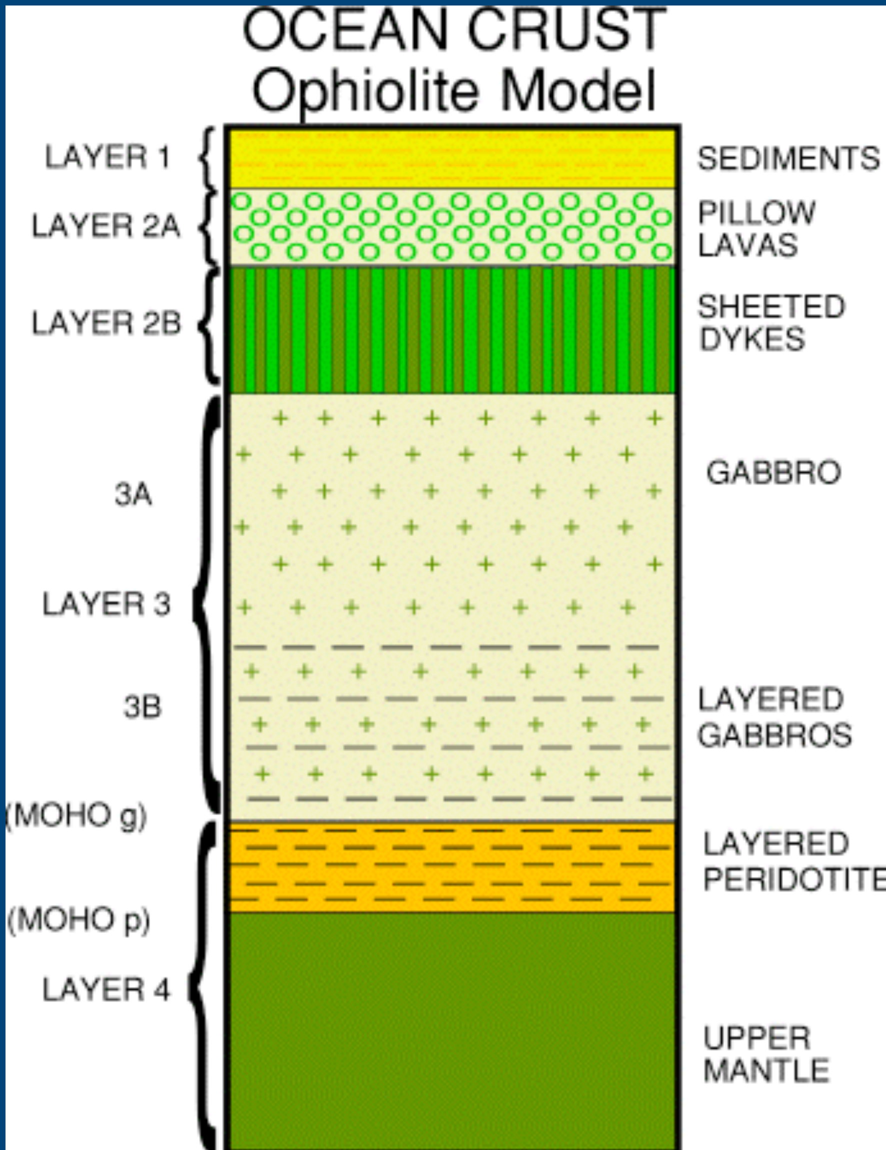
(Fig 11: Dunn and Forsyth, 2002)

1998 MELT team result

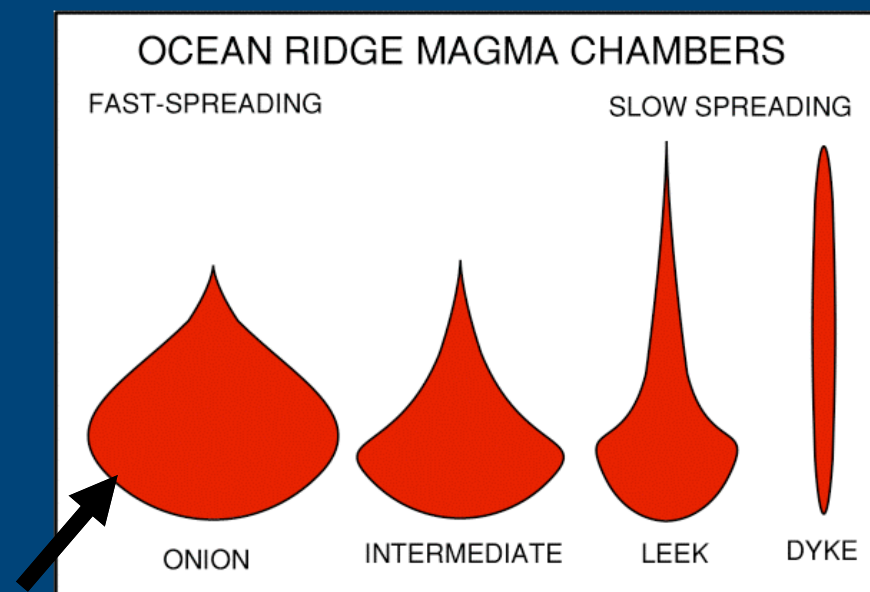


Questions unresolved:

1. Is there melt in the rigid plate part of the oceans?
3. Can we quantify velocity vs. temperature near ridges with OBSERVATIONS?
4. Is the mantle below East Pacific Rise the same from North to South?



ophiolite



Ocean Crust and magma Chambers. Shape of magma chamber depend on rate of spreading

Rheology of the Upper Mantle (Rheology = study of flow of unusual materials)

