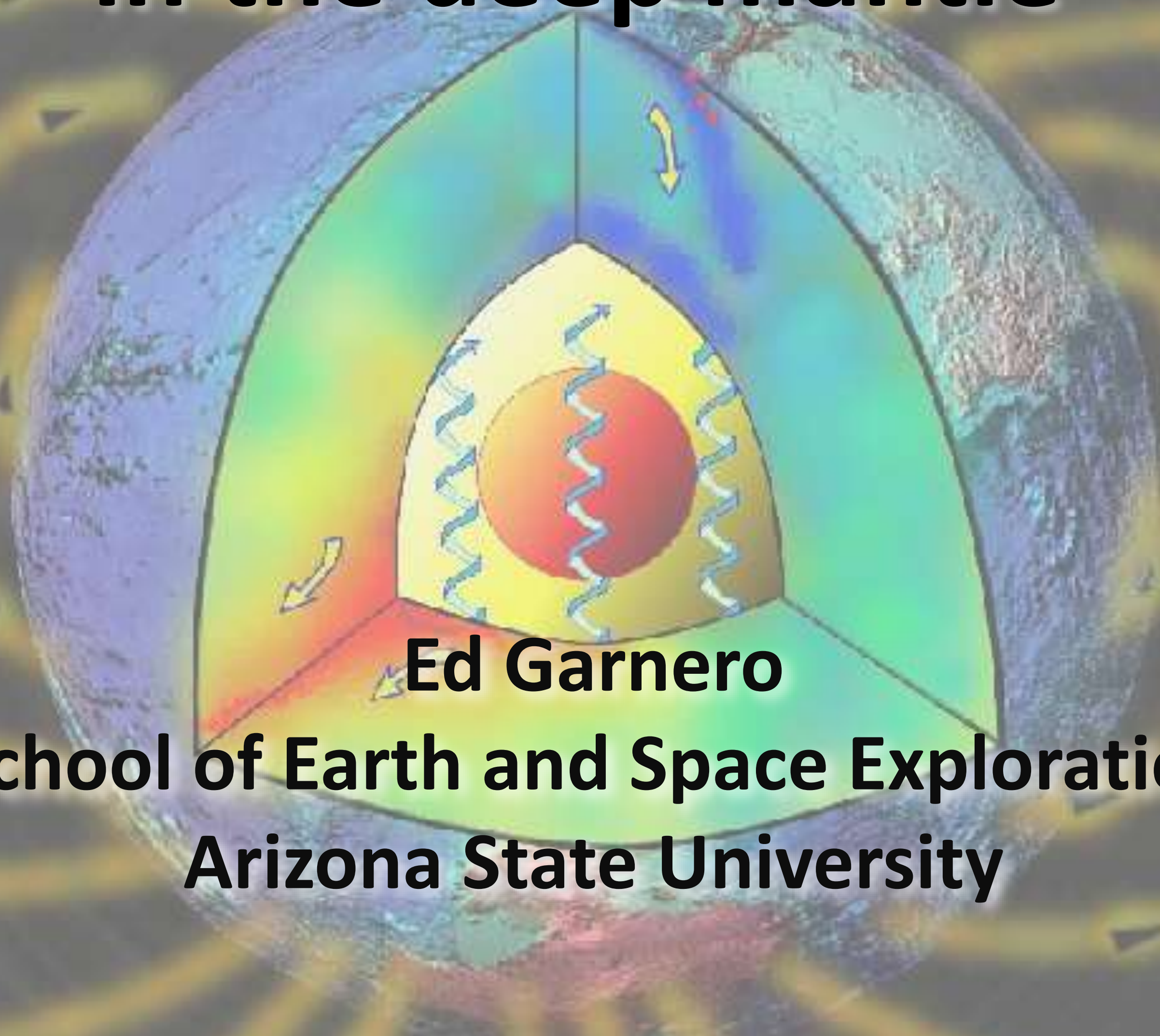
# Possible reservoirs of radioactivity in the deep mantle



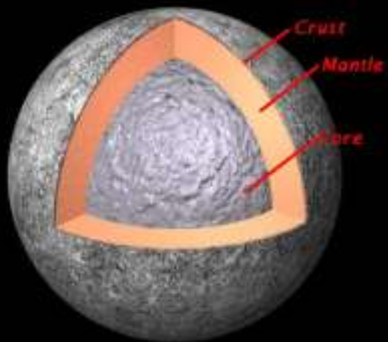
Ed Garnero
School of Earth and Space Exploration
Arizona State University

# Outline

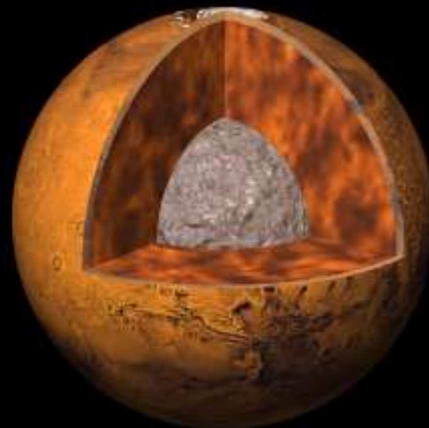
- Brief overview: motivation for investigating interiors; how seismology helps
- Large Low Shear Velocity Provinces (LLSVPs) at base of mantle: large-to-small scales
- Dynamical framework: how to build and maintain an LLSVP, and chemically sample it via plumes
- LLSVPs as reservoirs

# The main feature of planetary interiors:

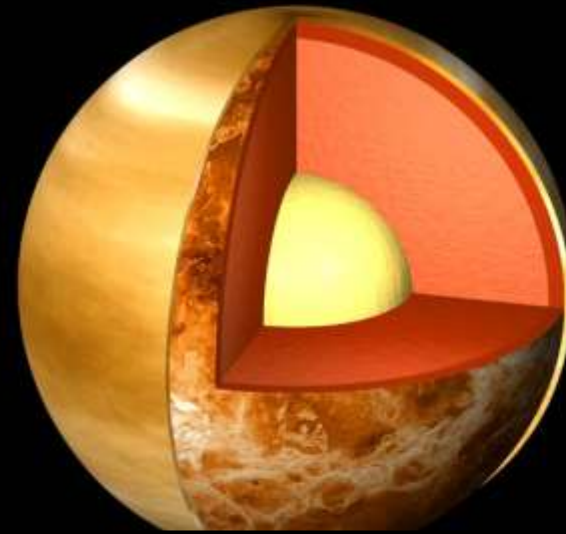
# ***stratification***



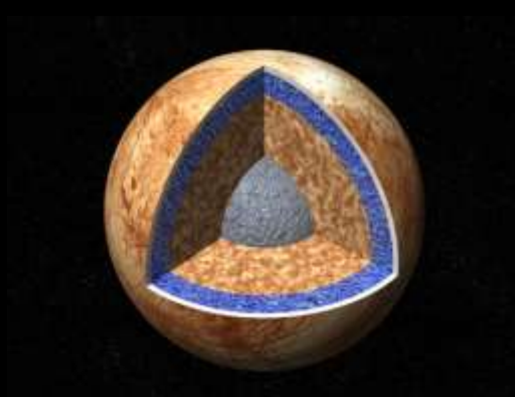

Mercury



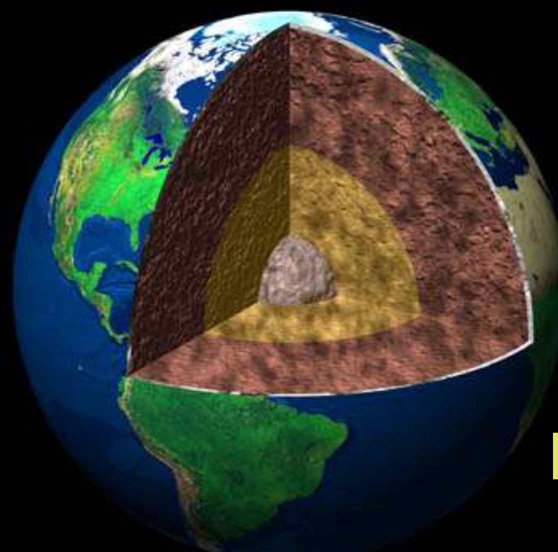
Mars



Venus

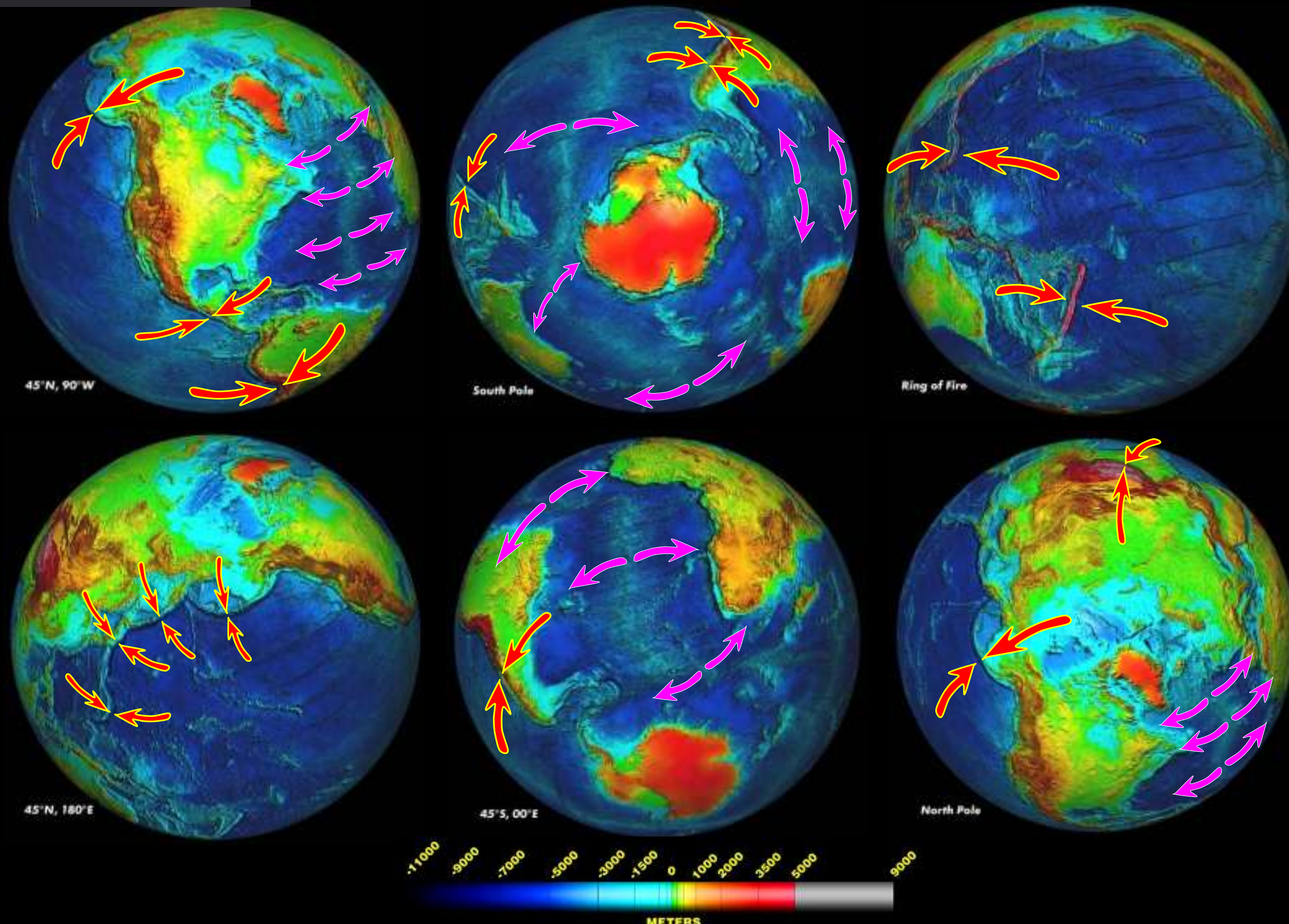


Europa



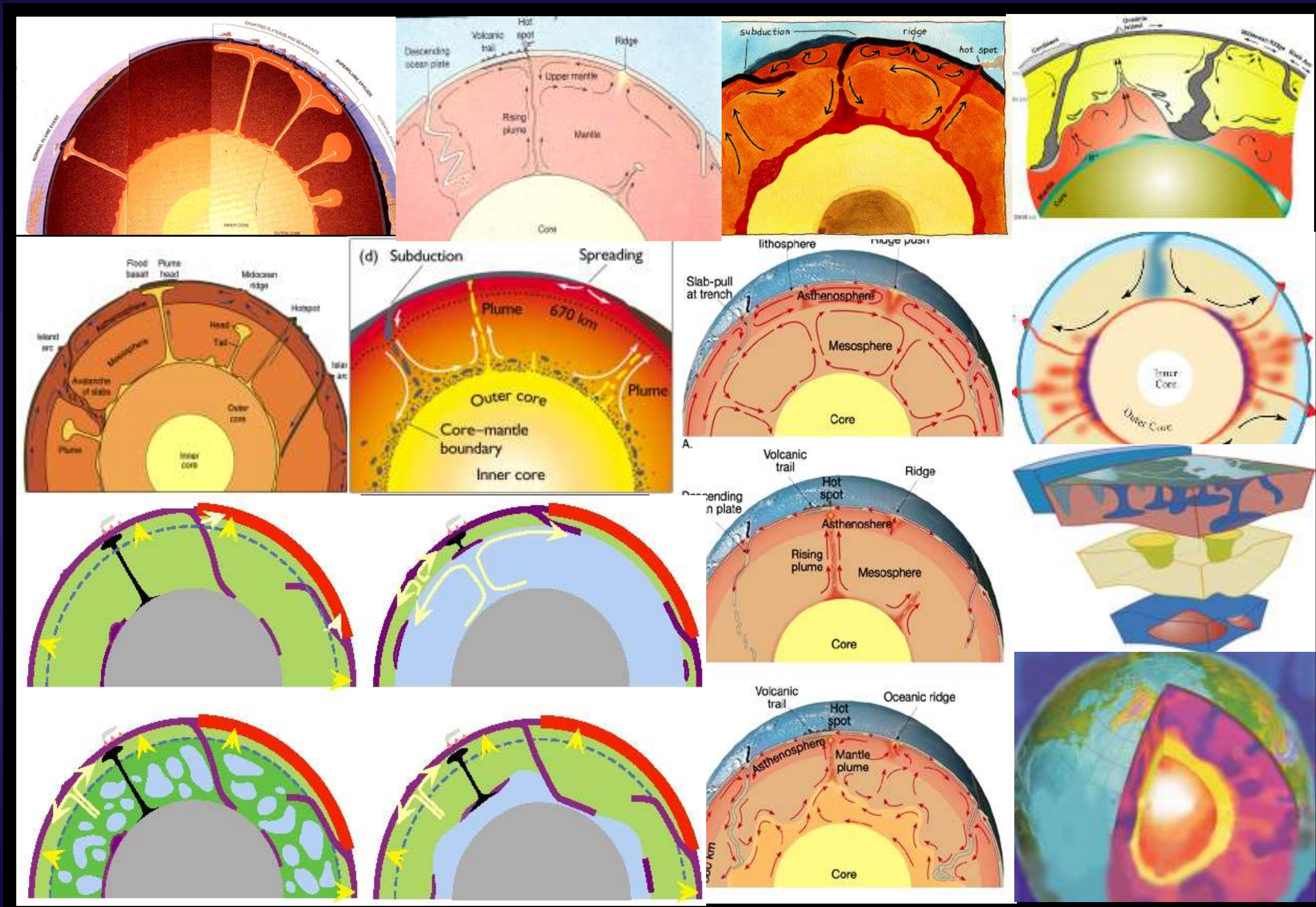
Earth

**DEATH** of plates **BIRTH** of plates




http://www.ngdc.noaa.gov/mgg/image/relief_slides1.html

# To explain surface observables: **many possibilities**

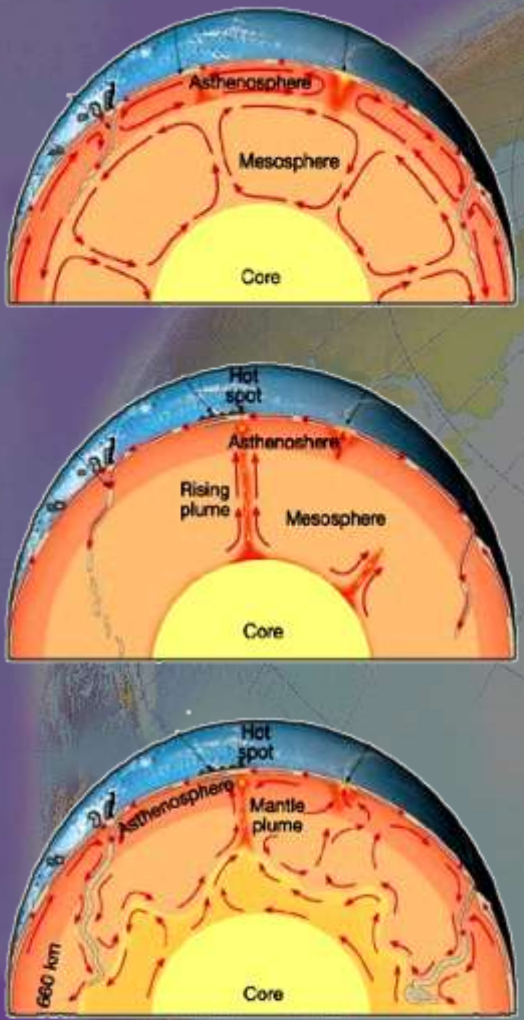



*[Alberede, Anderson, Davies, Hager, Jellinek, Kellogg, Manga, Tackley, van der Hilst, Wysession, Geo101 books…]*

## *Internal structure and circulation play a fundamental role in the nature and evolution of many phenomena*

- *Plate tectonic driving force*
- *Plumes & resulting volcanism*
- *Subduction and the fate of slabs*
- *Plate reorganization, super-continents*
- *Planetary heat budget/transfer*
- *Core processes & magnetic field*
- *Earth's chemical & water cycles*
- *Mantle outgassing → ocean & atmosphere chem.*
- *Mantle reservoirs*

# Studying planetary interiors

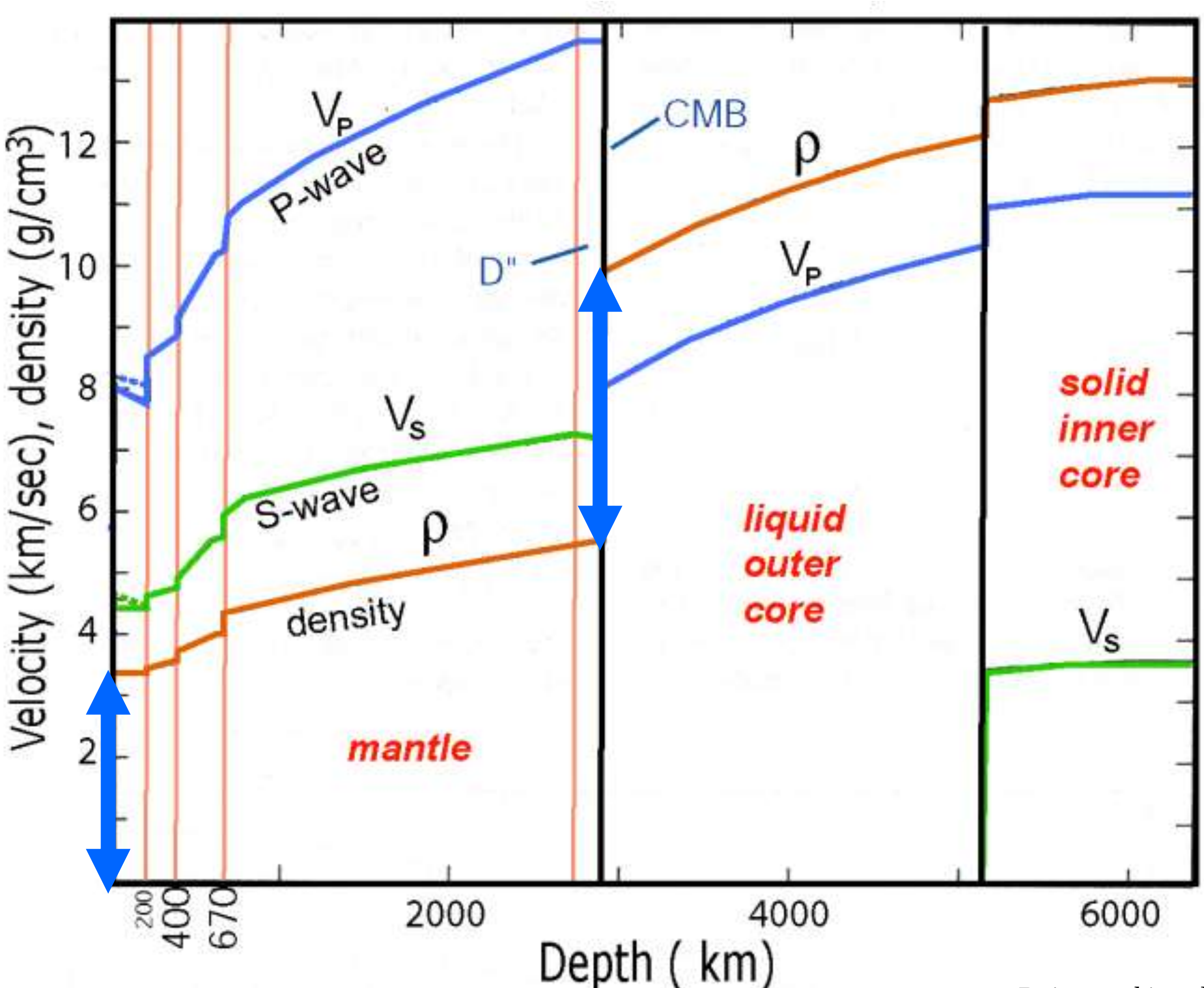



Tarbuck & Lutgens (Intro geology text)

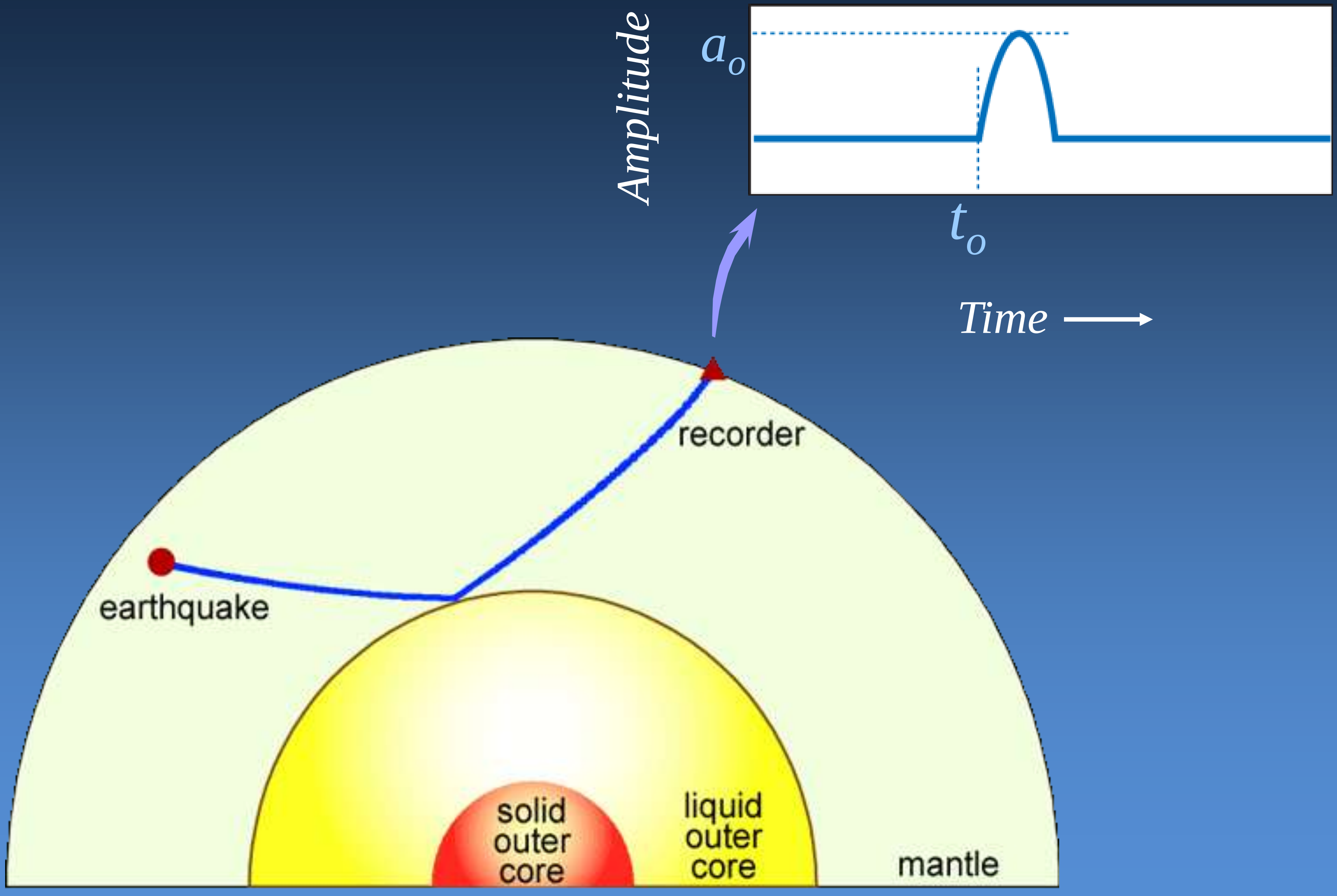
- Gravity / geoid
- Past / present magnetic field
- Chemistry of lavas, crust, etc.
- Current/past plate motions
- Seismic imaging
- Geodynamic experiments
- High pressure mineral physics
- Cosmochemistry / meteoritics
- Tectonics / geodesy
- Magnetotellurics
- Geoneutrinos

