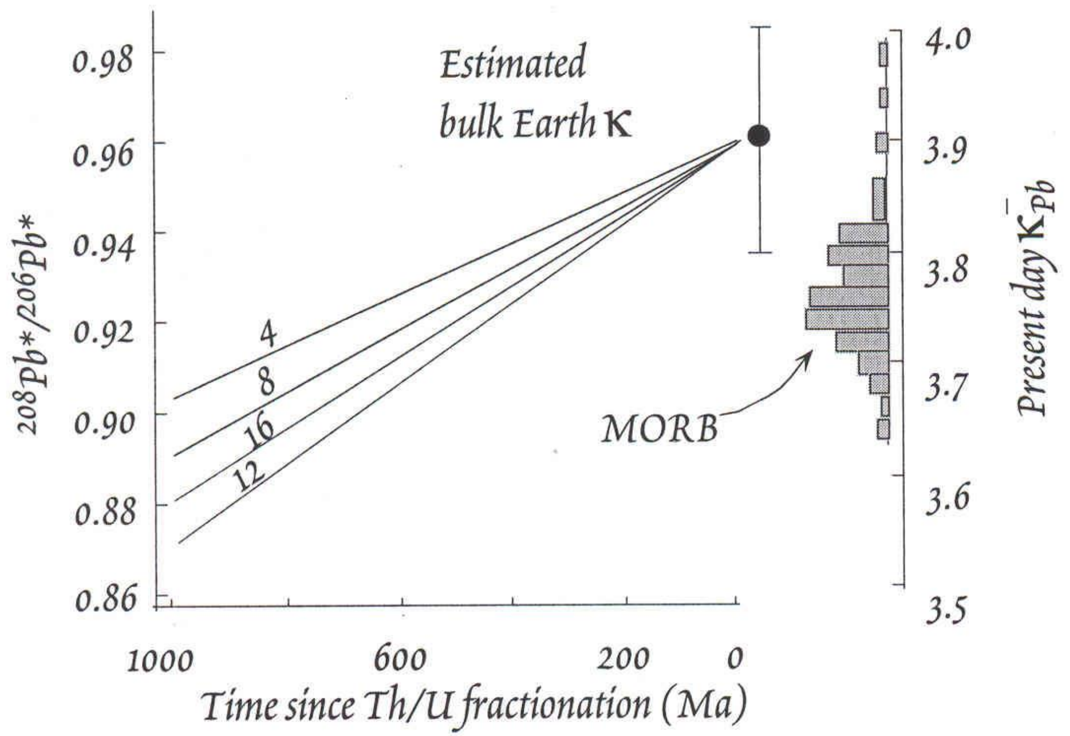
# Open system model of Pb isotope evolution of the Earth

Time integrated Th/U ratio (derived from Pb isotope data) of ~3.75 in MORB is much higher than the **„instantaneous“ present-day Th/U ratio of ~2.5!!**

→ MORB reservoir is buffered over geological time by a less depleted reservoir, i.e:

→ MORB source had a brief residence time in the depleted reservoir and spend most of Earth history in a reservoir with a Th/U ratio near Bulk Earth.

κ (kappa) = atomic Th/U ratio of Earth reservoir

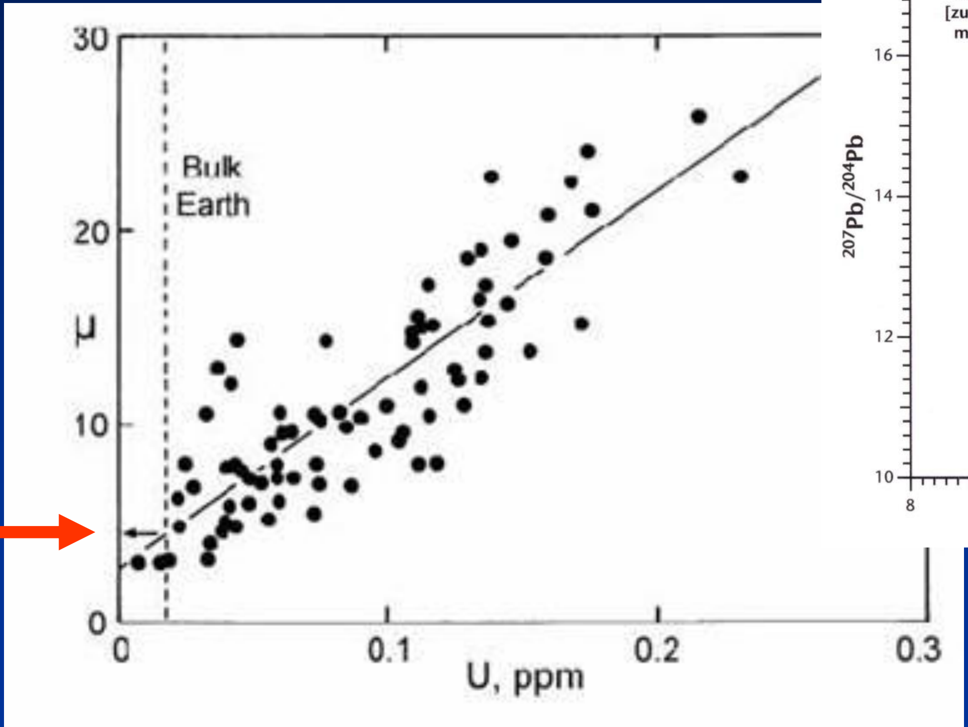


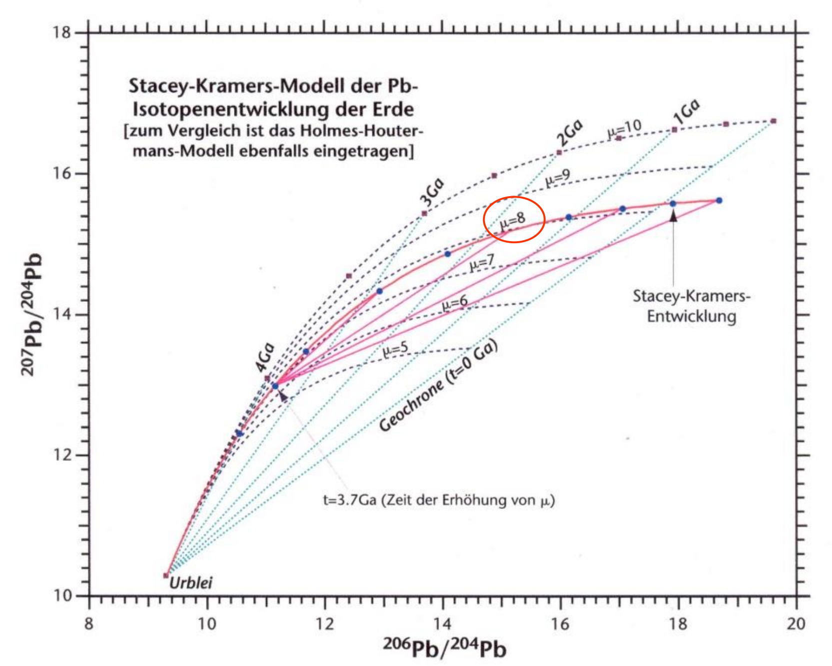

Galer & O'Nions (1985) Nature 316

# The upper mantle μ-value

$\frac{^{238}U}{^{204}Pb}$

$\mu = 4.5$




White (1993) EPSL 115

unradiogenic Pb in refractory or ‘shielded’ sulphide inclusions can represent a substantial mantle Pb reservoir, and therefore can contribute a solution for the first Pb paradox

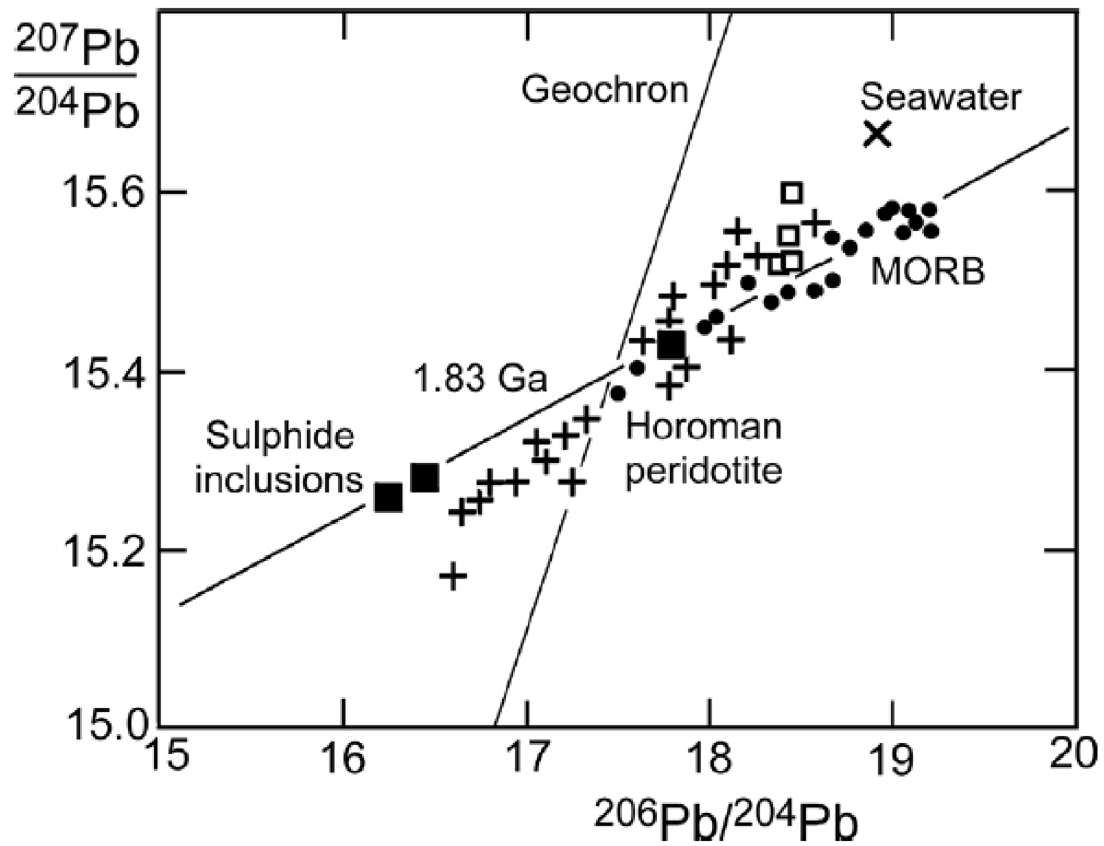
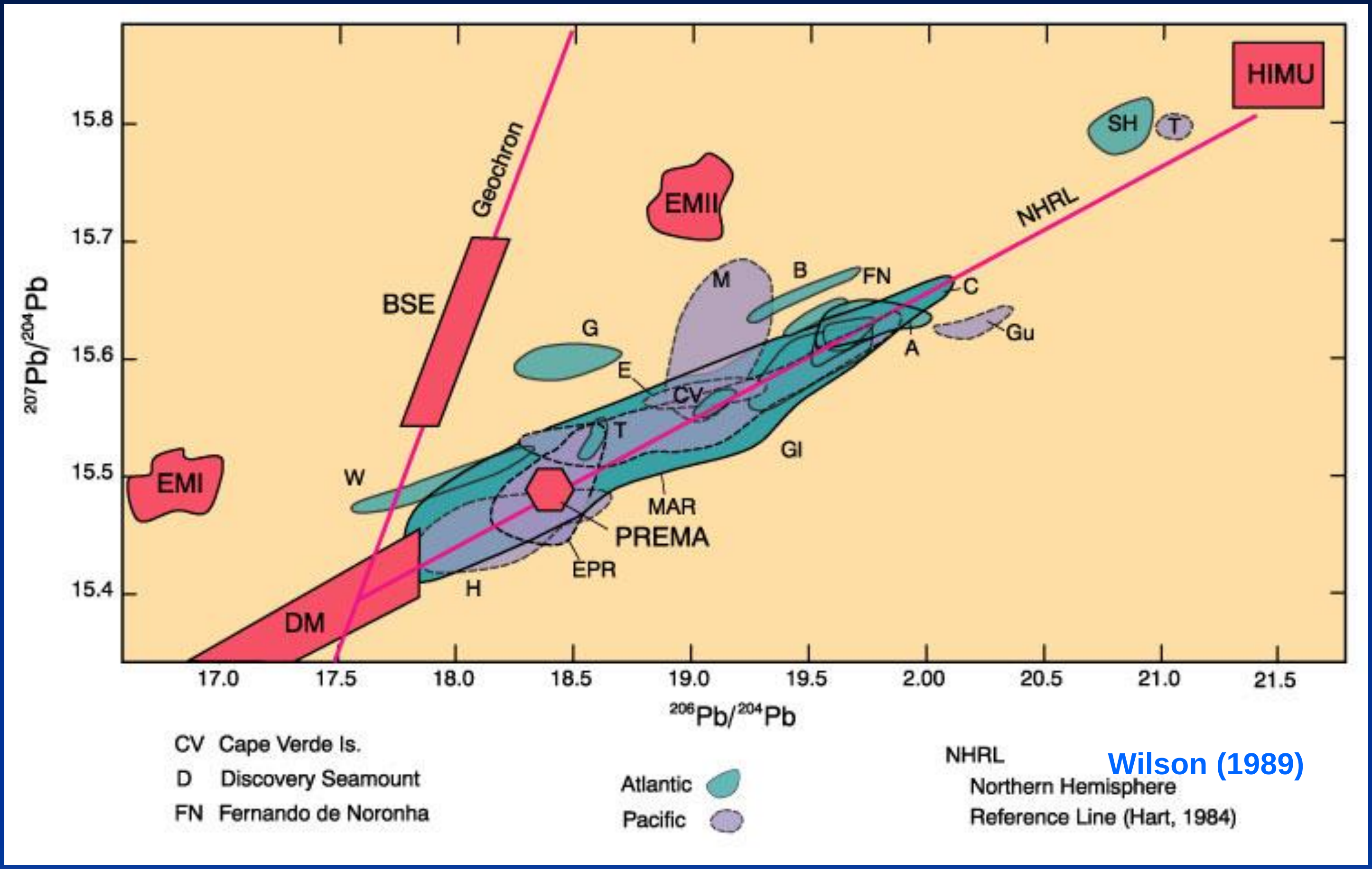



**Fig. 6.28** Pb/Pb plot for whole-rock samples of the Horoman peridotite (+), compared with MORB (•), sulphide inclusions (■) and interstitial sulphides (□) from the MAR. Data from Malaviarachchi *et al.* (2008) and Burton *et al.* (2012).

