Radiogenic Isotope and Deep Mantle Heterogeneity

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Reading materials:

How to Move Forward?
Need to Break some Boundaries ...

People who like Camping

Geochemists

Petrologists

Sedimentologists

Geochemists

Geophysicists

Geologists

Seismologists

Geodynamicists

Lab Rats

Thermal barrier

Computer Geeks

Experiments at 1 atm, 298 K

Catherine Armstrong
Makapu‘u - Hawai‘i
Enriched component

Nicole Williamson
Kaua‘i
1st island, 5 Ma and when many things change

Lauren Harrison
NWHR: Modeling, Mantle Geodynamics

NWHR
~47 - 6.5 Ma

Intermittent Loa
Kea

Hawaiian Islands
~6.5 - 0 Ma

Emperor Seamounts
~82 - 47 Ma

Kea

KeaLoa

Hawaiian Plume Formation

B

C

D

E

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Chart of the Nuclides: $^A_X$ or $^Z_XN$
Chart of the Nuclides
Low Masses
Chart of the Nuclides: Intermediate Masses

Half life
- Very short
- > 100,000 yr
- > 10 yr
- > 100 days
- > 10 days
- > 1 day
- > 1 hr
- > 1 min.
### High Masses

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</table>
Radioactive Decay Schemes

Note: important diagram for understanding radioactive decay!
Radioactive Decay

Law of Radioactive Decay:

\[- \frac{dN}{dt} \propto N \quad \text{or} \quad - \frac{dN}{dt} = \lambda N\]

The rate of decay of an unstable parent atom (N) at any time (t) is proportional to the number of parent atoms existing at that time.

Rearranging and integrating:

\[
\frac{N}{N_0} = e^{-\lambda t}
\]

where \(N_0\) is the original number of atoms of the radioactive nuclide, and \(N\) is the number after some time (t).

**Half-life (\(T_{1/2}\)) = the time required for half of the unstable atoms to decay**

\[
T_{1/2} = \ln 2/\lambda = 0.693/\lambda
\]
General equation:

\[
\frac{d}{d't} = \frac{d}{d't} \cdot 0 + \frac{P}{d't} \cdot (e^{\lambda t} - 1)
\]

\[
P = \frac{P_0}{2}
\]

After one half-life \(T\):

\[
P_0, D_0
\]

After two half-lives \(2T\):

\[
D_0 = 0
\]

Diagram:

- Parent
  - \(T = 0\)
  - \(P_0\)

- Daughter
  - \(D_0\)
General equation: \( \frac{D}{D'}_t = \frac{D}{D'}_0 + \left(\frac{P}{D'}\right) (e^{\lambda t} - 1) \)

Why Ratios? A mass spec measures isotopic ratios rather than absolute abundances.
The Isochron Equation

The equation \((D/D')_t = (D/D')_0 + (P/D') (e^{\lambda t} - 1)\) is the isochron equation.

In a plot of \(X = P/D'\) and \(Y = D/D'\), a set of geologic materials of the same age \(T\) and the same initial isotope ratio \((D/D')_0\) will lie on a straight line of slope \(e^{\lambda t} - 1\).

The \(P/D'\) ratio is usually referred to as the parent/daughter ratio.

This type of plot is called an Isochron plot!
The Isochron Equation: Rb-Sr

Example: in the Rb-Sr system, where \( P = ^{87}\text{Rb} \) and \( D = ^{87}\text{Sr} \), and \( D' = ^{86}\text{Sr} \)

\[
\left( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_t = \left( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_0 + \left( \frac{^{87}\text{Rb}}{^{86}\text{Sr}} \right)_t (e^{\lambda^{87}\text{Rbt}} - 1)
\]

This is the equation of a straight line, where:

\[
X = \left( \frac{^{87}\text{Rb}}{^{86}\text{Sr}} \right)_t
\]

\[
Y = \left( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_t
\]

Slope \( m = (e^{\lambda^{87}\text{Rbt}} - 1) \)

intercept \( y_0 = \left( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_t \)
**Rb-Sr Isochron**

*Plotted:* the isotopic compositions of 6 samples with variable Rb/Sr that formed from the same identical source – variable Rb/Sr, but constant $^{87}\text{Sr}/^{86}\text{Sr}$ at time-zero (before radioactive decay).