# ***Earth in 1-D***: *The Preliminary Reference Earth Model (PREM)*

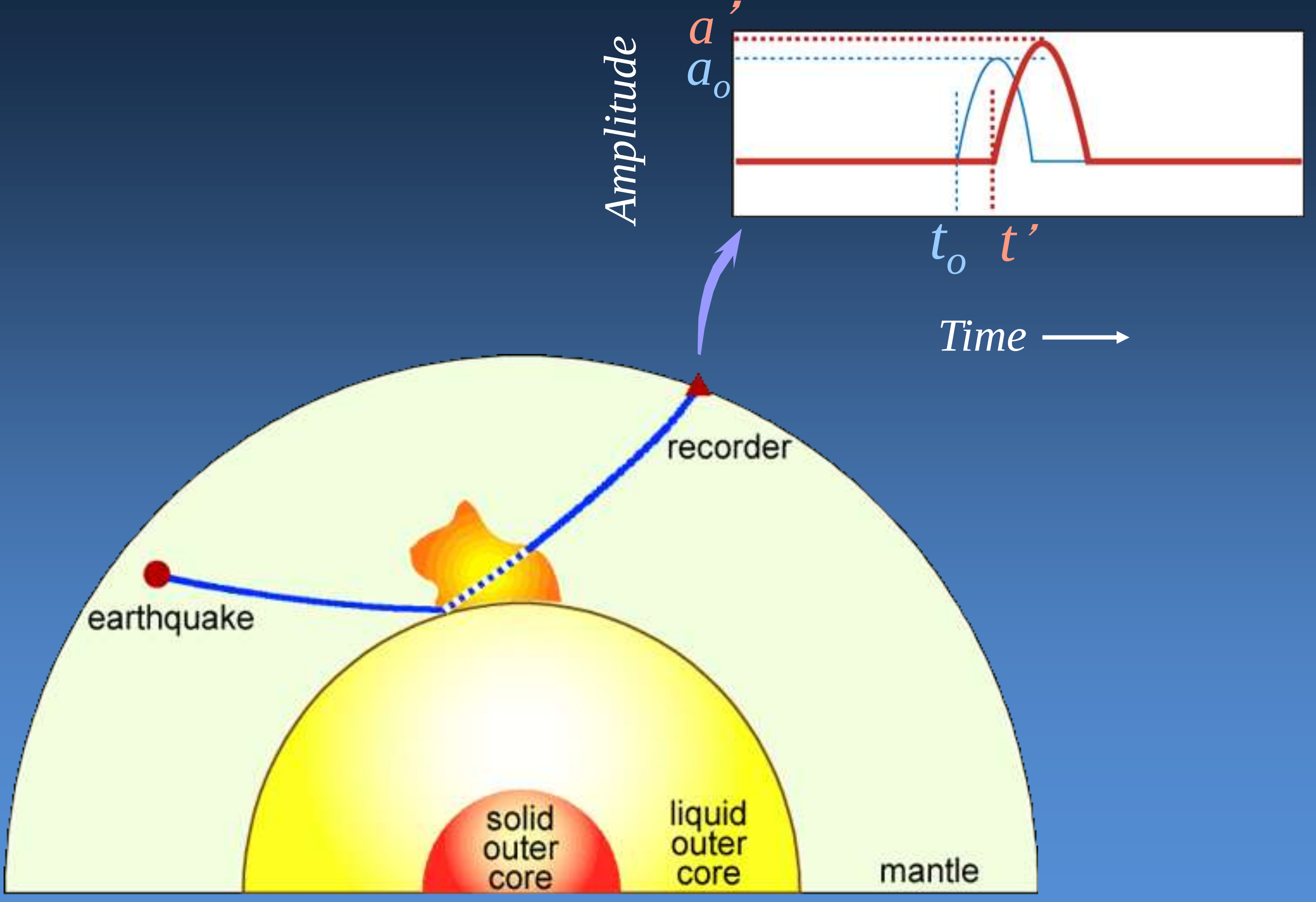
Nearly all seismic results are determined & presented relative to an assumed reference structure



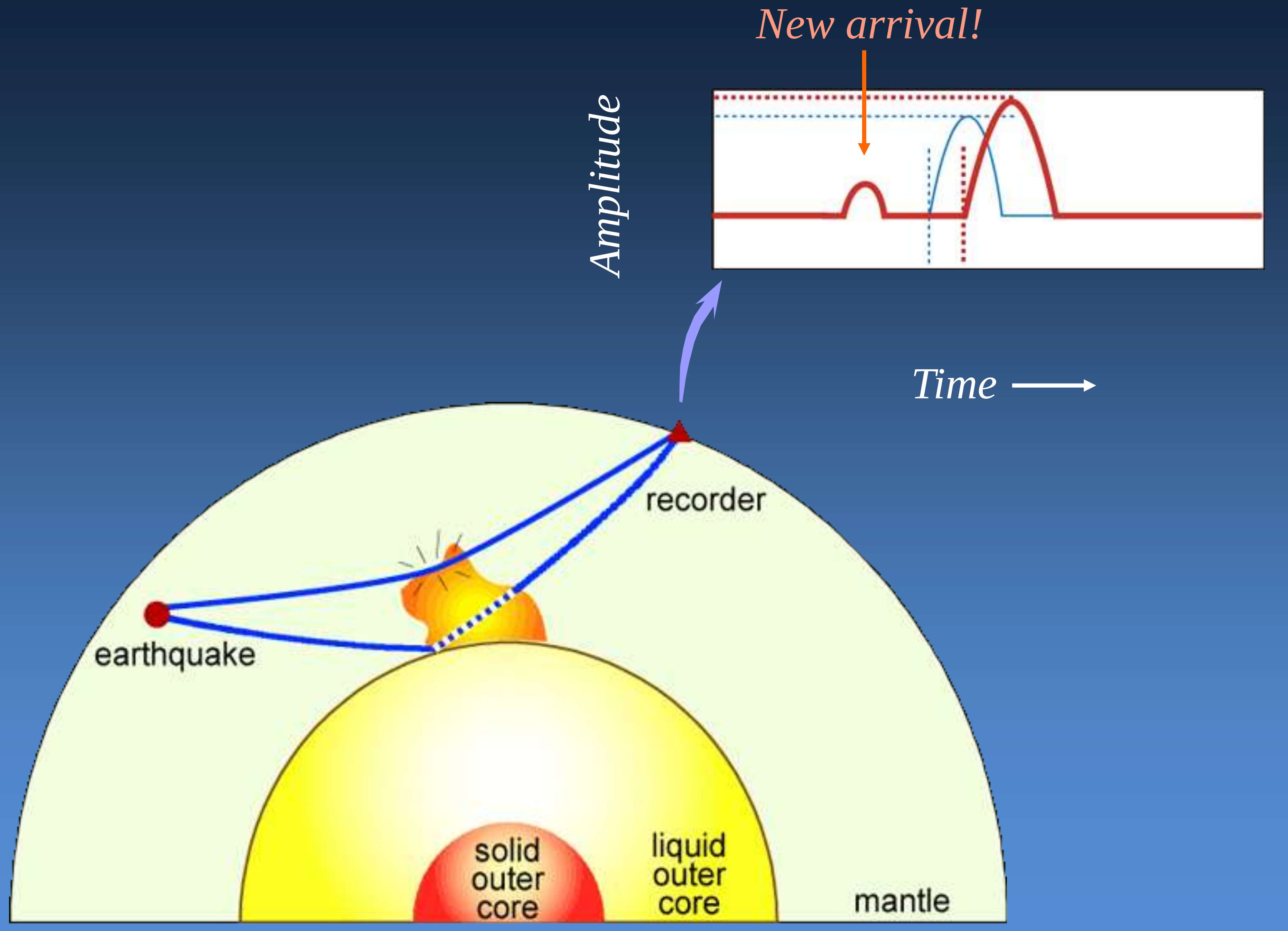

*Dziewonski and Anderson* [PEPI, 1981]

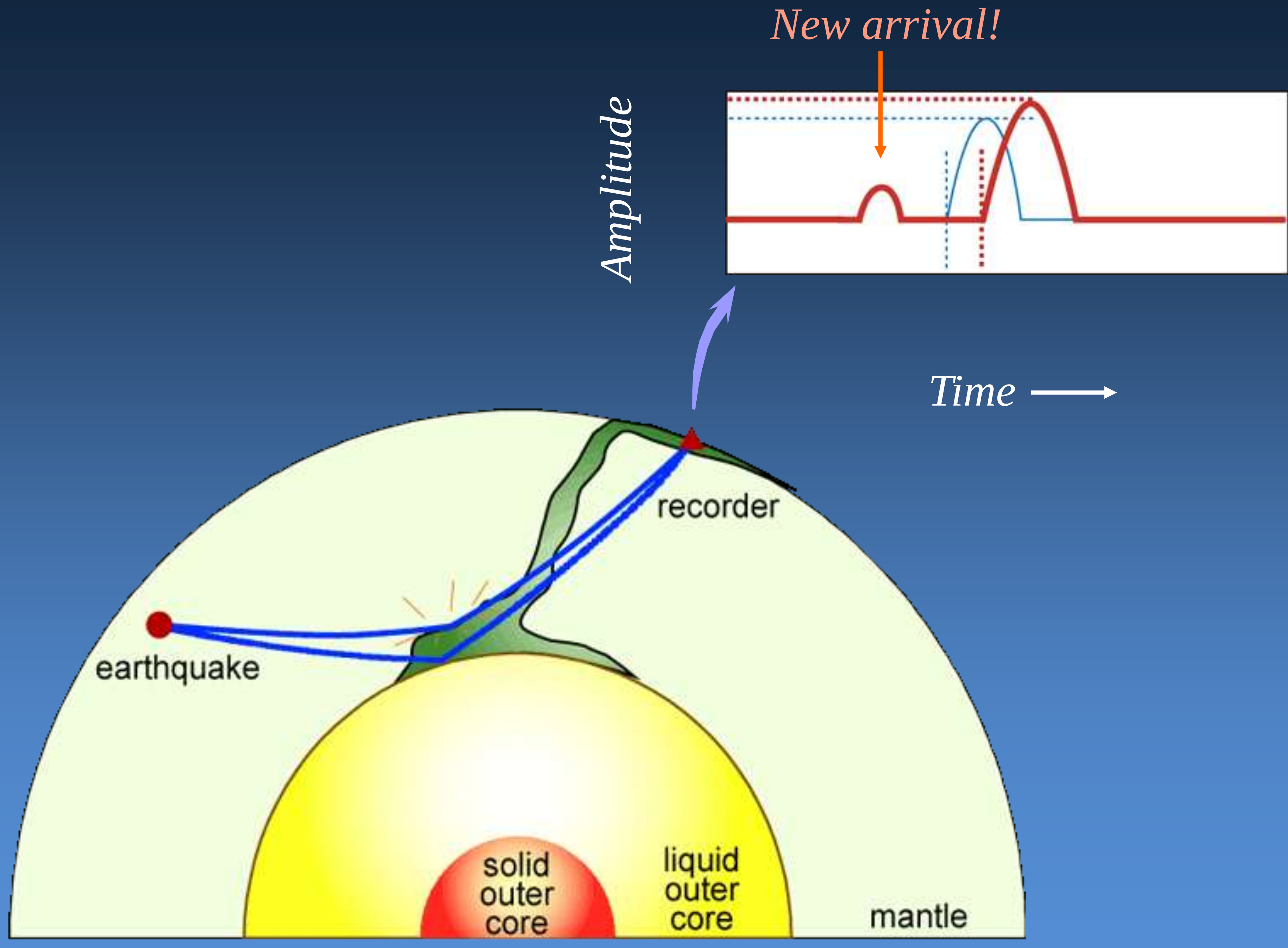


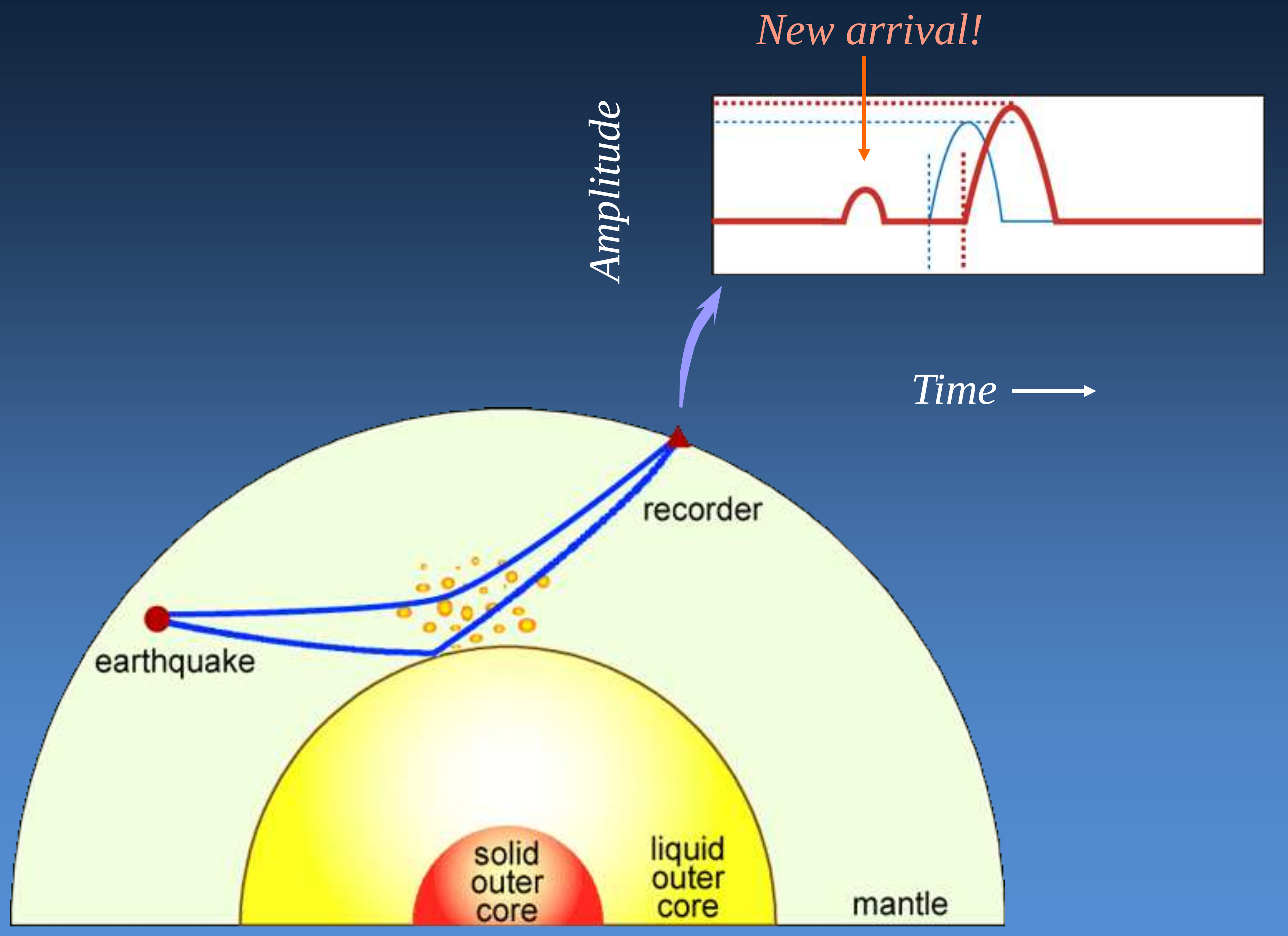
Amplitude
$a_o$
$t_o$
Time
recorder
earthquake
solid
outer
core
liquid
outer
core
mantle

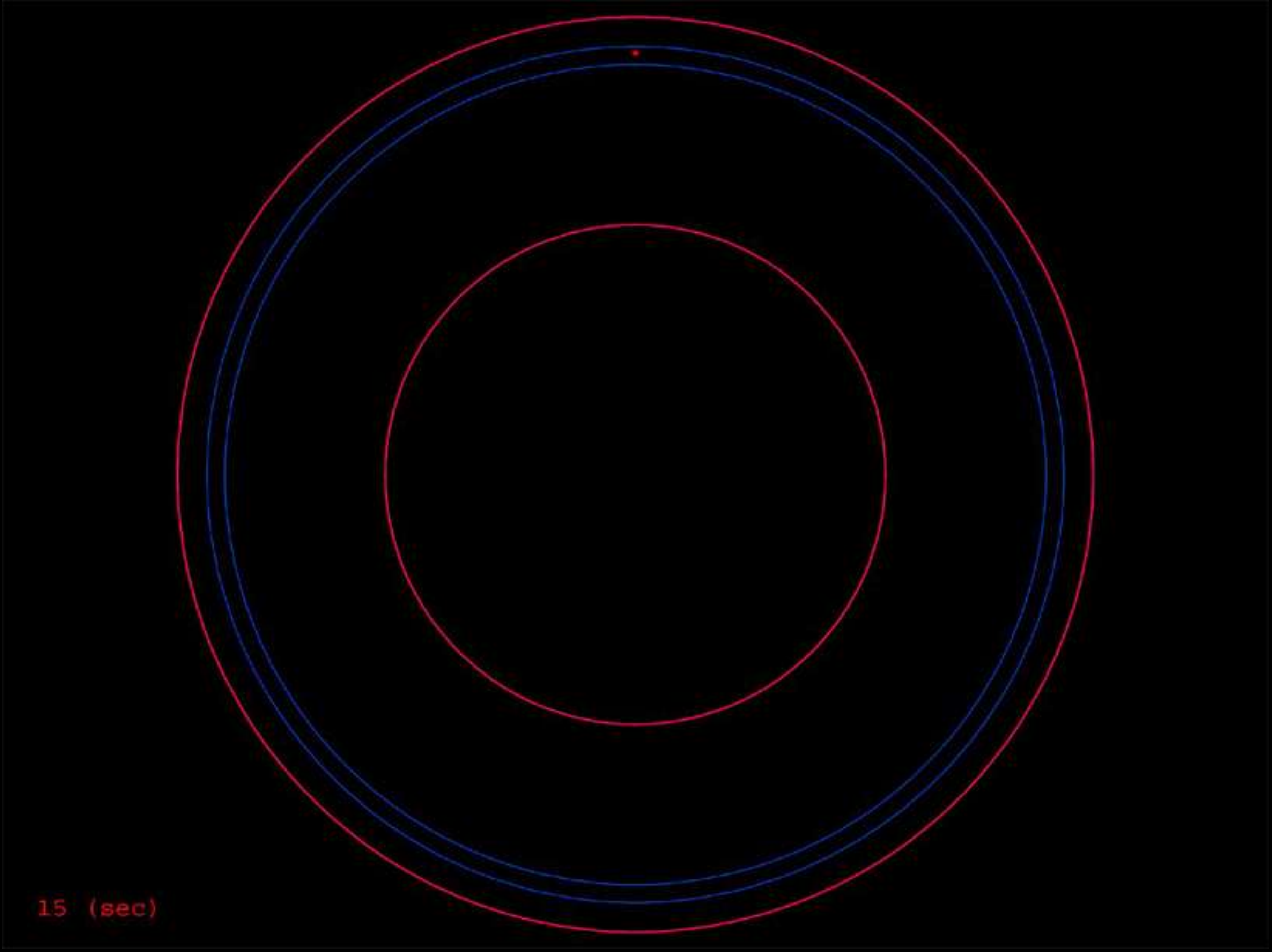


a'
a_o
Amplitude
t_o
t'
Time
recorder
earthquake
solid
outer
core
liquid
outer
core
mantle


New arrival!
Amplitude
Time
recorder
earthquake
solid
outer
core
liquid
outer
core
mantle

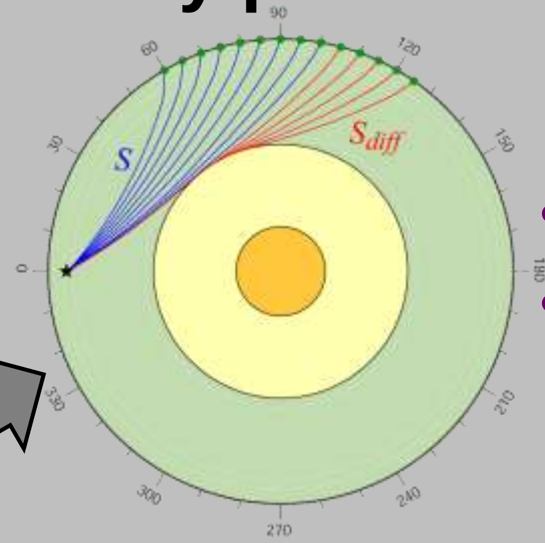

New arrival!
Amplitude
Time
recorder
earthquake
solid
outer
core
liquid
outer
core
mantle


New arrival!
Amplitude
Time
recorder
earthquake
solid
outer
core
liquid
outer
core
mantle



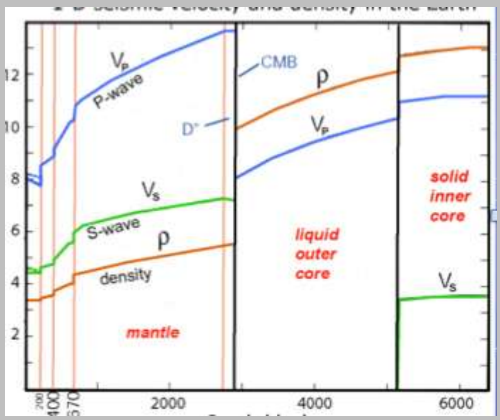

Mike Thorne (Univ. Utah)

## ray paths



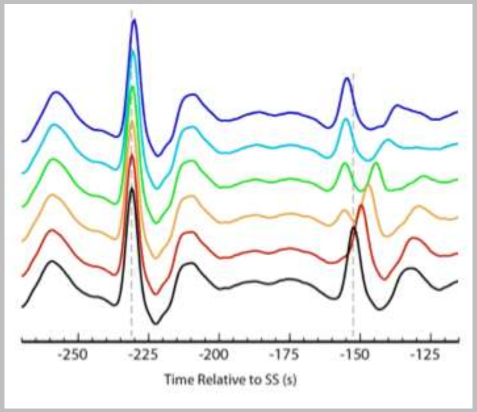

- *Wave travel times*
- *Path geometry*

## Reference model




V(z)

