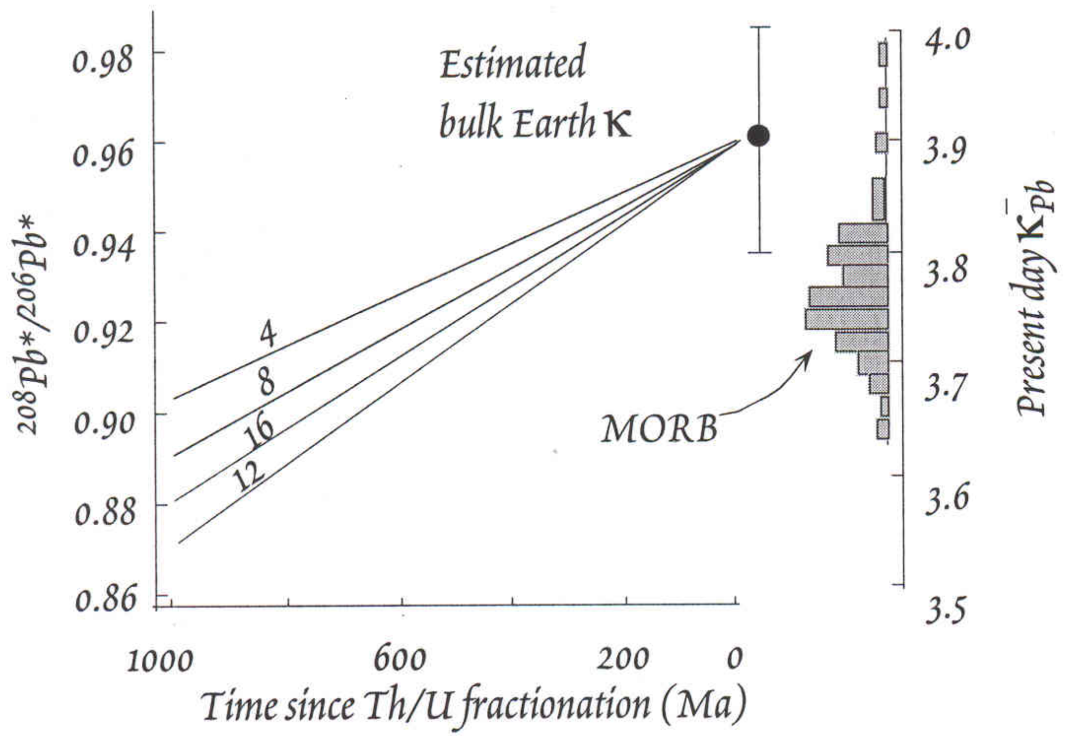
Open system model of Pb isotope evolution of the Earth

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

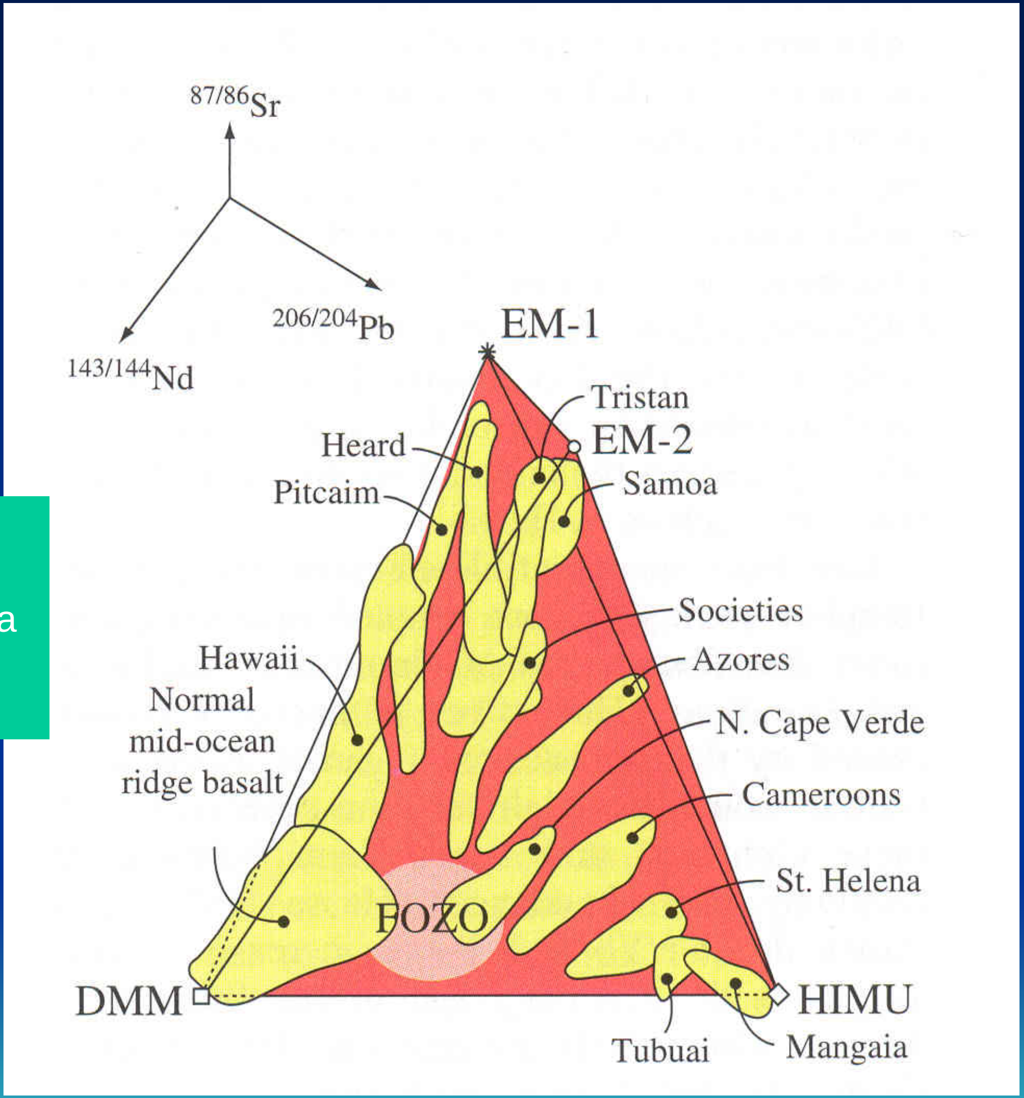


Galer & O'Nions (1985) Nature 316

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?