At $T=0$
Homogeneous source
i.e. initial ratio
Rb-Sr Isochron

\[(\frac{^{87}\text{Sr}}{^{86}\text{Sr}})_t = (\frac{^{87}\text{Sr}}{^{86}\text{Sr}})_0 + (\frac{^{87}\text{Rb}}{^{86}\text{Sr}})_t \left( e^{\lambda^{87}\text{Rb}t-1} \right) \]

At \( T = \tau \)

\(^{87}\text{Sr}/^{86}\text{Sr}\) ratios of the samples have grown by decay of \(^{87}\text{Rb}\) into \(^{87}\text{Sr}\)
Left Diagram: cats and dogs interact vigorously affecting site occupation (tree or yard). Just like two elements with different chemical properties, they arrange themselves so as to achieve the most stable configuration (e.g. Sr partitions strongly into feldspar relative to silicate melt).

Right Diagram: white cats and black cats have very similar properties and like isotopes of the same element are arranged randomly among the available sites. The most likely arrangement is an identical proportion of isotopes in each site (e.g. the initial ratio of $^{87}$Sr to $^{86}$Sr is the same in a feldspar and in the silicate magma from which it crystallizes, irrespective of concentration differences).
Unstable Nuclides

Range of measured half-lives ($t_{1/2}$) is $10^{15}$ to $10^{-12}$ seconds (range of $10^{35}$).

Terminology for Ages:

Absolute Age = Ka, Ma, Ga (an event thousands, millions, billions of years ago)

Relative Age = kyr, myr, gyr (an interval of thousands, millions, billions of years)
# Radioactive Decay Systems of Geochemical Interest

<table>
<thead>
<tr>
<th>Parent</th>
<th>Decay Mode</th>
<th>$\lambda$</th>
<th>Half-life</th>
<th>Daughter</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>$\beta^+,$ e.c., $\beta^-$</td>
<td>$5.543 \times 10^{-10} \text{ yr}^{-1}$</td>
<td>$1.28 \times 10^9 \text{ yr}$</td>
<td>$^{40}$Ar, $^{40}$Ca</td>
<td>$^{40}$Ar/$^{36}$Ar</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>$\beta^-$</td>
<td>$1.42 \times 10^{-11} \text{ yr}^{-1}$</td>
<td>$4.8 \times 10^{10} \text{ yr}$</td>
<td>$^{87}$Sr</td>
<td>$^{87}$Sr/$^{86}$Sr</td>
</tr>
<tr>
<td>$^{138}$La</td>
<td>$\beta^-$</td>
<td>$2.67 \times 10^{-12} \text{ yr}^{-1}$</td>
<td>$2.59 \times 10^{11} \text{ yr}$</td>
<td>$^{138}$Ce</td>
<td>$^{138}$Ce/$^{142}$Ce, $^{138}$Ce/$^{136}$Ce,</td>
</tr>
<tr>
<td>$^{147}$Sm</td>
<td>$\alpha$</td>
<td>$6.54 \times 10^{-12} \text{ yr}^{-1}$</td>
<td>$1.06 \times 10^{11} \text{ yr}$</td>
<td>$^{143}$Nd</td>
<td>$^{143}$Nd/$^{144}$Nd</td>
</tr>
<tr>
<td>$^{176}$Lu</td>
<td>$\beta^-$</td>
<td>$1.93-1.86 \times 10^{-11} \text{ yr}^{-1}$</td>
<td>$3.57 \times 10^{10} \text{ yr}$</td>
<td>$^{176}$Hf</td>
<td>$^{176}$Hf/$^{177}$Hf</td>
</tr>
<tr>
<td>$^{187}$Re</td>
<td>$\beta^-$</td>
<td>$1.64 \times 10^{-11} \text{ yr}^{-1}$</td>
<td>$4.23 \times 10^{10} \text{ yr}$</td>
<td>$^{187}$Os</td>
<td>$^{187}$Os/$^{186}$Os, $^{187}$Os/$^{188}$Os</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$\alpha$</td>
<td>$4.948 \times 10^{-11} \text{ yr}^{-1}$</td>
<td>$1.4 \times 10^{10} \text{ yr}$</td>
<td>$^{208}$Pb, $^4$He</td>
<td>$^{208}$Pb/$^{204}$Pb, $^3$He/$^4$He</td>
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<tr>
<td>$^{235}$U</td>
<td>$\alpha$</td>
<td>$9.849 \times 10^{-10} \text{ yr}^{-1}$</td>
<td>$7.07 \times 10^8 \text{ yr}$</td>
<td>$^{207}$Pb, $^4$He</td>
<td>$^{207}$Pb/$^{204}$Pb, $^3$He/$^4$He</td>
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<tr>
<td>$^{238}$U</td>
<td>$\alpha$</td>
<td>$1.551 \times 10^{-10} \text{ yr}^{-1}$</td>
<td>$4.47 \times 10^9 \text{ yr}$</td>
<td>$^{206}$Pb, $^4$He</td>
<td>$^{206}$Pb/$^{204}$Pb, $^3$He/$^4$He</td>
</tr>
</tbody>
</table>
Abundance of isotope