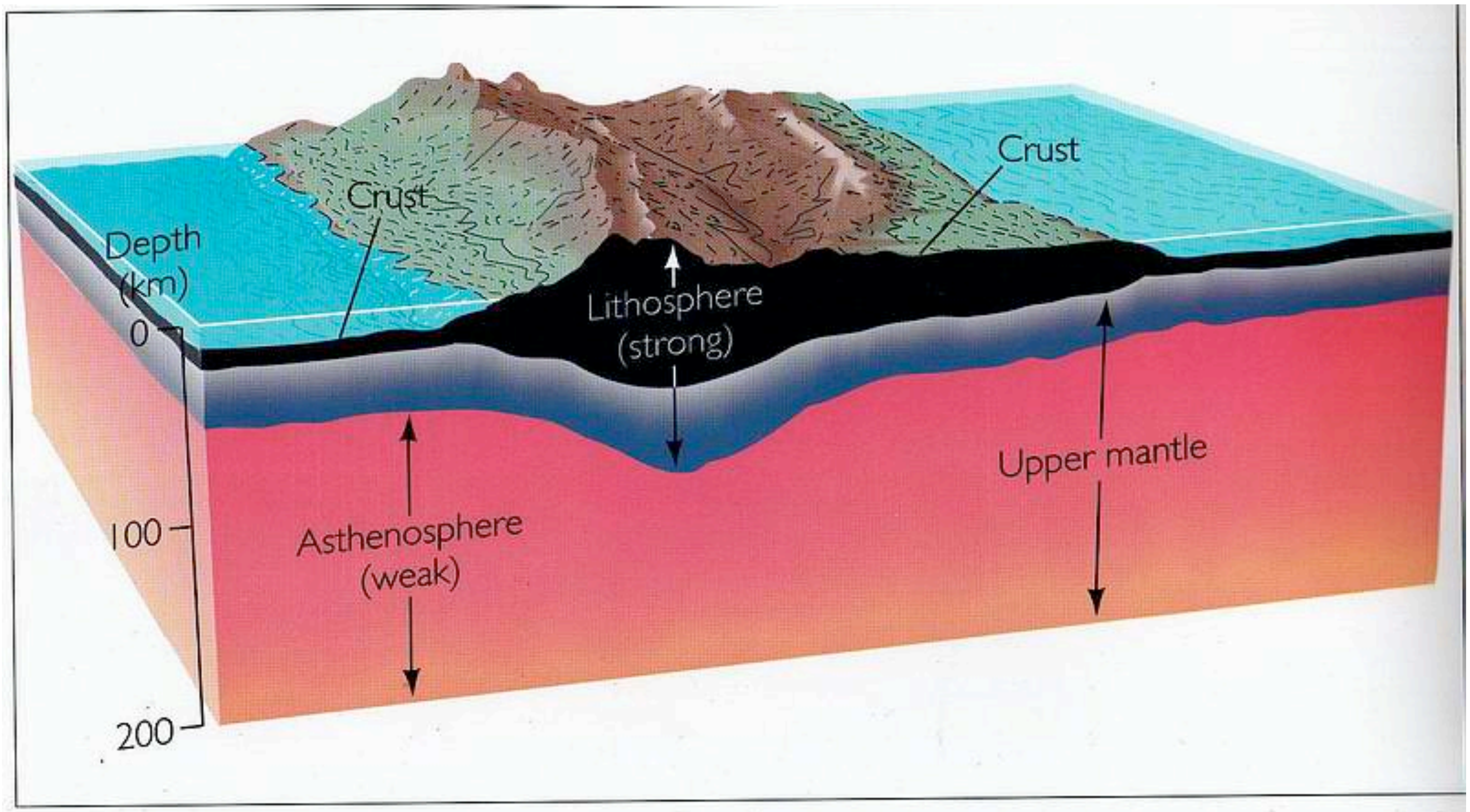
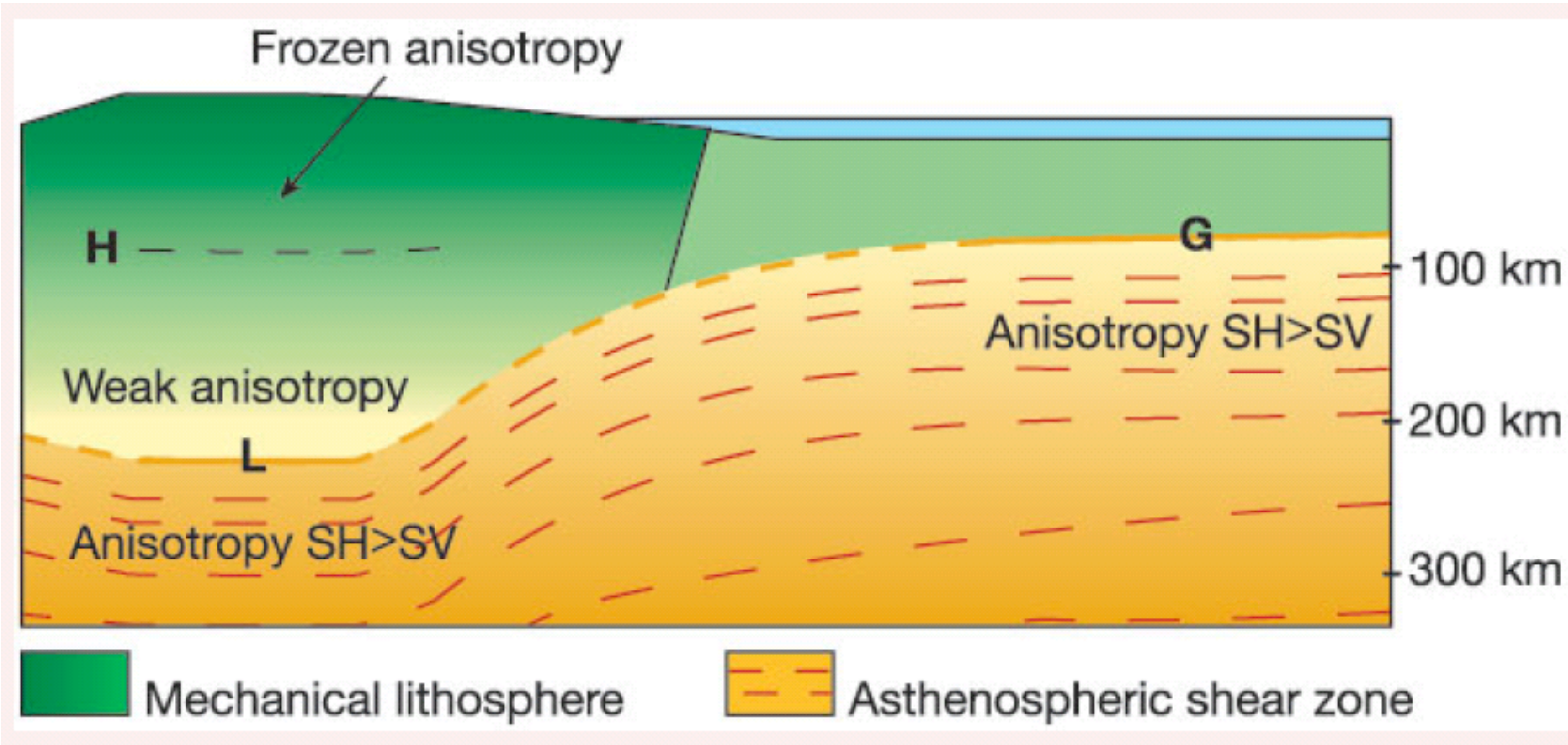


Figure 1.11
Press & Siever: UNDERSTANDING EARTH, Second Edition

lithosphere "strong" **asthenosphere "weak"**

Anisotropic Tomography: "Roots" under continents and oceans



Continents and oceans differ in the lithospher structures. While both are underlain by a weak, highly anisotropic "asthenospheric layer", the composition and depth of oceans and continents are different.

