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.

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

Galer & O'Nions (1985) Nature 316
Mantle isotope tetrahedron

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

Hart et al. (1992) Science 256
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)

Subducting Slab

Temperature

Pressure

Cold Warm

f1 f2

Plume

(660 km)

f1 f2

\[ \gamma \rightarrow P_v + P_c \text{ (660 km)}, \quad \text{Ilm} \rightarrow P_v \text{ (660 km)} \]

by Dan Shim
Mantle heat flux

Heat flow (TW)

based on Arevalo Jr et al., 2009

Total

40K

235U

238U

232Th

Heat flow (mW/m²)

- 23 - 45
- 45 - 55
- 55 - 65
- 65 - 75
- 75 - 85
- 85 - 95
- 95 - 150
- 150 - 450

4.5 Ga

present
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

Divisions of Earth (% of Earth's total heat flow, approx.)

Heat flow based on Dye, 2012 and Arevalo Jr et al., 2009

Heat transport mechanism
- Advection
- Convection
- Conduction
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 $^{187}\text{Os}/^{188}\text{Os}$ than the surrounding mantle.
Mass balance calculation

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.

<table>
<thead>
<tr>
<th>Element</th>
<th>BSE (p.p.m.)</th>
<th>CC (p.p.m.)</th>
<th>DM (p.p.m.)</th>
<th>Fraction of mantle that is depleted</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>250</td>
<td>15800</td>
<td>85</td>
<td>0.50</td>
</tr>
<tr>
<td>U</td>
<td>0.02</td>
<td>1.4</td>
<td>0.0065</td>
<td>0.54</td>
</tr>
<tr>
<td>Th</td>
<td>0.08</td>
<td>5.6</td>
<td>0.0164</td>
<td>0.46</td>
</tr>
</tbody>
</table>

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)

a) Two-layer circulation ("old standard model")
   - MORB, OIB, Arc
   - Continental lithosphere, Depleted upper mantle
   - Primitive lower mantle
   - Plume
   - 0 km, 660 km, 2,900 km
   - Liquid outer core

b) Two-layer circulation, complete isolation between layers
   - MORB, OIB, Arc
   - Continental lithosphere, Depleted upper mantle
   - Entrainment
   - Primitive lower mantle
   - 0 km, 660 km, 2,900 km
   - Liquid outer core

b) Whole-mantle, single-layer convection
   - MORB, OIB, Arc
   - Plume
   - Recycling?
   - 0 km, 660 km, 2,900 km
   - Liquid outer core

d) Hybrid model with limited exchange between layers
   - MORB, OIB, Arc
   - Plume
   - Upper mantle, Lower mantle
   - 0 km, 660 km, 2,900 km
   - Liquid outer core
Mantle models ("layer cake")

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
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
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)
The heterogeneities are remnants of recycled oceanic and continental crust.

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'.
Plum pudding or layered cake or modern art?

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