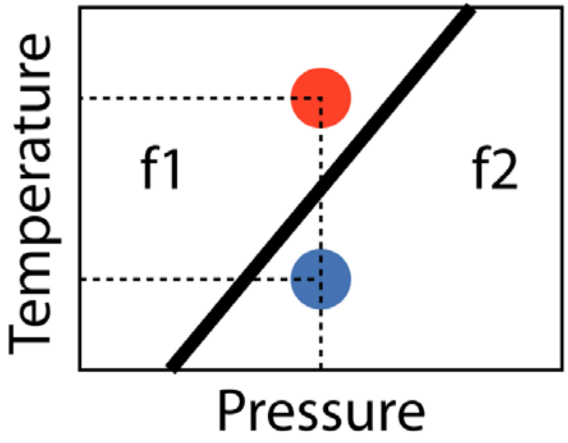
… mantle dynamics is in a state of turmoil (Hofmann)

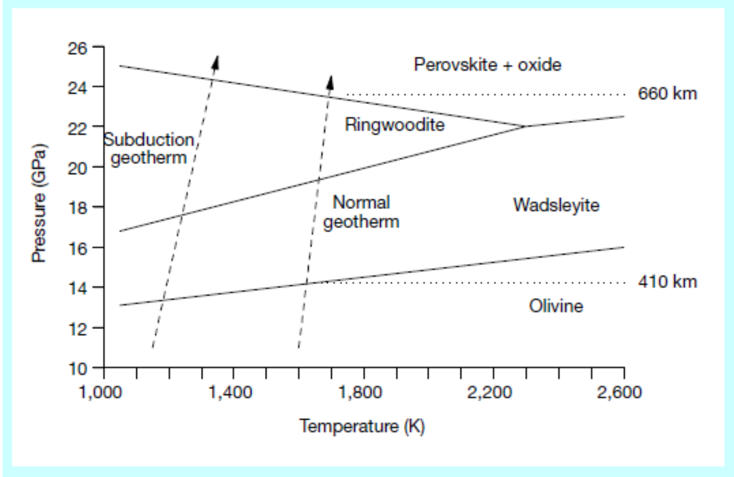
…. our view of the mantle is in a state of transition (Rollison)

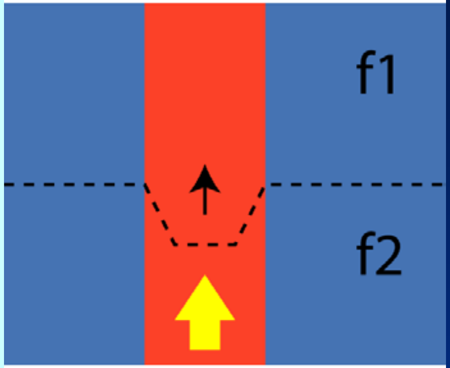
Cold Warm

Subducting Slab

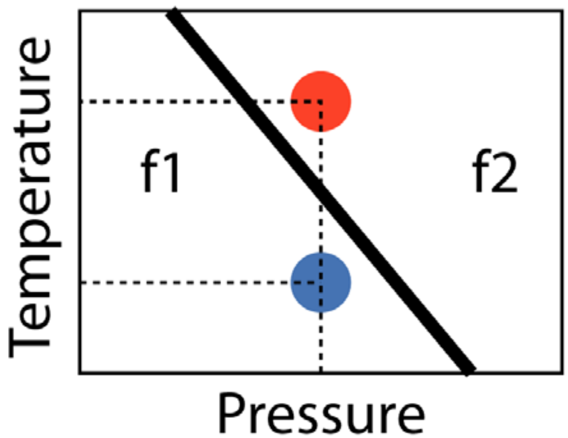
Plume

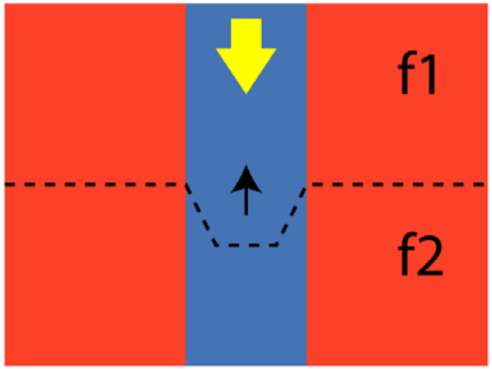


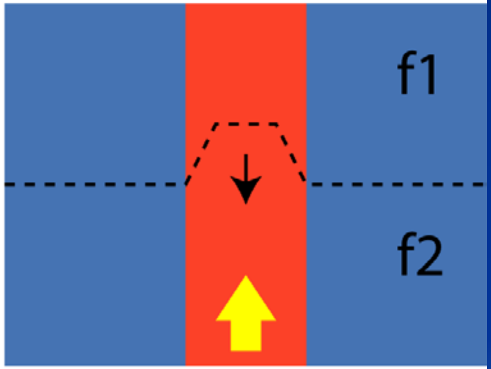




(660 km)