## synthetic waveforms



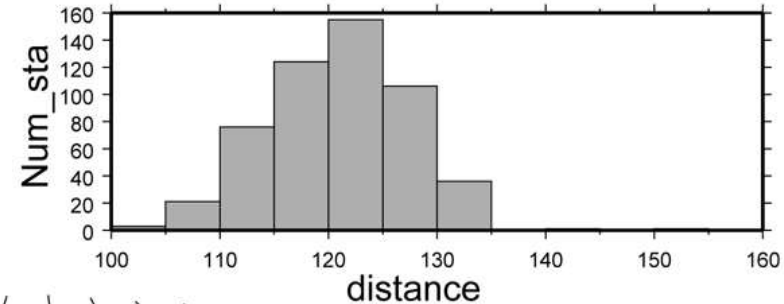

V(z)
ρ(z)

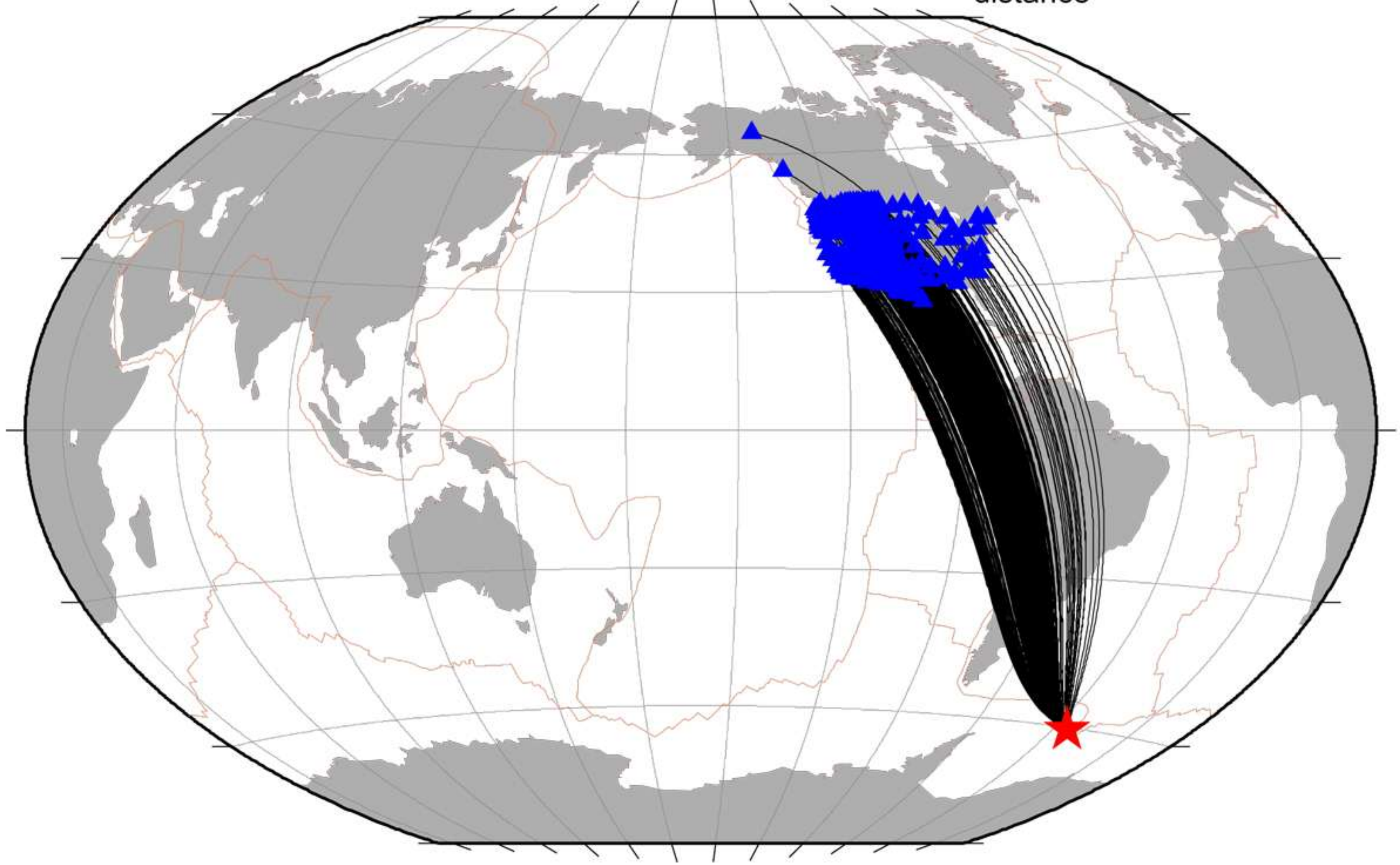
- *Wave shapes*
- *Frequency*

*Everything we do depends on our reliance on the starting model*

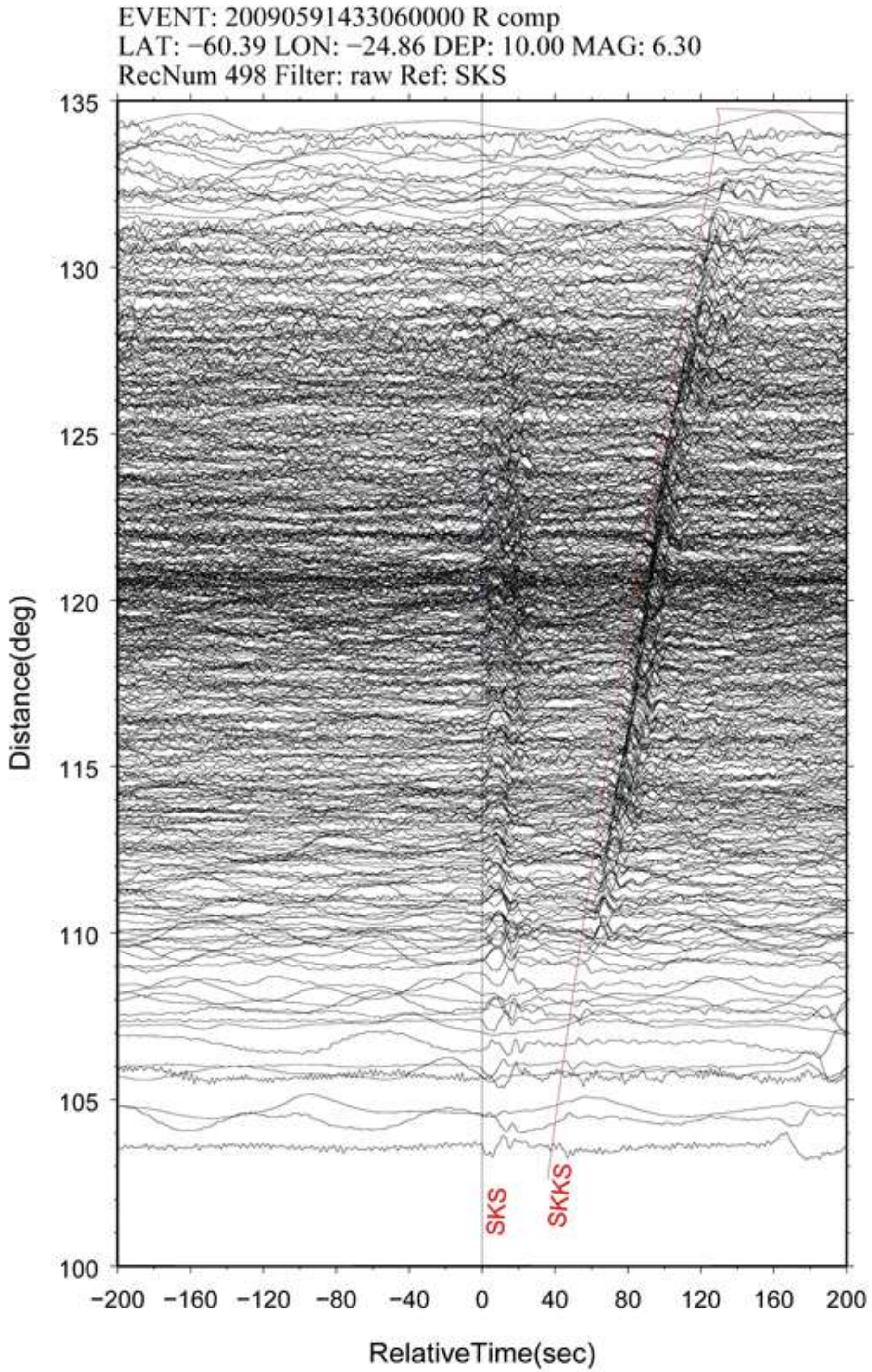
# South Sandwich Islands Feb 28, 2009

Event:2009/02/28_14:33:06.0000
lat: −60.394 lon: −24.863
Depth=10.00km
Mag=6.30 #=523

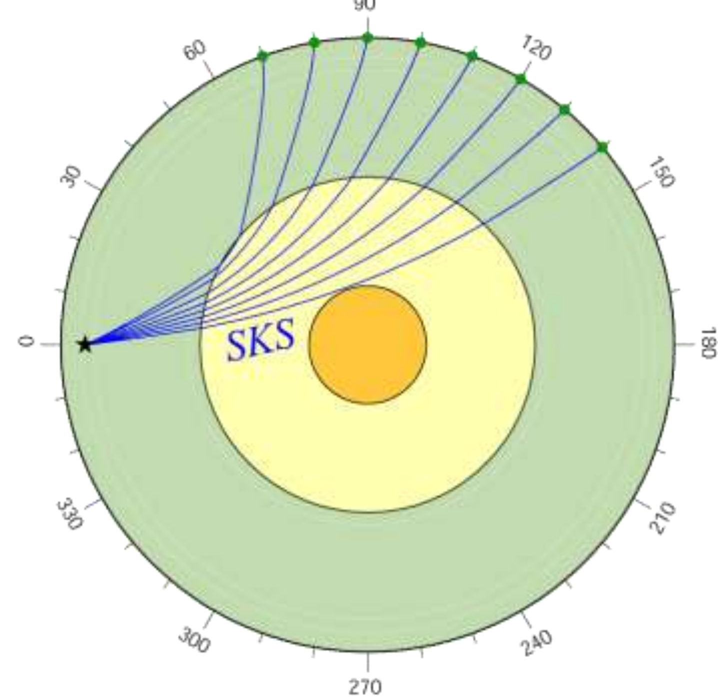


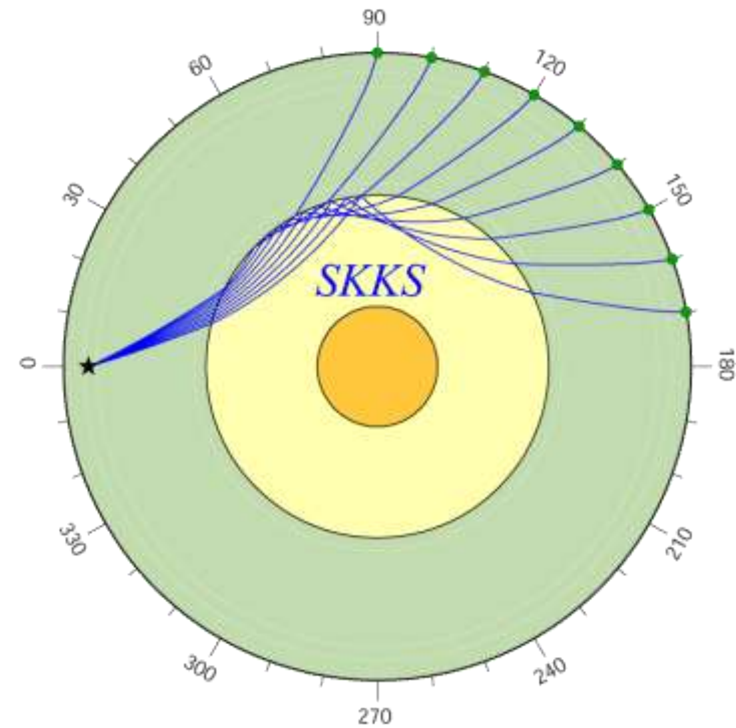
Raw data



EVENT: 200905914330600000 R comp
LAT: −60.39 LON: −24.86 DEP: 10.00 MAG: 6.30
RecNum 498 Filter: raw Ref: SKS
135
130
125
120
115
110
105
100
Distance(deg)
−200 −160 −120 −80 −40 0 40 80 120 160 200
RelativeTime(sec)
SKS
SKKS

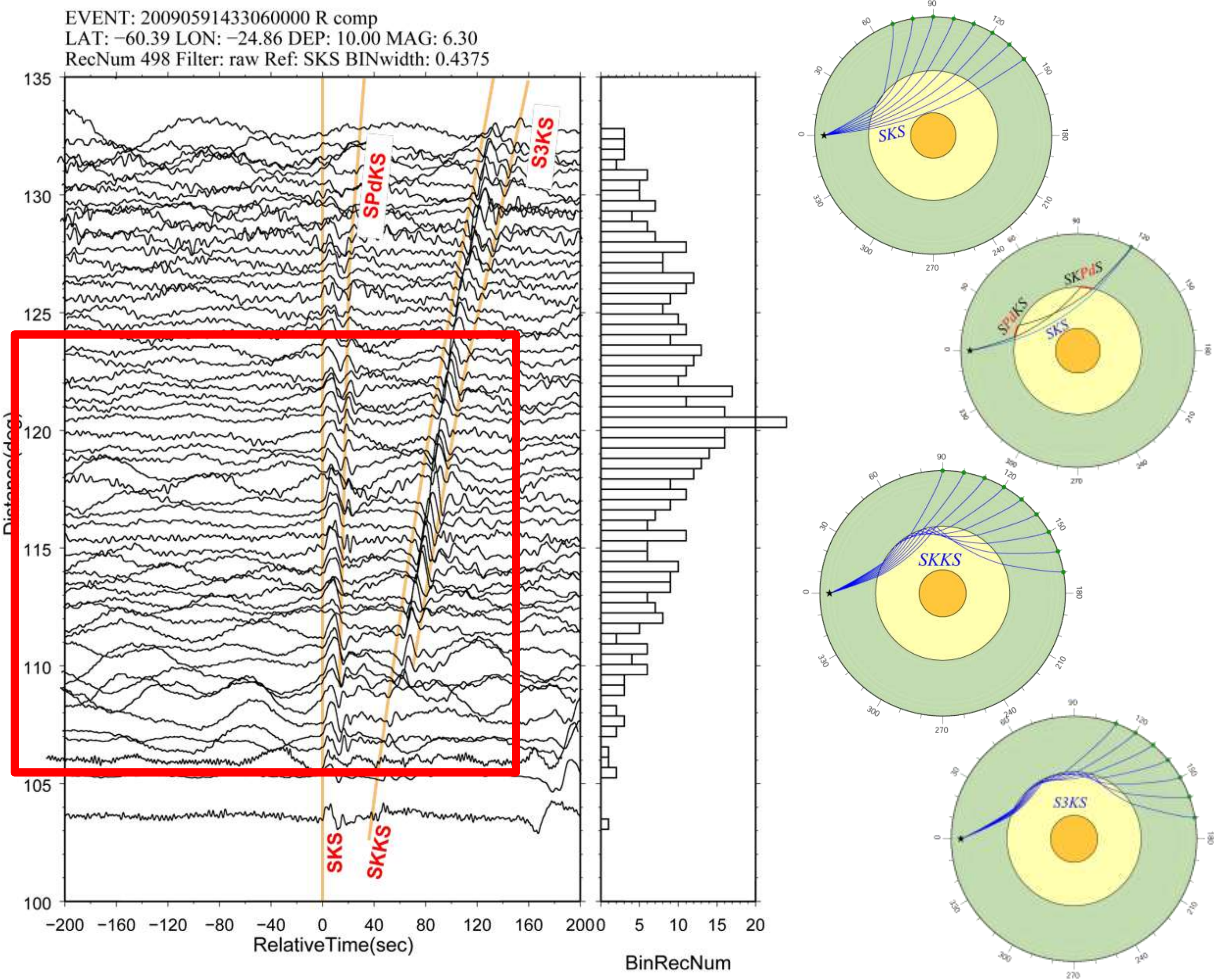



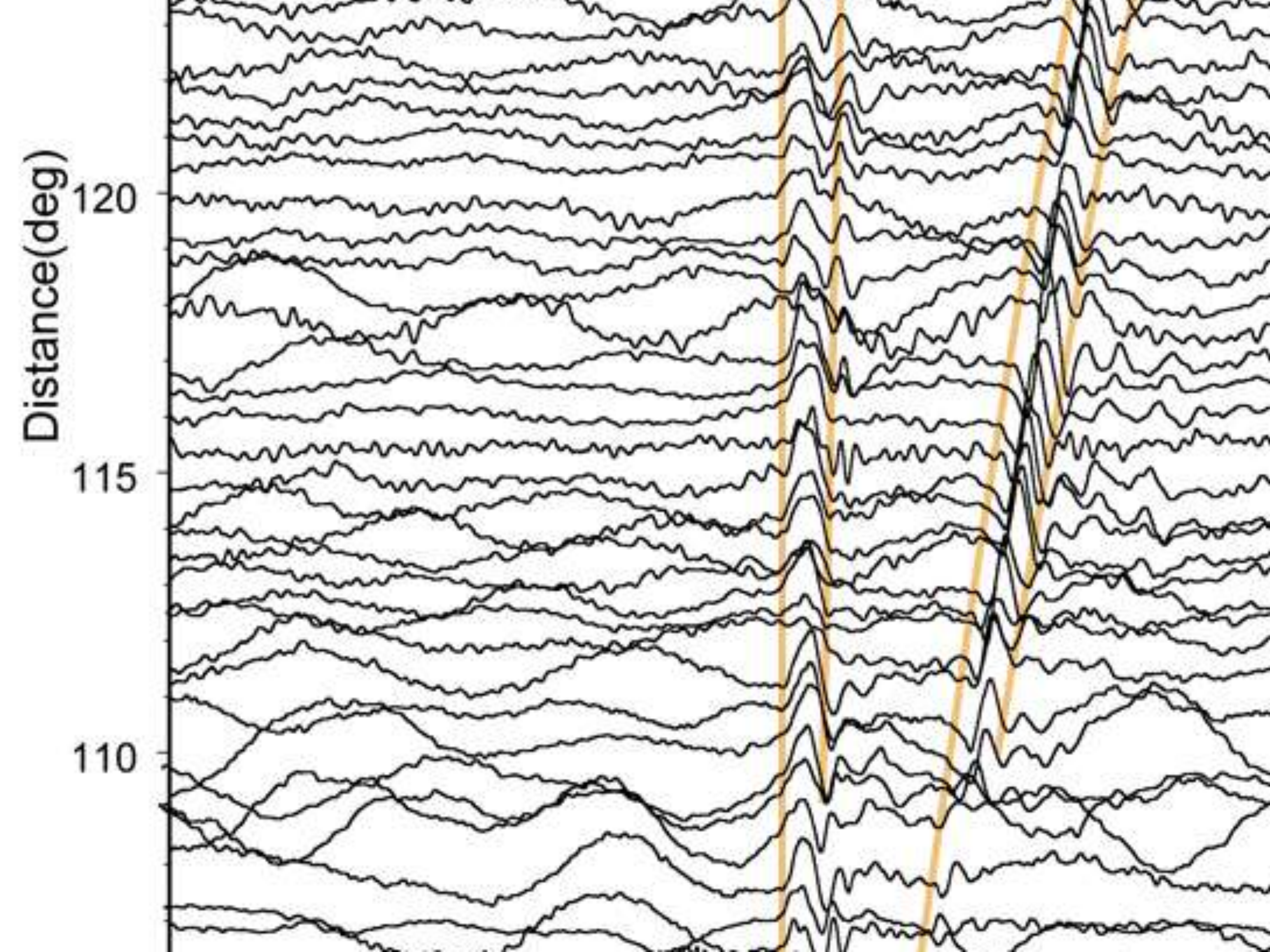
90
60
120
30
150
0
180
SKS
330
210
300
240
270

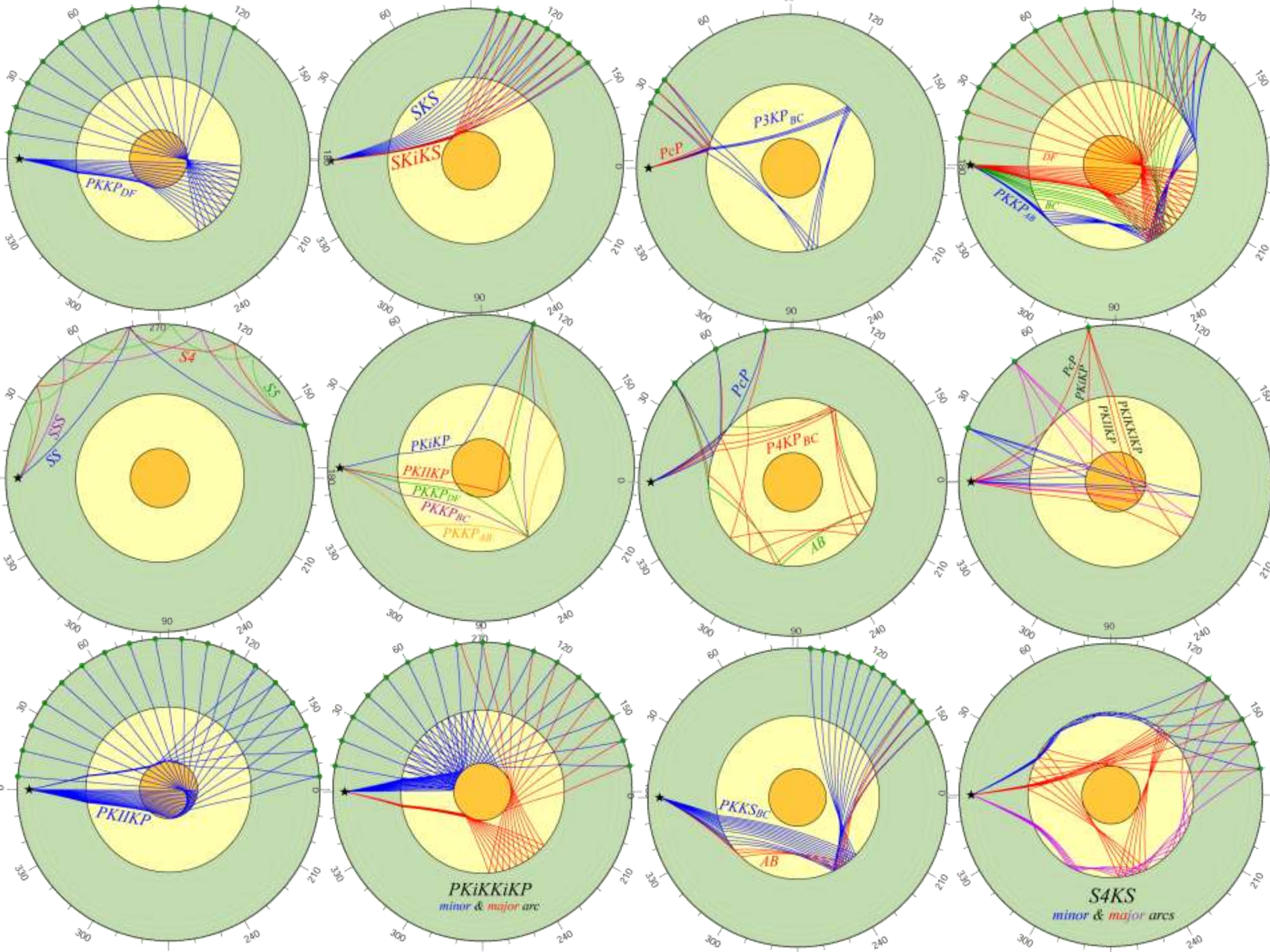



90
60
120
30
150
0
180
SKKS
330
210
300
240
270

# Distance-stacked data



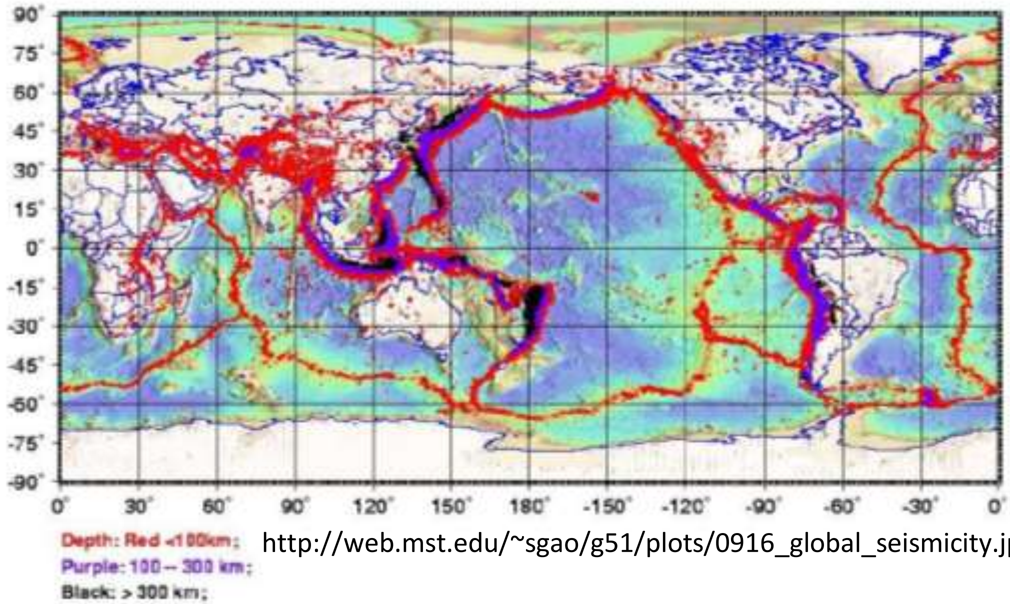

Distance(deg)
120
115
110



PKKP$_{DF}$
SKS
SKiKS
P3KP$_{BC}$
PcP
DF
PKKP$_{AB}$
BC
S4
SS
SSS
PKiKP
PKIIKP
PKKP$_{DF}$
PKKP$_{BC}$
PKKP$_{AB}$
PcP
P4KP$_{BC}$
AB
PcP
PKIKP
PKIIKP
PKIKKIKP
PKIIKP
PKiKKiKP
minor & major arc
PKKS$_{BC}$
AB
S4KS
minor & major arcs