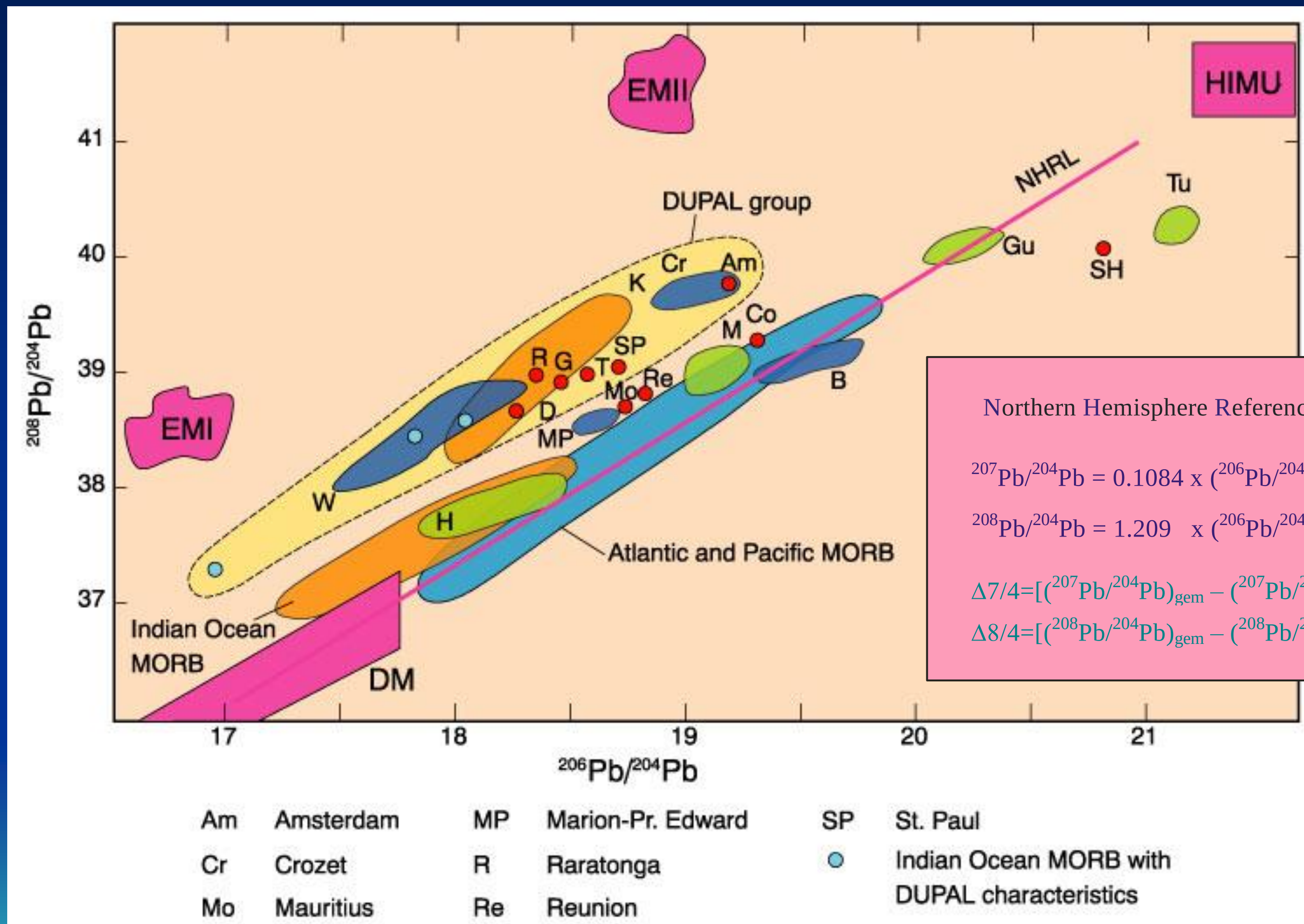
# Pb isotope geochemistry




The $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ data, especially from the northern hemisphere form a linear mixing line between DM and HIMU, a line called the **Northern Hemisphere Reference Line (NHRL)**

# Pb isotope geochemistry

**Data from Hamelin and Allègre (1985), Hart (1984), Vidal et al. (1984)**




Northern Hemisphere Reference Lines (NHRL)

$$^{207}Pb/^{204}Pb = 0.1084 \times (^{206}Pb/^{204}Pb) + 13.491$$

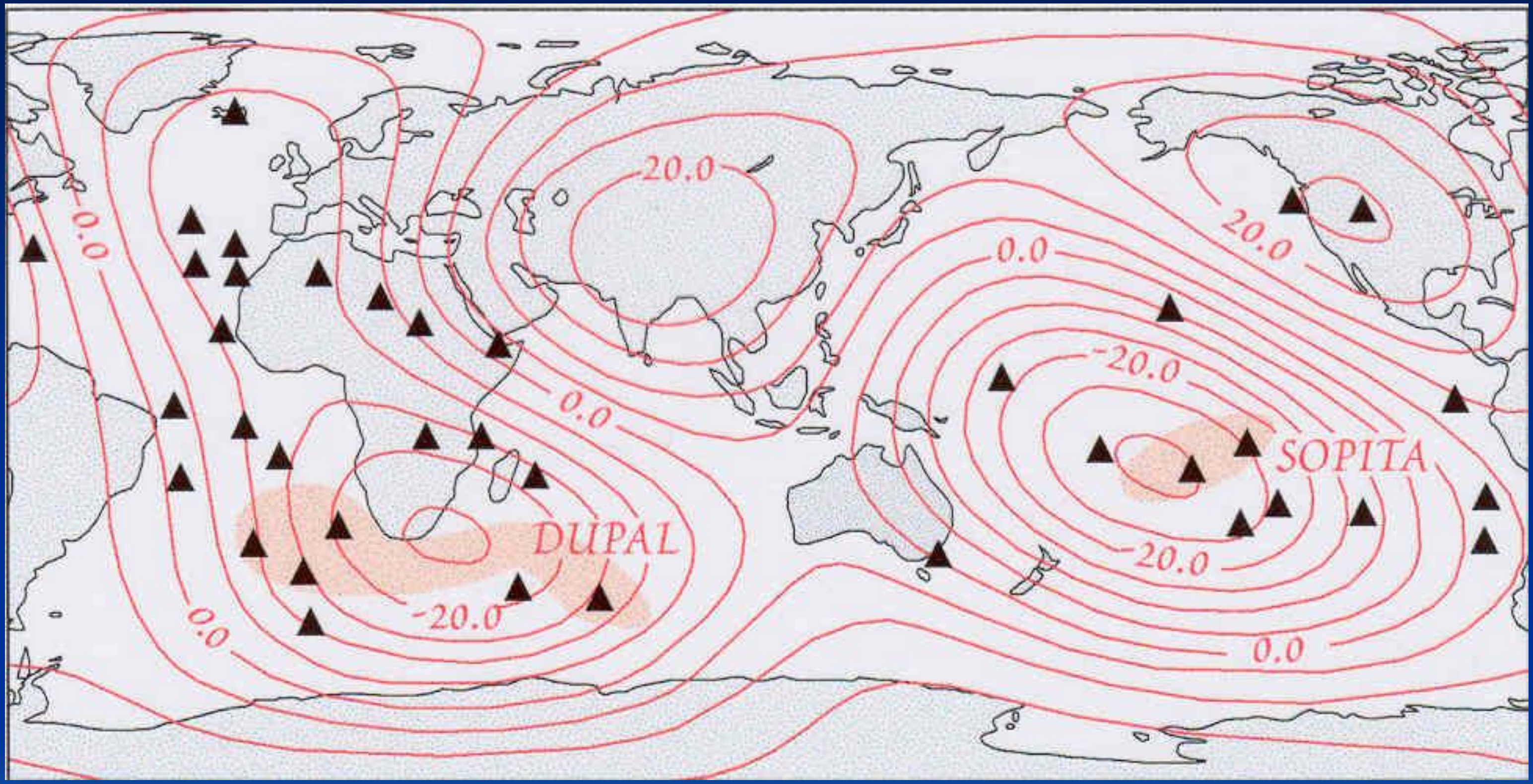
$$^{208}Pb/^{204}Pb = 1.209 \times (^{206}Pb/^{204}Pb) + 15.627$$

$$\Delta 7/4=[(^{207}Pb/^{204}Pb)_{gem} - (^{207}Pb/^{204}Pb)_{NHRL}] \times 100$$

$$\Delta 8/4=[(^{208}Pb/^{204}Pb)_{gem} - (^{208}Pb/^{204}Pb)_{NHRL}] \times 100$$

# Pb isotope geochemistry

Mapping the geographic distribution of isotopic data

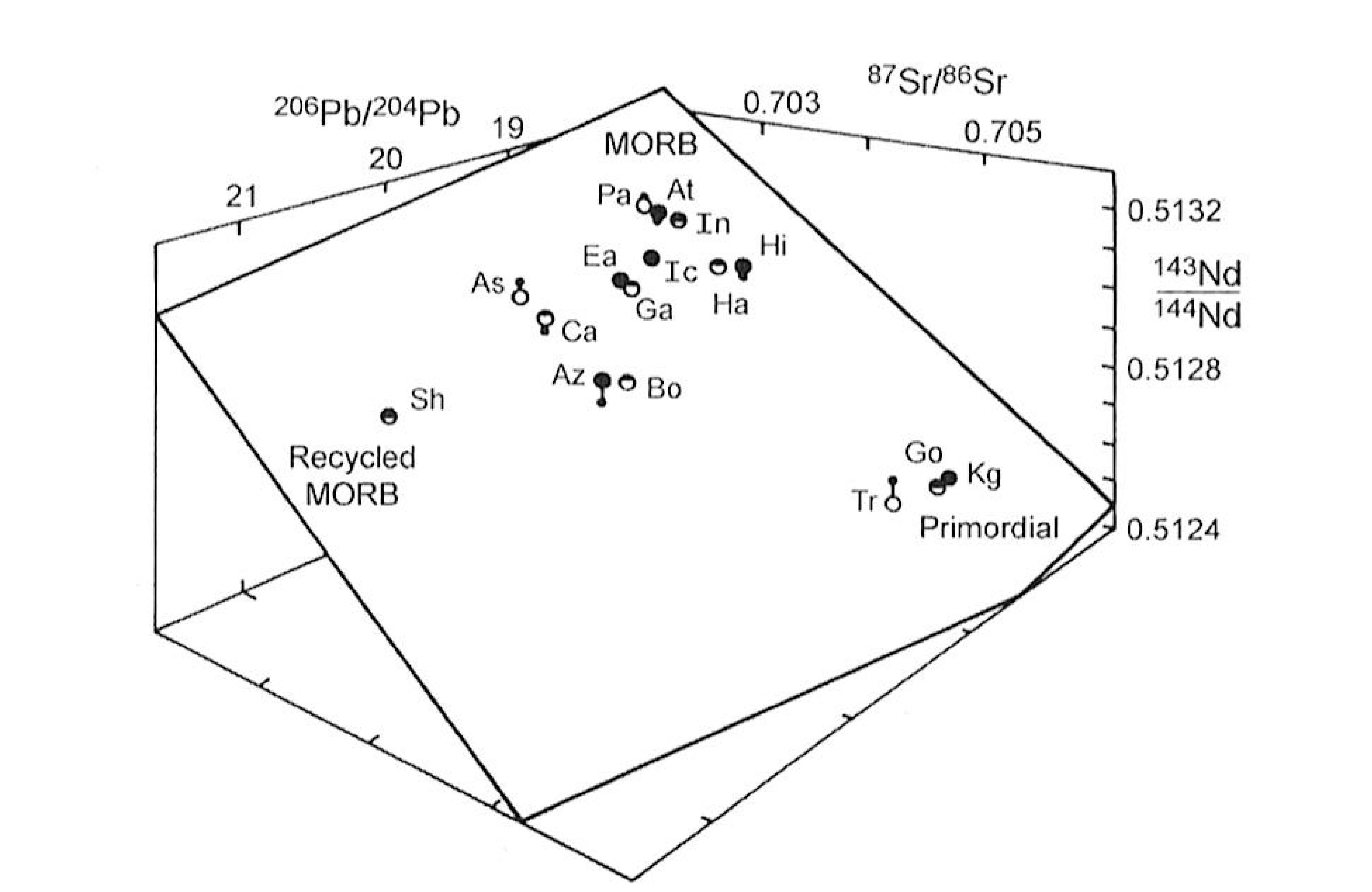



Hart (1984)

DUPAL = DUPre & ALlegre

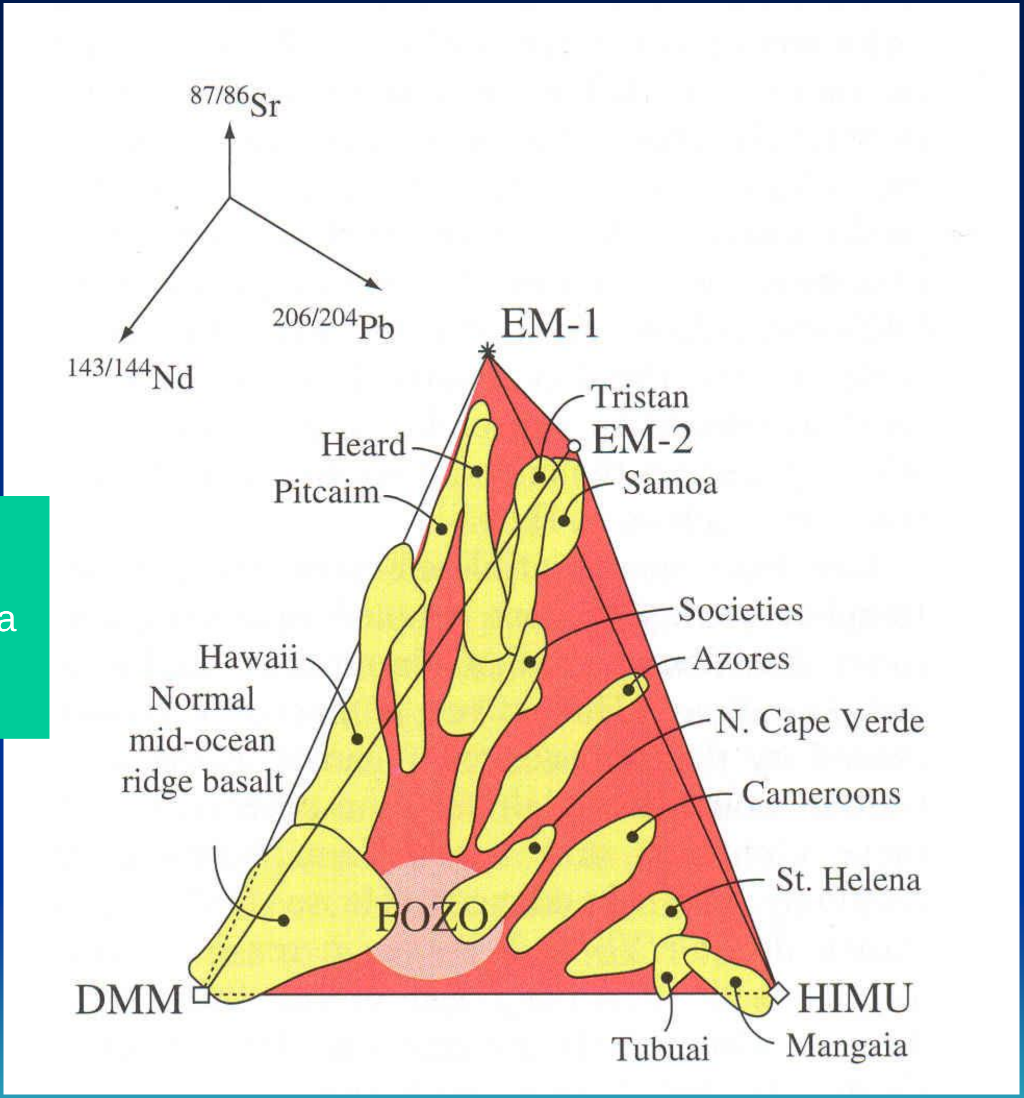
SOPITA = SOuth Pacific Isotopic and Thermal Anomaly

# Zindlers mantle plane



# Mantle isotope tetrahedron

*Hart et al. (1992) Science 256*




FOZO (for focal zone): material from the lower mantle that is present as a mixing component in all deep-mantle plumes

# Developing a picture from the Earth's mantle

## Mantle geodynamics

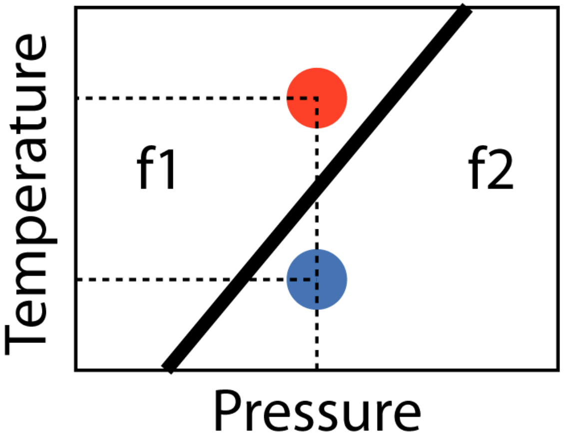
## How does the mantle work?