H: Hale's Discontinuity, G: Gutenberg Discontinuity, L: Lithosphere

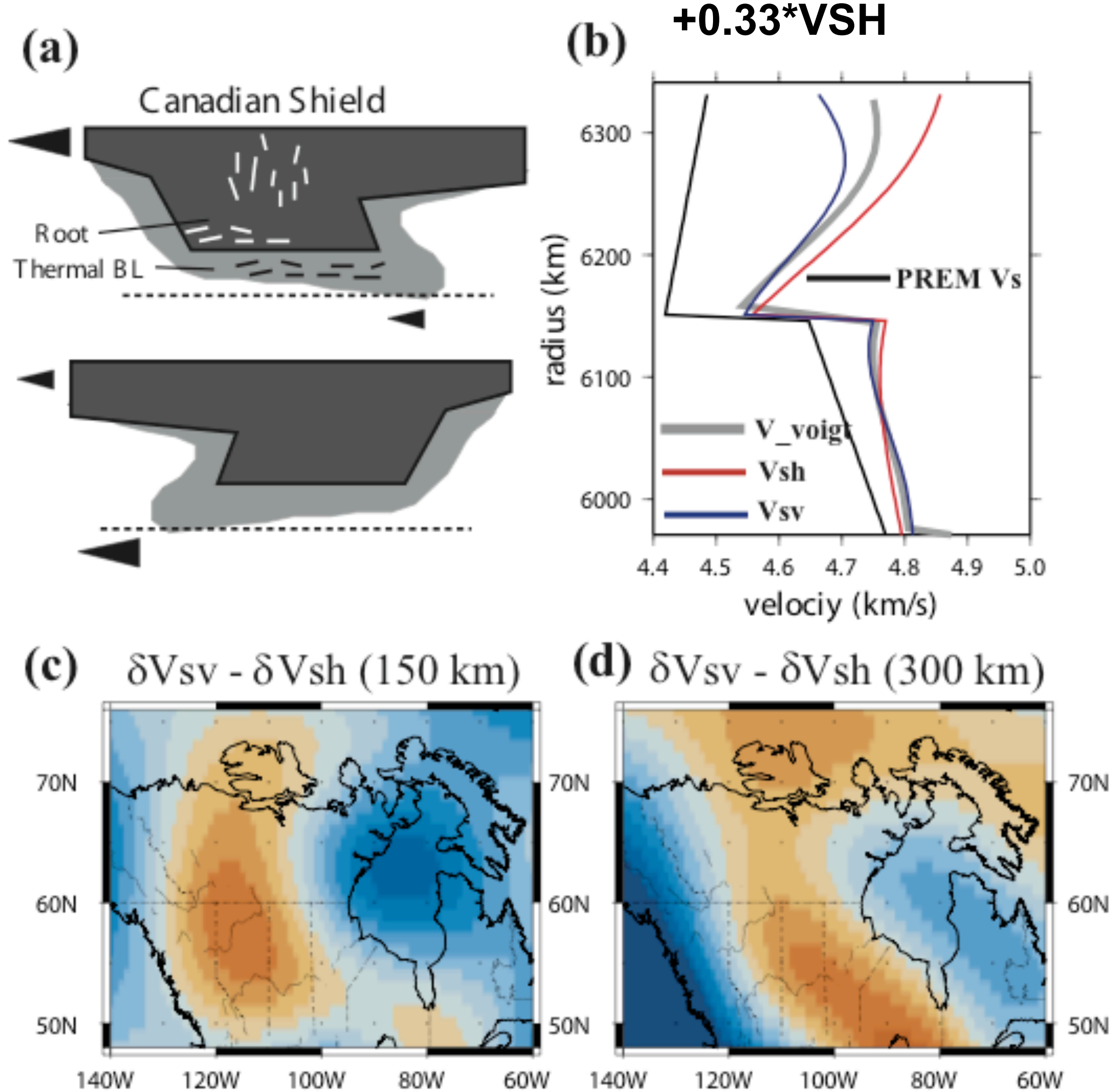
Red = horizontal speed perturbation > vertical speed perturbation

Blue= Vertical speed > horizontal speed (NOT perturbation)

Continents are floating bodies that shear the mantle!