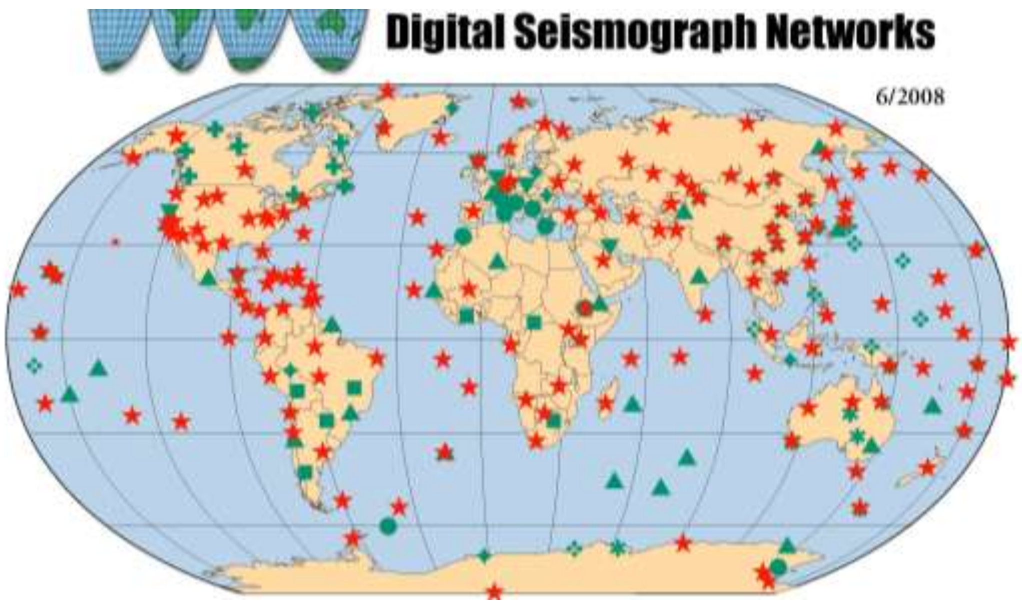
# earthquakes

(sources of energy)




http://web.mst.edu/~sgao/g51/plots/0916_global_seismicity.jpg

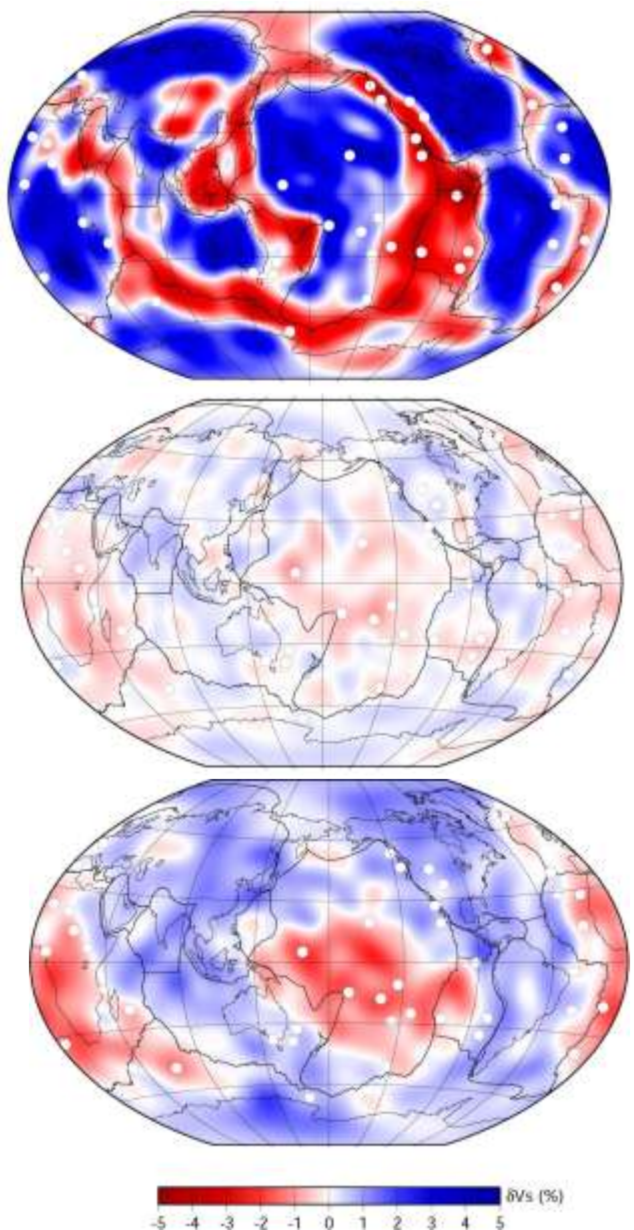
# sensors




http://www.iris.edu

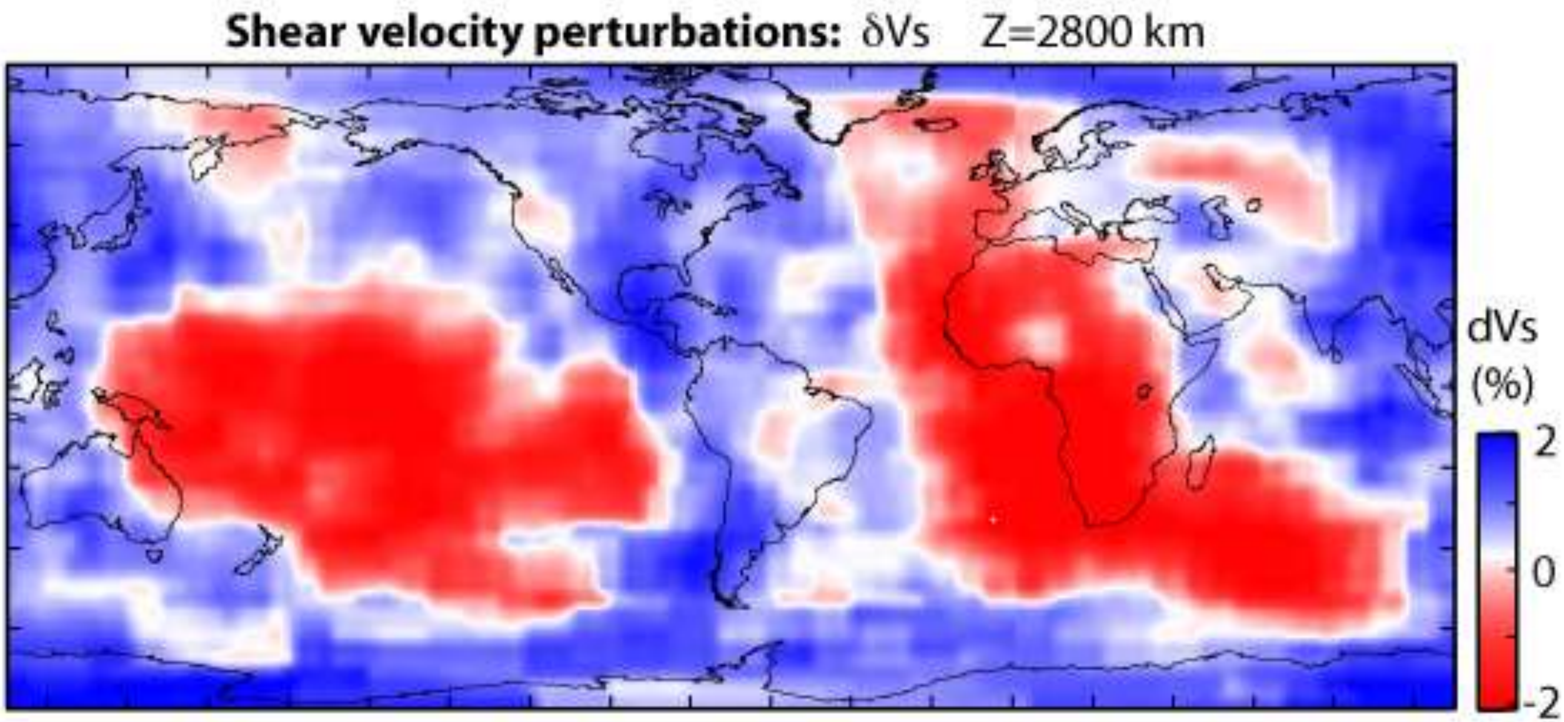
# ***Earth in 3-D***: *Heterogeneity from* ***seismic tomography***

| DEPTH | | HETEROGENEITY |
|---|---|---|
| **Z=50 km** | | **stongest** |
| **Z=1500 km** | | **weakest** |
| **Z=2880 km** | | **strong again** |




[after Ritsema and van Heijst, 2001]

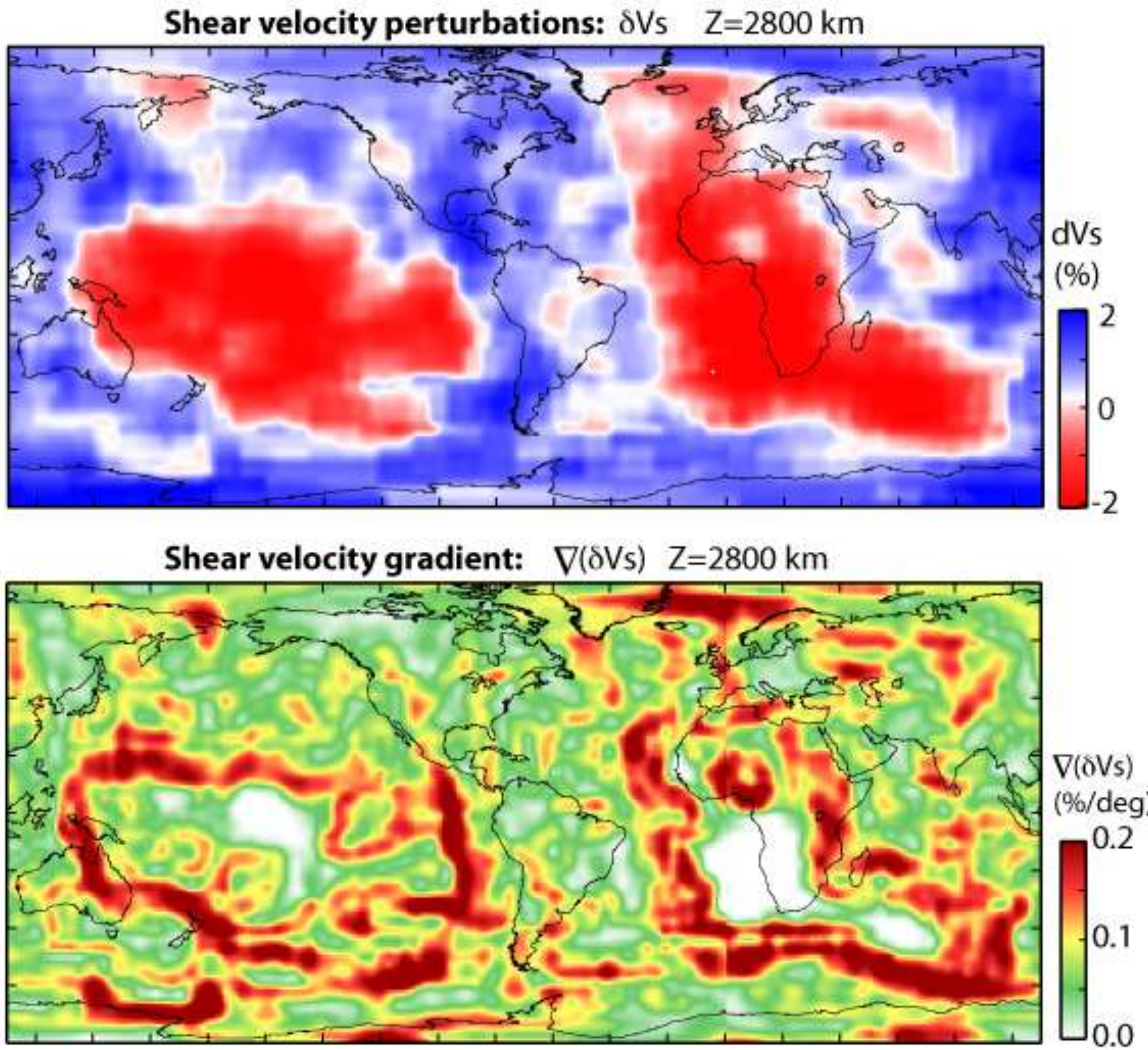
# Base of Earth's mantle




“Large Low Shear Velocity Provinces”: LLSVPs

*Model of Jeroen Ritsema*

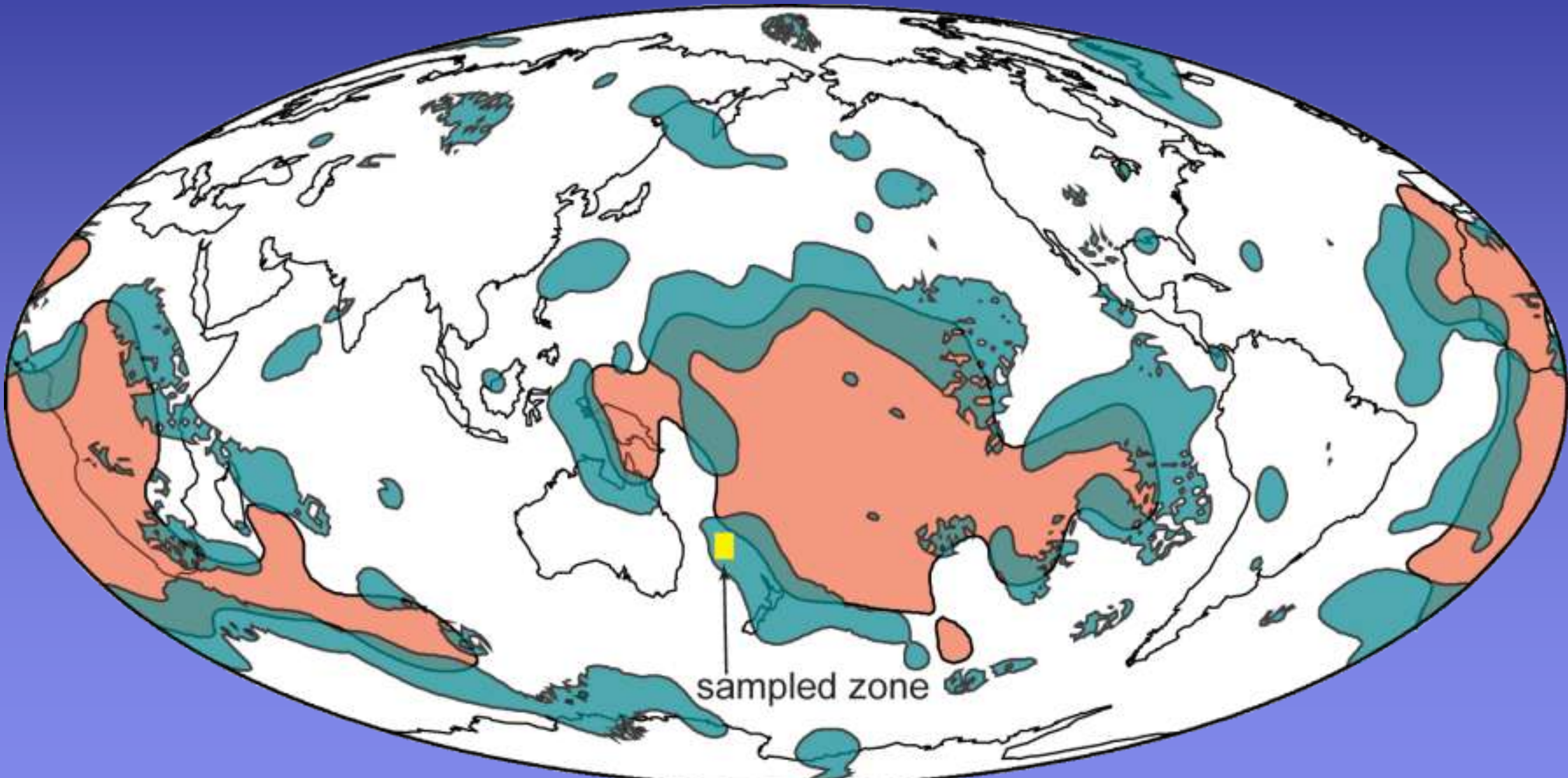
# LLSVP margins



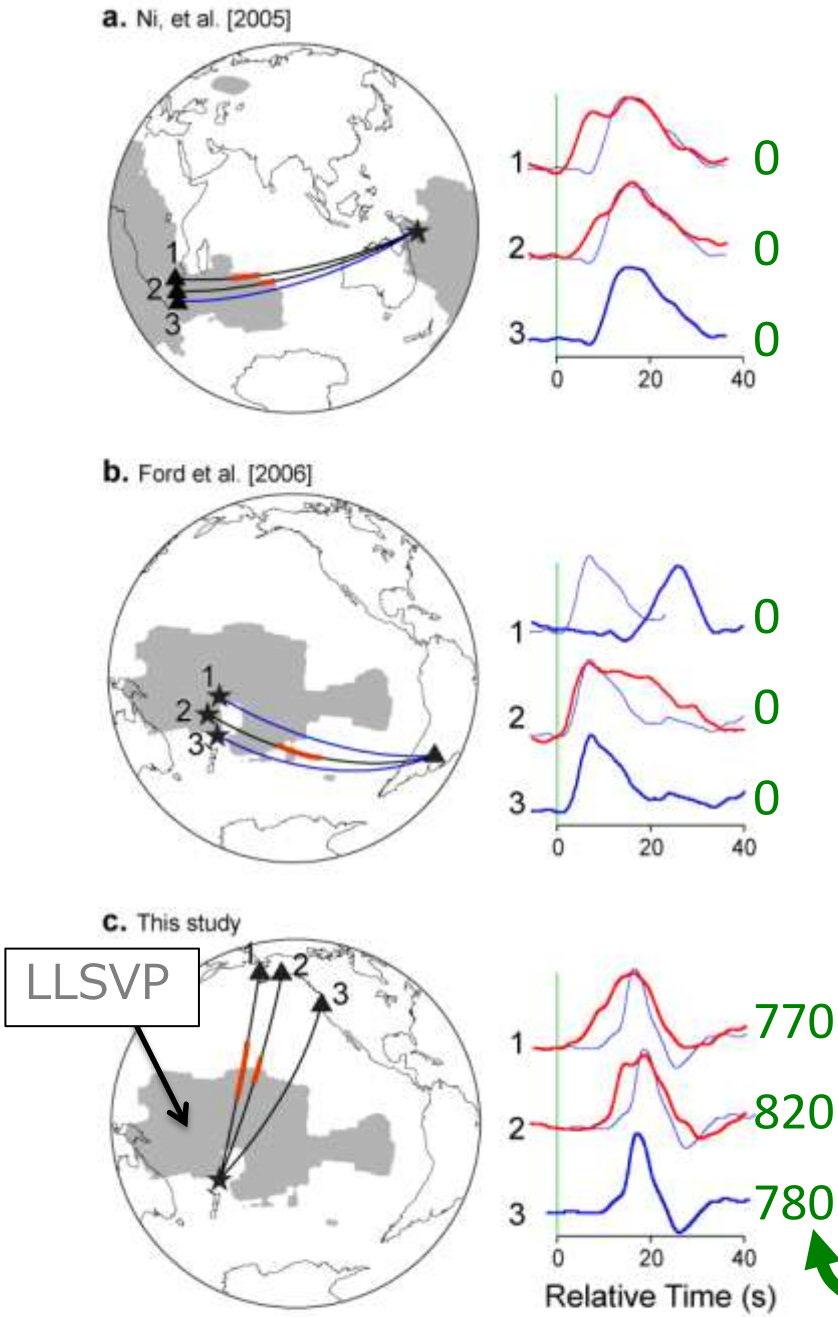

**Strongest lateral gradients are at LLSVP edges**

red: lowest velocities for S20RTS

green: strongest lateral $V_S$ gradients




Thorne, Garnero, Grand, PEPI., 2004

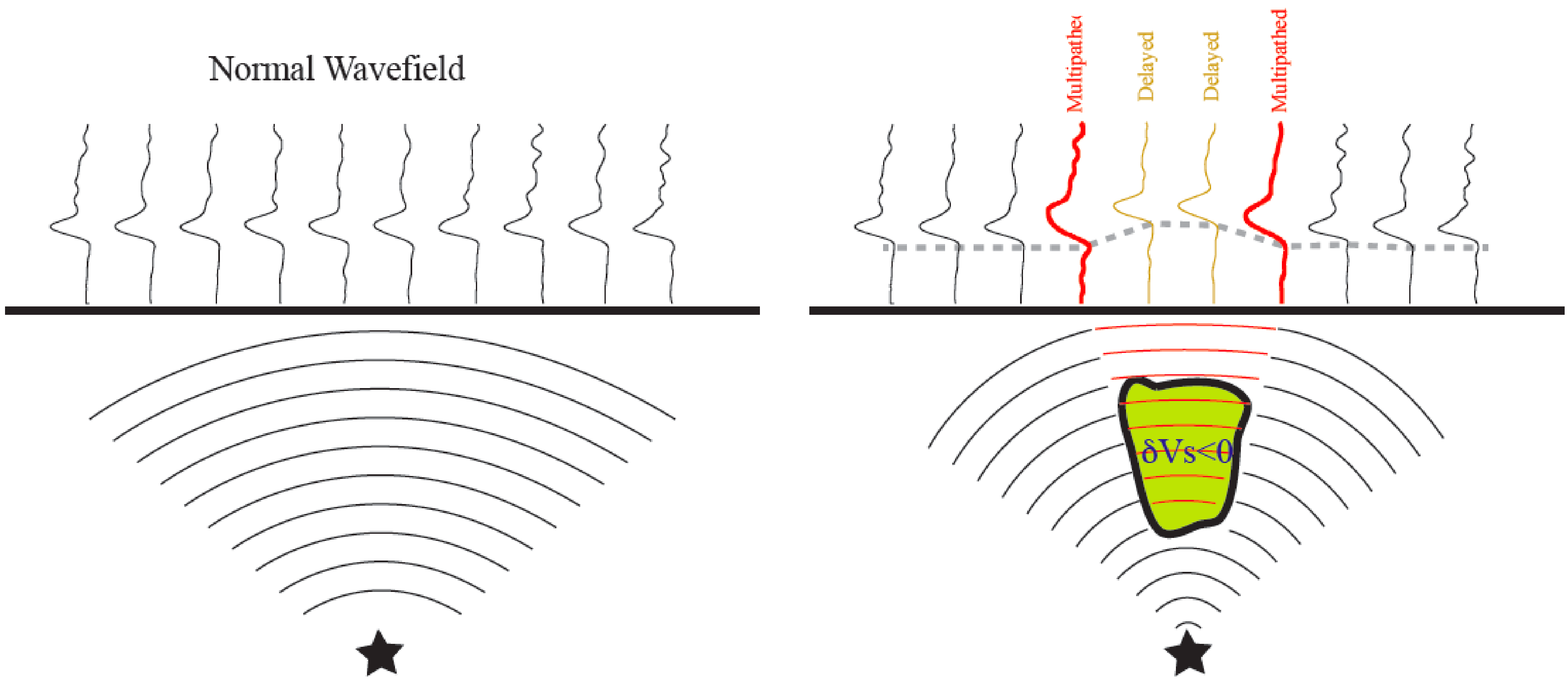



**Seismic waves that propagate near LLSVP edges are broadened, sometimes multi-pulsed**

Raypath PREM-predicted bottoming depth

Zhao et al (2013 in prep)