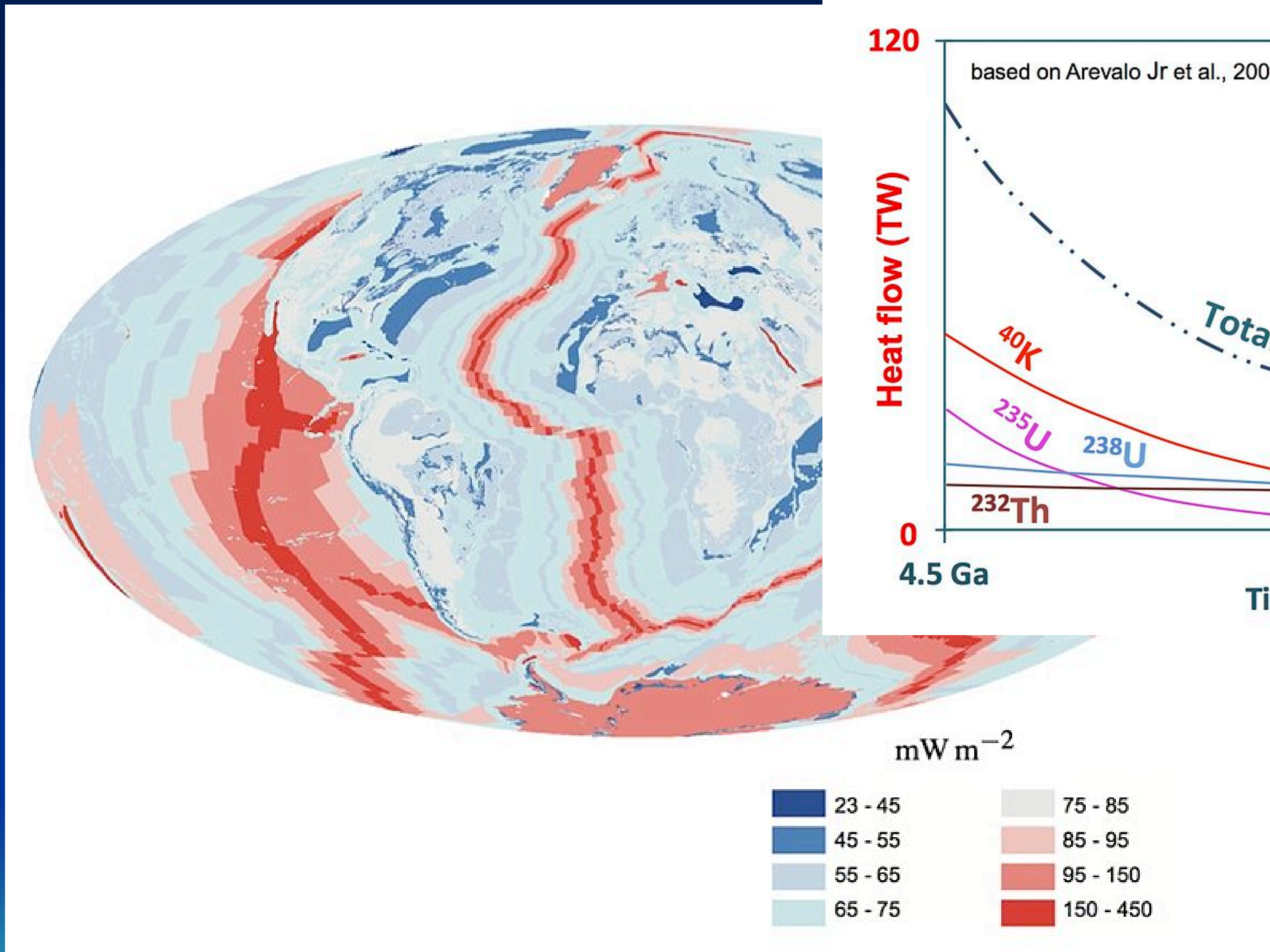


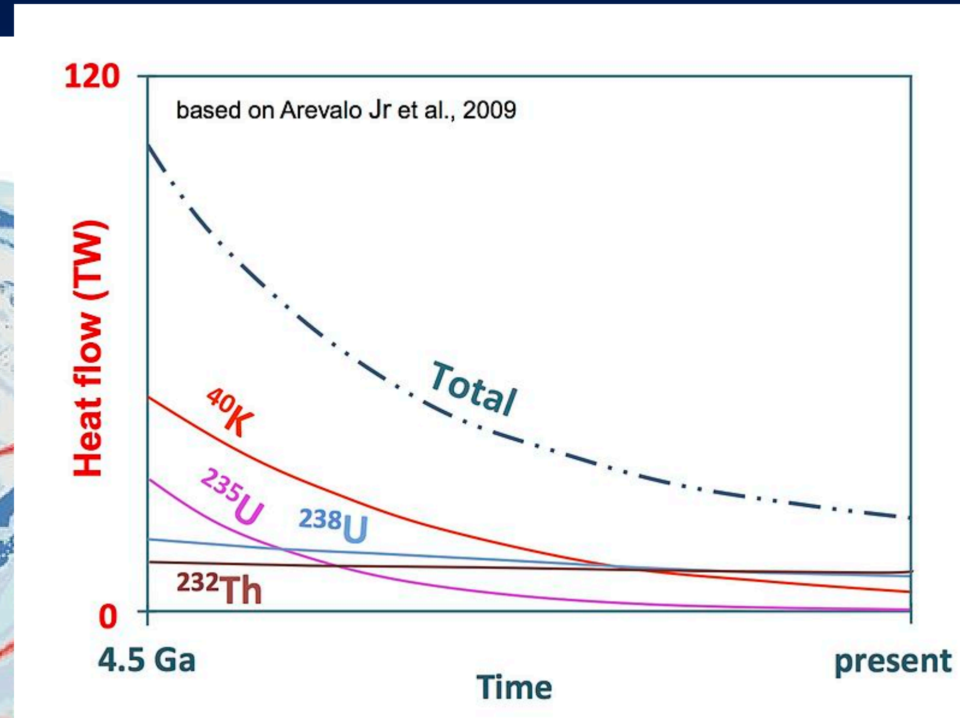
$\gamma \rightarrow$ Pv + Pc (660 km), Ilm $\rightarrow$ Pv (660 km)

by Dan Shim

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

Mantle heat flux





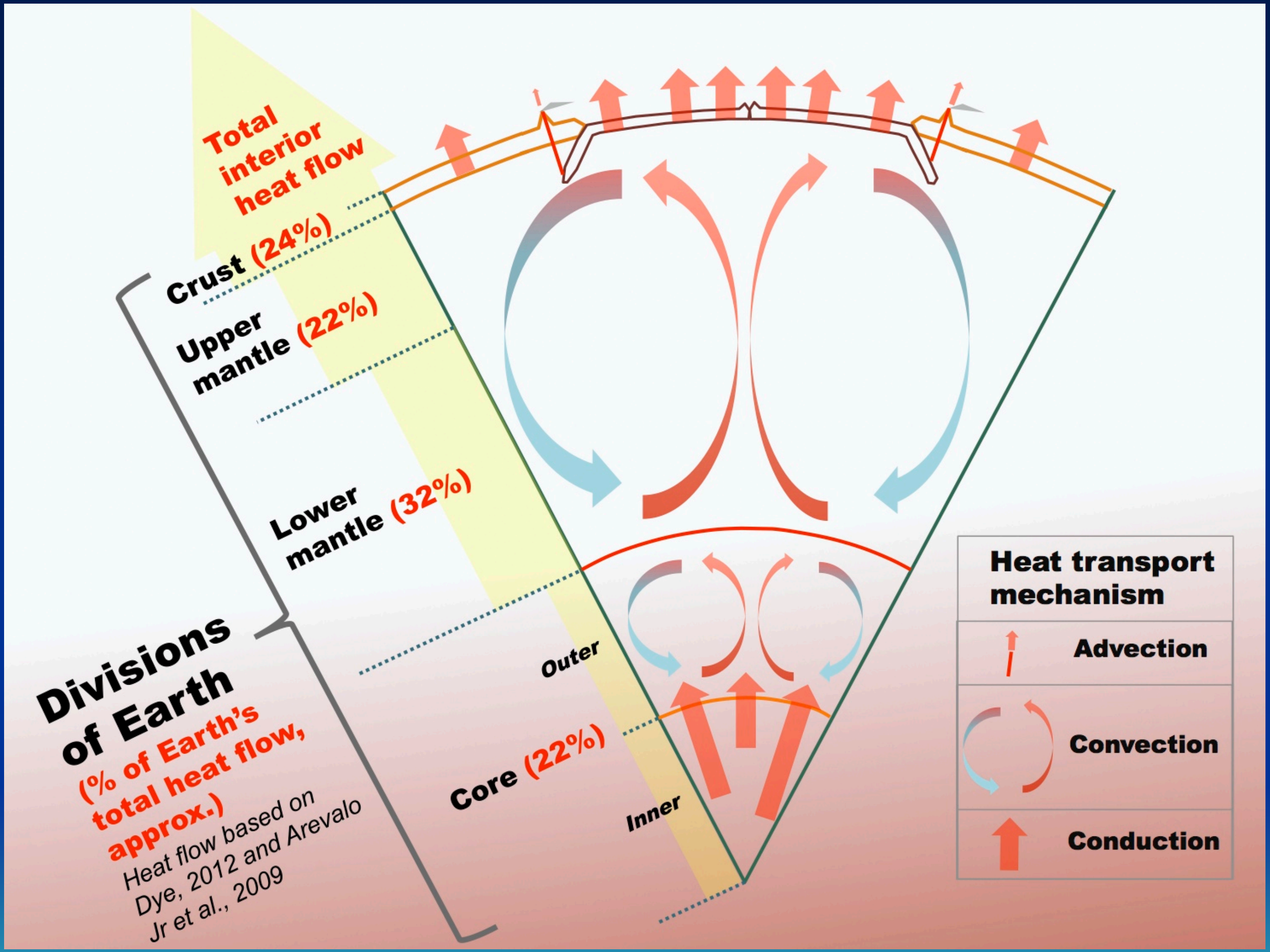
Mantle heat flux

Current heat flux at the Earth's surface is about 44 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 2 to 6 TW