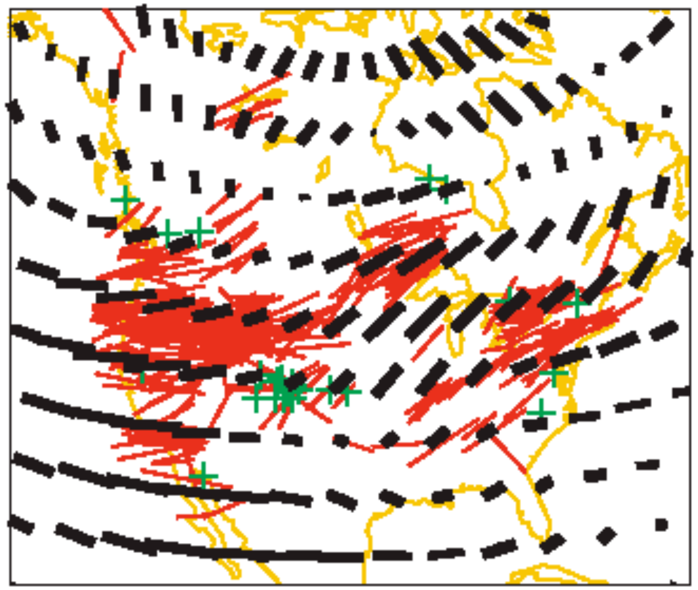
Voigt Average

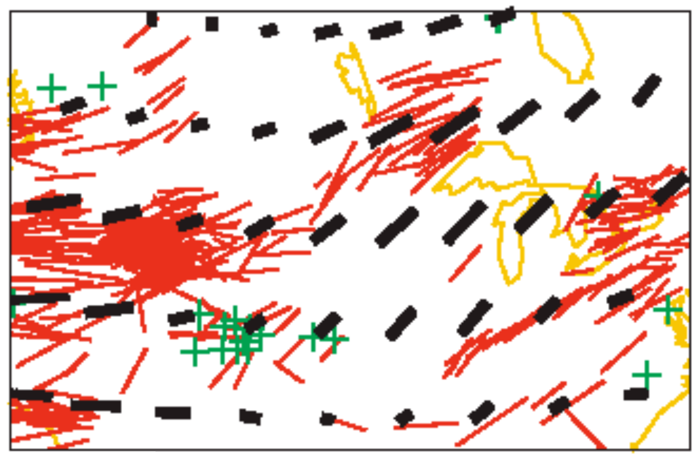
V_voigt = 0.67*VSV +0.33*VSH



Lithosphere: Highly anisotropic

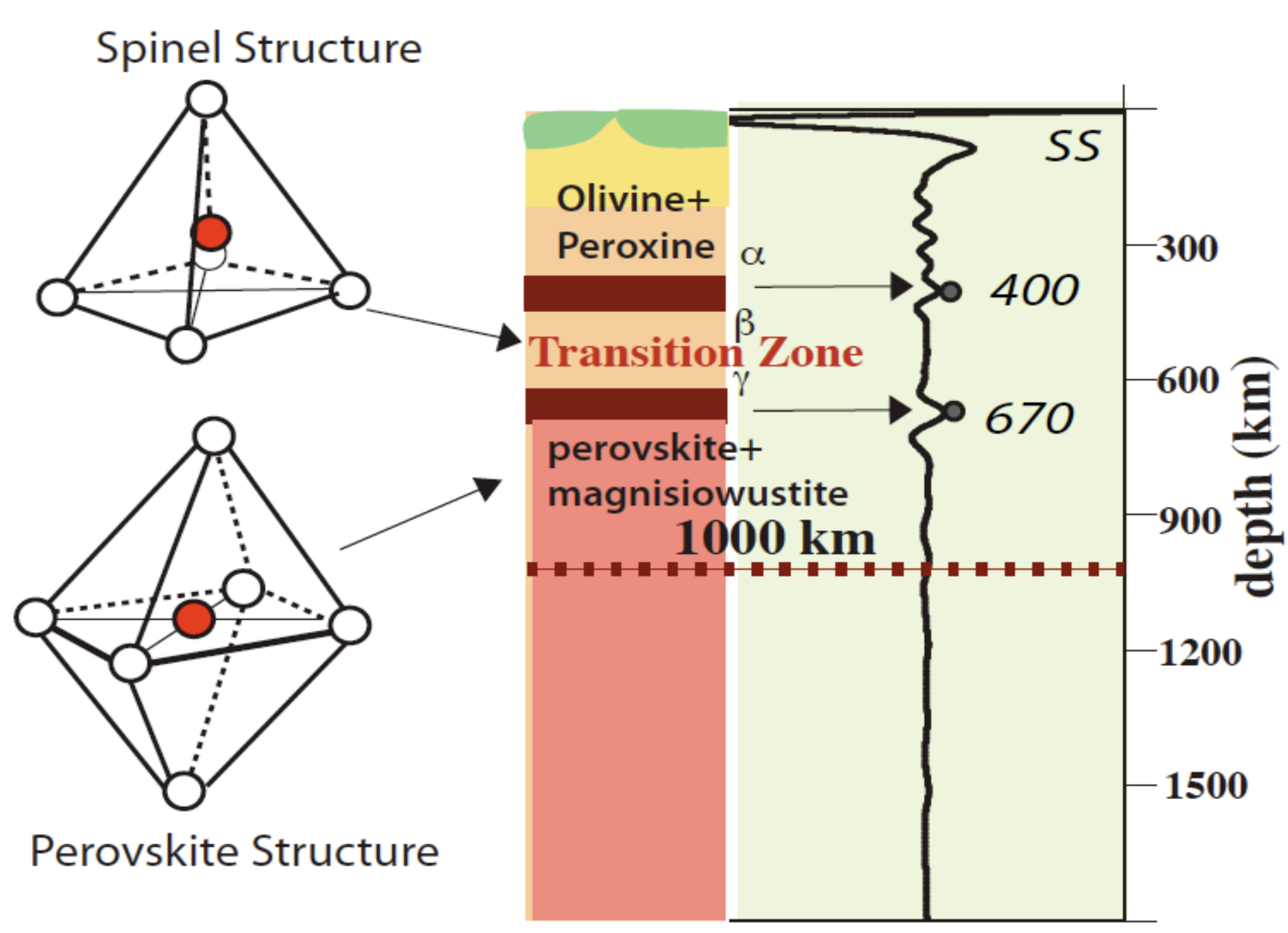
These are SKS waves that are "split" into fast and slow speeds. The direction of the lines indicate the Fast Splitting direction. The difference in speeds reflect the amount of anisotropy and the orientation of olivine crystals in the mantle. Plate motion can generate such shear dislocations, resulting in anisotropy. This anisotropy is mainly associated with the thin asthenosphere at the base of lithosphere. Multiple layers of such anisotropic regimes could exist, reflecting rigid lithosphere and fluid-like astheonsphere.



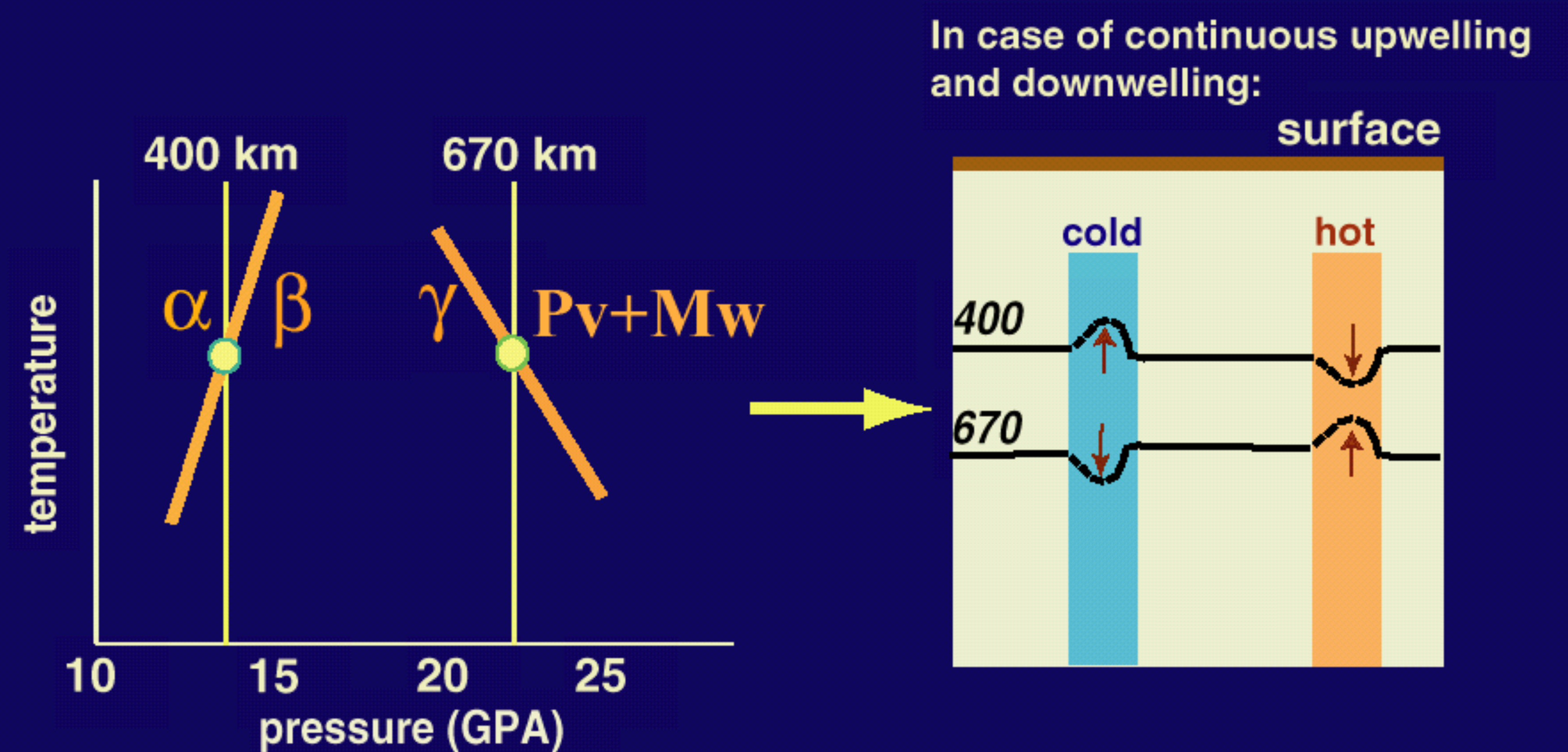


after Marone and Romanowicz, 2007

A Easy Target for Flow Disruption: "Transition Zone"