# Wave multi-pathing and broadening from refraction along heterogeneities



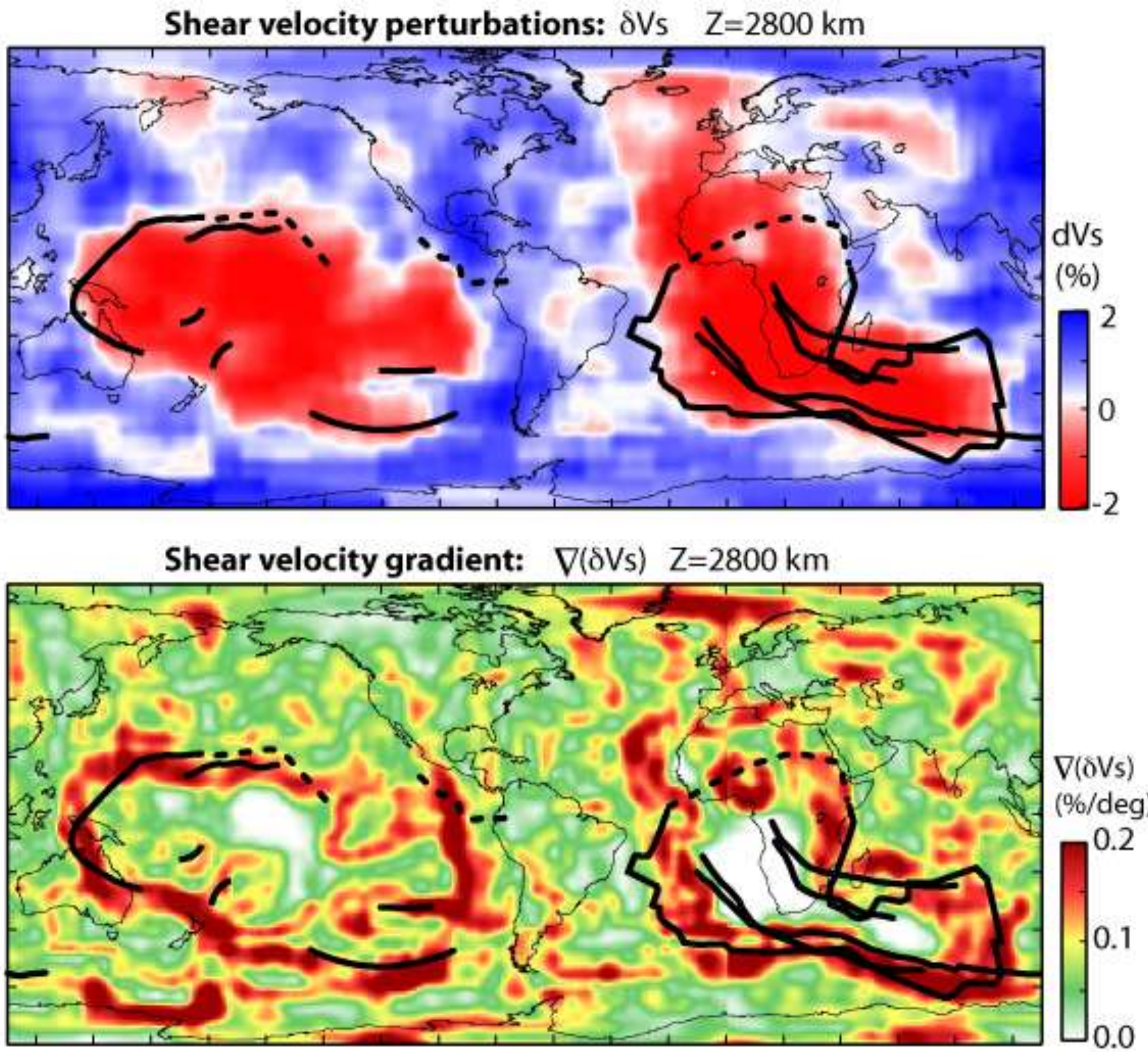

Courtesy of Chunpeng Zhao

**Table S1.** Past seismic studies that image Large Low Shear Velocity Province (LLSVP) margins. The Location Number corresponds to Figure 1b and 1c in the main text.

| Study Reference | Location Number | Seismic Phases Used |
|---|---|---|
| *Bréger and Romanowicz* [1998] | 3 | *S, SKS, SKKS* |
| *Luo et al.* [2001] | 2 | *PKP* |
| *Ni et al.* [2002] | 10 | *S, ScS, SKS* |
| *Ni and Helmberger* [2003a] | 10 | *S, ScS, SKS, SKKS* |
| *Ni and Helmberger* [2003b] | 10 | *S, ScS, SKS* |
| *Ni and Helmberger* [2003c] | 10 | *S, ScS, SKS, P, PcP* |
| *Wang and Wen* [2004] | 8 | *S, ScS, SKS, SKKS* |
| *Ni et al.* [2005] | 10 | *S, ScS, SKS* |
| *To et al.* [2005] | 5 | *S, SKS, SKKS* |
| *Ford et al.* [2006] | 6 | *S, SKS, SKKS* |
| *He et al.* [2006] | 1 | *S, ScS* |
| *Sun et al.* [2007] | 9 | *S, ScS, SKS, SKKS* |
| *Sun X. et al.* [2007] | 4 | *PKP* |
| *He and Wen* [2009] | 7 | *S, ScS, SKS, SKKS* |
| *Sun et al.* [2009] | 9 | *S, ScS, SKS, SKKS* |

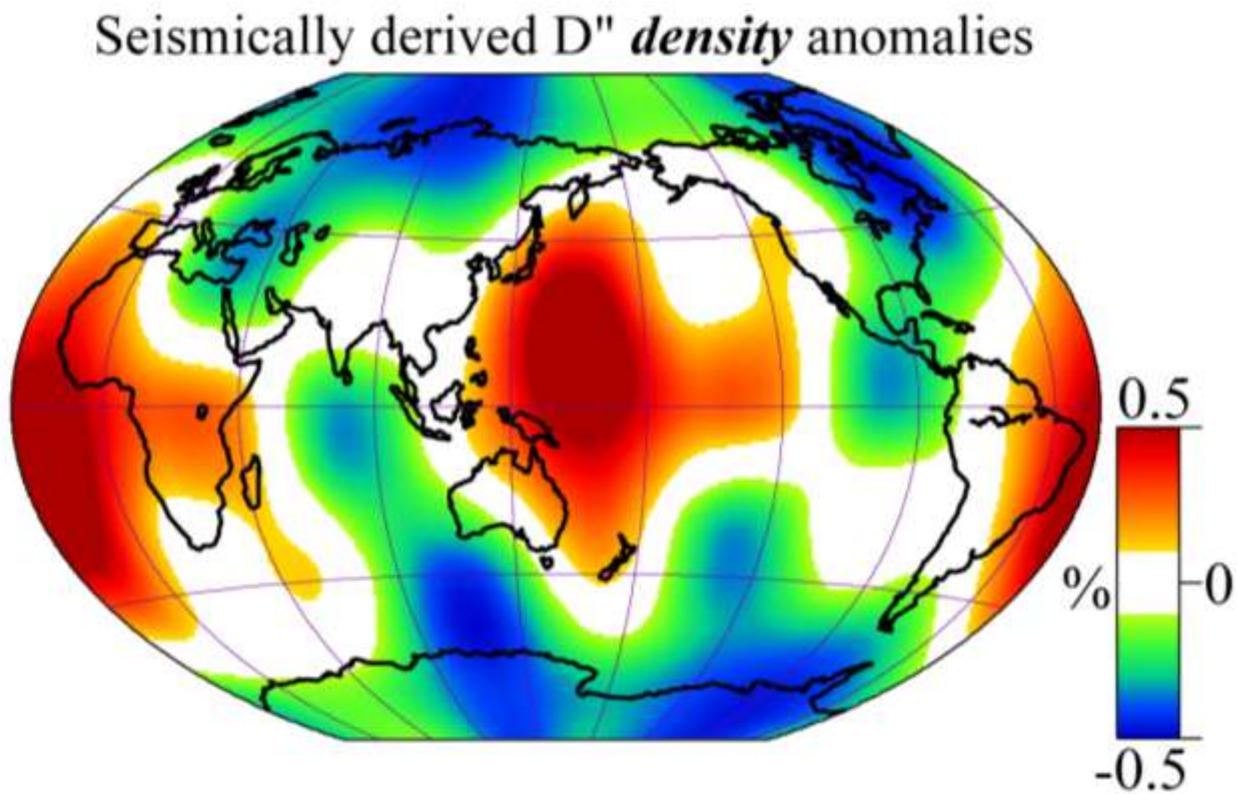
Zhao et al (2013 in prep)

# Deep mantle heterogeneity



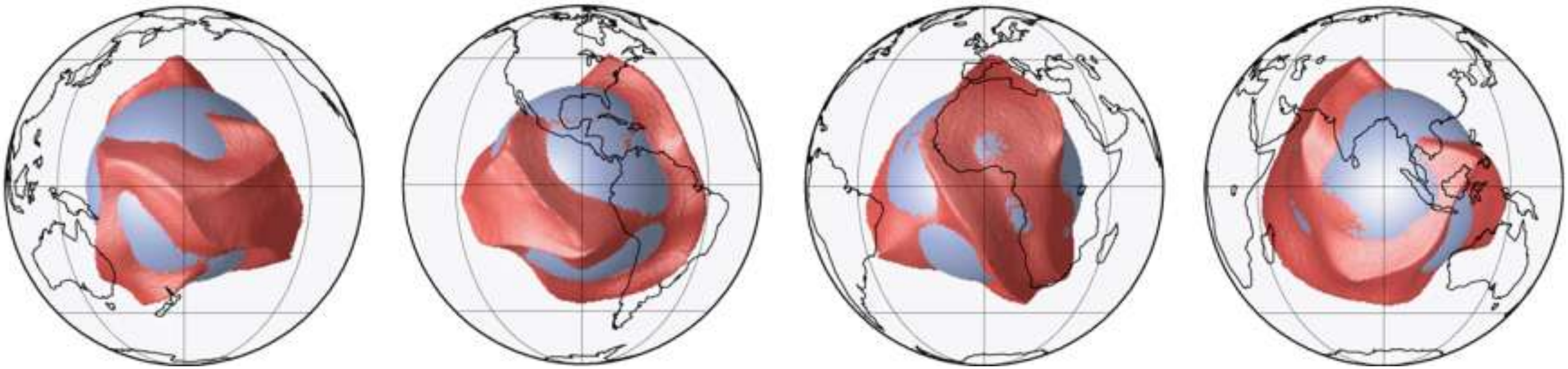

**Forward modeling studies find "edges" at LLSVP boundaries**

# Large low shear velocity provinces: DENSE




Trampert, Deschaps, Resovsky, Yuen (2004)
Also, Ishii & Tromp (2004)

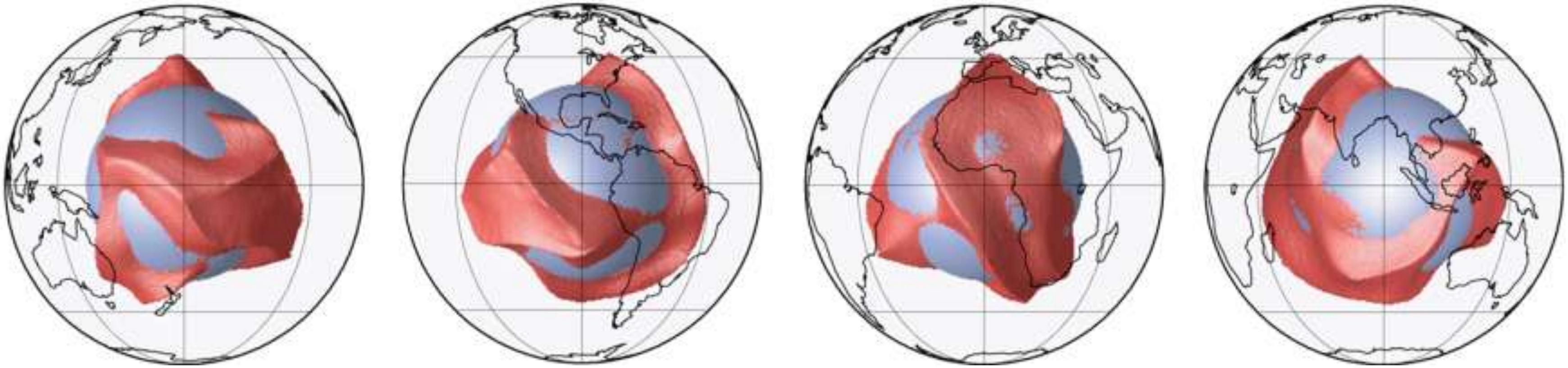
**Dense material (red) in thermochemical convection calculation**



McNamara & Zhong (2005, Nature)

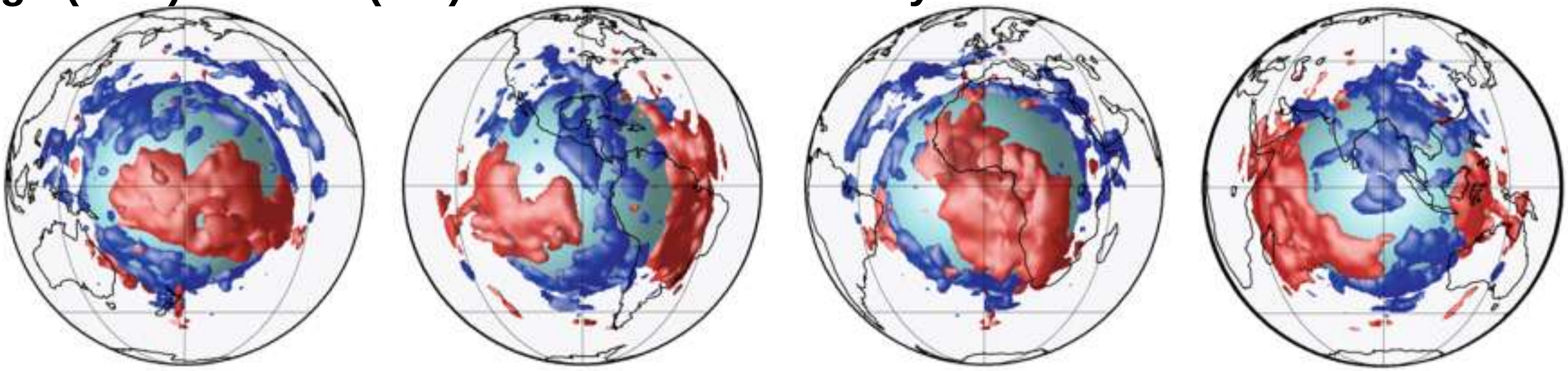
- thermochemical convection: initially uniform dense layer at base of mantle
- surface boundary condition: 119 My past plate motions
- downwellings “sweep” dense material into piles

**Dense material (red) in thermochemical convection calculation**



McNamara & Zhong (2005, Nature)

**High (blue) and low (red) seismic shear velocity**

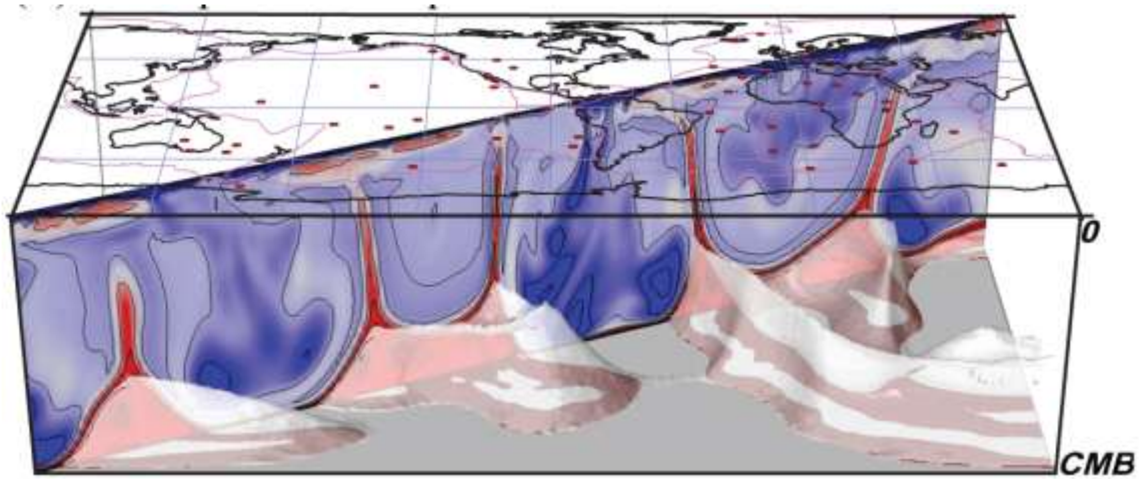


Grand (2002, Phil. Trans. R. Soc. Lond.)

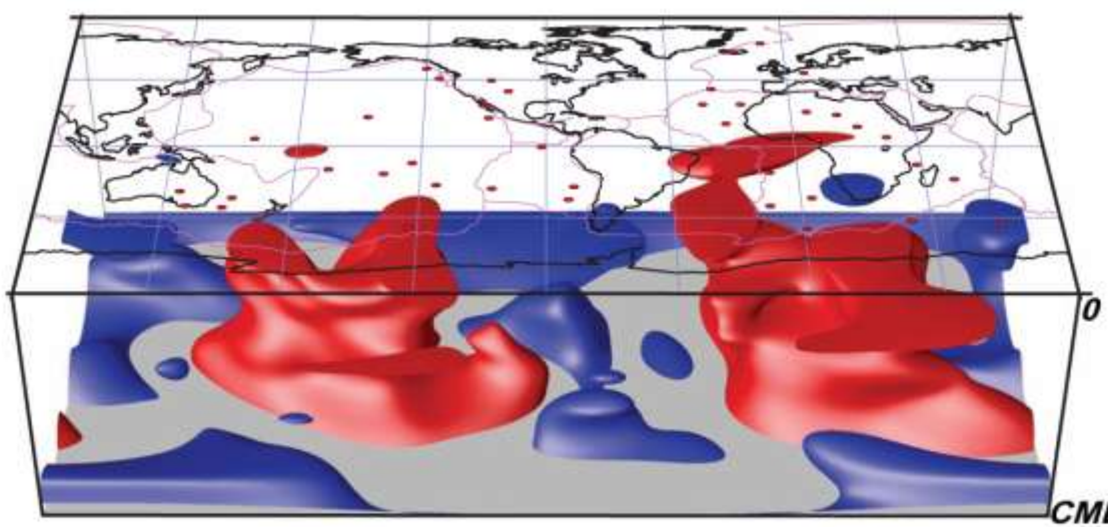
## ❖ Striking agreement

# Plumes from pile ridges

Numerical geodynamics

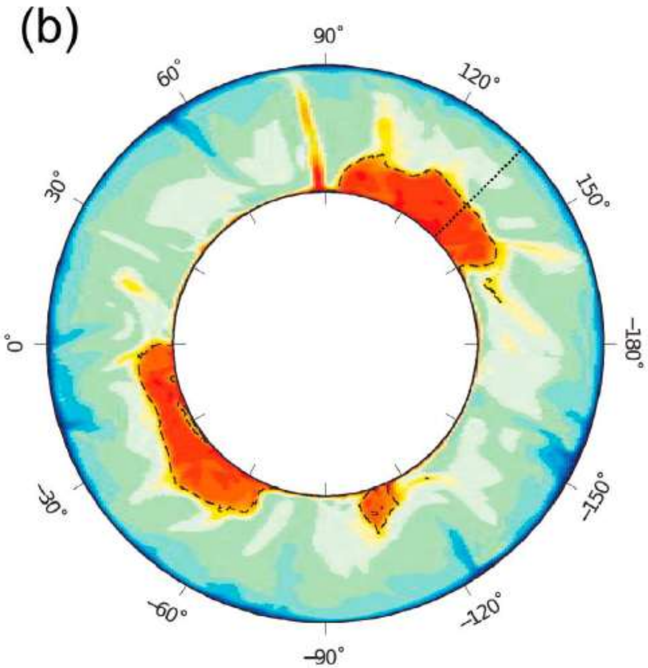



Seismic tomography




Garnero, Lay, McNamara (2007, GSA Monograph on Superplumes)

# Prediction: plumes from thermochemical pile margins



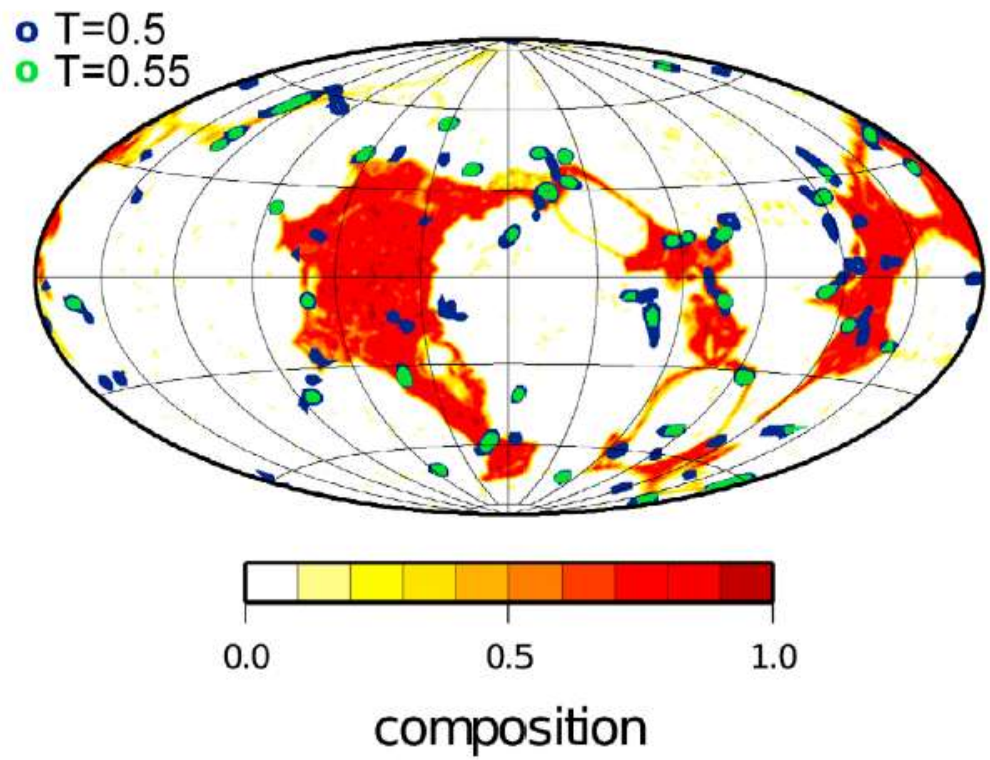
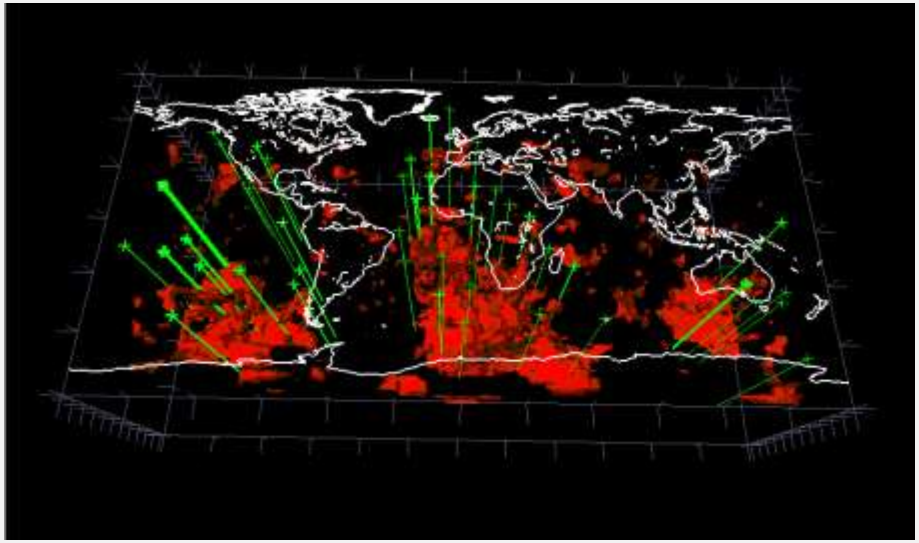




**Figure 5.** The locations of plumes at upper mantle plotted on top of the composition field at 2800 km depth. The blue contours are plumes ($T$ = 0.5) at 1000 km depth, and the green contours are strong plumes ($T$ = 0.55) at 1000 km depth.