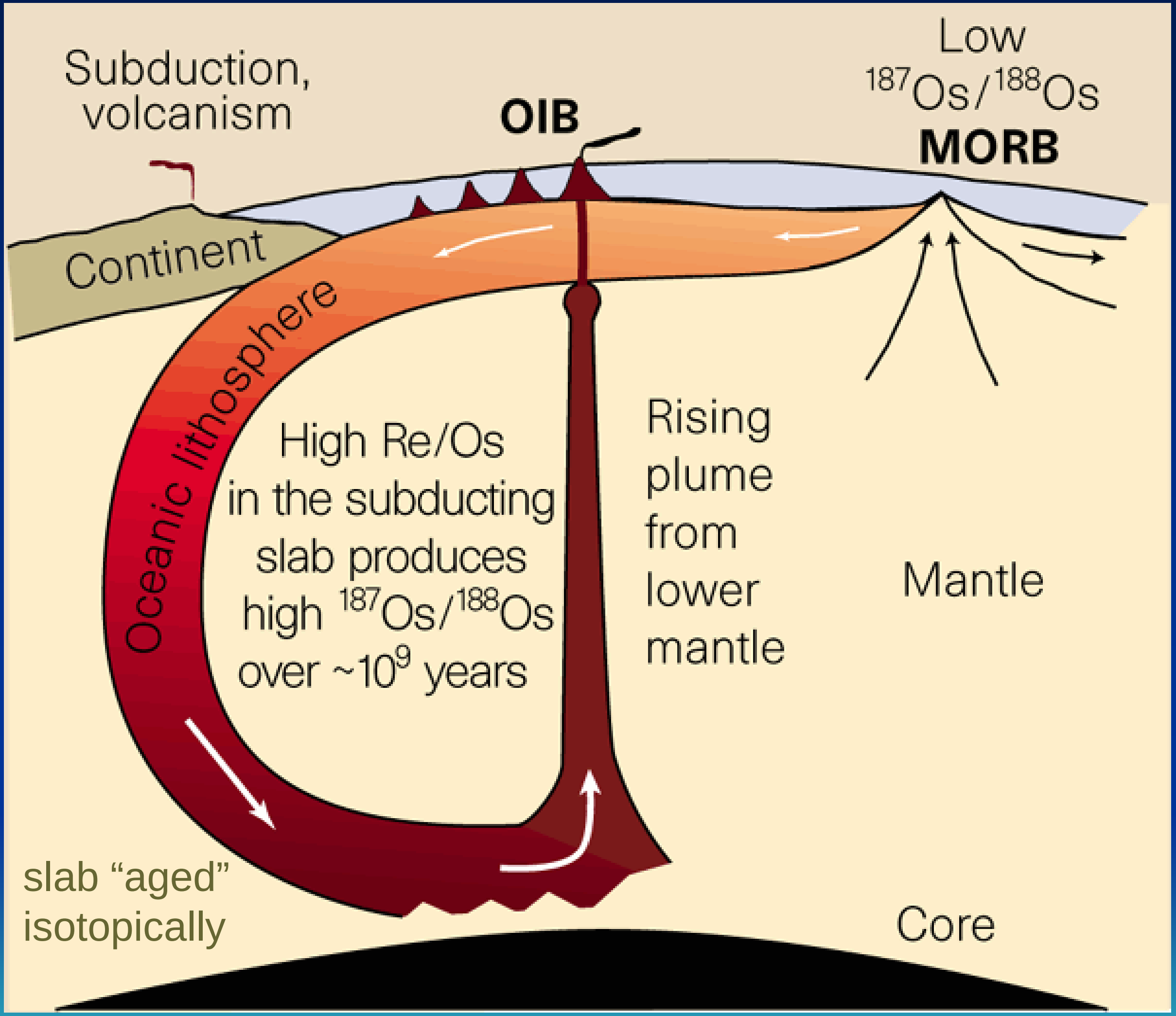
→ there is a lower layer enriched in the heat-producing elements (32 to 36 TW)

Mantle heat flux



Re-melting of ancient ocean floor

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



Halliday (1999) Nature 399

Mass balance calculation

Element	BSE (p.p.m.)	CC (p.p.m.)	DM (p.p.m.)	Fraction of mantle that is depleted
K	250	15800	85	0.50
U	0.02	1.4	0.0065	0.54
Th	0.08	5.6	0.0164	0.46

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

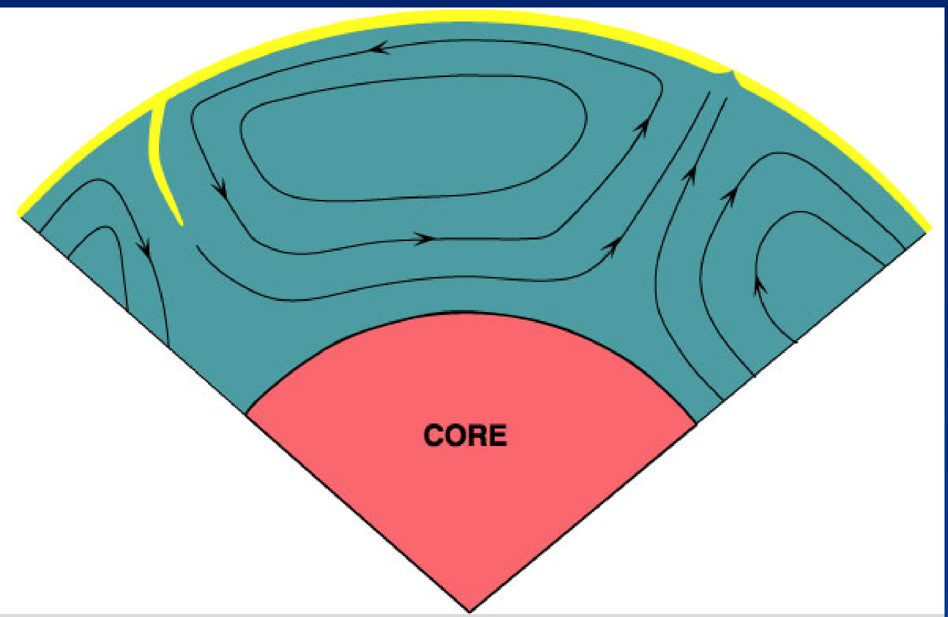
"layer cake" = distinctly chemically stratified