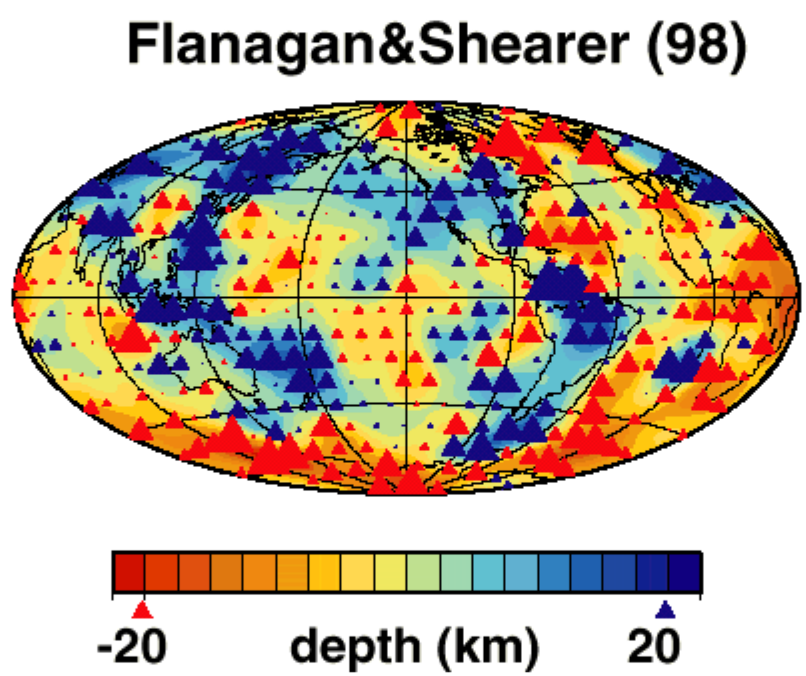


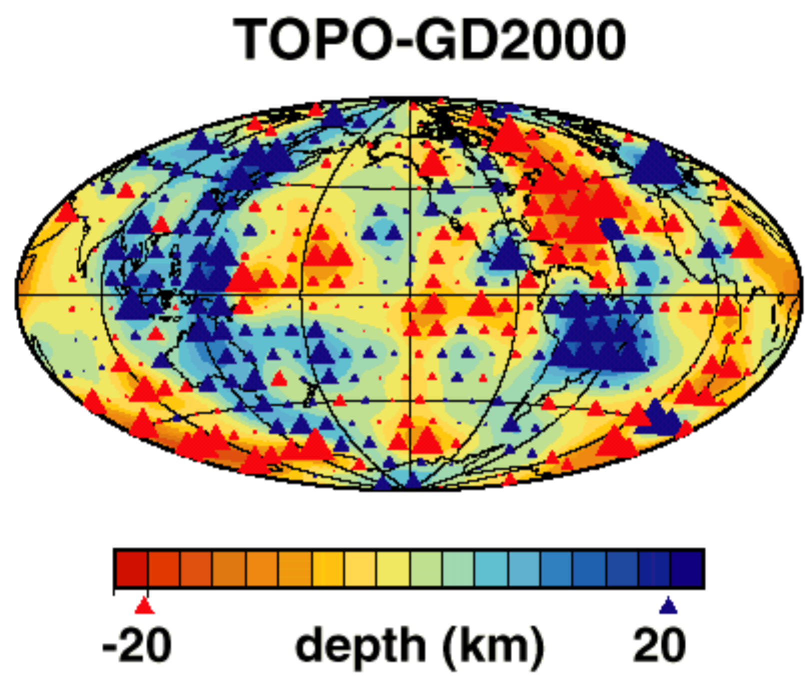
Upper Mantle Phase Transitions



Reflector depth could determine temperature: Pressure is ~equivalent to depth, hence, the phase boundaries (left) for the two major transitions are sensitive functions of temperature (These P-T line slops are also called Clapeyron Slopes)

Depth Perturbation of the *670* discontinuity

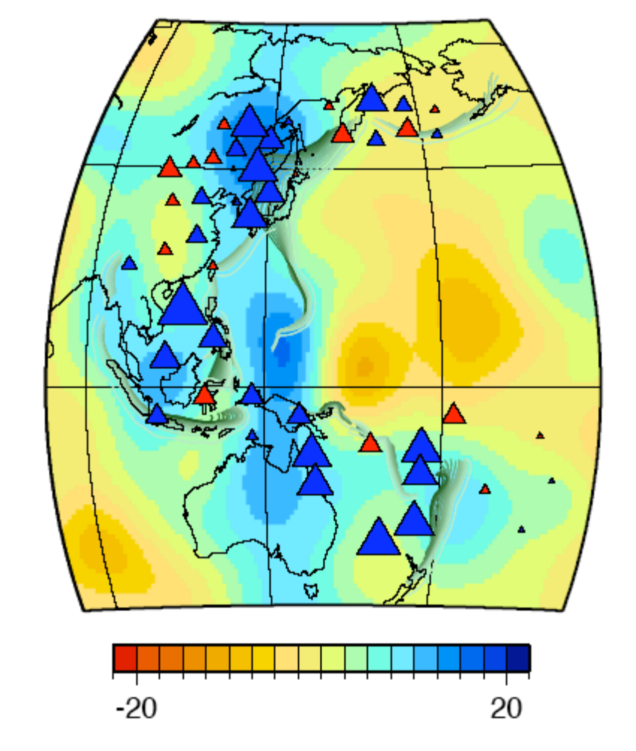




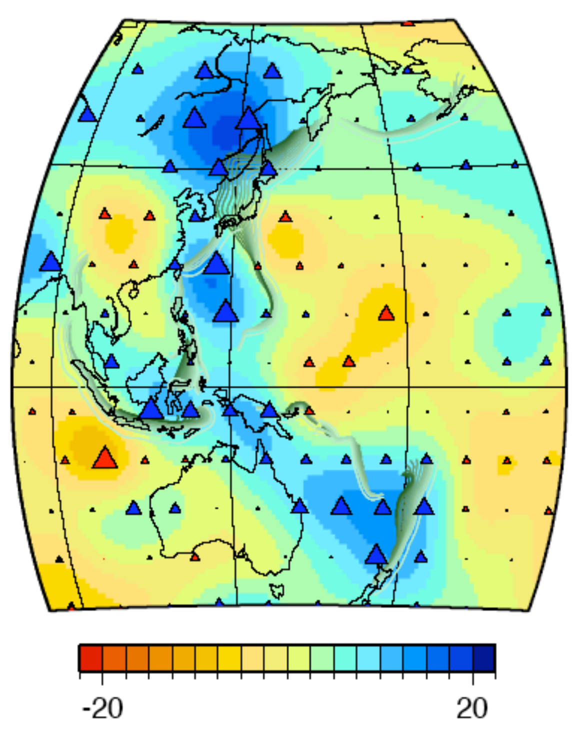
These are resulting topography at the base of upper mantle. Red shows elevation And blue show depression. The fact that the pattern is similar to seismic velocity Suggest a common origin. Interpretation: significant flattening and ponding of Cold ocean sediments at the base of upper mantle.