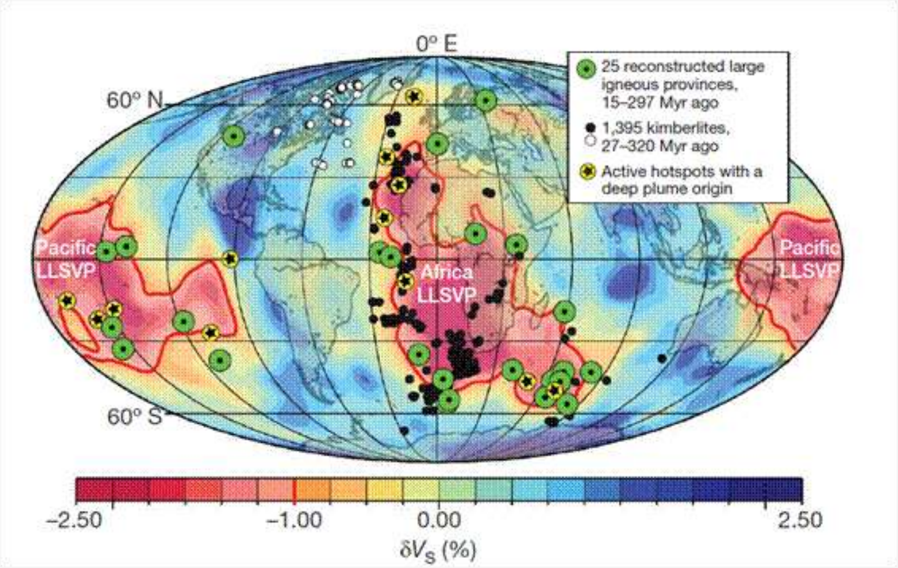
Tan, Leng, Zhong, Gurnis (2011, G^3)

# Observation: hotspots & reconstructed LIPs from LLSVP margins



## Hotspots

*Thorne, Garnero, Grand [2004, PEPI]*
**δVs:** *Grand [Phil. Trans. R. Soc., 2002]*
**Hotspots:** *Sleep [JGR, 1981]*
*Also, Wen* [2006, EPSL]




## Large Igneous Provinces

*Torsvik et al. [Nature 2010]*
*Torsvik et al [EPSL 2008]*
*Burke, Steinbergerb, Torsvik, Smethurst* [EPSL, 2007]
*Steinberger & Torsvik (2012, G^3)*

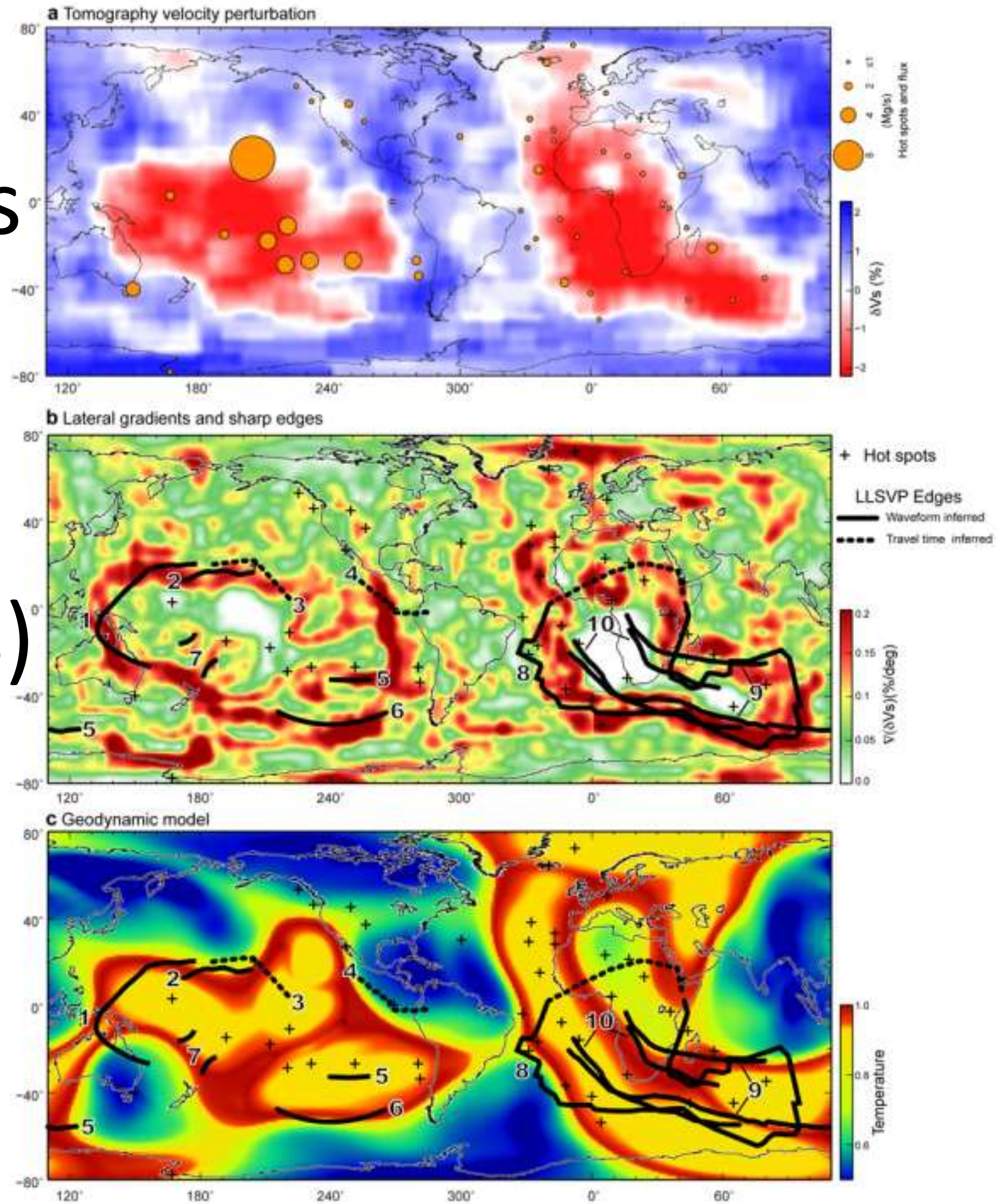
*Seismic Tomography*

dVs

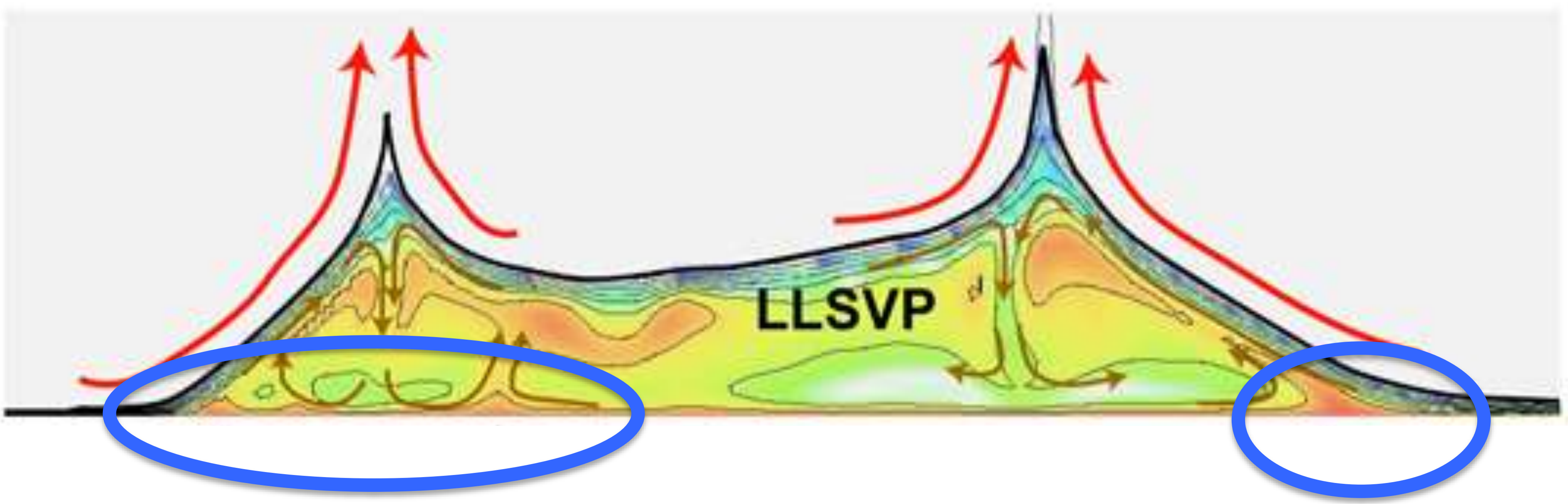
$\nabla$(dVs)

*Geodynamics calculation*

T



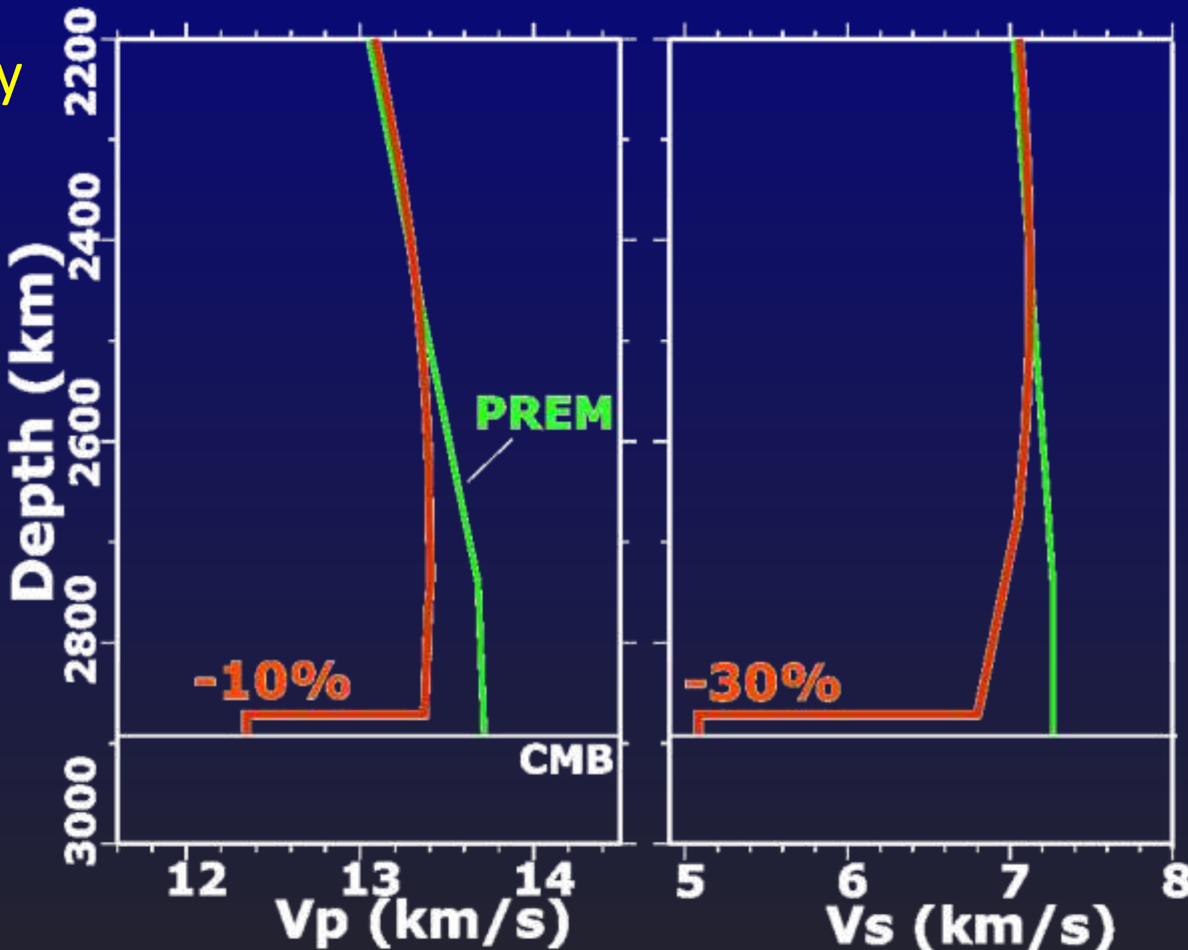
# *Thermochemical pile internal temperatures*




*Garnero, Lay, and McNamara.* [P4  Monograph, GSA, 2007]

# Ultra-Low Velocity Zone (*ULVZ*)

- **LARGE** seismic velocity reductions
  *(up to 10's %)*
- **THIN** layering
  *(usually 5-20 km)*
- **AT** the CMB

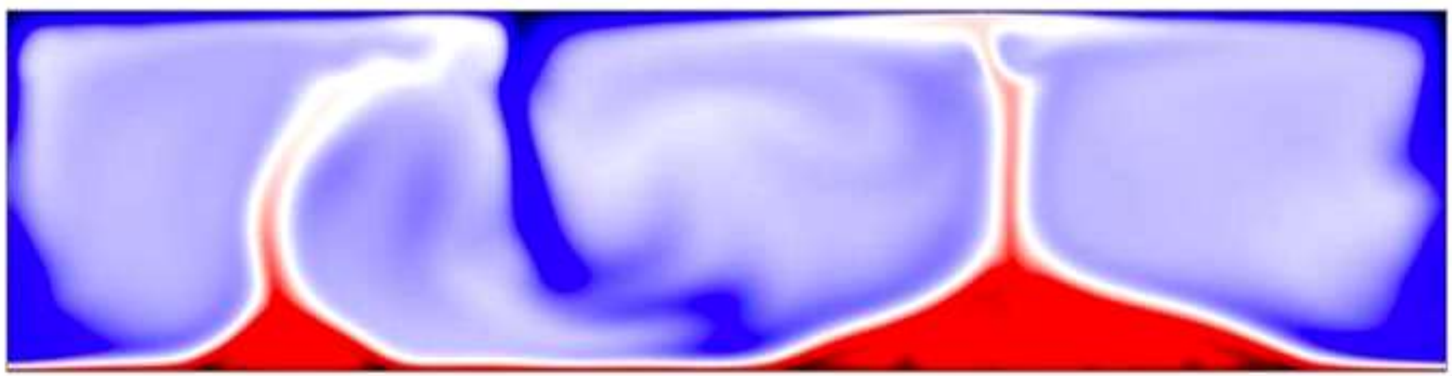


*Composition*

**BLACK**
(mantle)
**PINK**
(LLSVP)
**RED**
(ULVZ)

*Temperature*

**BLUE**
**(cold)**
**RED**
(hot)
**BLACK**
(hottest)



**Whole mantle convection, 3 distinct compositions (mantle, LLSVP, ULVZ), 4 billion years**

*McNamara et al (2010)*

# Key points:

*large-low shear velocity provinces*

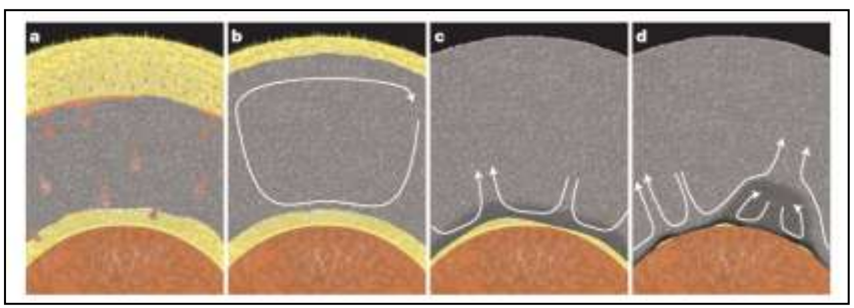
- are chemically distinct
- are shaped by subduction downwellings
- may act as deep mantle chemical reservoirs
- guide plumes
- Not “hidden”…

Matt: Collision modelers tell me a dense basal layer can survive moon forming impact

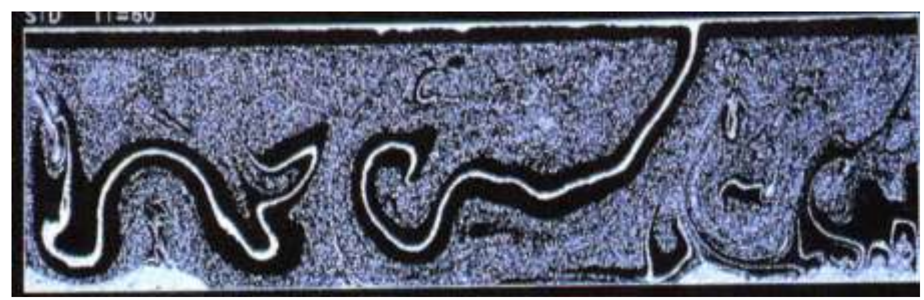
Zhao, Garnero, McNamara (2013, *in prep*)

# LLSVP origin

- Primordial *(early differentiation)*
- Basal magma ocean *(BMO)*
- Build through time *(MORB, CMB rxn products)*

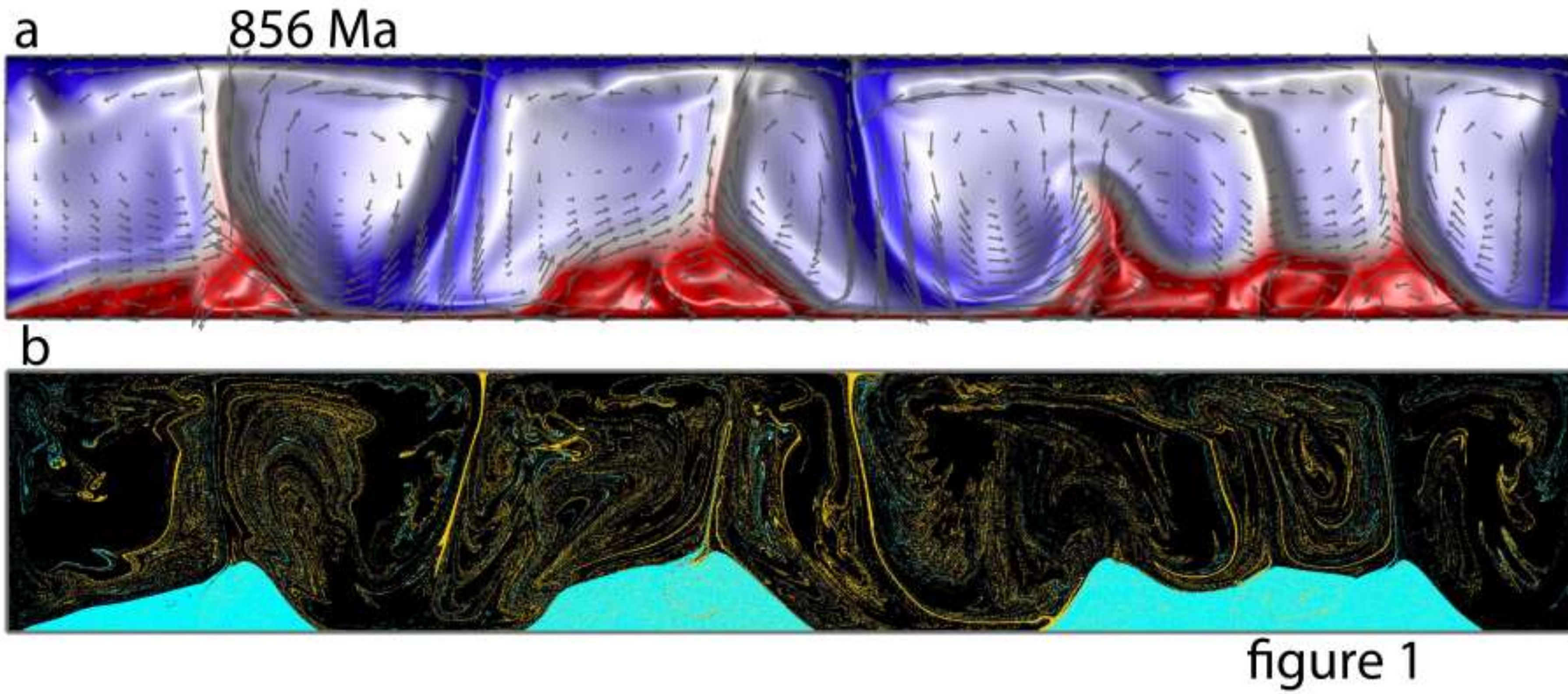



Labrosse et al. (2007)



Christensen and Hofmann (1994)

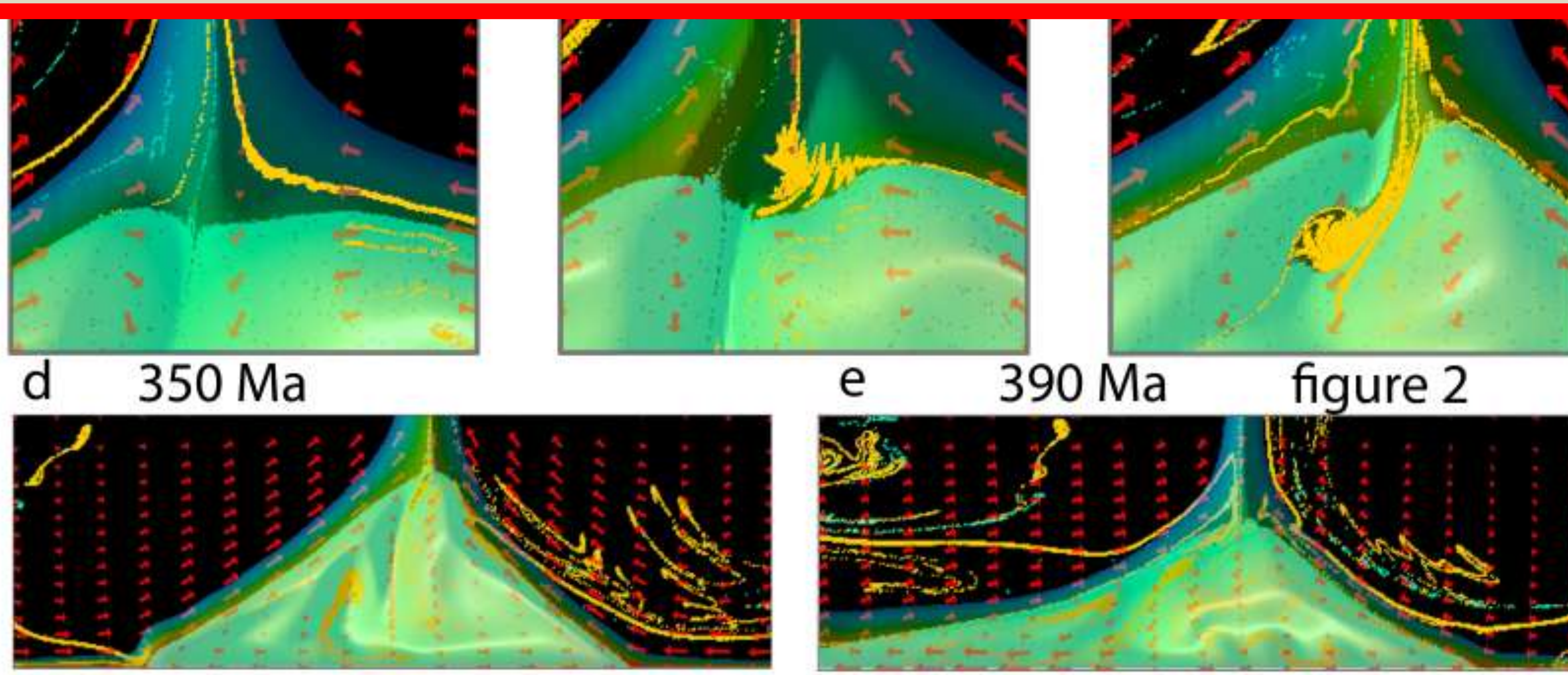
# Subducting MORB




Li and McNamara (2013x)