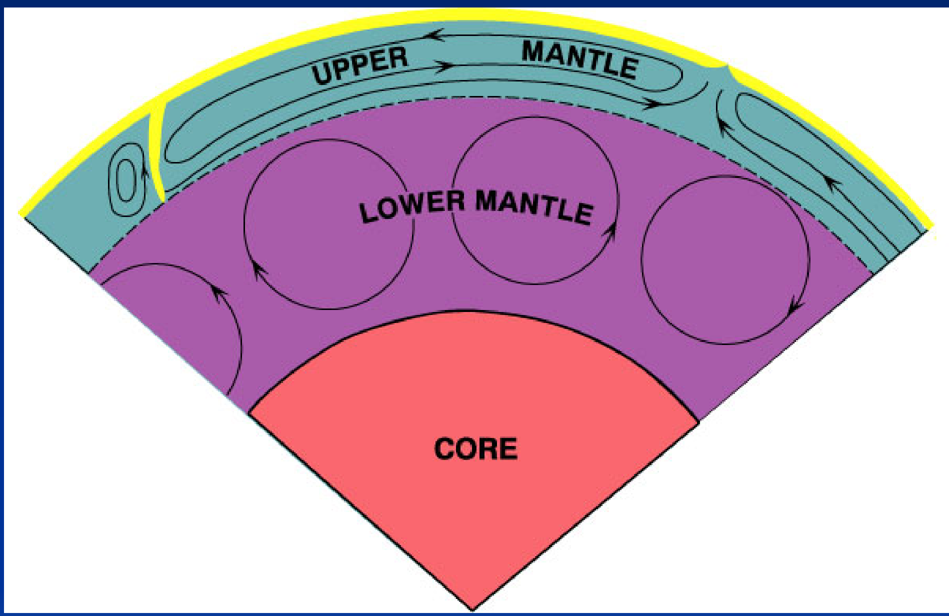
"plum pudding" = pudding with "plums" of chemically distinct source regions

Mantle models ("layer cake")