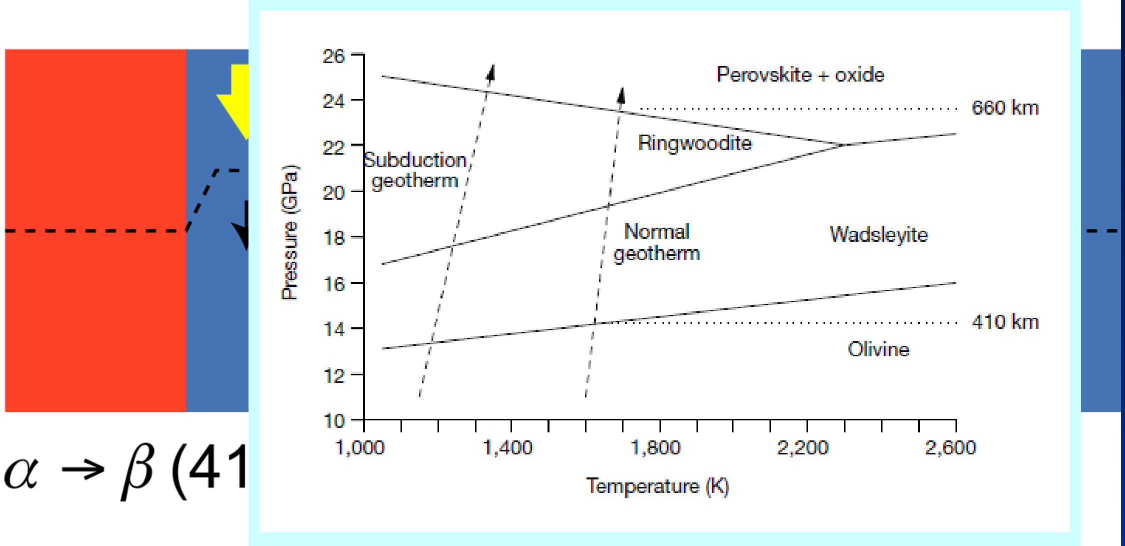
… mantle dynamics is in a state of turmoil (Al Hofmann)

…. our view of the mantle is in a state of transition (Rollison)

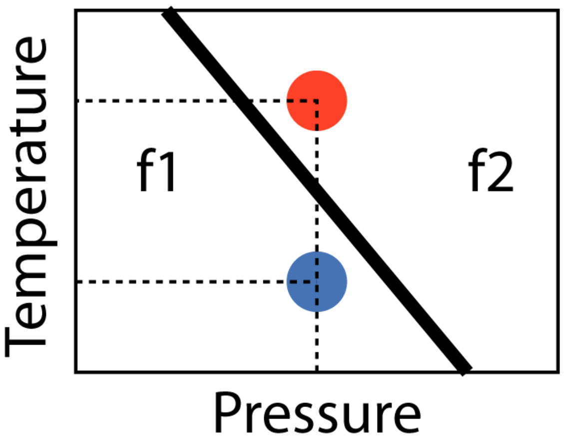
Cold Warm

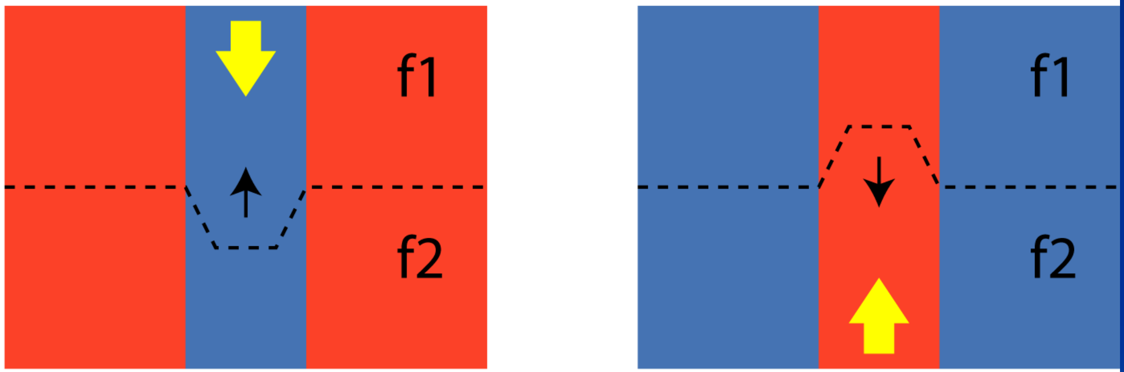
# Subducting Slab Plume




$\alpha \rightarrow \beta$ (41



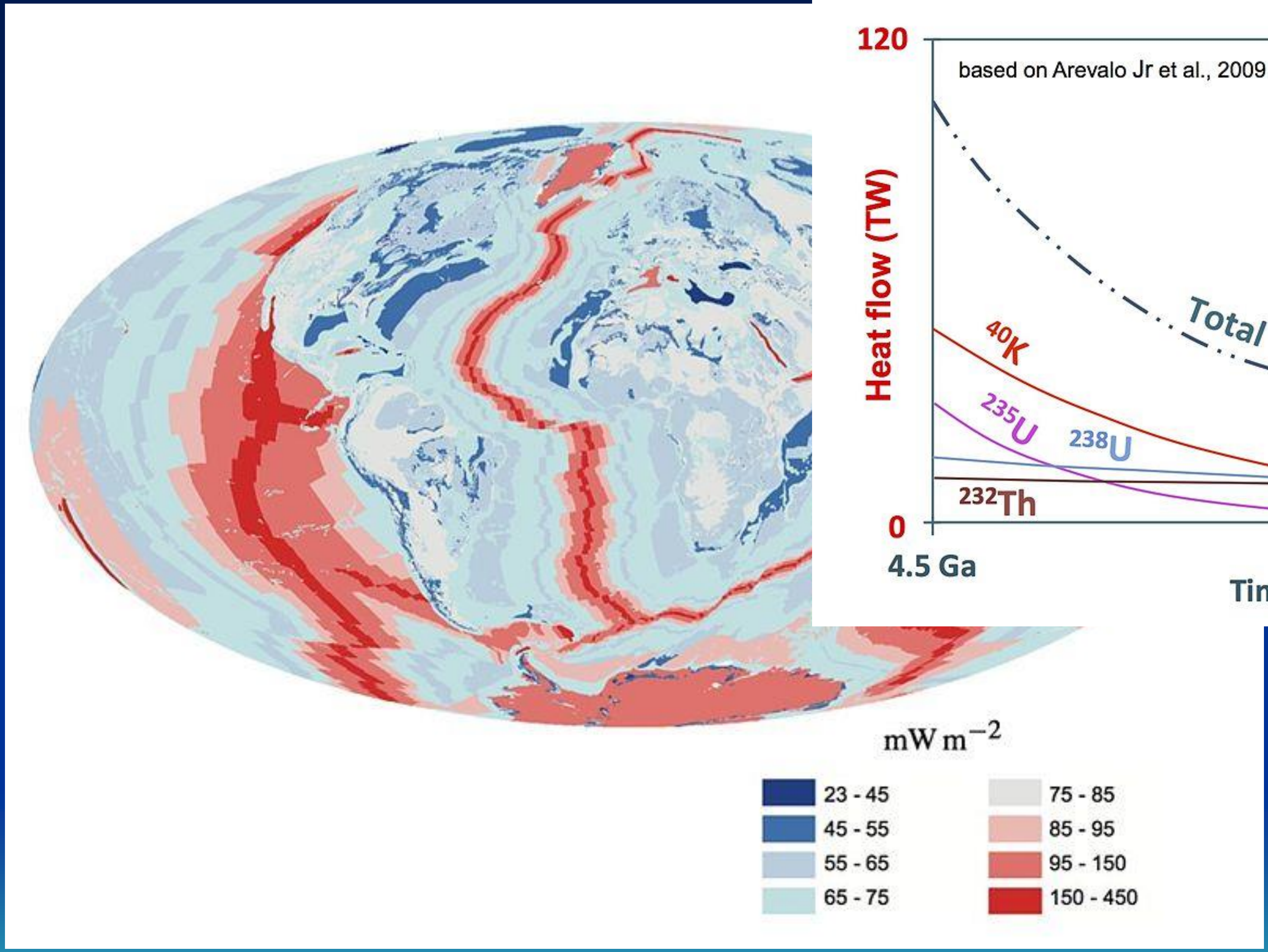



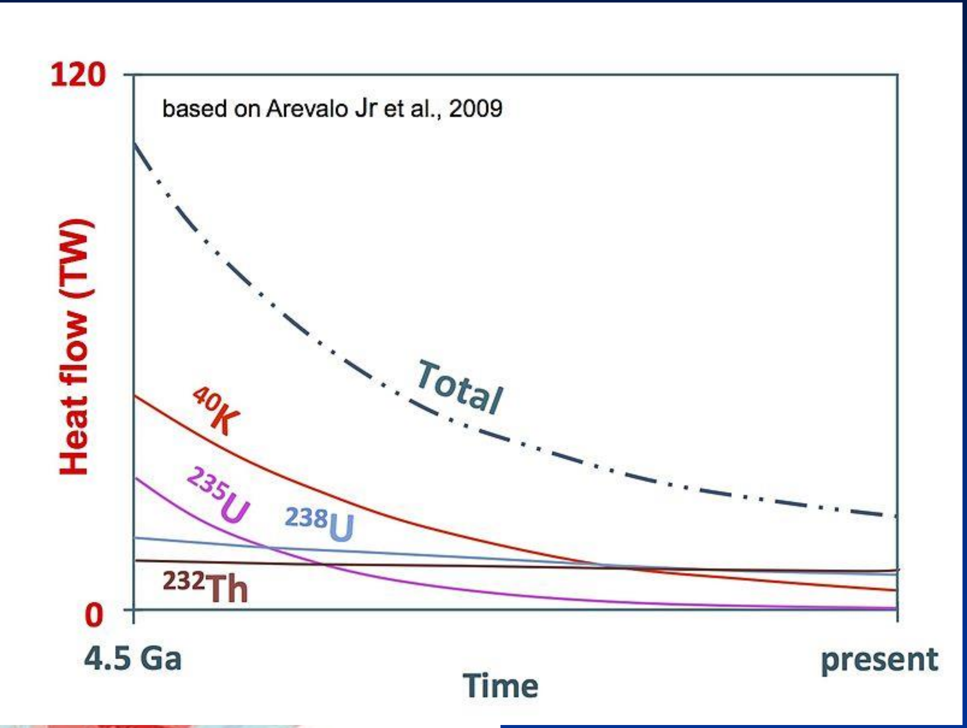

$\gamma \rightarrow$ Pv + Pc (660 km), Ilm $\rightarrow$ Pv (660 km)

by Dan Shim

Christensen (2001) Physics of the Earth and Planetary Interiors 127, 25–34

# Mantle heat flux



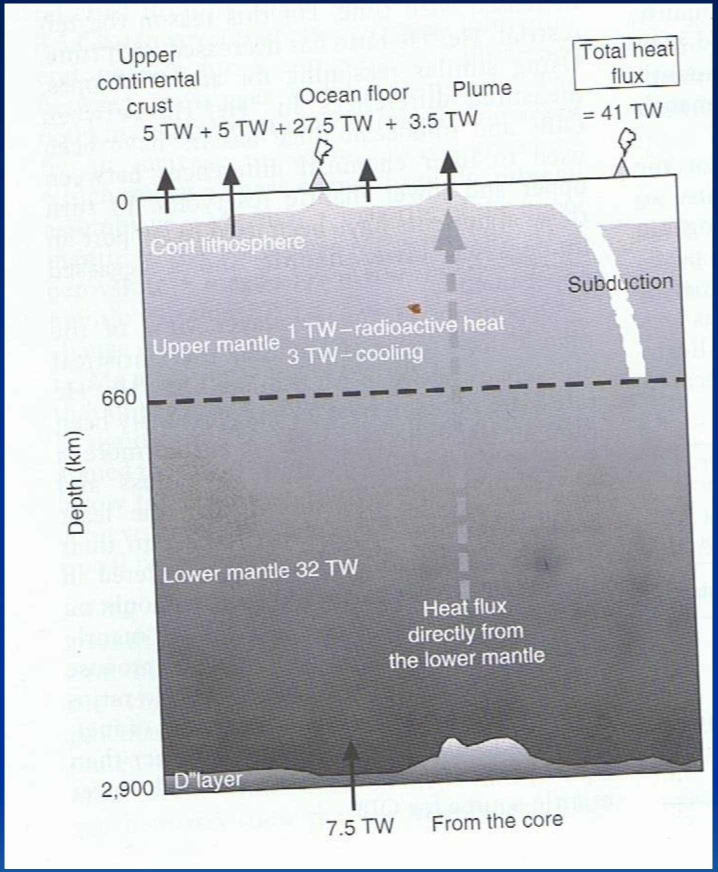



# Mantle heat flux

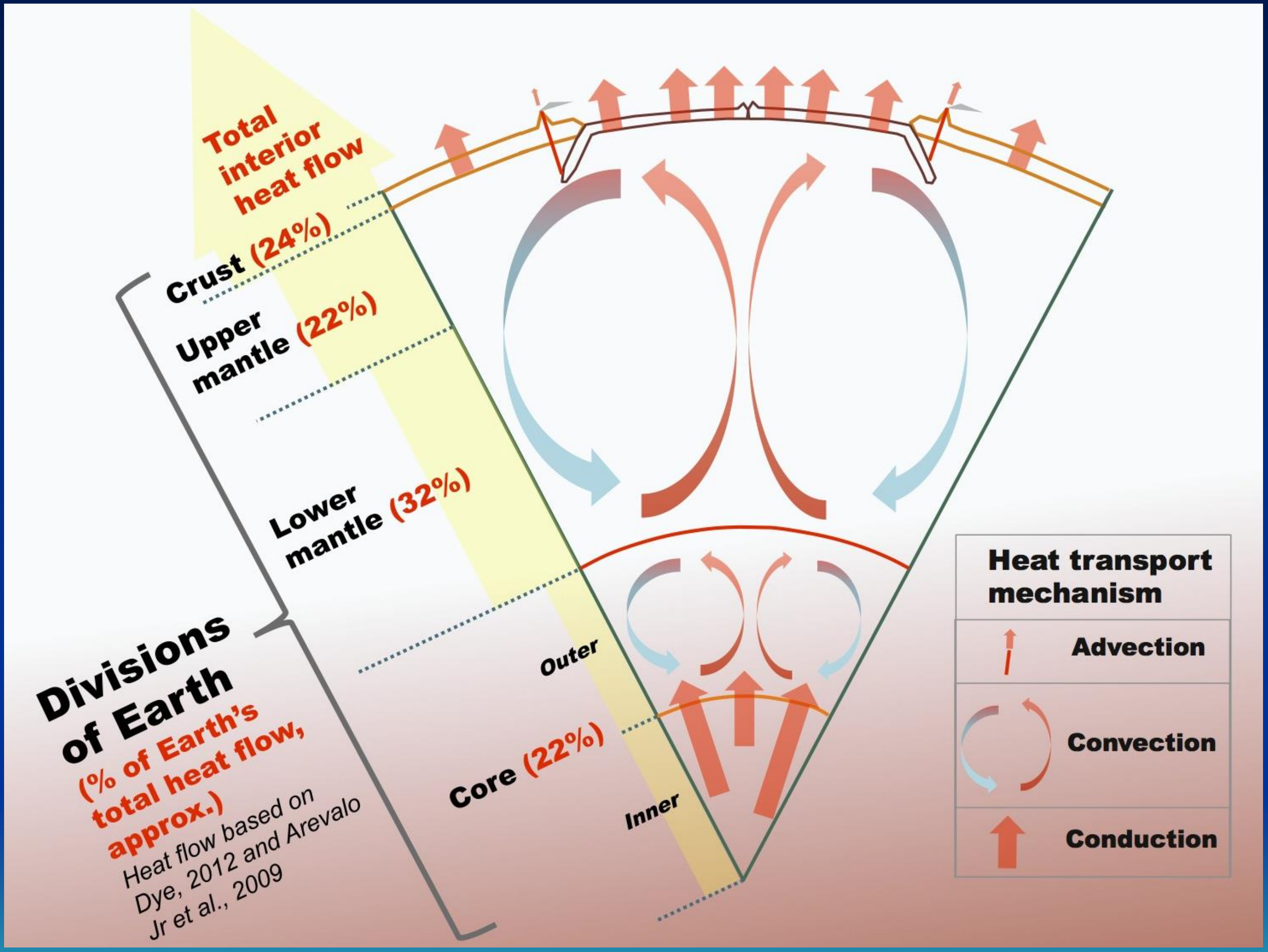
Current heat flux at the Earth's surface is about 41 TW, half of which can be attributed to radioactive decay of K, U and Th