**Key point:**

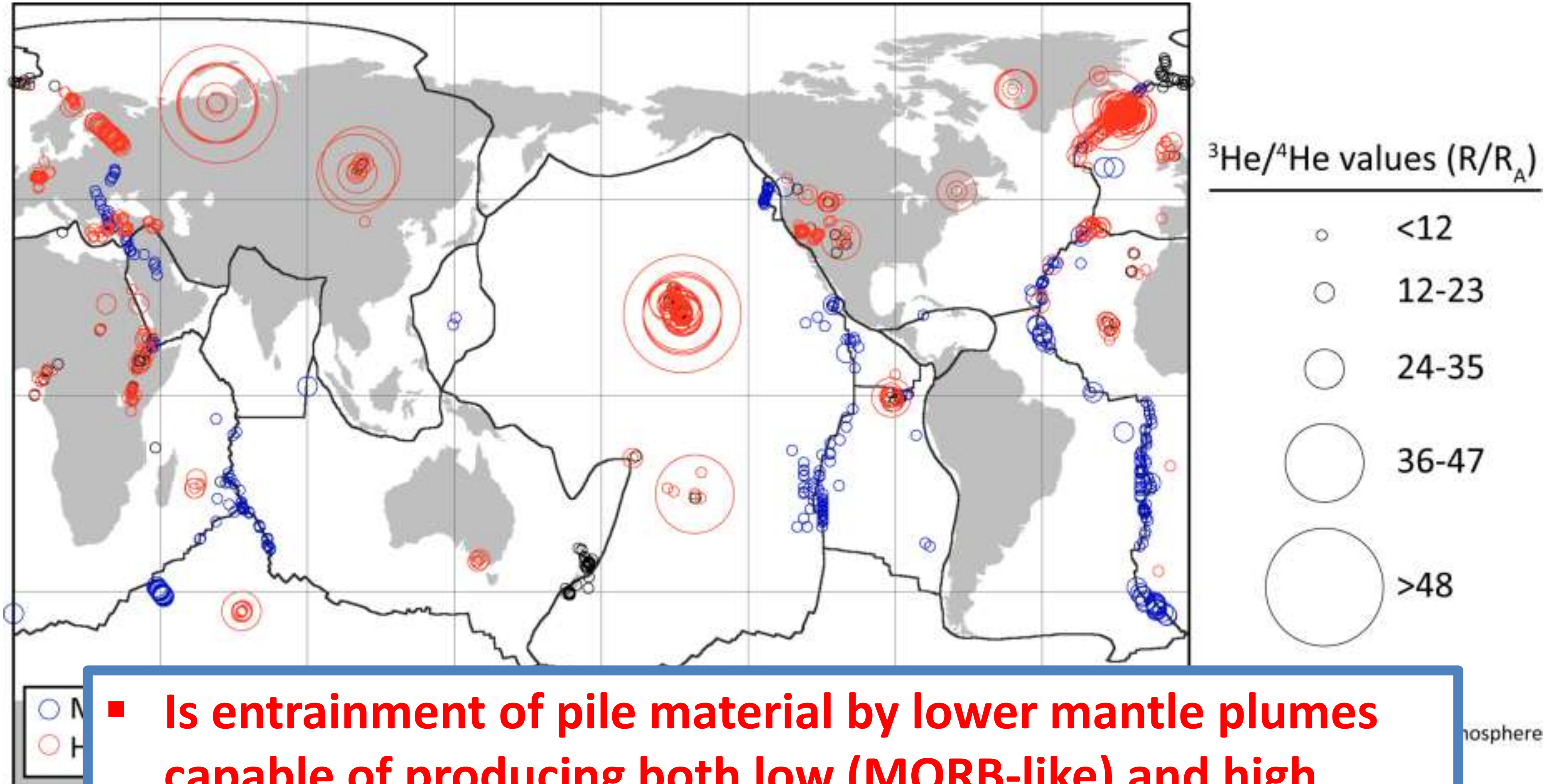
MORB does not likely form piles, but small amounts can go in, mix, & even come back out in plumes




- *Material can accumulate beneath plume roots, then become entrained into pile.*
- *May be a source of observed LLSVP heterogeneity.*
- *But most MORB is entrained in mantle circulation currents.*

Li and McNamara (2012, in prep)

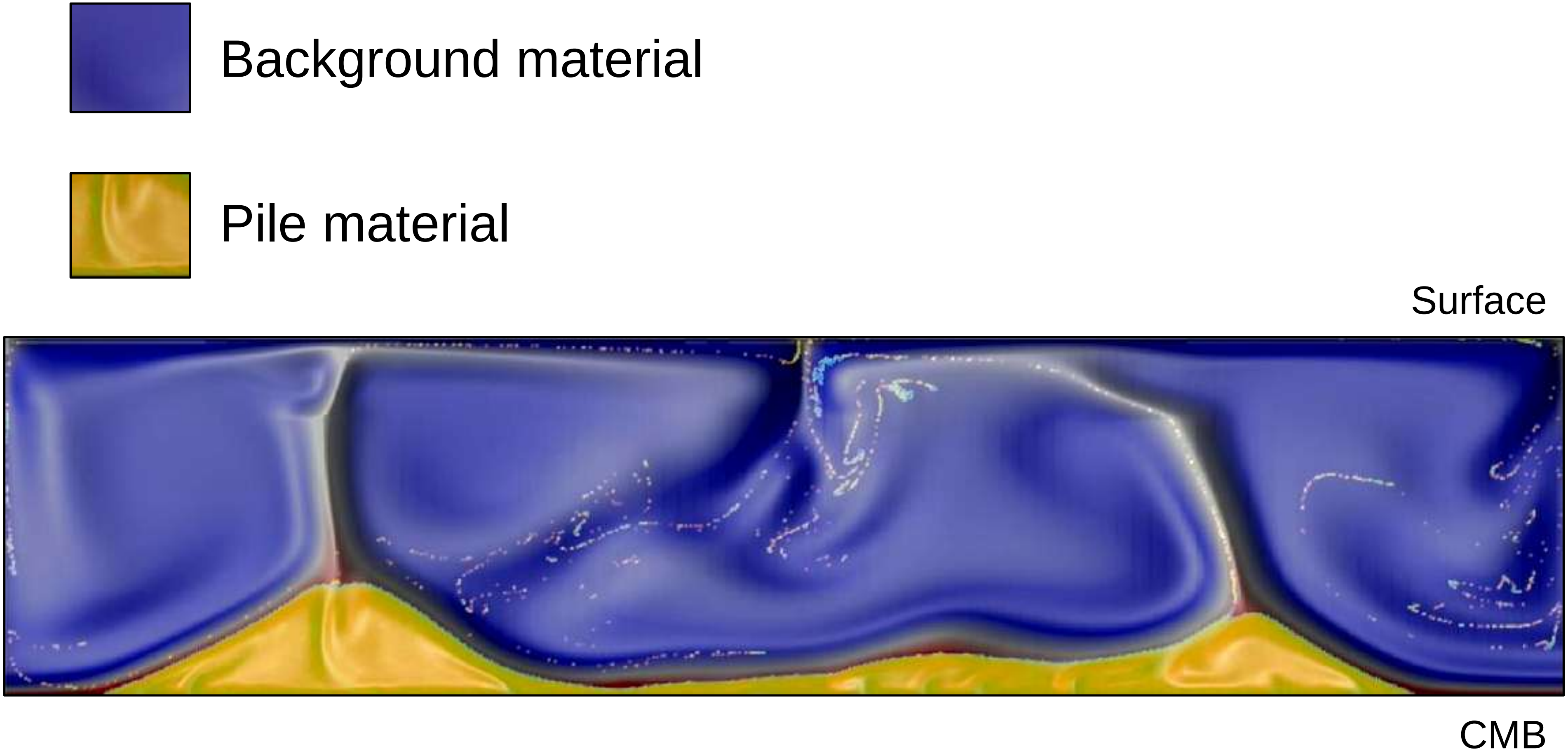
# Hotspots & $^3He/^4He$ ratios




- **Is entrainment of pile material by lower mantle plumes capable of producing both low (MORB-like) and high (Hotspot-like) $^3He/^4He$ ratios?**

- Several Hotspots show MORB-like $^3He/^4He$ ratios

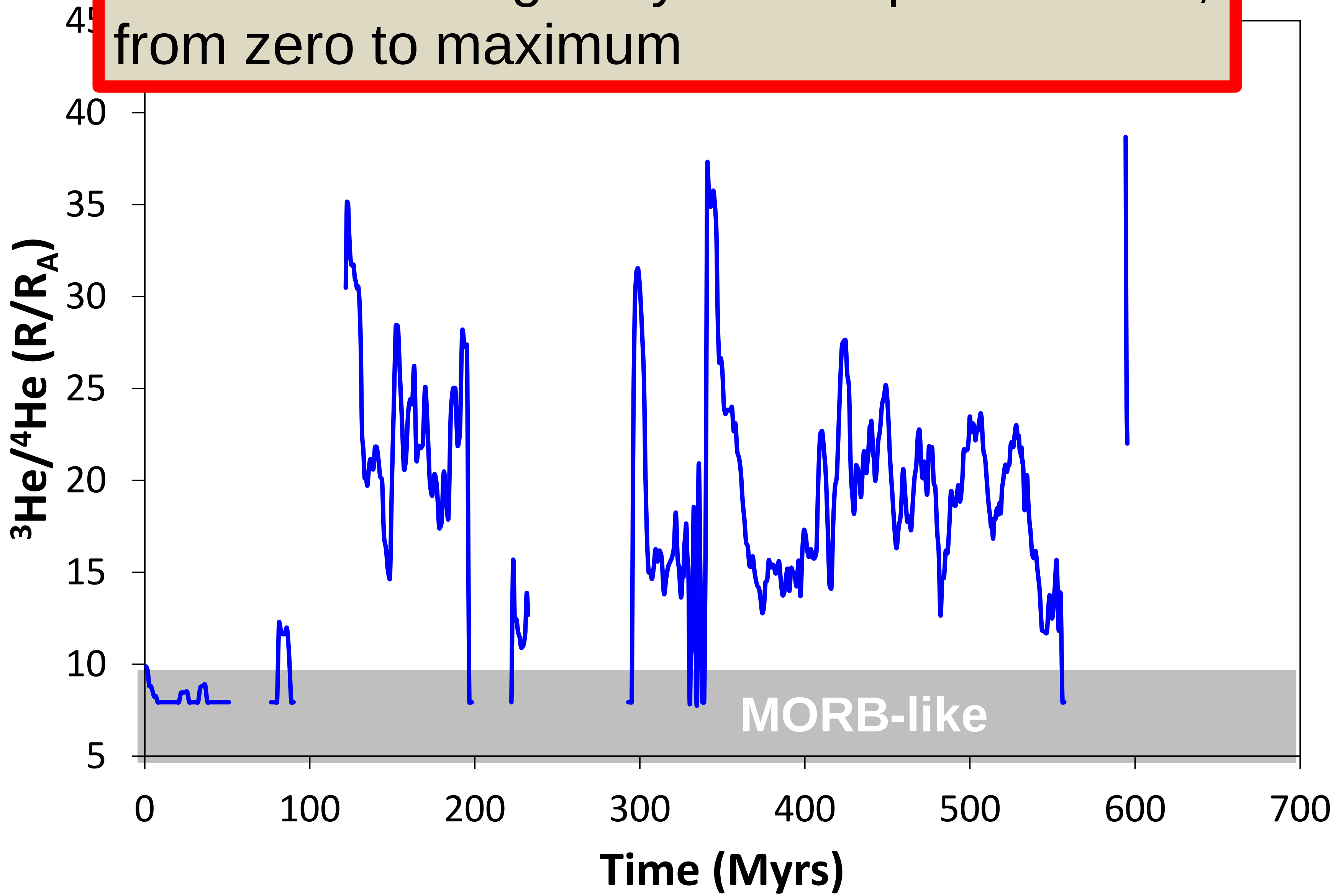
Courtesy Curtis Williams / Allen McNamara




Courtesy Curtis Williams / Allen McNamara

***Key point:***

Plumes can irregularly entrain pile material, from zero to maximum




Courtesy Curtis Williams / Allen McNamara

# Some vocabulary review

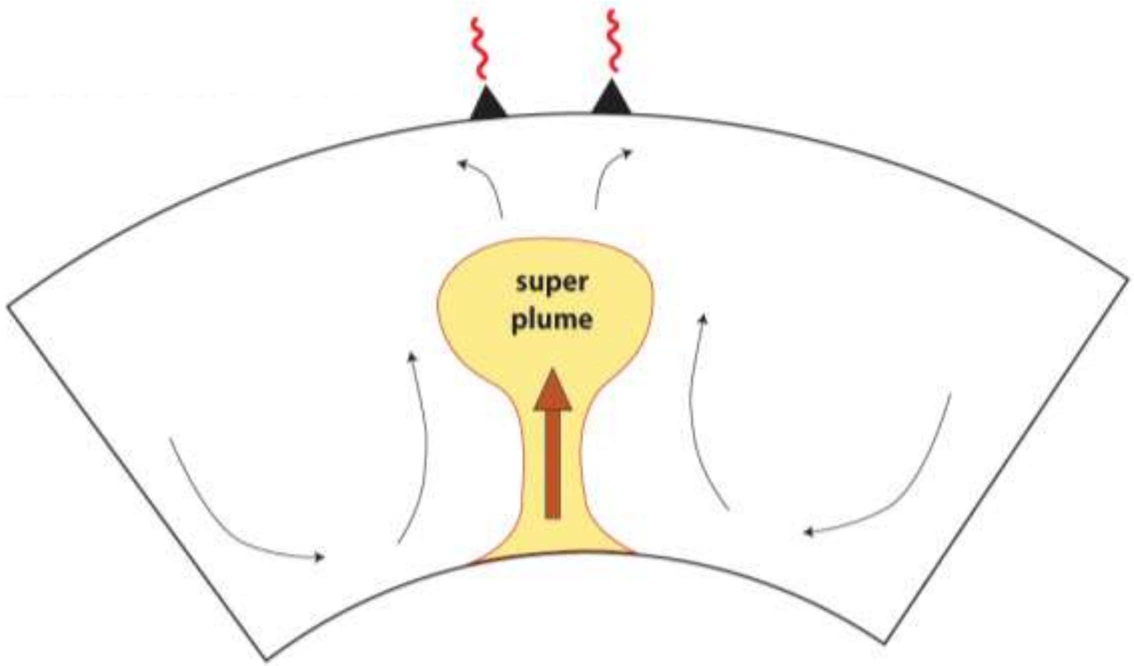
*D"* depth shell: lowest 200-300 km of mantle

*LLSVP* name for the distribution of ~deg 2 low shear velocity in lowest 100's km of mantle

*Pile* geodynamically inspired ***interpretation*** of LLSVP. Dense. Stable. Usually primordial in calculations. Sometimes "thermochemical pile"

*Superplume* An ***interpretation*** of an LLSVP. Sort of slang (term used without any intention of the consequences of such a model)

# Note on “superplume”

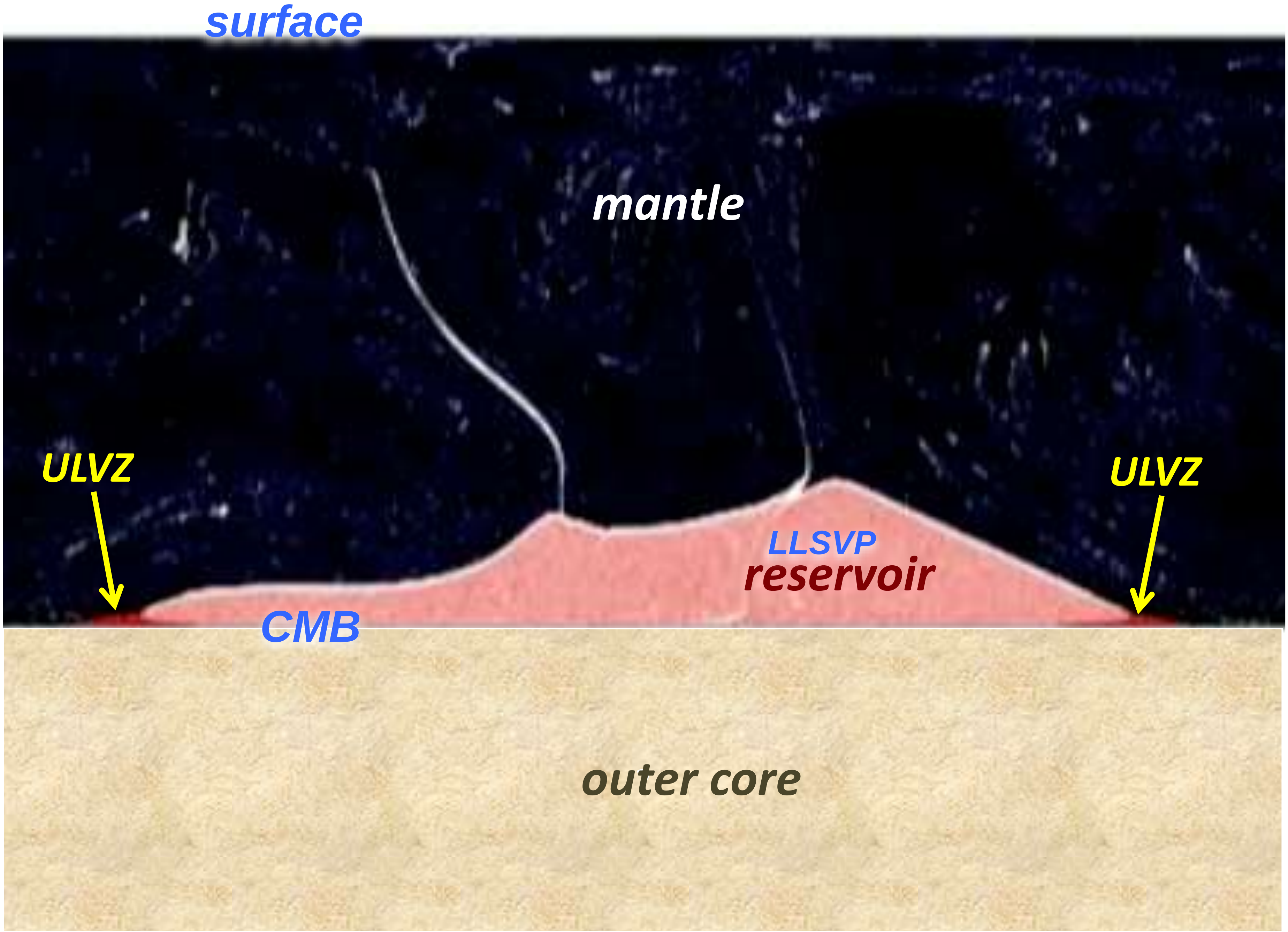



If thermochemical piles leave the CMB in superplume events, geodynamic predictions suggest it will be mixed into the mantle over time (i.e., and not settle back at CMB)

*Implication*: today’s large thermochemical piles: **not superplume**
*Implication*: today’s piles are long-lived (regardless of origin)

# Geochemists:

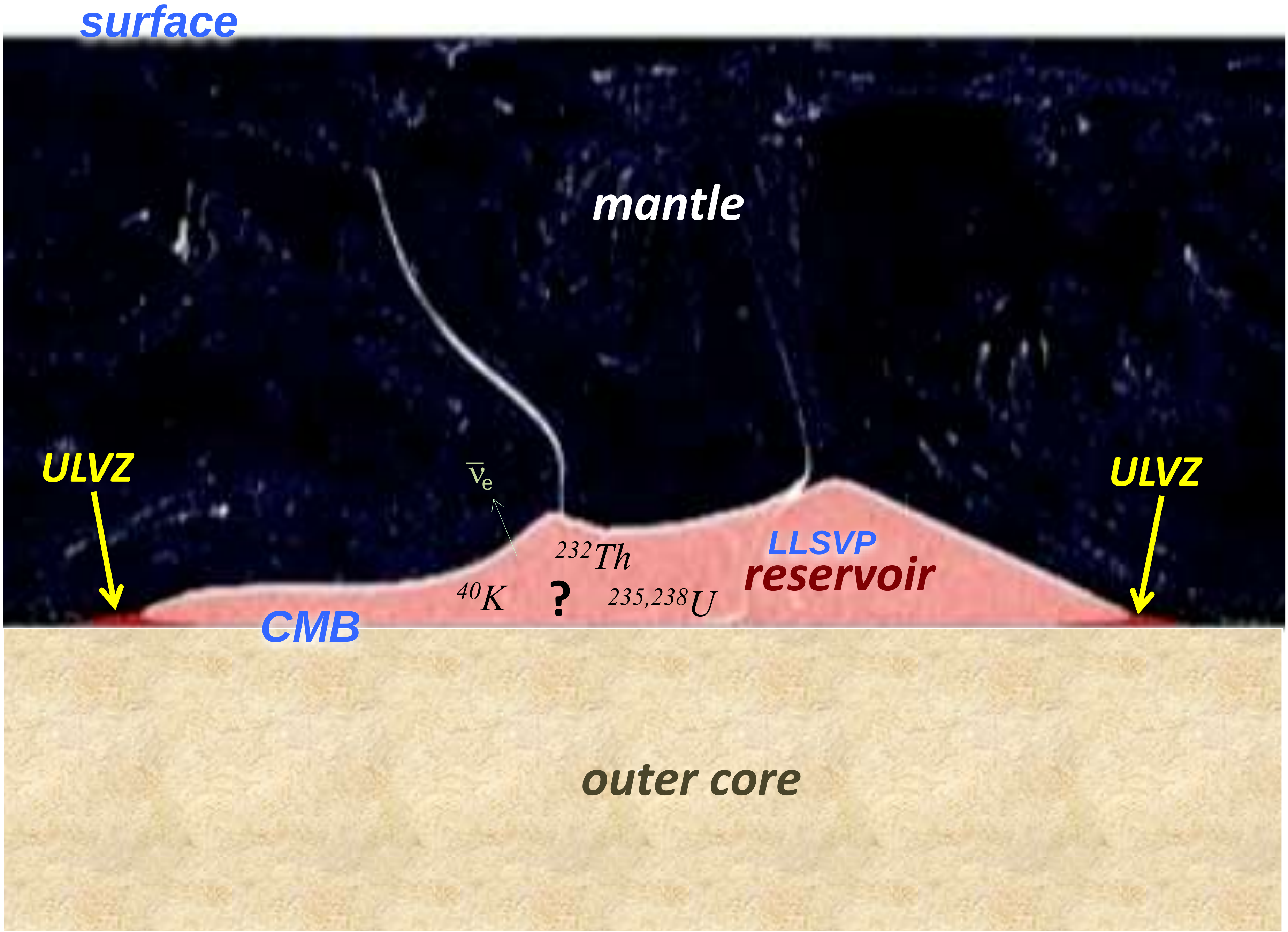
- Primitive
- Primordial
- Recycled
- BSE
- Isotopic ratio key