Upper depleted mantle = MORB source

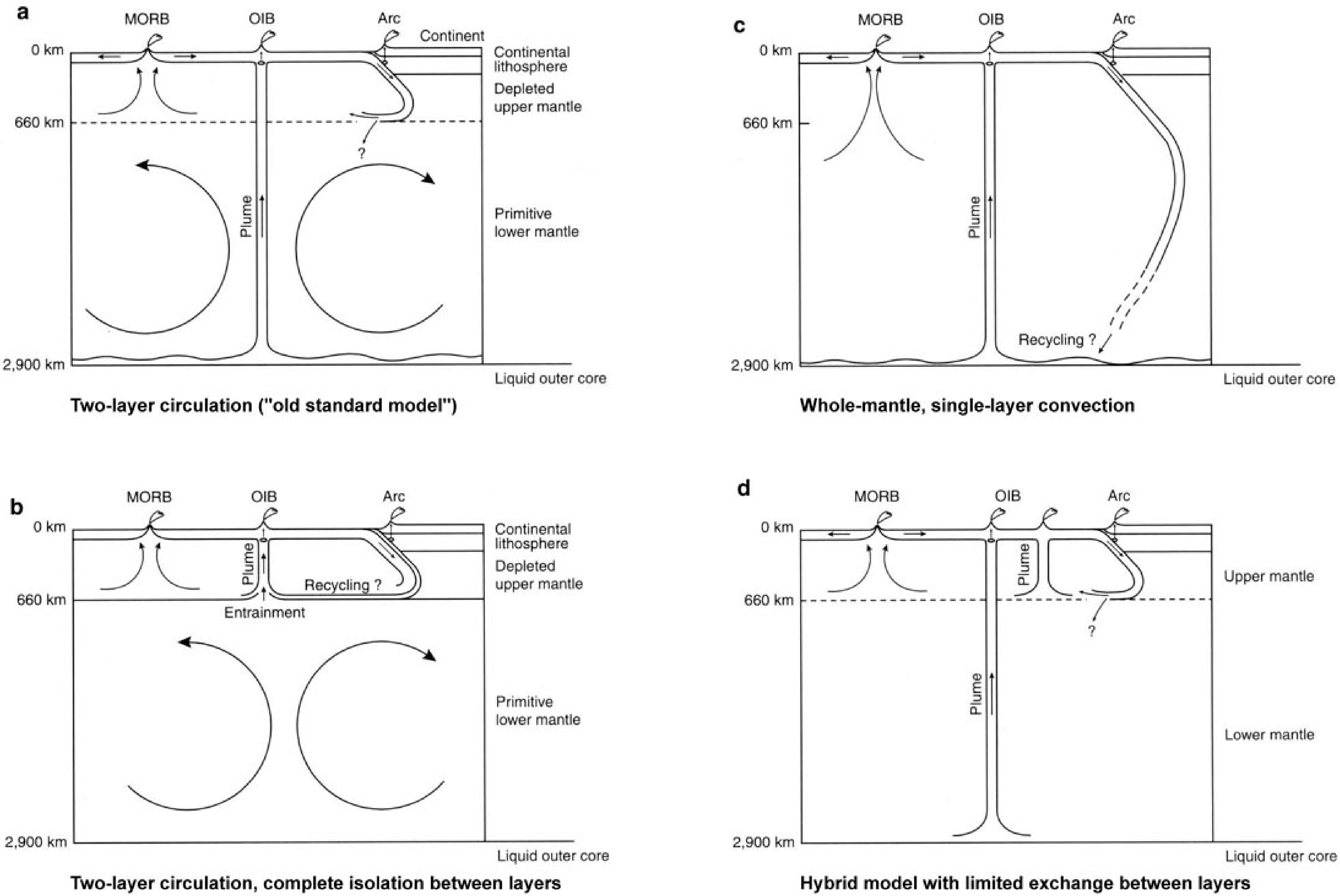
Lower undepleted & enriched OIB source



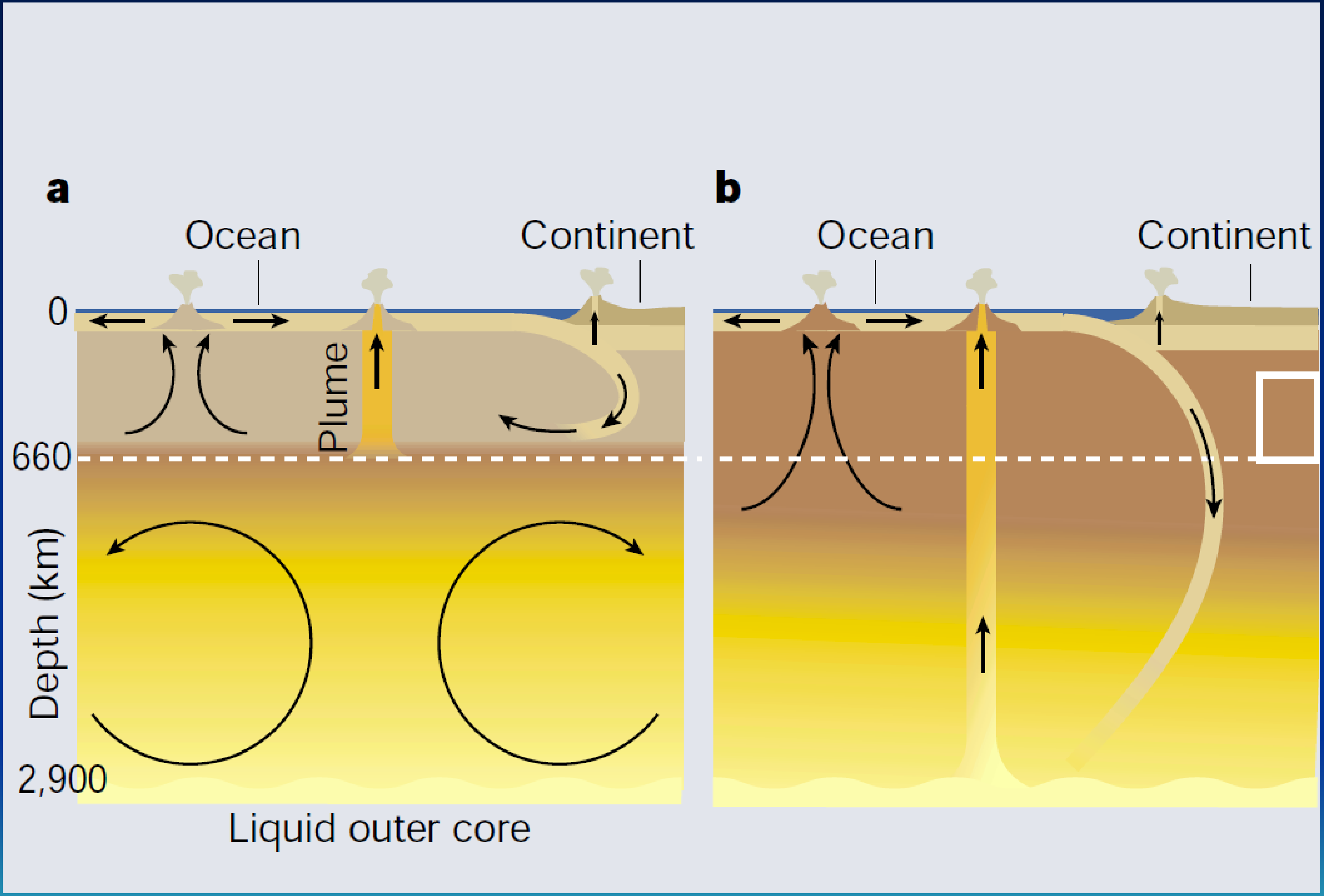


1982: Allègre *Chemical Geodynamics* (integrated study of chemical and physical structure and evolution of the solid Earth)

Models of mantle circulation (from Hofmann, Nature Vol. 385, 1997)



Mantle models ("layer cake")

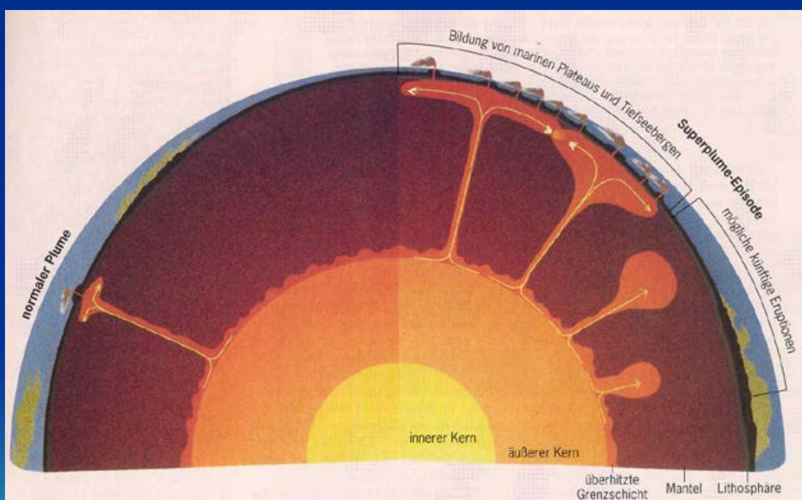


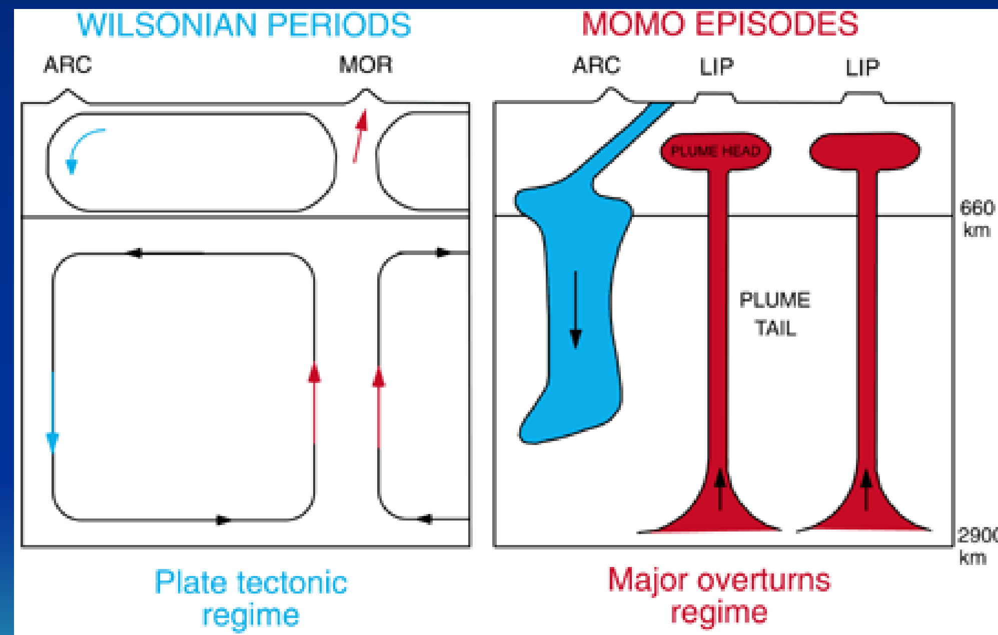
Hofmann (1997) Nature 385
Hofmann (2003) Nature 425

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

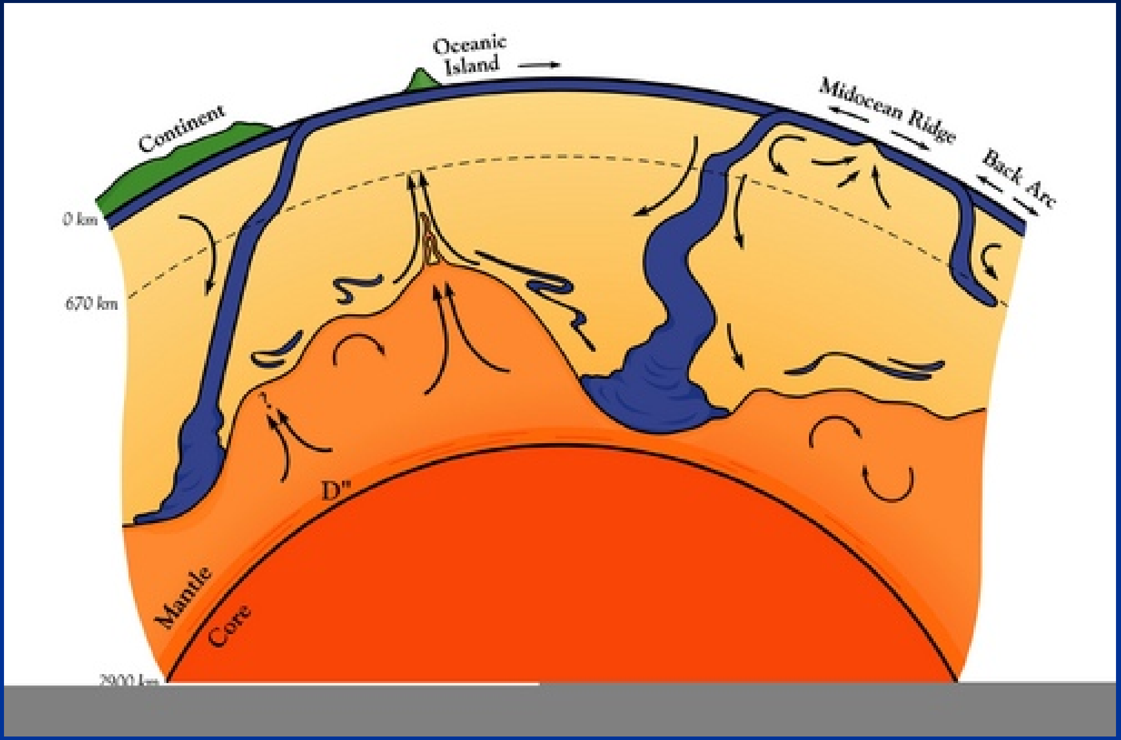




Mantle models ("layer cake")