The upper-mantle source region of mid-ocean ridge basalt is depleted in these elements and only produces 3 to 5 TW

→ there is a lower layer enriched in the heat-producing elements (32 TW)



# Mantle heat flux



# Terrestrial argon distribution

## Mass balance calculations

TABLE 3.5 Argon isotopic compositions and K/U ratios in MORB, OIB and the atmosphere.

| | MORB | OIB | Atmosphere |
|---|---|---|---|
| **Original estimates – Allegre et al. (1986a)** | | | |
| $^{40}Ar/^{36}Ar$ | 16,700 | 390 | 295 |
| $K/U$ | 12,700 | 12,700 | |
| **Recent estimates – Trieloff et al. (2003); Albarede (1998)** | | | |
| $^{40}Ar/^{36}Ar$ | 32,000 ± 4,000 | 8,000 | 295 |
| $K/U$ | 6,200 | 6,200 | |

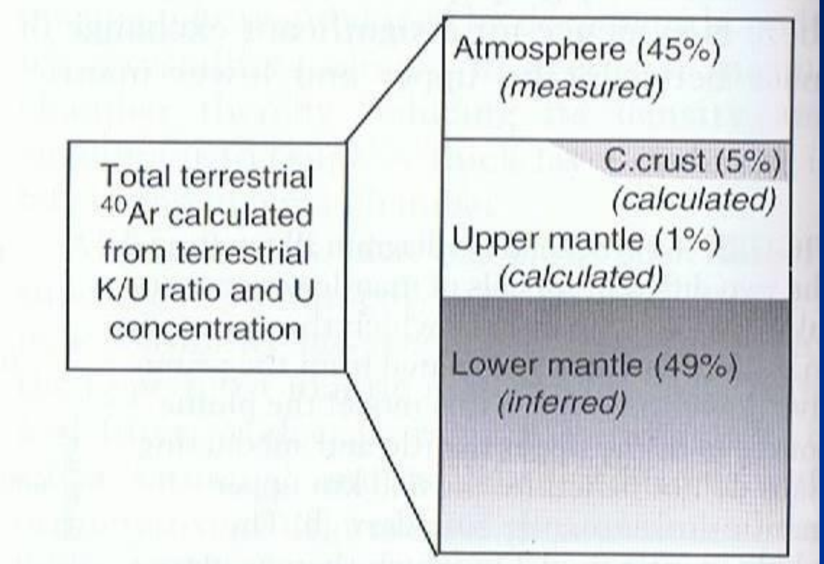
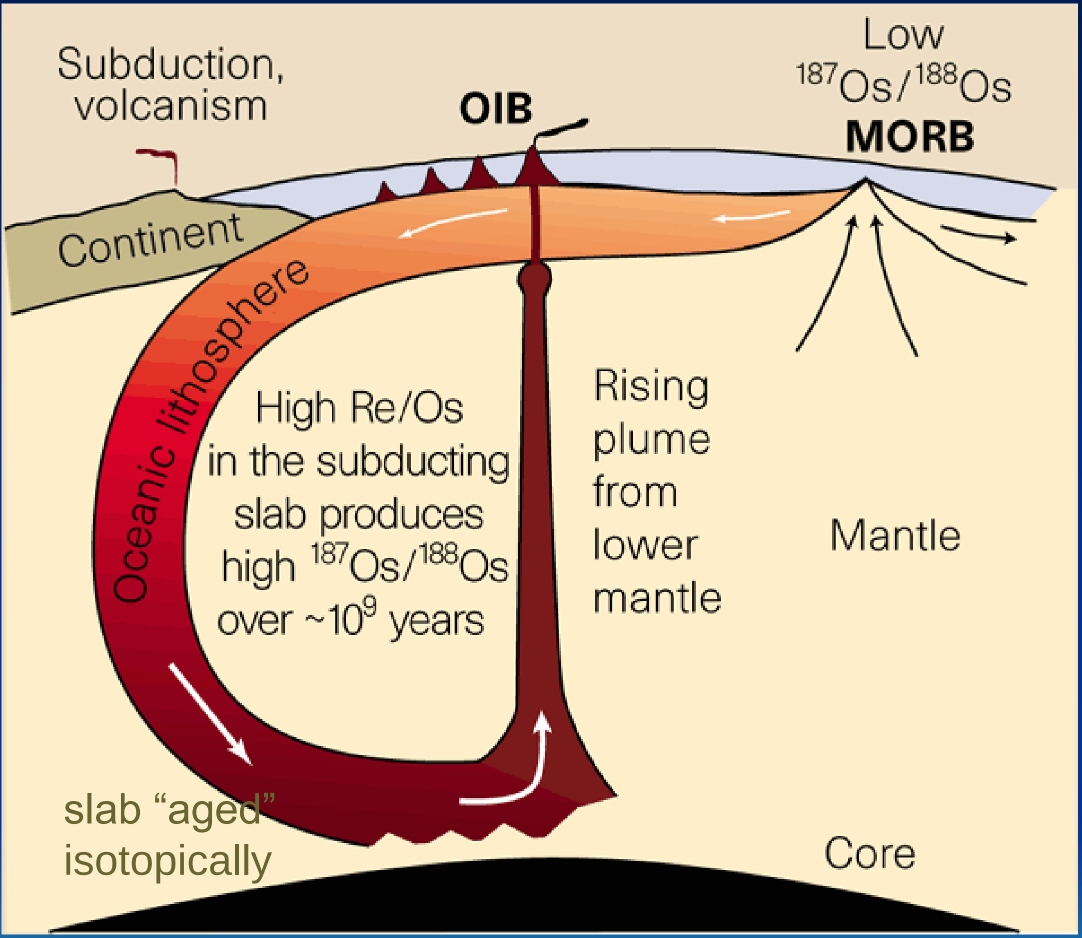



FIGURE 3.18 Present-day terrestrial $^{40}Ar$ distribution showing the very large difference between upper and lower mantle.

Hugh Rollison (2007)
Early Earth

# Re-Os isotope system

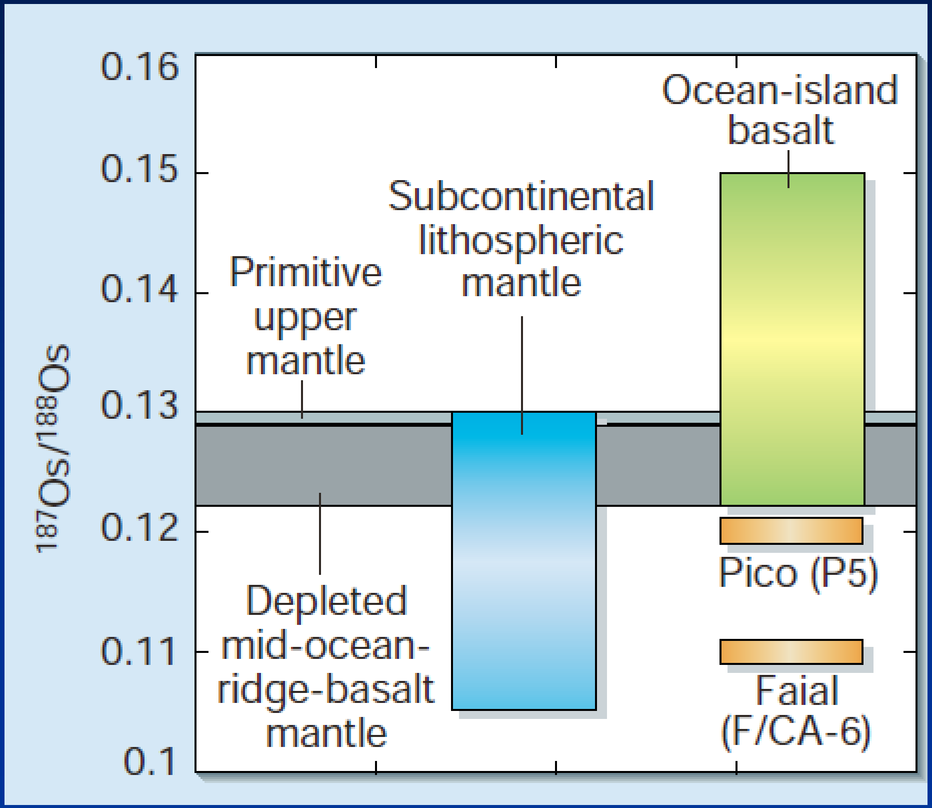
## Slab-recycling model (re-melting of ancient ocean floor)




*Halliday (1999) Nature 399*

The time taken for this recycling process is thought to be 1-2 Ga. By the time the plume melts to produce OIB it has 'aged' isotopically and has higher $^{187}Os/^{188}Os$ than the surrounding mantle

# Re-Os isotope system




*Schaefer et al. (2002) Nature 420*
*Widom (2002) Nature 422*

# Mass balance calculation

| Element | BSE (p.p.m.) | CC (p.p.m.) | DM (p.p.m.) | Fraction of mantle that is depleted |
|---|---|---|---|---|
| K | ? | 15800 | 85 | ? |
| U | 0.02 | 1.4 | 0.0065 | ? |
| Th | 0.08 | 5.6 | 0.0164 | ? |

K/U-ratio of global igneous rocks: 12500

Bulk silicate Earth consists of 0.56% continental crust

Helffrich & Wood Nature 412 (2001)

Bulk silicate Earth consists of 0.56% continental crust

Uran

$$0.02 = 1.4 \times 0.0056 + 0.0065a + 0.02b$$

$$0.0056 + a + b = 1$$

$$0.0065a + 0.02b = 0.01216$$

$$a + b = 0.9944 \quad / * 0.0065$$

$$0.0065a + 0.02b = 0.01216$$

$$0.0065a + 0.0065b = 0.00646$$

$$0.0135b = 0.0057$$

$$b = 0.422$$

$$a + b = 0.9944$$

$$a = 0.9944 - 0.422$$

$$a = 0.57$$

| Element | BSE (p.p.m.) | CC (p.p.m.) | DM (p.p.m.) | Fraction of mantle that is depleted |
|---|---|---|---|---|
| K | 250 | 15800 | 85 | |
| U | 0.02 | 1.4 | 0.0065 | |
| Th | 0.08 | 5.6 | 0.0164 | |

# Übung Massenbilanzierung

| Element | BSE (p.p.m.) | CC (p.p.m.) | DM (p.p.m.) | Fraction of mantle that is depleted |
|---|---|---|---|---|
| K | 250 | 15800 | 85 | 0.52 |
| U | 0.02 | 1.4 | 0.0065 | 0.57 |
| Th | 0.08 | 5.6 | 0.0164 | 0.45 |

Assuming a constant rate of subduction for 4 Ga, mantle should contain 5% recycled oceanic crust, 45% recycled “sterile” mantle and about 0.3% recycled continental material

Helffrich & Wood Nature 412 (2001)

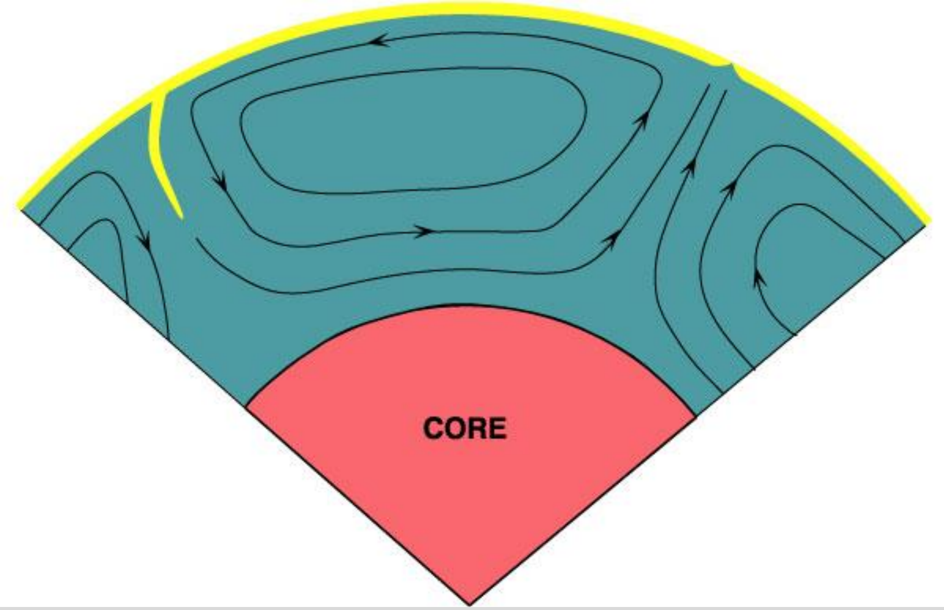
# Mantle models

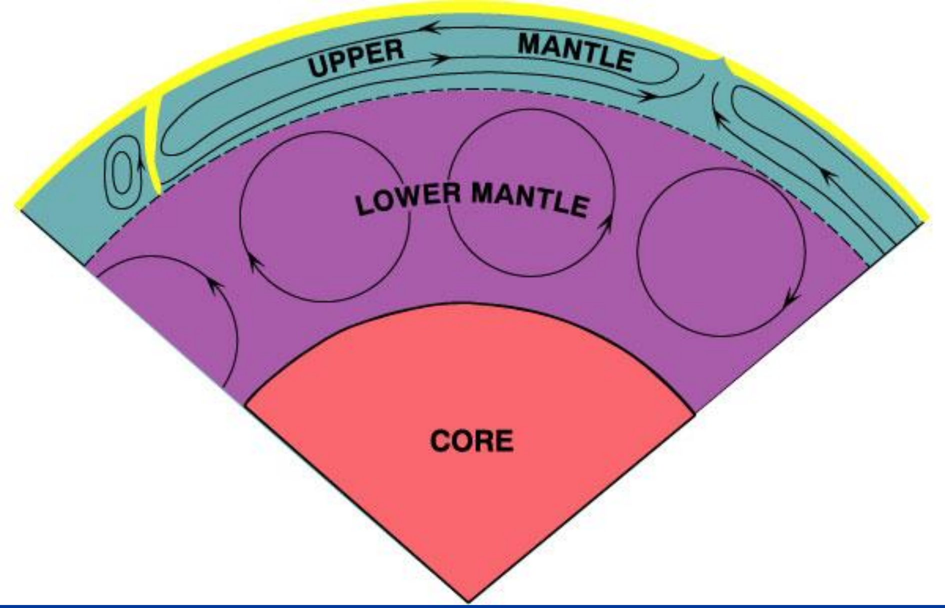
"layer cake" = distinctly chemically stratified