surface
mantle
ULVZ
ULVZ
LLSVP
reservoir
CMB
outer core

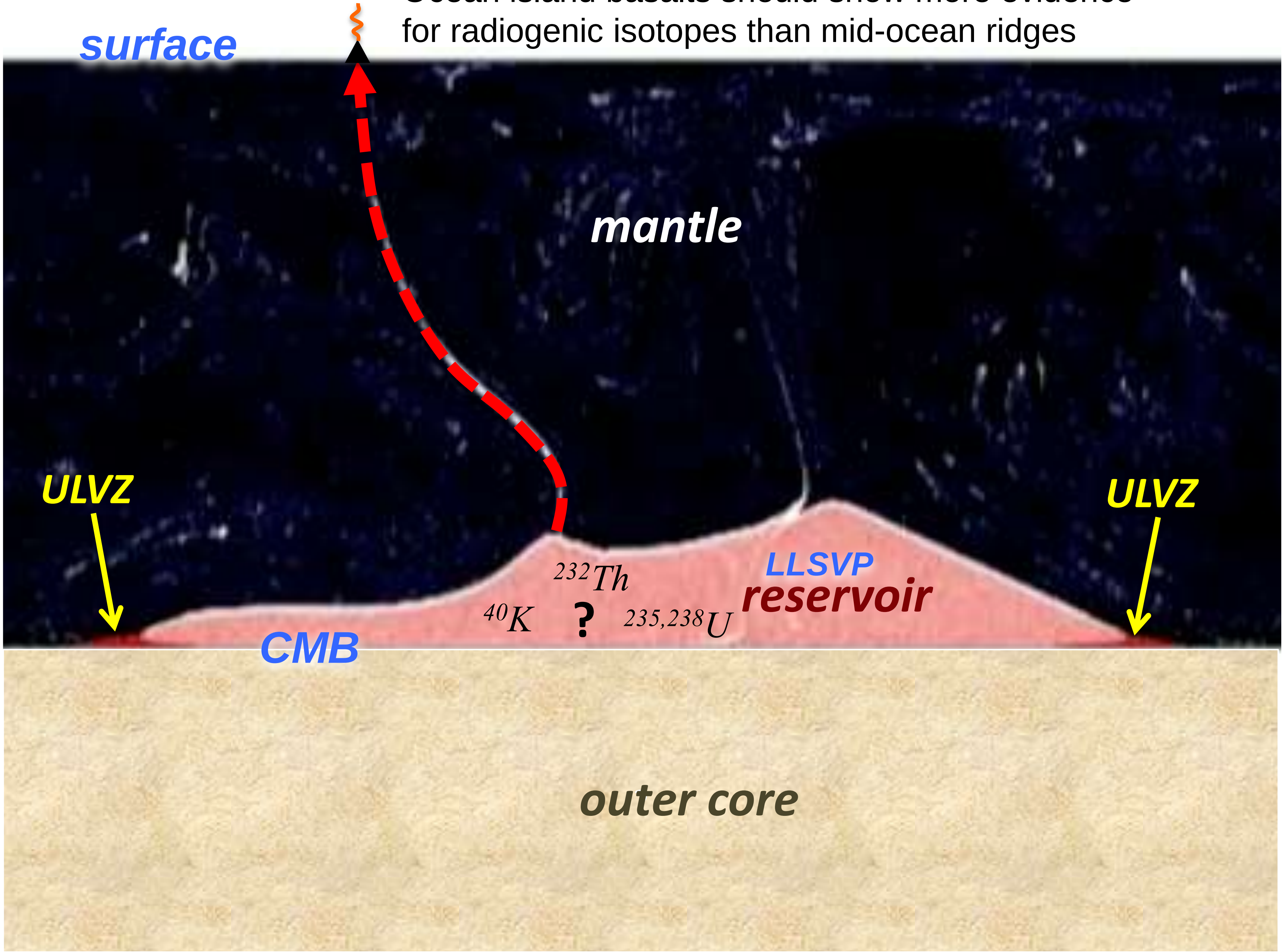
**Geologically significant antineutrino- and heat-producing radioactive decays and decay chains**[10]

$$
\begin{array}{rcl}
{}^{238}_{92}\mathrm{U} & \longrightarrow & {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^{-} + 6\bar{\nu}_e + 51.698\,\mathrm{MeV} \\
{}^{235}_{92}\mathrm{U} & \longrightarrow & {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^{-} + 4\bar{\nu}_e + 46.402\,\mathrm{MeV} \\
{}^{232}_{90}\mathrm{Th} & \longrightarrow & {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^{-} + 4\bar{\nu}_e + 42.652\,\mathrm{MeV} \\
{}^{40}_{19}\mathrm{K} & \xrightarrow{89.3\,\%} & {}^{40}_{20}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.311\,\mathrm{MeV} \\
{}^{40}_{19}\mathrm{K} + e^{-} & \xrightarrow{10.7\,\%} & {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\,\mathrm{MeV}
\end{array}
$$

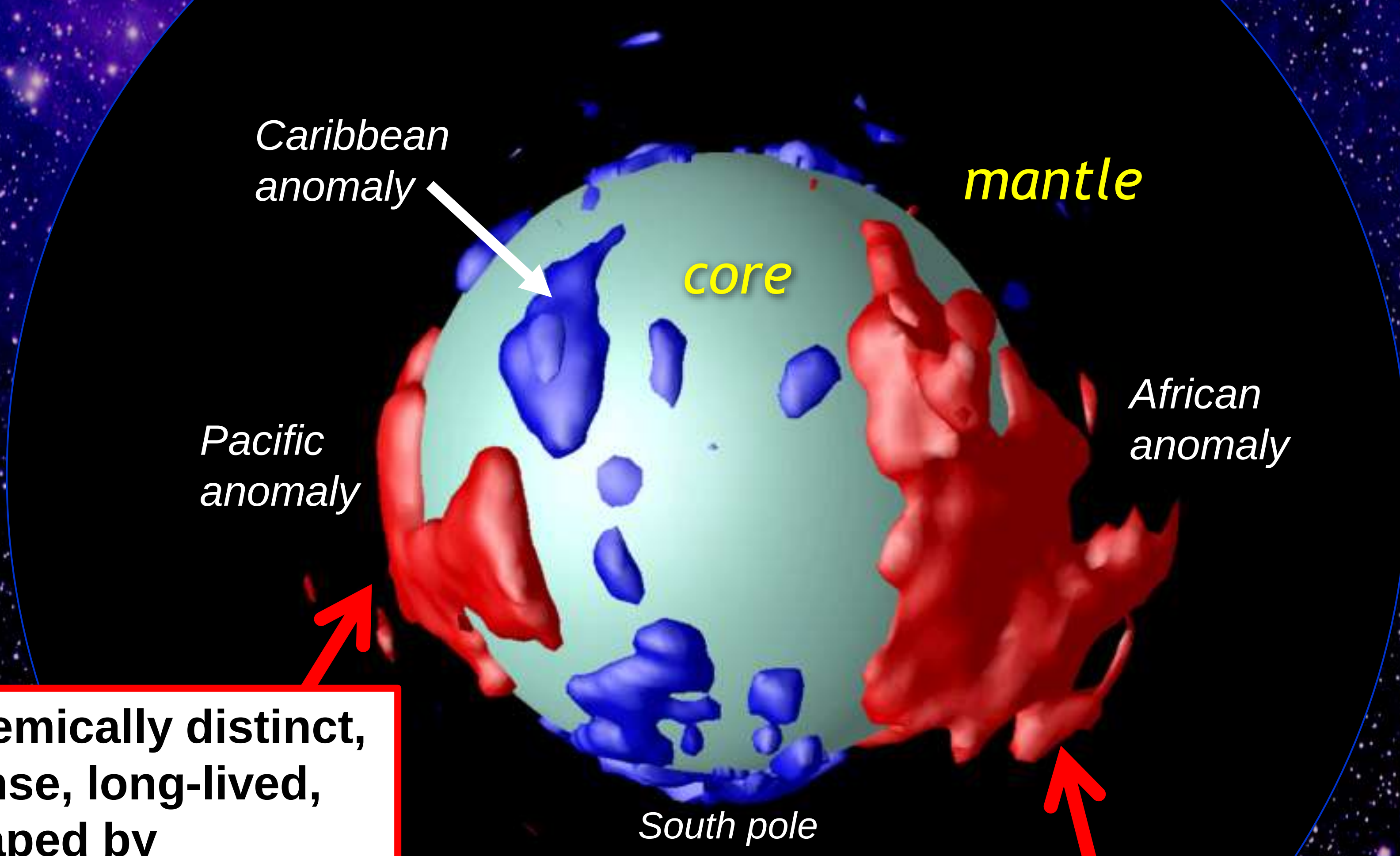
Dye, S. T. (2012). "Geoneutrinos and the radioactive power of the Earth". Rev. Geophys. 50 (3).


surface
mantle
ULVZ
$\overline{\nu}_e$
$^{232}Th$
LLSVP
reservoir
ULVZ
$^{40}K$
?
$^{235,238}U$
CMB
outer core

Ocean island basalts should show more evidence for radiogenic isotopes than mid-ocean ridges



# *Tomographically derived LLSVPs (red)*



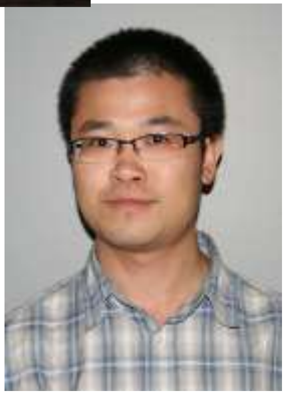

**Chemically distinct, dense, long-lived, shaped by subduction-related downwelling, guide plumes.**

**Long-lived reservoirs of radiogenic materials?**

# Acknowledgements:

Chunpeng Zhao

Allen McNamara

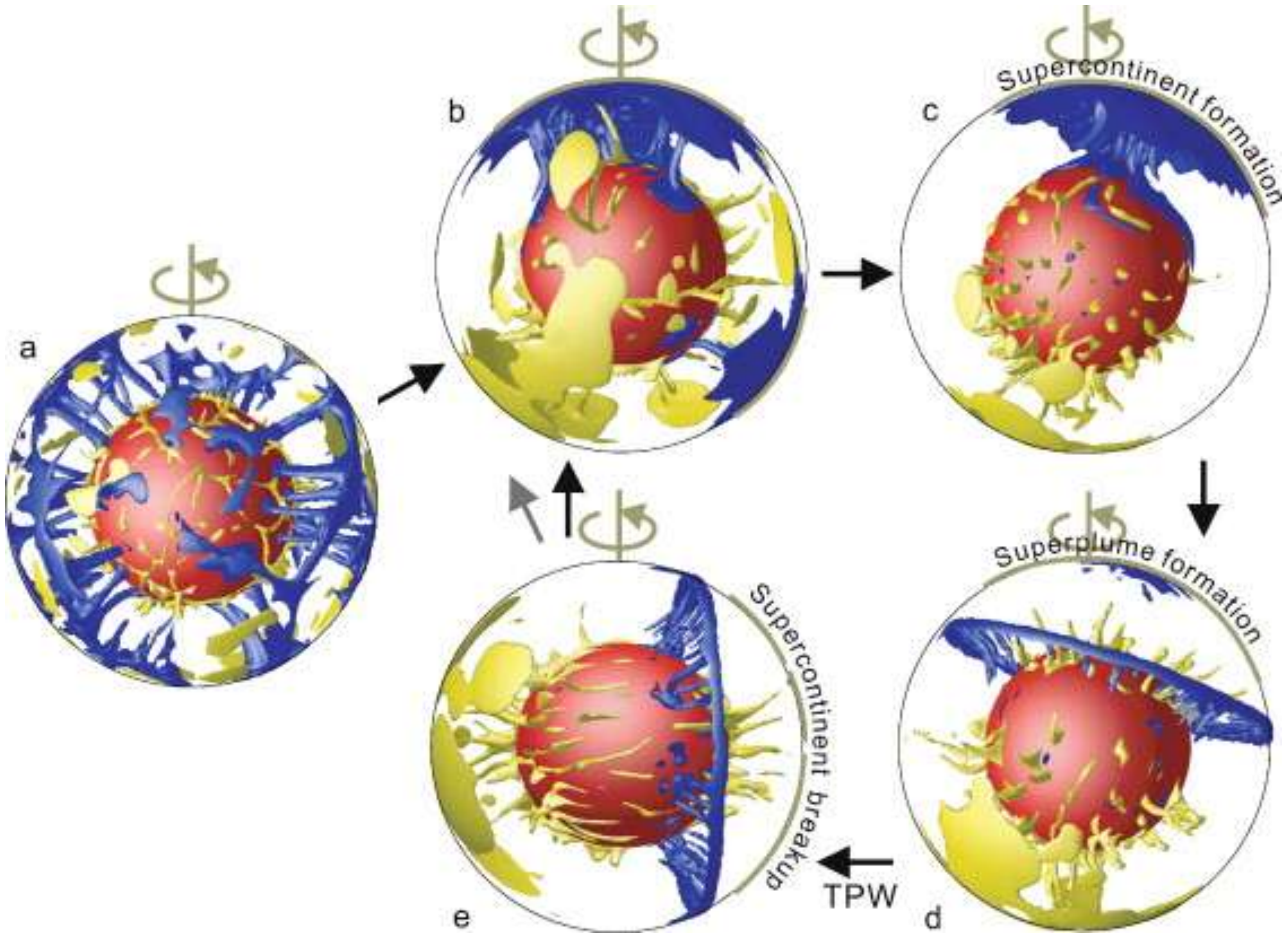


Mingming Li

EXTRA

# Thermochemical pile temporal evolution

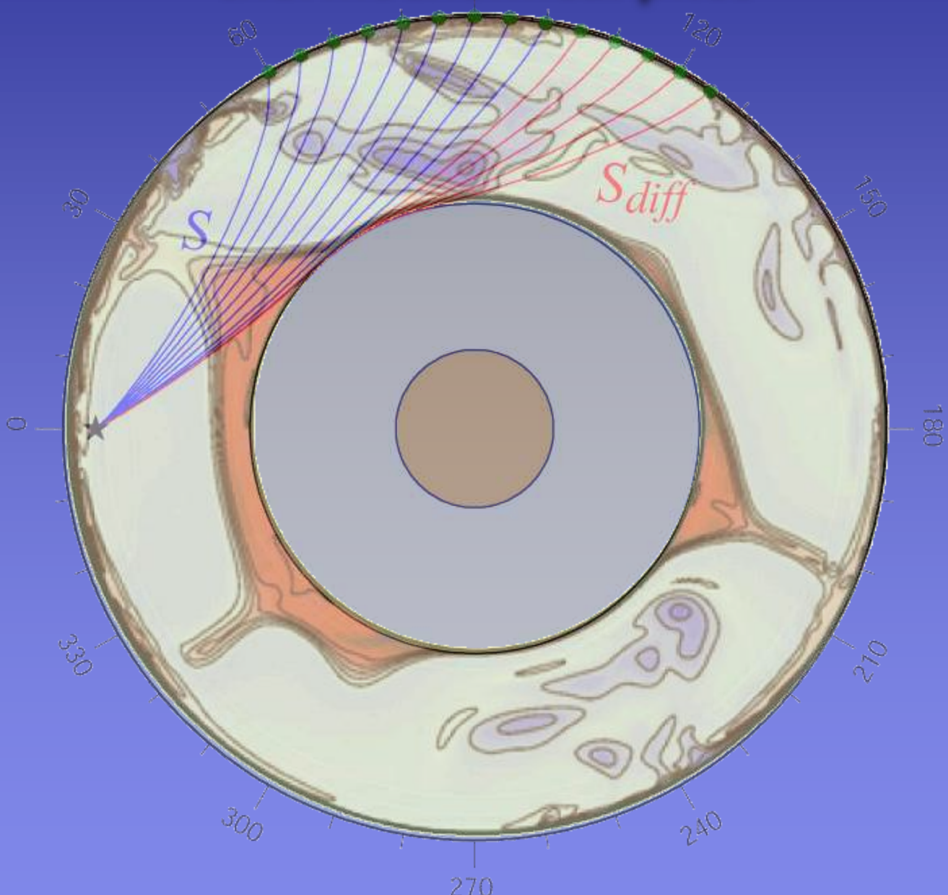
*deg 2 → deg 1 associated with super continent construction/break up cycles?*




Li & Zhong (EPSL, 2009)

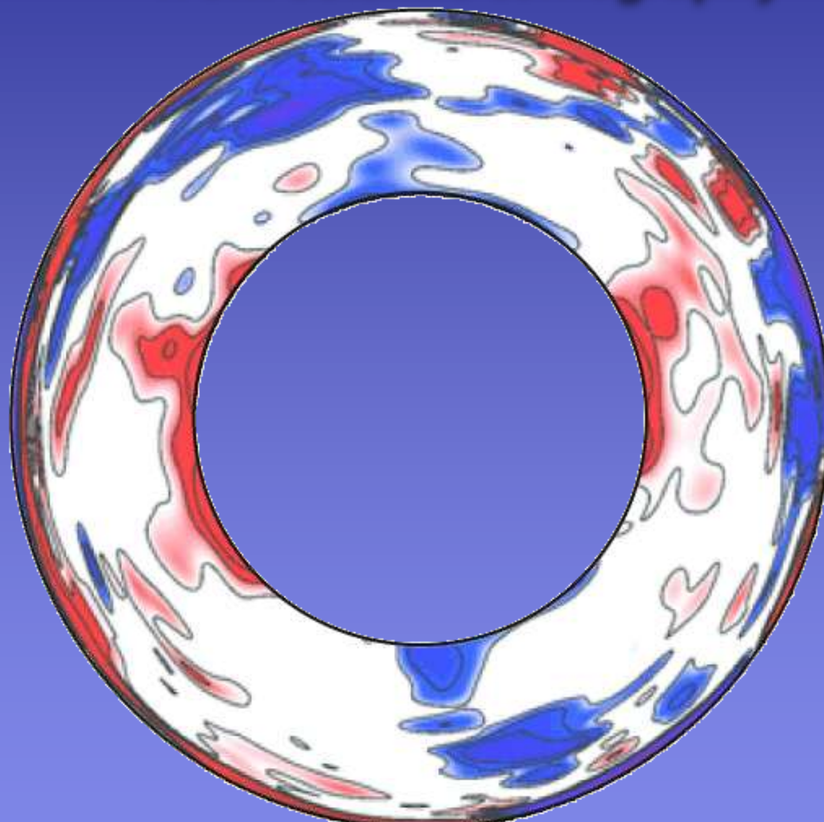
# *If S waves graze a low velocity thermochemical pile, what do we expect?*

**Temperature field for thermochemical piles**

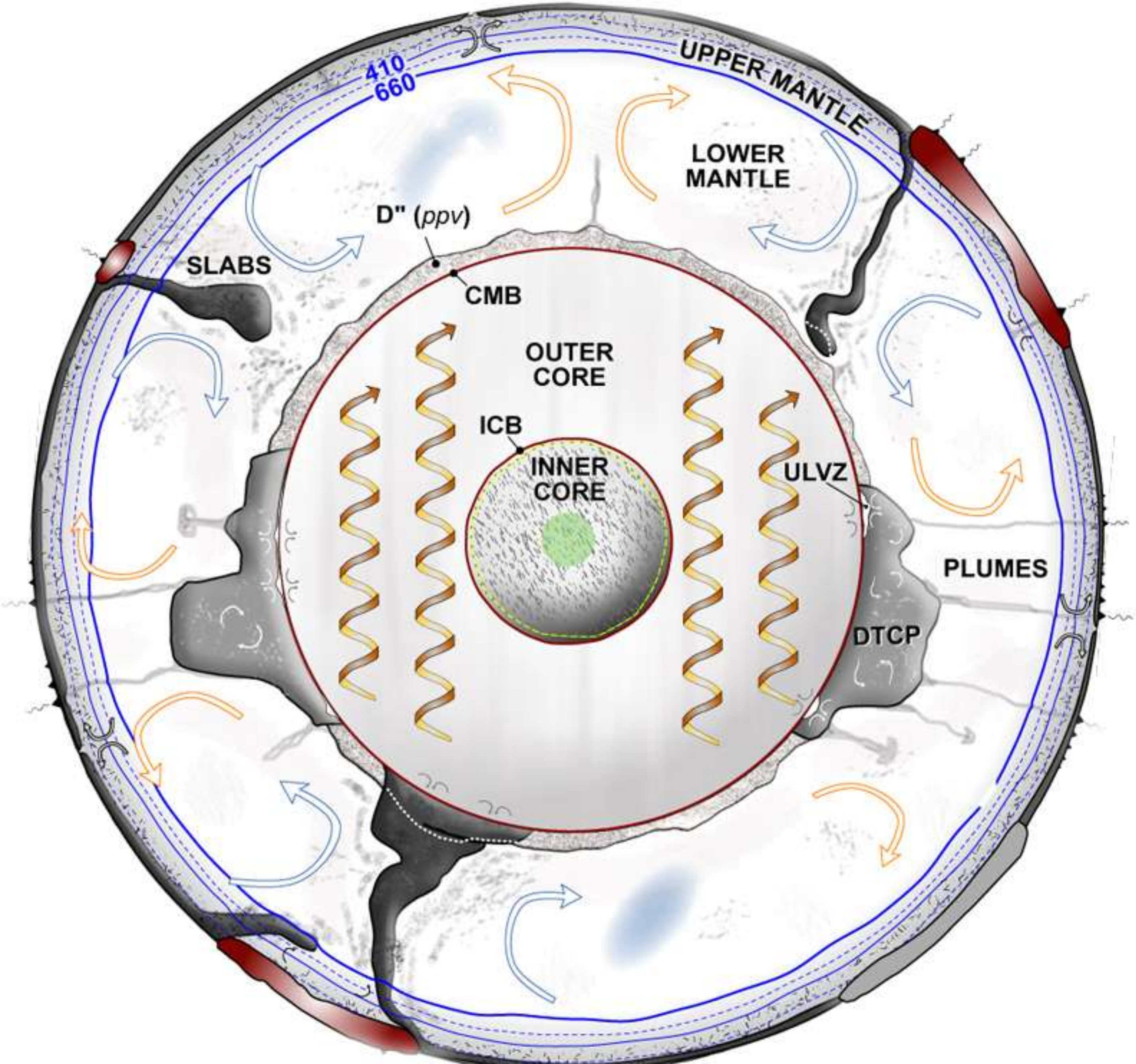



McNamara & Zhong [Nature, 2005]

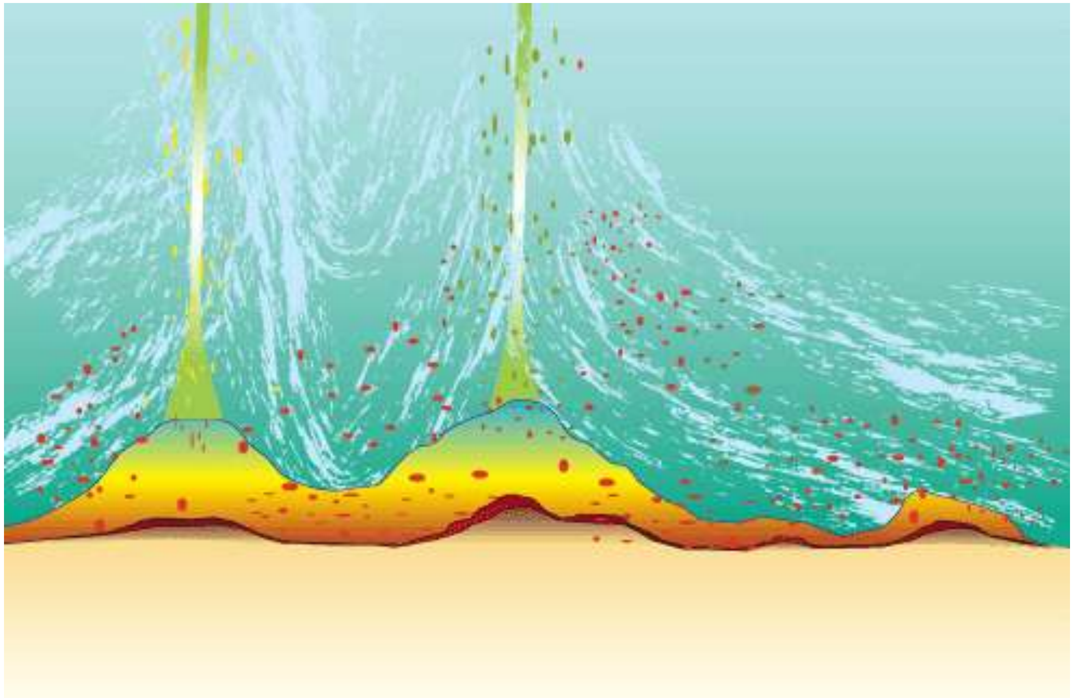
**Shear velocity heterogeneity from seismic tomography**



Ritsema [Sci. Tech, 2000]




Garnero, Kennett, Loper [PEPI, 2005]



http://garnero.asu.edu