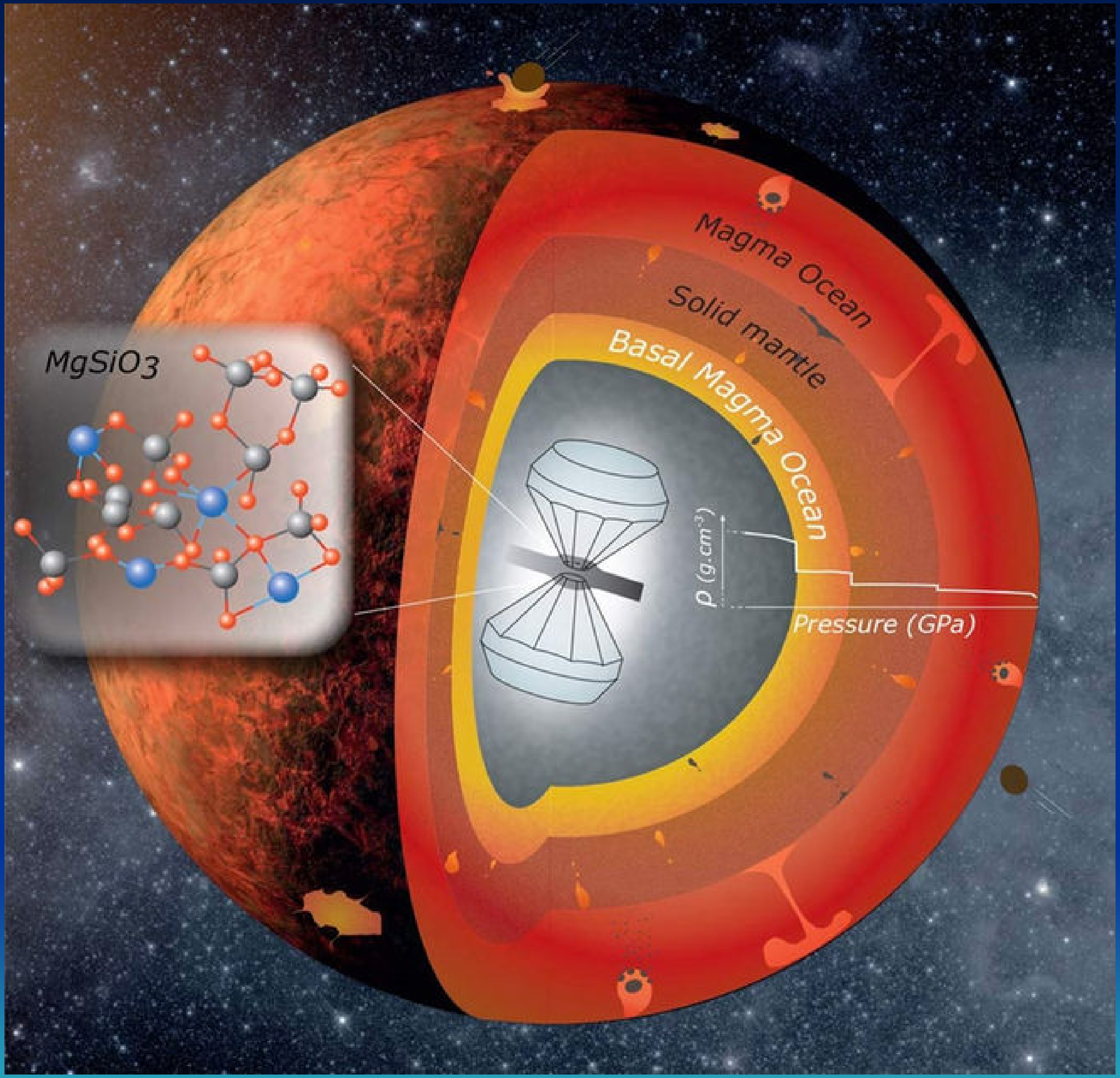
Lava-lamb model: Compositional stratification in the deep mantle

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 ("layer cake")



D'' model

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

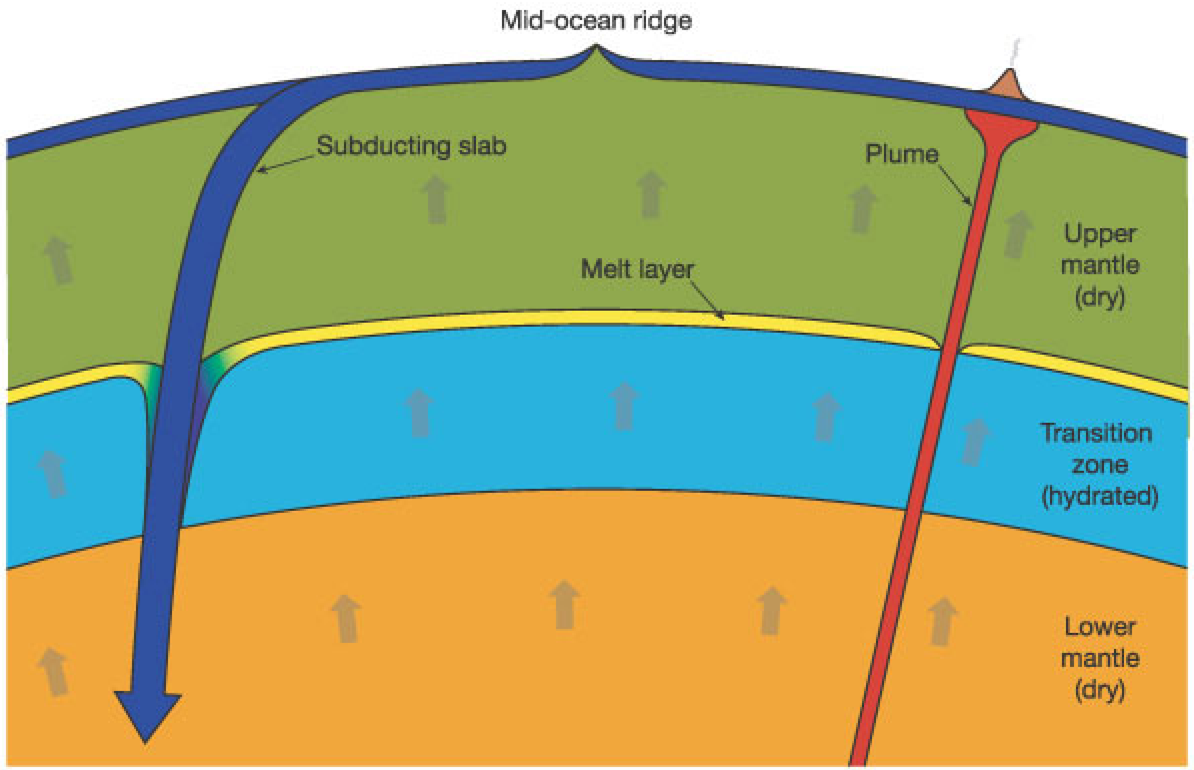
(Tolstikin & Hofmann 2005)
Petitgirard et al. (2015) PNAS