660 Topography

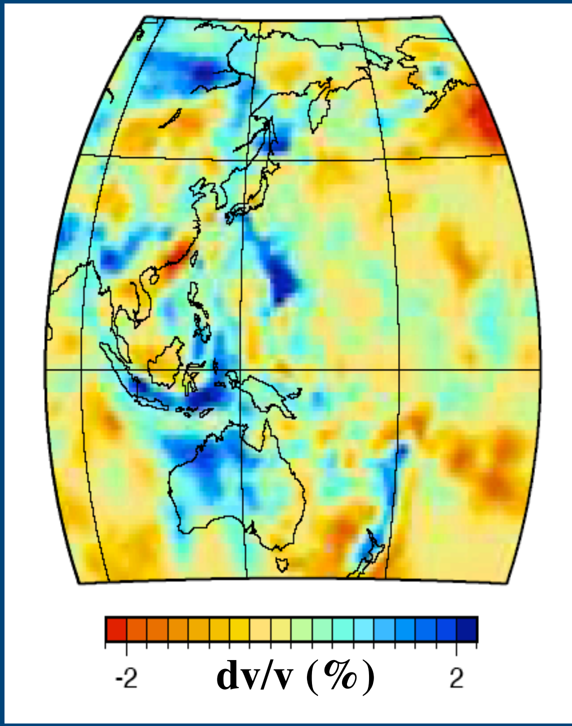
This study



Flanagan & Shearer (98)



PRI-5 (Montelli et al.)
shear velocity
(620 km)



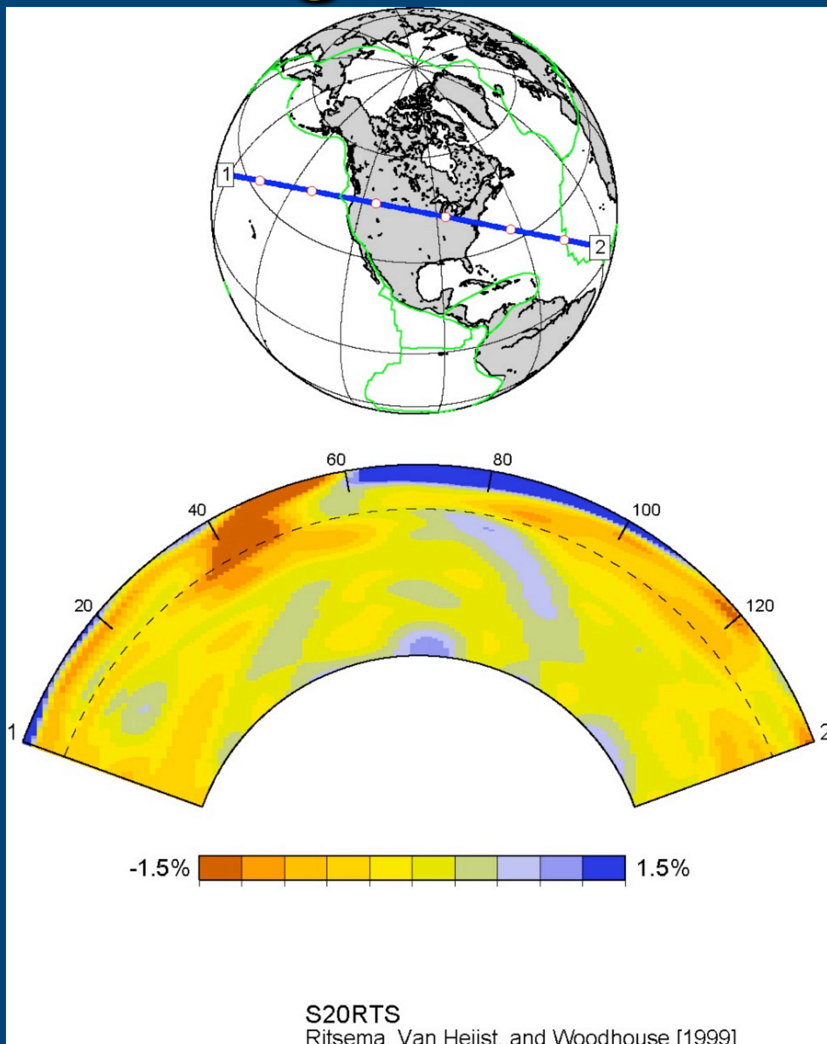
Observations:

General agreements close to the subduction zones.

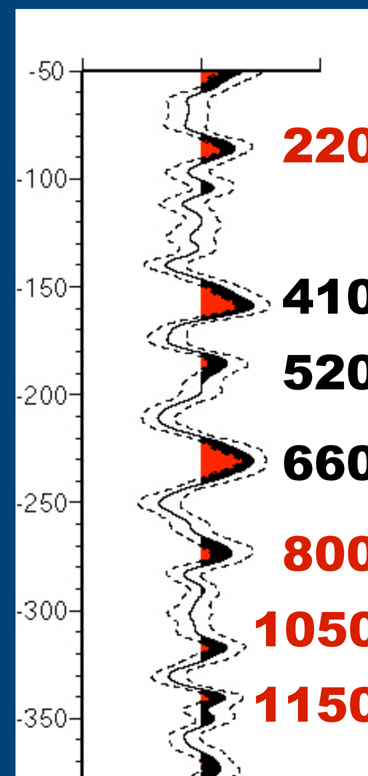
<u>Disagreements</u>: western Aleutian arc, amplitude of observations

Mid mantle (700-2000 km): quiet regime

Precursors

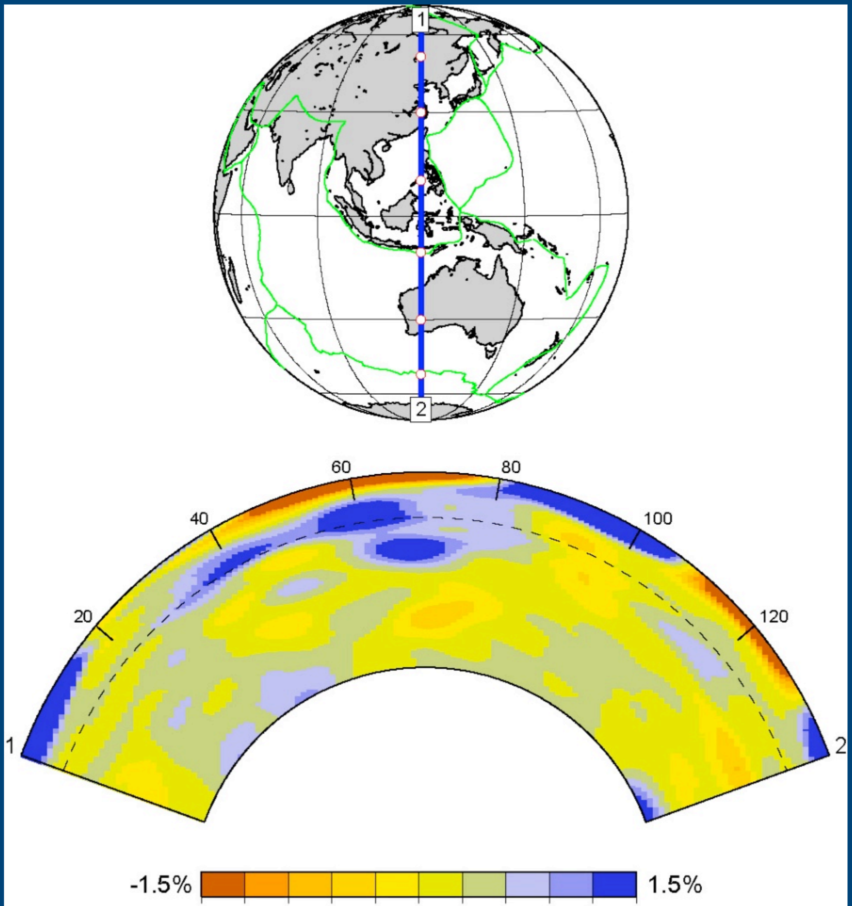


Stack for North America



(Deuss & Woodhouse, GRL, 2002)