# Mantle models ("layer cake")

Upper depleted mantle = MORB source

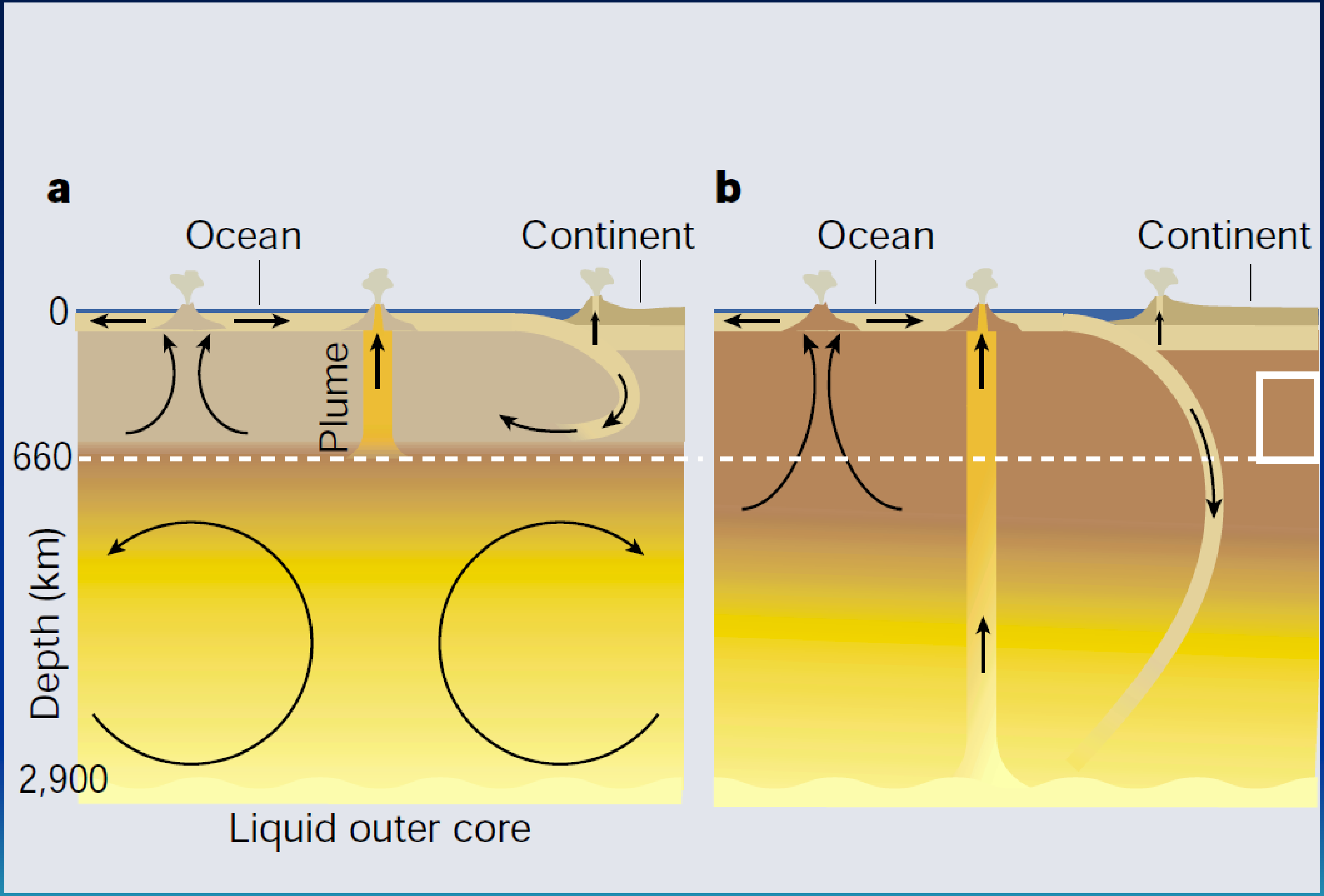
Lower undepleted & enriched OIB source




1982: Allègre *Chemical Geodynamics*
(integrated study of chemical and physical structure and evolution of the solid Earth)

# Mantle models ("layer cake")

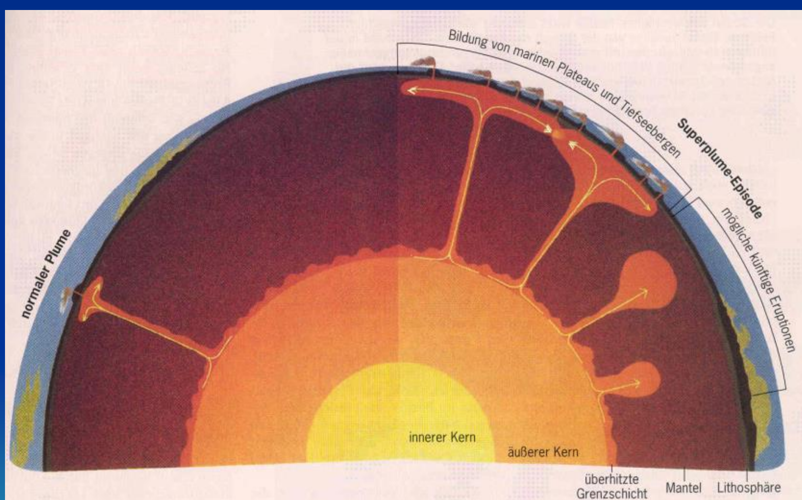


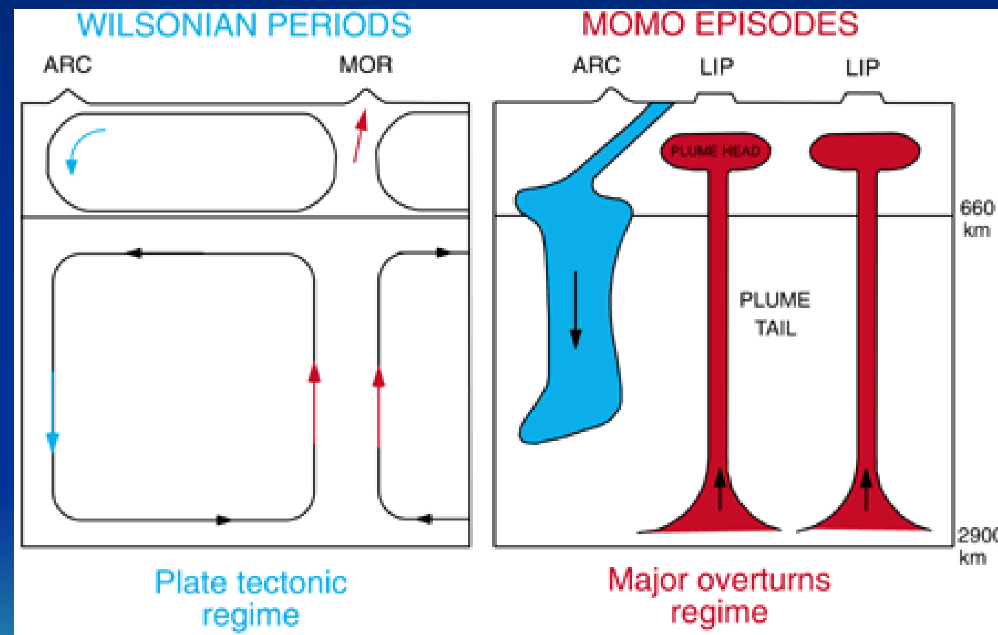

*Hofmann (1997) Nature 385*
*Hofmann (2003) Nature 425*

# Models for Oceanic Magmatism

Left: normal mode of plate tectonics, with opening and closing of oceans and mantle convection with isolated upper and lower mantle. Plumes originate predominantly from the base of the upper layer. Right: MOMO episode - accumulated cold material descends from the 660-km boundary layer into the lower mantle, and multiple major plumes rise from the core-mantle boundary to form large igneous provinces (LIPs) at the surface.

Stein & Hofmann 1994, Nature 372

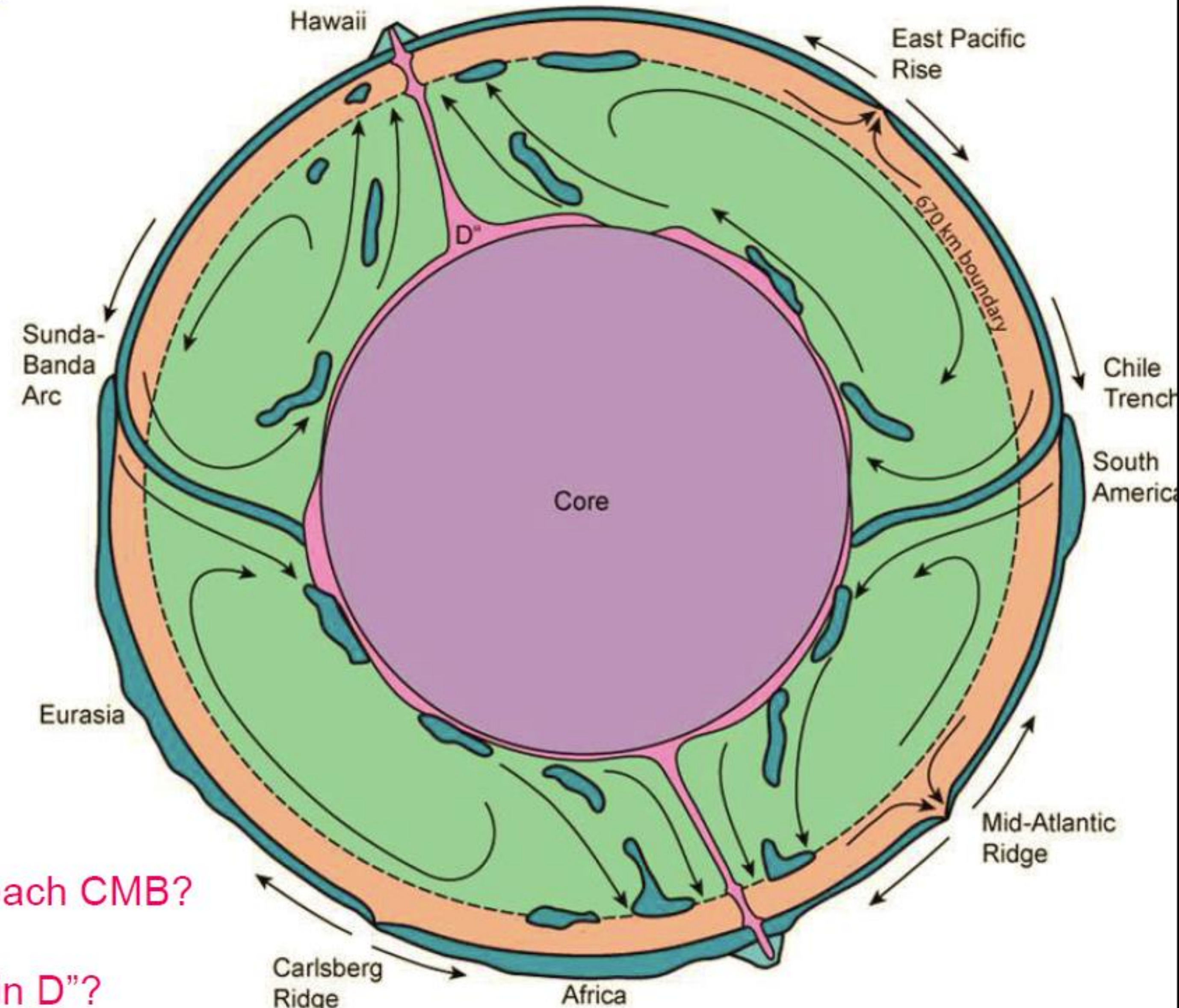


Global schematic view of plate tectonics and mantle convection

Subducted plates are shown descending to the core--mantle boundary

Hot spot volcanism is shown arising from thermal anomalies at the core--mantle boundary (D" layer)

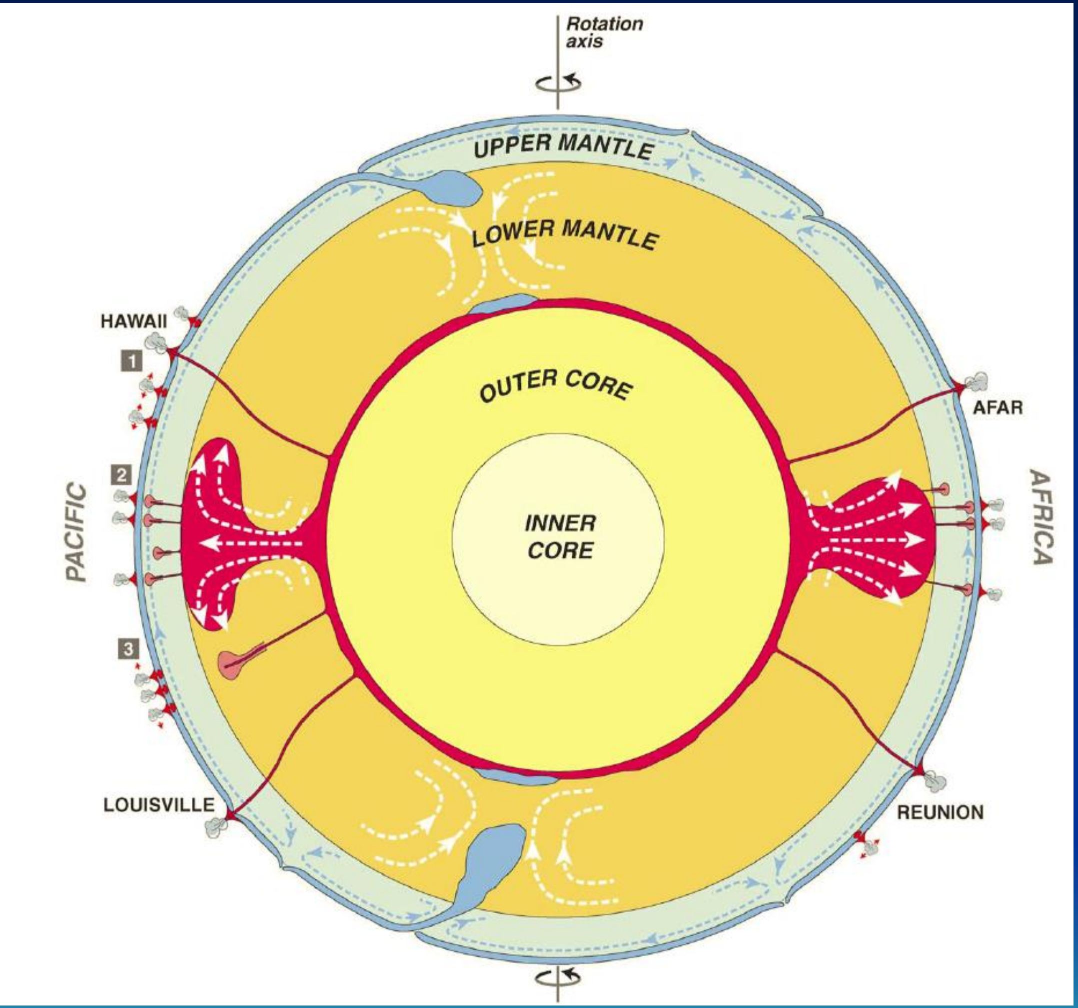



**Questions:**

1. Do subducted slabs reach CMB?
2. What is the D" layer?
3. Do hotspots originate in D"?
4. Single layer or two layer mantle convection?

# Models for oceanic magmatism

What is the exact nature of the mantle plumes?



