Mantle mixing
Peter van Keken (Carnegie Institution for Science)

with participation from:
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Present day mantle structure
Geodynamical stability of lower mantle heterogeneity
Role of MORB recycling
Time integrated view from geochemistry
A case study (to inspire?)
Correlations exist between LLSVP and ULVZ (Garnero et al., 1998; Cottaar and Romanowicz, 2012).
Garnero & McNamara, Science, 2008
See also review by Tackley, ESR, 2012
Possible dynamical explanation: thermochemical piles kept in shape by past plate tectonic movement
LLSVP explanations

• Early earth differentiation (‘primordial’) – e.g., due to magma ocean differentiation (Labrosse et al., 2007; Carlson et al., 2014)

• Recycling (and mixing back in) of oceanic crust (Christensen and Hofmann, 1994; Brandenburg et al., 2008)

• Thermal only (Schubert et al., 2004; Davies et al., 2012).
Recycling of dense oceanic crust
Preservation of a ‘primordial’ layer

Li et al., 2014; see also, Li et al., 2015, 2016 (+pPv); Li and McNamara, 2013 (- MORB); Mulyukova et al., 2015; Nakagawa and Tackley, 2014; Ulvrova et al., 2012 (basal magma ocean)).
Various species in the mantle ‘zoo’

Hofmann, Treatise on Geochemistry, 2003; updated 2014

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Could Be</th>
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<tbody>
<tr>
<td>DMM</td>
<td>Depleted MORB Mantle</td>
<td>Upper mantle</td>
</tr>
<tr>
<td>HIMU</td>
<td>High original U/Pb (‘mu’)</td>
<td>Recycled oceanic crust</td>
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<tr>
<td>EM1</td>
<td>Enriched Mantle 1</td>
<td>Sediments / cont. crust?</td>
</tr>
<tr>
<td>EM2</td>
<td>Enriched Mantle 2</td>
<td>Sediments / cont. crust?</td>
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</tbody>
</table>
OIB (ocean island basalts) have biggest spread
MORB (mid-oceanic ridge basalts) cluster more but are not homogenous
Isotope ratios in oceanic basalts: Pb/Pb

Any process that increases U/Pb

Any process that decreases U/Pb

compiled from the PetDB Database http://www.petdb.org
Isotope ratios in oceanic basalts: Sr/Nd

Addition of sediment from continental crust compiled from the PetDB Database  http://www.petdb.org
Evidence of preservation of very old ‘primordial’ mantle

$^3$He

Hf-W (Rizo et al., 2016)

Sm-Nd (Boyet and Carlson, 2005)

Ne + Xe (Mukhopadhyay, 2012)
Constraints for mantle convection and mixing

Present day heat flow 44 TW (Pollack et al., 1993)

Present day plate velocities 4-5 cm/yr; ~30% toroidal (Lithgow-Bertelloni and Richards, 1998; Gordon, 2001; Bird, 2003)

LM is ~30x times more viscous than UM (Mitrovica and Forte, 2004; Lithgow-Bertelloni and Richards, 1998)

Slabs penetrate into lower mantle in some places (Grand, van der Hilst, Ritsema, many others)

50% of produced \(^{40}\text{Ar}\) in atmosphere

Earth has plate tectonics and has had it for a while
Brandenburg and van Keken, 2007, G-Cubed
Oceanic crust extraction and recycling; no CC formation
Oceanic crust extraction and recycling; one stage CC formation
Oceanic crust extraction and recycling; two stage CC formation: take into account fluid mobility of Pb, Rb, Nd after 2.3 Ga.
Geochemical Model: Extraction of the continental crust

Model predictions vs. Rudnick and Gao, 2003

Overall preferred model
30% of mantle has never seen melting
N&V for Chauvel et al., Nature Geoscience, 2008 indicating both oceanic crust and sediments are recycled through deep mantle

**GEODYNAMICS**

**The ups and downs of sediments**

Neither recycled oceanic crust nor sediments alone can explain the composition of ocean-island basalts, but how about a mixture of the two? Recent modelling using the isotopes of hafnium and neodymium appears to support this contention.

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For us, recycling involves great effort — sorting empty bottles, collecting old newspapers and taking the broken fridge to the recycling site. The Earth, however, can recycle its
Convert T and C to dVs using method from Cobden et al. (2008) based on Perple_X (Connolly et al., 2005), Stixrude & Lithgow-Bertelloni (2005), Khan et al. (2006).

Find tomographic expression as if modeled by S40RTS (Ritsema et al., 2011) model without excess eclogite density.
$T$ (0-3000 C)

$\text{dVs predicted}$

-5% to 5%

$\text{dVs recovered in S40RTS}$

-2.5% to 2.5%