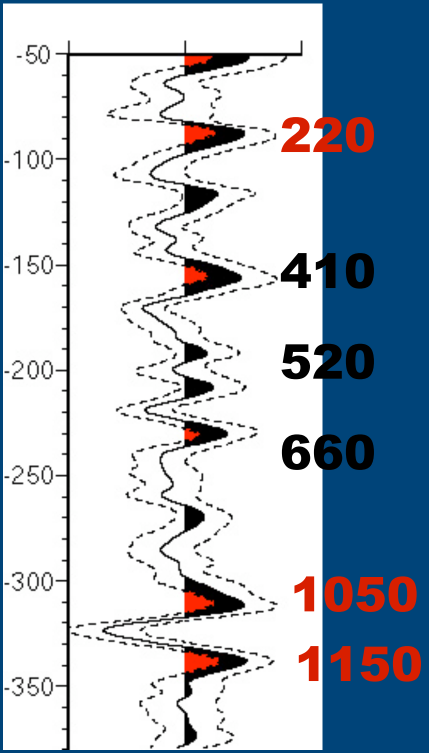
Mid mantle



S20RTS
Ritsema, Van Heijst, and Woodhouse [1999]

Precursors

Stack for Indonesia



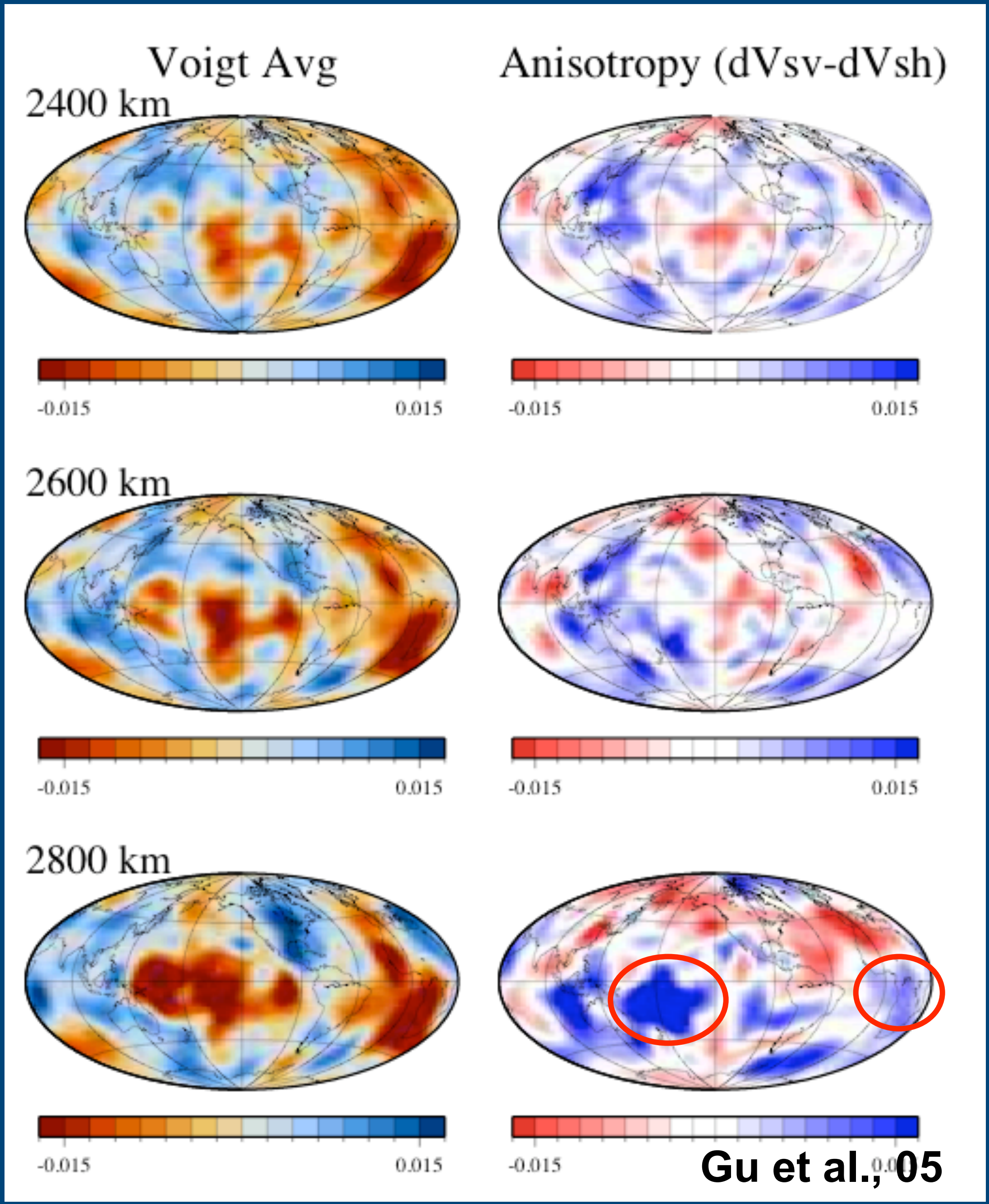
(Deuss & Woodhouse, GRL, 2002)

The bottom layer:

Kellog et al. suggested a HAL (Hot Abyssal Layer) which is considered "different" or "primordial" (authentic) in comparison with the rest of the Earth. Is it true?

Counter arguments:

1. This layer is not found
2. This layer is hot, so it will be lower density, so will likely rise, then why can it stay down there? (people counter with high densities, but the balance is very hard to achieve gravitationally.
3. Some now suggest this layer could mark the phase transformation of so called Post-Perovskite, from high pressure experiments.
4. Where does the compositional difference come from? The core (mostly liquid iron and nickel)? Or the "unaltered" (old) mantle?



Lowermost mantle:

Anisotropic beneath the South/Central Pacific, slightly anisotropic beneath Southern Africa/ Atlantic.

Pacific ocean = more iron?

Orientation: **Vertical**

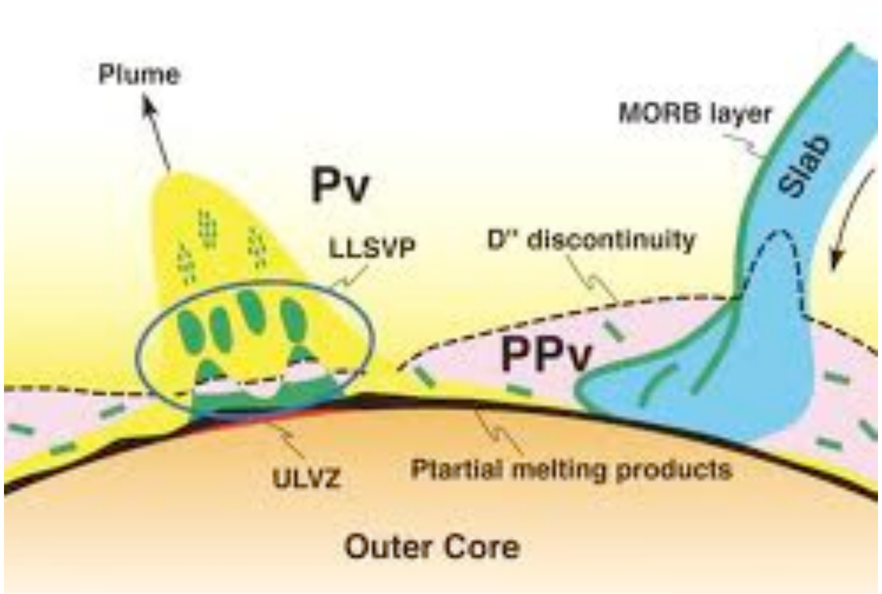
Interpretation:

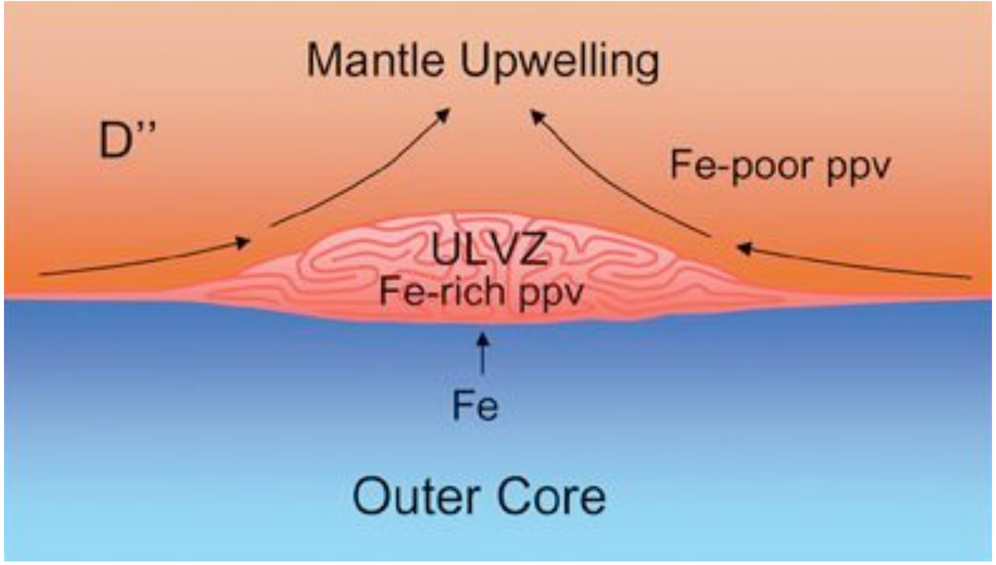
Vertical Shear of Perovskite?

Vertical layering or columns?

General Assumption: D'' layer (~2-300 km thick on top of the Core-mantle boundary is potentially caused by phase transformation of Perovskite ((Mg,Fe)SiO3). It is however, highly heterogeneous.

Places where it is red: Ultra Low Velocity Zone (ULVZ)



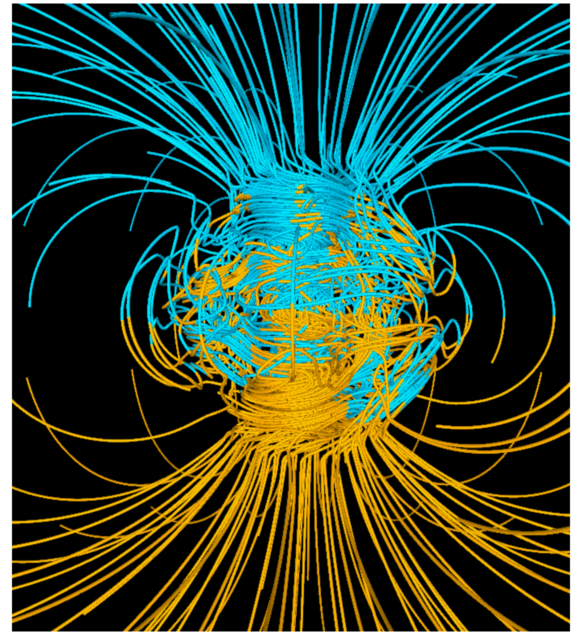


Outer core:

Key properties: 2200 km thick, 4000+ deg C, generates dynamo --- i.e., the source of Earth's magnetic field due to the rotating, convecting and electrically conducting fluid.

Minerology: Dominated by molten iron (Fe), but also had some lighter elements such as sulphur, silicone, oxygen.

Geodynamo

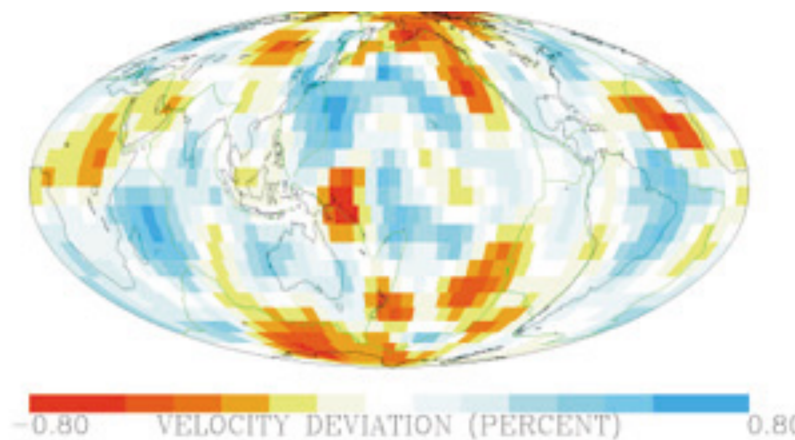


Magnetic field lines,
Gary Glatzmaier & coworkers

Seismic Tomgraphic Inversion result (Vasco & Johnson, 1998):

Heterogeneous according to some (), but highly doubtful for such a fast convecting fluid

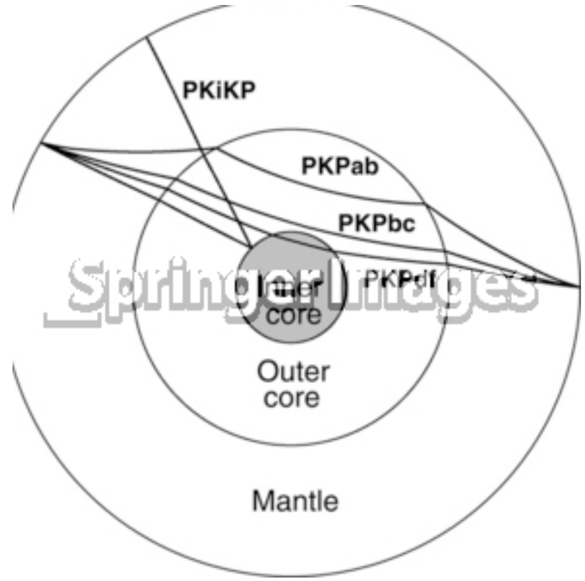
Outer Core heterogeneity?



The Come-back of heterogeneous outer core

Recent seismic observations from travel times of outer core phases (Hellfrich and colleagues, 2010)

Different speeds between top few hundred kilometers of outer core and the rest of it.



<u>Possible reasons</u>: different levels of *oxidation* during the outer core formation at the beginning

This was suggested by 'shock wave" experiments, conducted by mineral physicists

<u>*Key implication*</u>: low level of oxygen in the outer core.

Based on work by Huang, Fei et al., 2010