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)

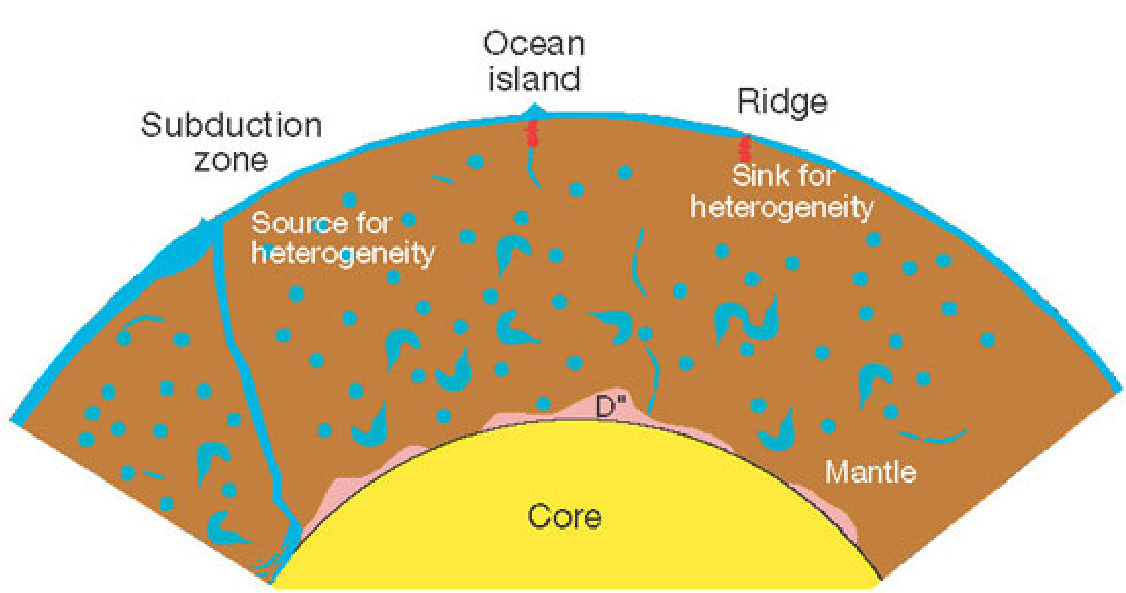
Transition-zone water filter model



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

Plum pudding model

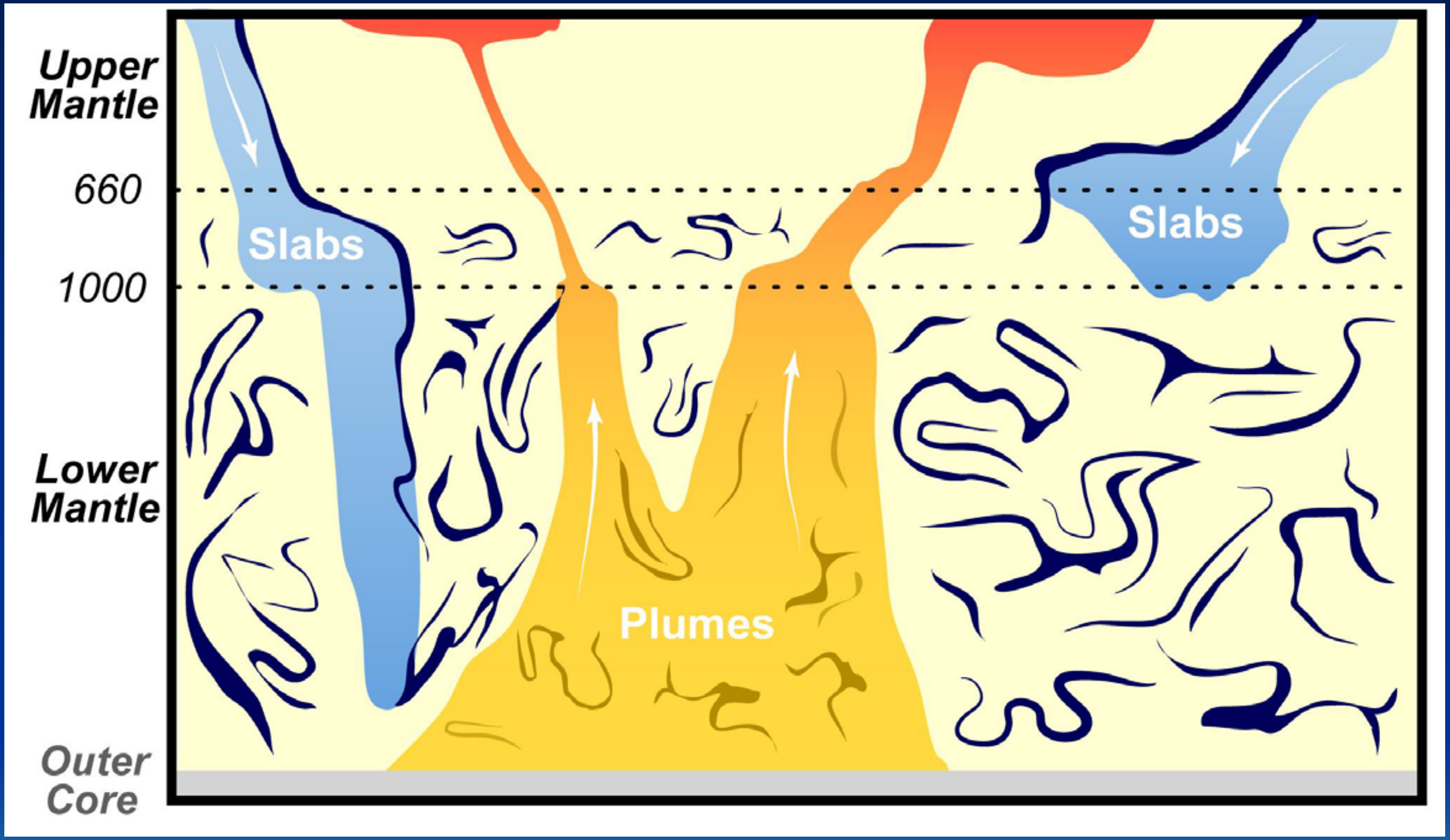
Model of a chemically **unstratified mantle**. Subduction of oceanic lithosphere introduces heterogeneity into the mantle. Mixing by **convective stirring** of the mantle disaggregates the subducted lithosphere and minor continental material, producing isolated heterogeneities that scatter seismic energy 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 or modern art?



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

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