**Time**
- **Start of nucleosynthesis**
- **End of nucleosynthesis or collapse of solar nebula**
- **Present day**

- **Stable isotope**
  - Constant production rate

- **Long-lived radioactive isotope** $T_{1/2} > 10^8$
  - Always in low abundance

- **Short-lived extinct radioactive isotope** $T_{1/2} < 10^8$

**Timescales for Planetary Processes**
Figure 2.1. Periodic Table showing the elements having naturally occurring radioactive isotopes and the elements produced by their decay.

White, fig. 2.1
Fingerprinting

Potential use of metal isotopic compositions to trace the source of various materials

★ **Isotopes:** same Z, different N, i.e. same chemical properties - slight mass differences.

★ **Use of radiogenic isotopes** (e.g., Pb), where the isotopic composition reflects the origin of the sample or source = **fingerprinting**.

★ **or stable isotopes**, where equilibrium and non-equilibrium (kinetic) isotopic fractionation (mass-dependent) of elements results from physical (e.g., evaporation, diffusion), chemical (e.g., adsorption, redox reaction, crystallization) and biological (e.g., nutrient uptake) processes. The isotopic composition reflects the source (**isotopic baseline**) plus any isotopic fractionation (**process identification**).
The Extent of Isotopic Variability for an Element Decreases with Increasing Atomic Number, for $\Delta m=1$

($\Delta m$: mass difference for the isotope pair $m$:average mass of the element’s isotopes)
Hazardous Air Pollutants: Sb, Cd, Cr, Hg, Pb, Ni, Se
Priority Pollutants: Sb, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Tl, Zn
Primordial Nucleosynthesis

Galactic Cosmic Rays

Helium burning

Carbon-Neon burning

Oxygen burning

Nuclear Statistical Equilibrium
(if the star collapses, more energy is released: supernova)

Neutron captures
(s- or r-process)
Binding Energy per Nucleon vs. Mass Number

– Controlled by the balance between the strong nuclear attractive force (holding nuclei together) vs. the electromagnetic force (repulsion of positively charged protons within the nucleus)

$^{56}\text{Fe}$ is the most stable nucleus!
Abundance of the Elements in BSE
Earth’s Structure

Mantle

2883 km thick
84% volume of the Earth

Crust
Continental crust (granitic)
Oceanic crust (basaltic)
Kola Superdeep Borehole (KSDB) - IGCP 408: "Rocks and Minerals at Great Depths and on the Surface"

Description

The Kola Superdeep Borehole (KSDB-3) reached a final depth of 12,261 m. It was drilled since the seventies in the framework of the programme "Investigation of the continental crust by means of deep drilling" of the former USSR.

The main results of the technical experience gained from this record-deep drilling, of the investigation of the cores and the geophysical logging were presented and discussed at several international congresses and conferences, including the 27th International Geological Congress held in Moscow (1986), and have been published in numerous papers and books. Of these, the following are the best known to the international community of geologists:


A third monograph - Mirofanov, P.P. (Ed.), 1991. Archean Complex in the Section of the KSDB-3. Apatity, Kola Science Centre RAS, presents a discussion of the structure and composition of the Archean complex cut by the Kola Super-Deep Well in the interval of 6.84-12.26 km. For the first time a detailed study of the granite-diorite and the isotope composition of noble gases has been carried out. The description and classification of amphibole-bearing rocks, ore mineralization, mafic silicates, and the knowledge on rock mechanical properties have been significantly extended. Geochronological data and information pertaining to the distribution and composition of water/rock gases and inclusions in the section have been systematized.