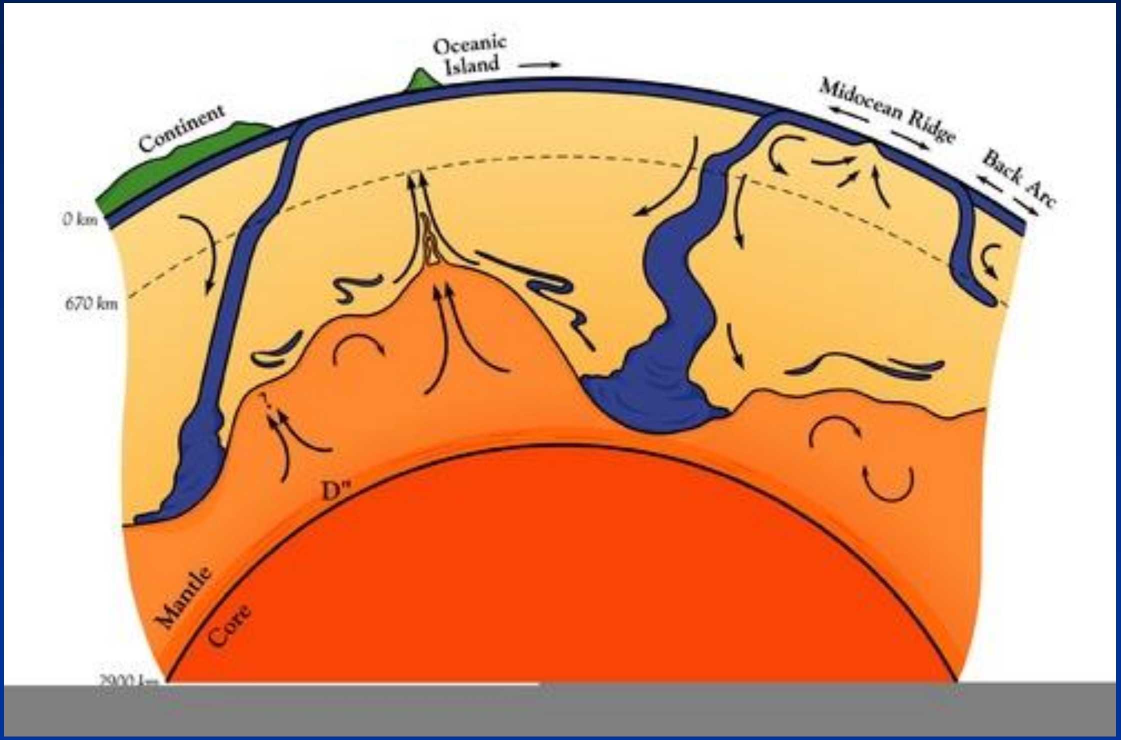

*Courtillot et al. (2003) EPSL 205*

# Mantle models ("layer cake")

## Lava-lamb model: Compositional stratification in the deep mantle

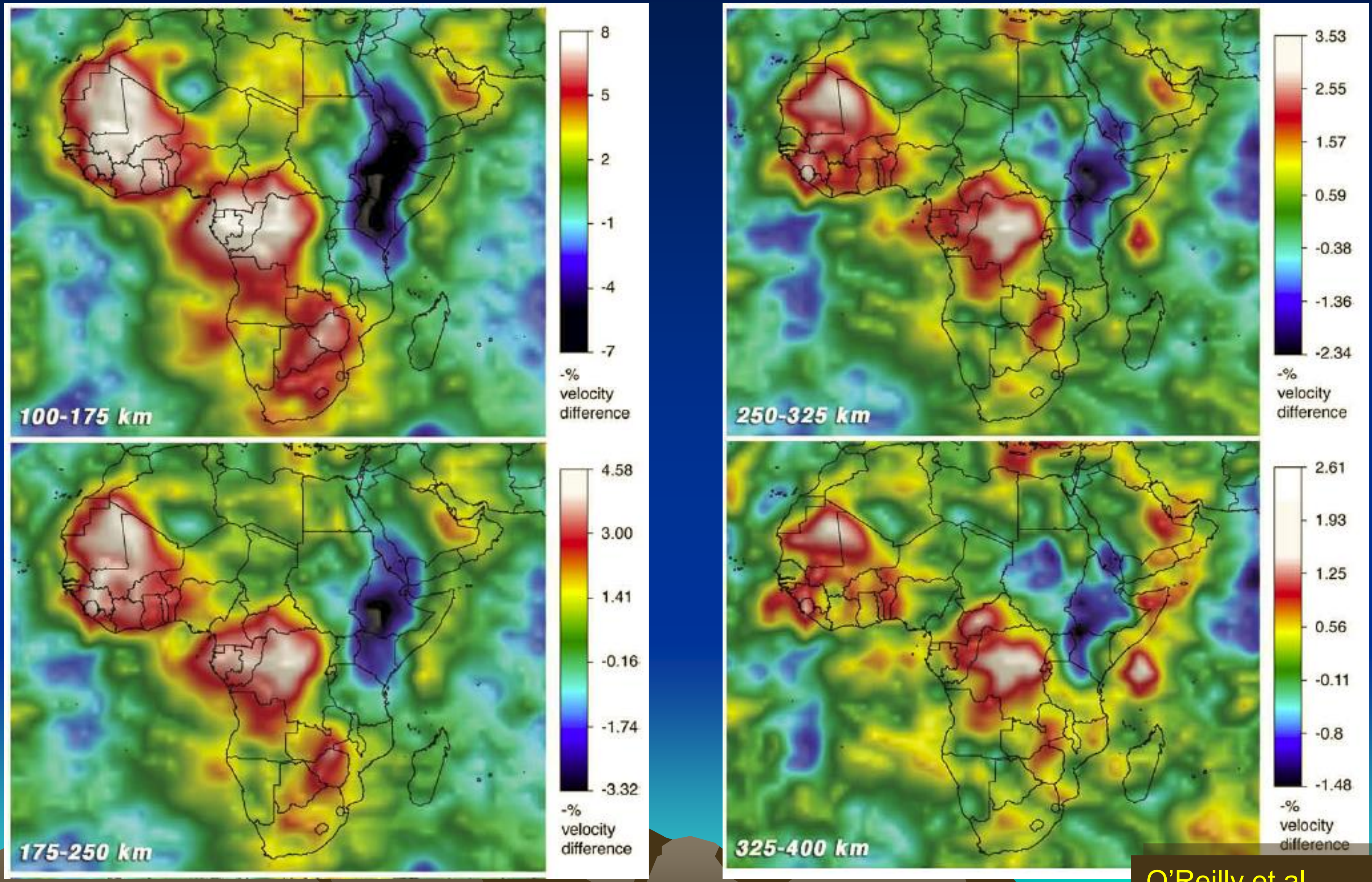
Dense layer in the lower mantle. Depth to the top of the layer ranges from ~1600 km to near the CMB, where it is deflected by downwelling slabs. Internal circulation within the layer is driven by internal heating and by heat flow across the CMB.

A thermal boundary layer develops at the interface, and plumes arise from local high spots, carrying recycled slab and some primordial material



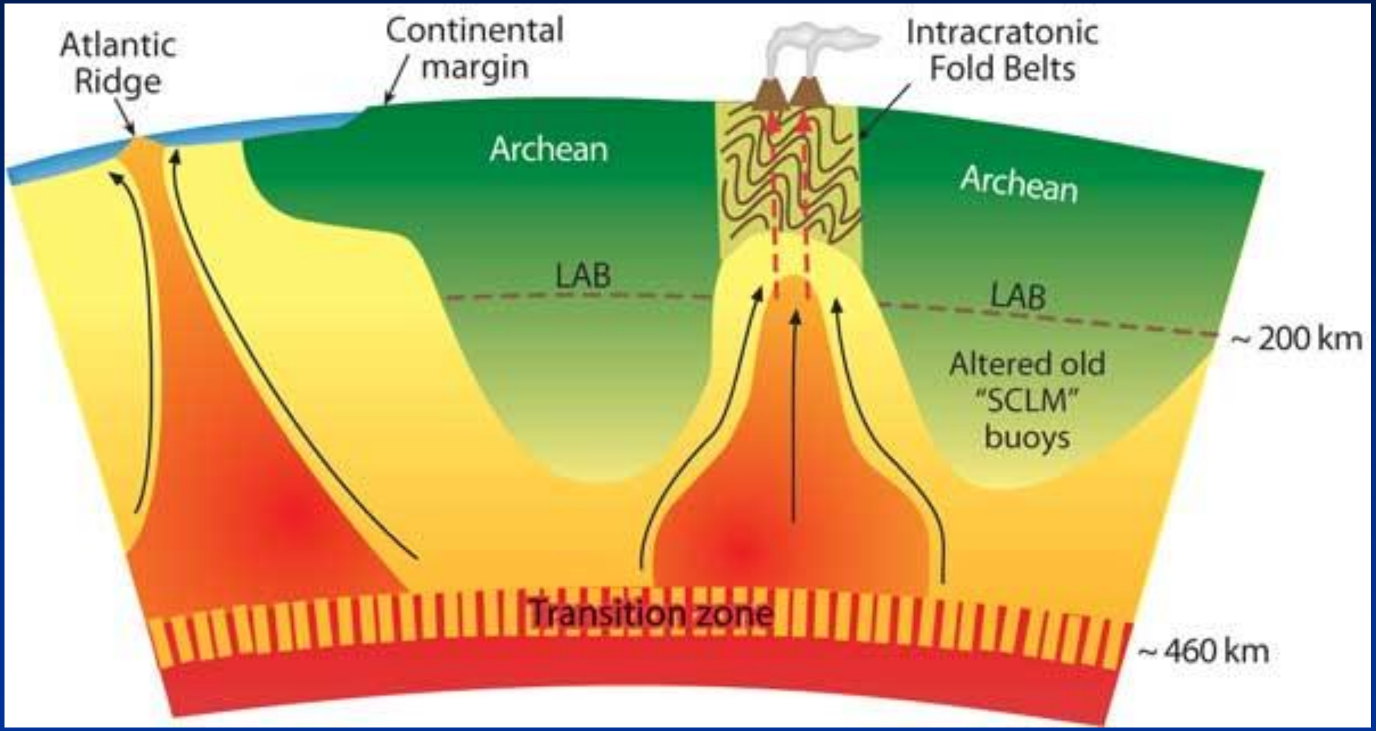

Kellogg et al. 1999, Science 283

# Mantle models – vertical convection




O'Reilly et al. 2009, Lithos 2115

# Mantle models – vertical convection




LAB: lithosphere – asthenosphere boundary

O'Reilly et al. 2009, Lithos 2115

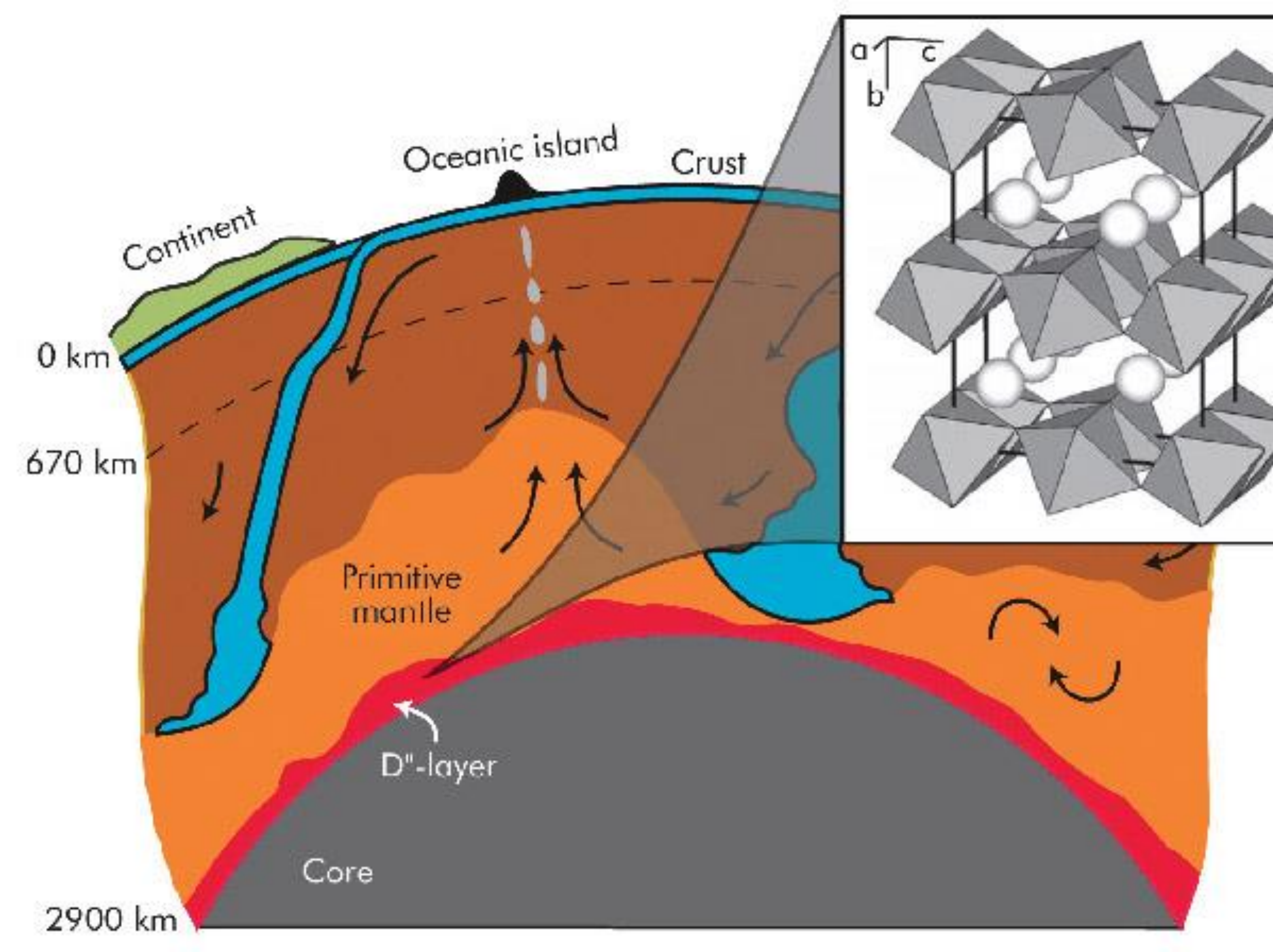
# Perovskite to post-perovskite transition and the nature of D’’

Near the base of the mantle $MgSiO_3$ perovskite transforms to high-pressure form with stacked $SiO_6$-octahedral sheet structure.

Increase in density of 1.0 to 1.2%.

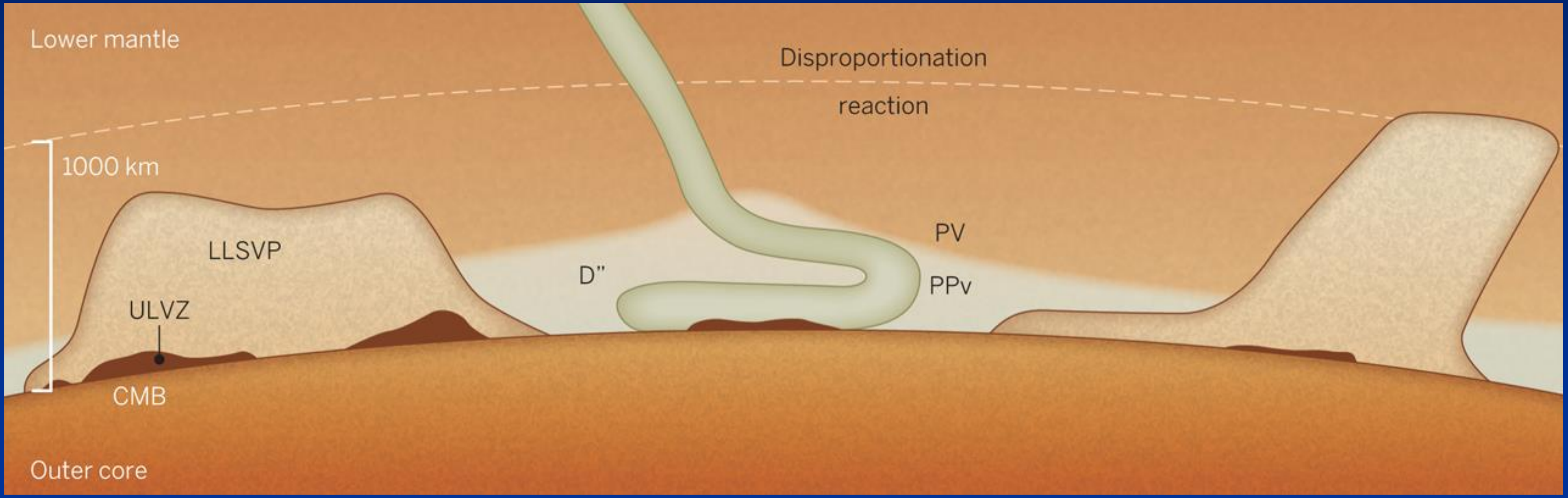
Origin of the D″ seismic discontinuity related to this post-perovskite phase transition?

The new phase has preferred orientation with platy crystal shape that can cause the seismic anisotropy in the D″ layer.



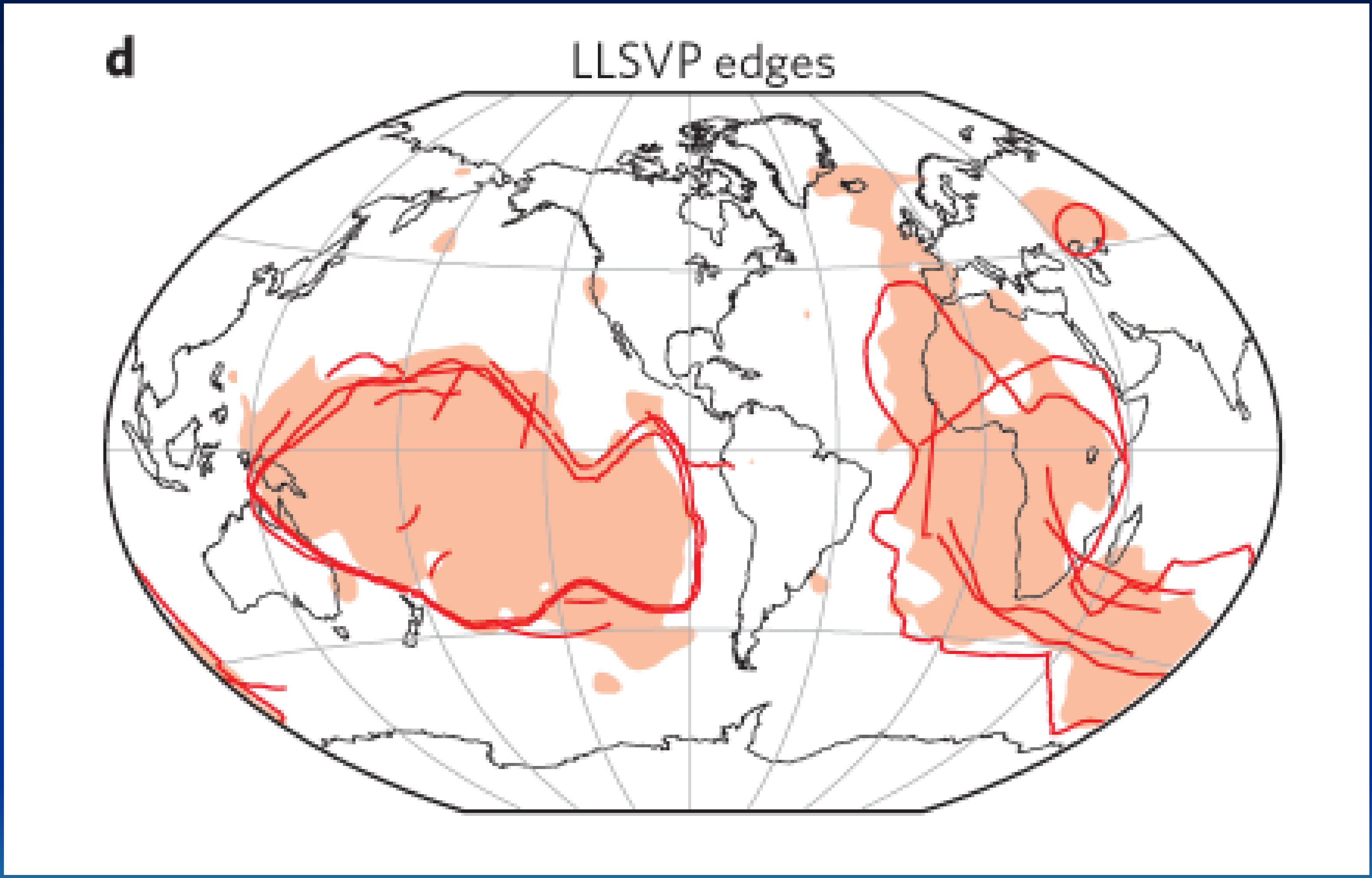

*Murakami et al. (2004) Science* ***304****, 855-858*
*Andrault et al. (2010) Earth Planet Sci Lett* ***293****, 90-96*