The main borehole (and several complementary ones) intersected the entire sedimentary-volcanic sequence of the Lower Proterozoic Pechenga Formation (6-8,842 m) and a considerable part (6,842 - 12,261 m) of the Archean granitic-metamorphic complex of the basement (gneisses, amphibolites, migmatites and granitoids).
The $1 billion mission to reach the Earth's mantle

By Tom Levitt, for CNN

October 2, 2012 — Updated 10:54 GMT (02:54 HKT)

A team of international scientists are planning to drill into the Earth's mantle in an attempt to answer questions about the origins and evolution of life. The drill will need to get through around 6 km of oceanic crust to reach the mantle.

Mission impossible?
The $1 billion mission to reach Earth's mantle

By Tom LeVit, for CNN

October 22, 2012 – Updated 1954 GMT (2254 HKT)

Mission impossible?

A team of international scientists are planning to drill into the Earth’s mantle in an attempt to answer questions about the origin and evolution of life. The drill will need to get through around 6 km of oceanic crust to reach the mantle.

A limited lifespan

A new research body at Arizona State University is bridging the gap between the lab and the most provocative inventions of the sci-fi genre.

Scientists to simulate human brain

It sounds like a sci-fi nightmare, but scientists working on the Human Brain Project hope to improve our understanding of diseases of the mind.

Alien research key to our own survival

Astrobiologist Charles Cockell says searching for signs of alien life on Earth and in space will help us solve our environmental challenges.
Age of the Oceanic Crust

Message from the Mantle: MORB geochemistry

Dark red = zero-age; dark blue = 180-200 million years before present
Framework: elements/isotopes – data - source/model

DM is not directly accessible, so its composition has to be inferred via constraints derived from rocks whose composition and origin are related to the DM.

1. Use parent-daughter ratios
2. Using TE ratios and patterns in MORB
3. Composition of peridotites (compatible elements), chondritic meteorites and continental crust.

The genealogy shows how Salters and Stracke derived the estimates for the individual elements and the inter-relationships between those estimates.

The estimates will be more accurate the closer the relation between the source of information and the DM.

MORB (melting products) and peridotites (residues) are directly related by partial melting. Isotopic compositions of MORB = isotopic composition of source, i.e. the DM. The calculated P/D ratios form the framework for the estimates for other TE ratios.

TE ratios of highly incompatible elements are not fractionated, so they are the same than in the source.
MORB & Initial Isotopic Ratios: Source

\[ \frac{\text{Sr}}{86\text{Sr}}_t = \frac{\text{Sr}}{86\text{Sr}}_0 + \left( \frac{\text{Rb}}{86\text{Sr}} \right)_t e^{\lambda_87\text{Rb}(t-1)} \]

The isochron equation above shows that the \( \frac{\text{Sr}}{86\text{Sr}} \) ratio in a given system depends on:

- the \( \frac{\text{Sr}}{86\text{Sr}} \) at time \( t=0 \).
- the \( \frac{\text{Rb}}{86\text{Sr}} \) ratio of the system (in most cases, directly proportional to Rb/Sr)
- the time elapsed since \( t=0 \)
- The decay constant (lambda) of \( \text{Rb} \)

**MORB: \( t=0 \)**

\[ \frac{\text{Sr}}{86\text{Sr}}_t = \frac{\text{Sr}}{86\text{Sr}}_0 \]

\[ \frac{\text{Nd}}{144\text{Nd}}_t = \frac{\text{Nd}}{144\text{Nd}}_0 \]

and same for Pb, Hf, etc.

The measured isotopic ratios of MORB samples do not have to be corrected for the presence of radiogenic daughter isotopes!
Depleted MORB Isotope Geochemistry

MORB samples the upper mantle, which is “depleted” in incompatible elements:

- MORB has low Rb/Sr compared to continental crust = unradiogenic $^{87}\text{Sr}/^{86}\text{Sr}$.
- MORB has high Sm/Nd compared to continental crust = radiogenic $^{143}\text{Nd}/^{144}\text{Nd}$.
- Depleted MORB and its source, depleted mantle (DM or DMM), have low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{143}\text{Nd}/^{144}\text{Nd}$ (or $\varepsilon_{\text{Nd}}$) values relative to all other reservoirs in the Earth.