# Mantle core boundary



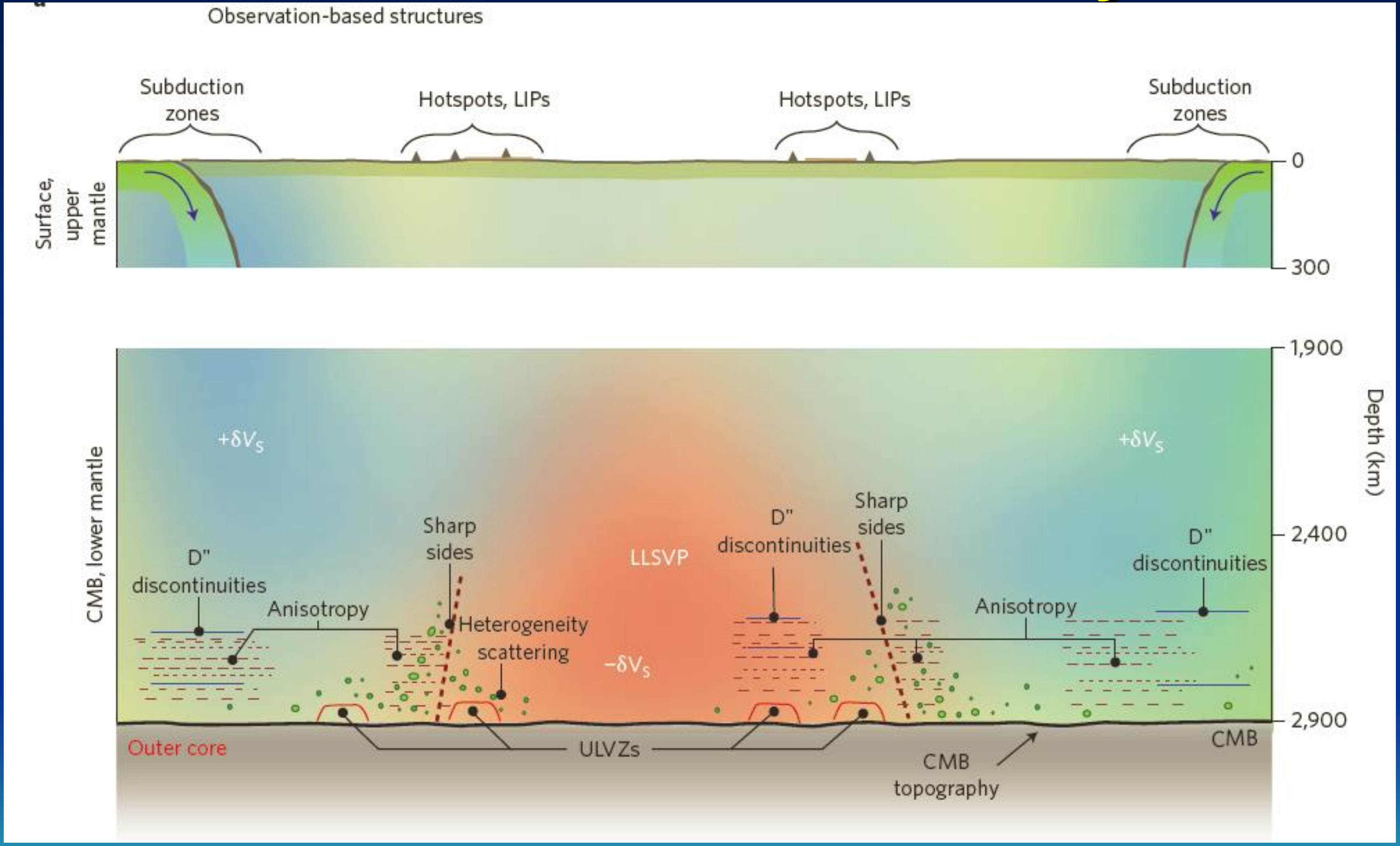

**Quentin Williams Science 2014;344:800-801**

Published by AAAS



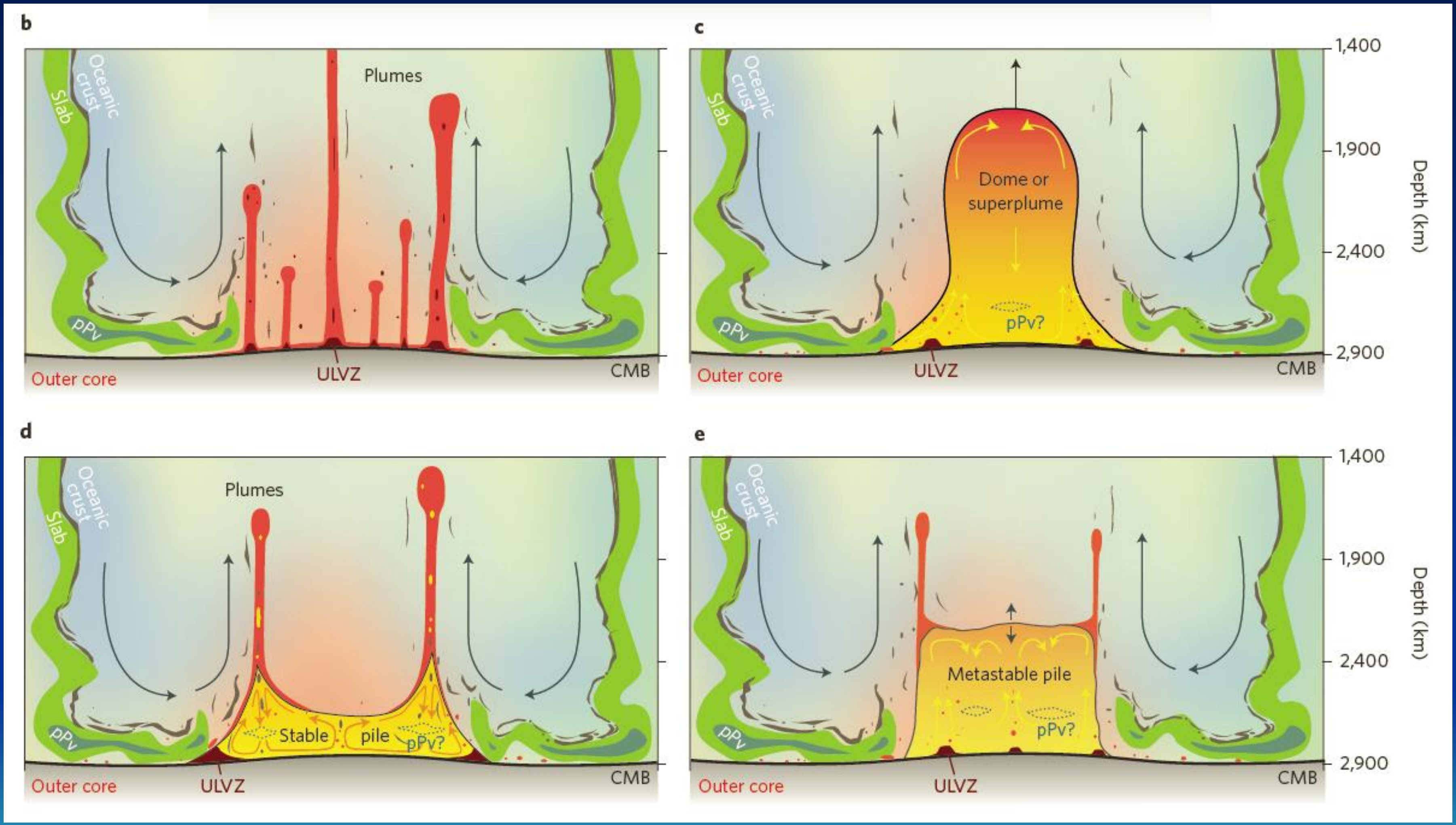

*Garnero et al. (2016) Nature Geoscience*

# Mantle core boundary



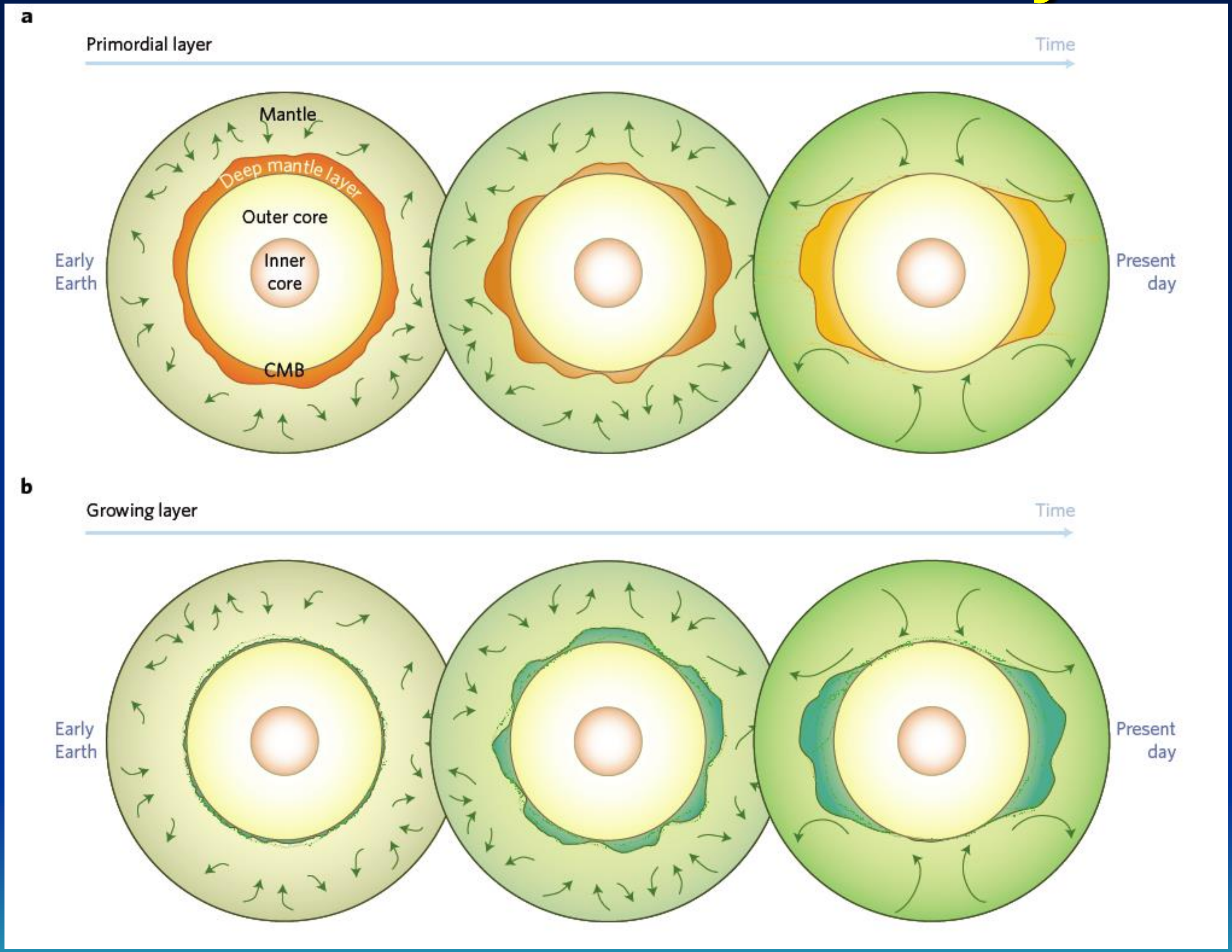

*Garnero et al. (2016) Nature Geoscience*

# Mantle core boundary



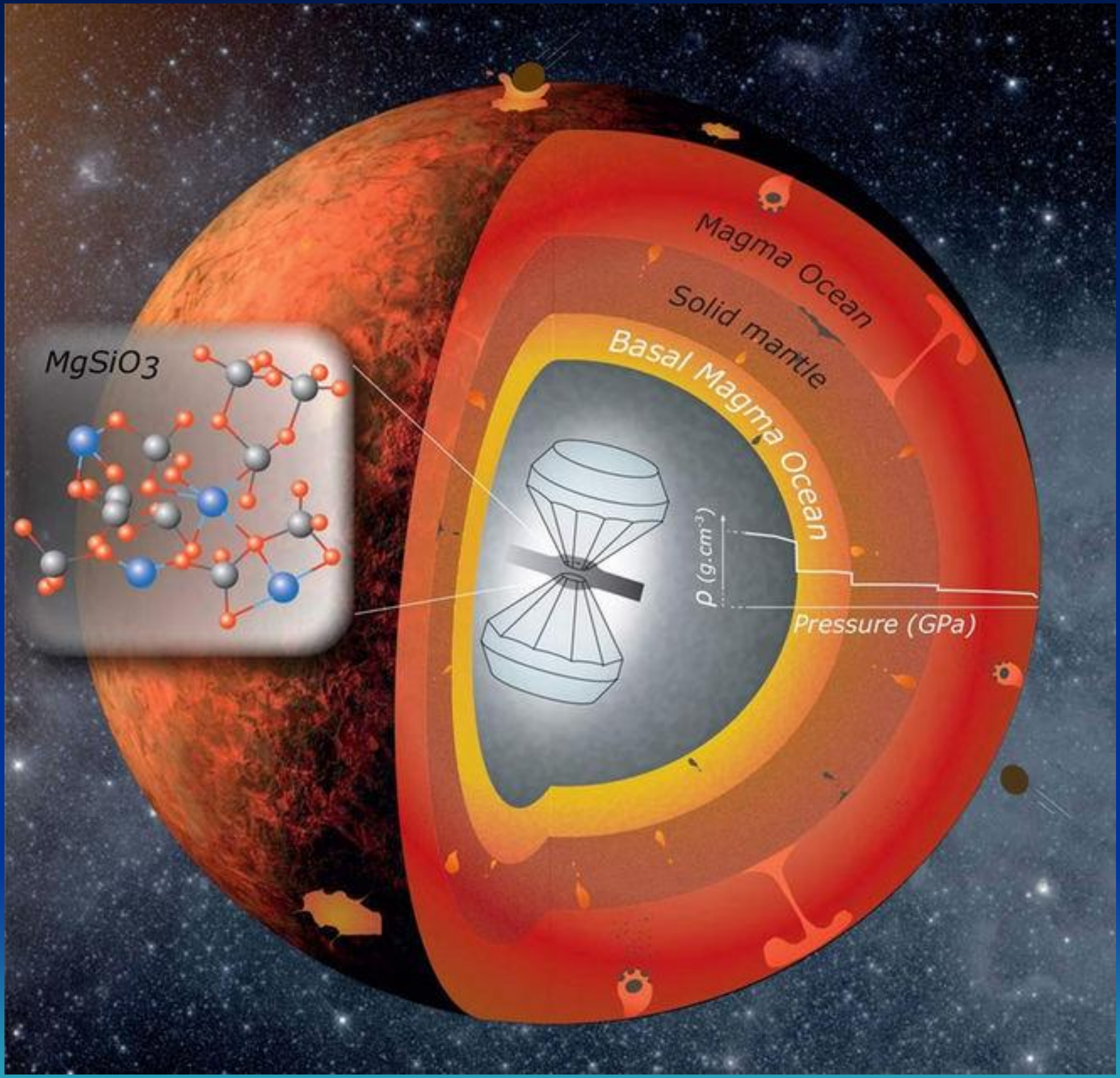

*Garnero et al. (2016) Nature Geoscience*

# Mantle core boundary




*Garnero et al. (2016) Nature Geoscience*

# Mantle models ("layer cake")




## D'' model

Early crust or ancient magma ocean on top of the Earth's core

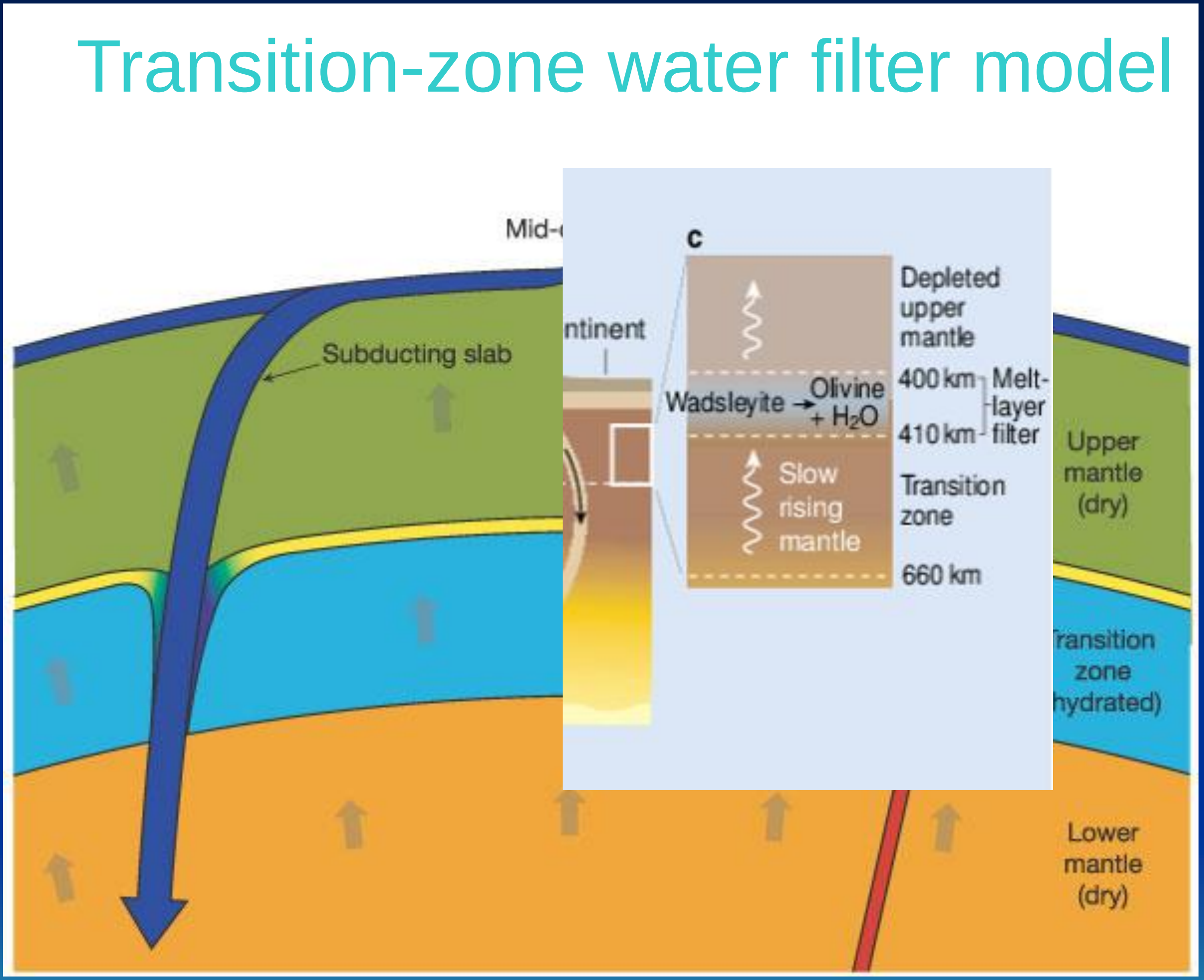
Tolstikin & Hofmann (2005)
Petitgirard et al. (2015) PNAS

when $MgSiO_3$ melts it becomes heavier (denser) → would accumulate at the core-mantle boundary and form a magma ocean

# Mantle models ("layer cake")

This model could explain why Earth's upper mantle is depleted of many trace elements. At a certain depth, minerals might release water, creating a molten filter that traps trace elements in the mantle beneath

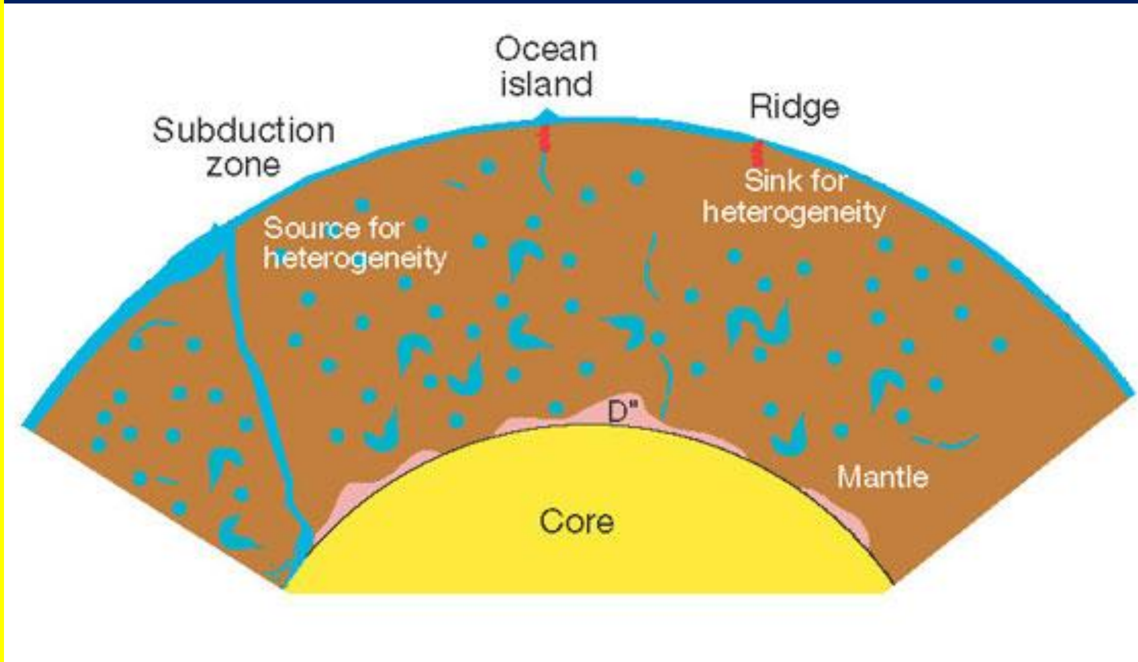
„Just add water"
Al Hofmann (2003)




*Bercovici & Karato (2003) Nature 425: 39-44*

# Plum pudding model

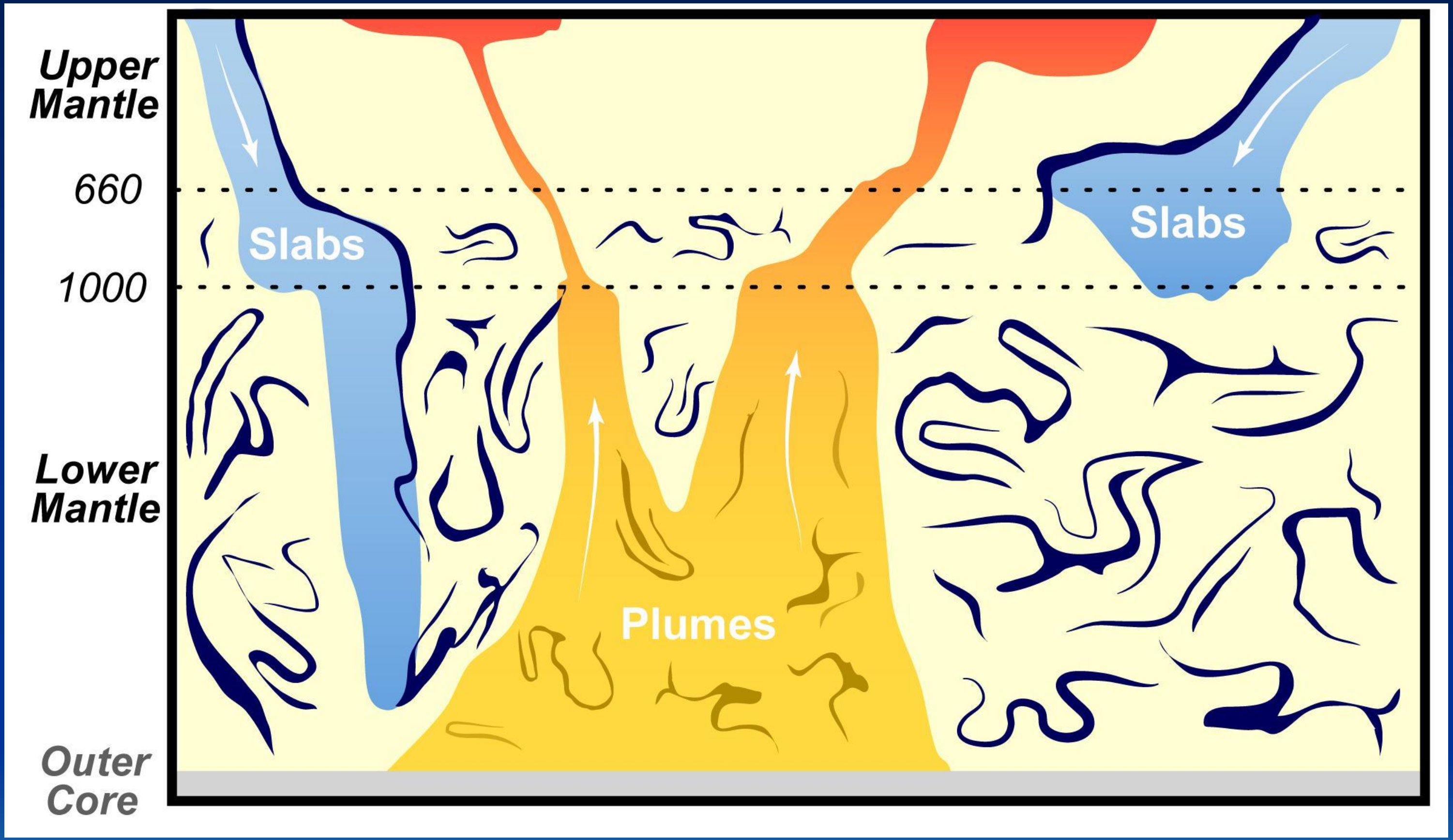
Model of a chemically **unstratified mantle**. Subduction of oceanic lithosphere introduces heterogeneity into the mantle. Mixing by **convective stirring** of the mantle disaggregates the subducted lithosphere and minor continental material, producing isolated heterogeneities that scatter seismic energy but are too small to be observed tomographically. Melting at mid-ocean ridges and at ocean islands produces basalts and homogenizes the two types of mantle material, one enriched in incompatible elements and the other 'sterile'.




The heterogeneities are remnants of recycled oceanic and continental crust

*Helffrich & Wood (2001) Nature 412*

# Plum pudding or layered cake?




*Ballmer et al. (2015) Science Advances*

## *Literature on mantle models, geochemistry, geodynamics…*


Ballmer M et al. (2015). Compositional mantle layering revealed by slab stagnation at ~1000-km depth, Science Advances. DOI: 10.1126/sciadv.1500815

Bercovici D, Karato S (2003) Whole-mantle concection and the transition-zone water filter. Nature 425: 39-44

Helfrich GR, Wood BJ (2001) The Earth's mantle. Nature 412: 501-507

Hofmann AW (2003) Sampling mantle heterogeneity through oceanic basalts: isotopes and trace elements. In: Treatise on Geochemistry Vol. 2:61-101

Hofmann AW (1997) Mantle geochemistry: the message from oceanic volcanism. Nature 385: 219-229

Kellogg LH, Hager BH, van der Hilst RD (1999) Compositional stratification in the deep mantel. Science 283: 1881-1884

# *Literature on mantle models, geochemistry, geodynamics…*


Tolstikhin I, Hofmann AW (2005). Early crust on top of the Earth's core. Physics of the Earth and Planetary Interiors 148: 109–130

O'Reilly et al. (2009) Ultradeep continental roots and their oceanic remnants: A solution to the geochemical "mantle reservoir"problem? Lithos 2115: 1043-1054

Garnero et al. (2016) Continental-sized anomalous zones with low seismic velocity at the base of Earth's mantle. Nature Geoscience