Relative differences in parent-daughter concentrations of major isotopic systems in different reservoirs
MORB from the Indian Ocean is distinctly higher in $^{87}\text{Sr}/^{86}\text{Sr}$ and lower in $\varepsilon_{\text{Nd}}$ than MORB from the Pacific and Atlantic ocean basins.
MORB & Pb Isotopes

Pb isotopic compositions are expressed as ratios of the radiogenic daughter isotopes ($^{206}\text{Pb}$, $^{207}\text{Pb}$, $^{208}\text{Pb}$) to the stable isotope of Pb ($^{204}\text{Pb}$):

- Note that these diagrams have a common denominator on both axes ($^{204}\text{Pb}$), thus linear relationships may represent either isochrons or mixing.

Observations*:

- There is no single Pb isotope composition of MORB.
- MORB are relatively unradiogenic in Pb compared to most other reservoirs (more on this later), therefore MORB mantle has relatively low U/Pb and Th/Pb.
- Indian MORB are shifted to higher $^{208}\text{Pb}/^{204}\text{Pb}$ for a given $^{206}\text{Pb}/^{204}\text{Pb}$ value (implies a distinct Th/U ratio of Indian Ocean mantle).

*Compare with OIB isotope variations in lectures to come.
Message from the Mantle: OIB geochemistry

Head = Large Igneous Province (LIP)

Tail = Ocean Island Basalt (OIB)
Continental flood basalts/volcanic rifted margins

Oceanic flood basalts

adapted from Coffin et al. (2006)
*Goodliffe & Martinez (1997)
Rising plumes of hot, solid material migrate through the Earth’s mantle; where the head of the plume reaches the base of the lithosphere, partial melting begins to form basaltic magma that rises to the surface to form a LIP.

**NAVP** = North Atlantic Volcanic Province
**CRFB** = Columbia River Flood Basalts

Modified from Coffin & Eldholm 1994
Assuming 5% and 30% partial melting, and knowing the volume of the following LIPs, calculate the volume of the mantle sampled to form this giant field of lavas:

Ontong-Java: $36 \times 10^6$ km$^3$

Kerguelen: $20 \times 10^6$ km$^3$

OJP and KP have about the same surface area but OJP is significantly thicker.

Columbia River basalts:
$1.3 \times 10^6$ km$^3$

The volume of a sphere is:

$$V = \frac{4}{3}\pi r^3$$

What is the minimum depth sampled?

$\Pi = 3.142$
## Volume of Mantle Sampled to Form LIPs

<table>
<thead>
<tr>
<th>LIP</th>
<th>Volume mantle 5, 30% partial melt</th>
<th>Radius (km)</th>
<th>Diameter (km)</th>
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<tbody>
<tr>
<td>OJP</td>
<td>3.60 $10^7$</td>
<td>7.20 $10^8$</td>
<td>556 1112</td>
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<tr>
<td></td>
<td>1.20 $10^8$</td>
<td>1.20 306</td>
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<td>Ker</td>
<td>2.00 $10^7$</td>
<td>4.00 $10^8$</td>
<td>457 914</td>
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<td>6.67 252</td>
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<td>2.60 $10^7$</td>
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<td>4.33 $10^6$</td>
<td>4.33 101</td>
<td>202</td>
</tr>
</tbody>
</table>

Minimum and maximum “spherical” diameters of mantle melting required for 5 LIPs assuming 5% (large circle) and 30% (small circle) partial melting.

NAVPS = North Atlantic Volcanic Province
CRFB = Columbia River Flood Basalts

Modified from Coffin & Eldholm 1994
Oceanic Islands tell us much about the chemistry of the Earth’s Mantle

“The islands of the deep oceans have geological importance out of all proportion to their individual areas or their total area, when compared with equal areas of the continents. Small as it is, a deep-sea island tells us practically all we shall ever directly ascertain concerning the nature of the solid suboceanic material throughout a much more extensive region.”

R.A. Daly
The Geology of Ascension Island
American Academy of Arts and Sciences Proceedings 60:1-80 (+21 plates), 1925
OIB Source Components: Hawai‘i and Kerguelen both have EM-I characteristics

“fingerprinting mantle sources”
Lavas as Probes of the Mantle’s Composition

Radiogenic isotopes (e.g., $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$) and some trace element ratios are not changed between solid and melt.

$^{87}\text{Sr}/^{86}\text{Sr}$ solid mantle (peridotite) = $^{87}\text{Sr}/^{86}\text{Sr}$ melt (basalt)
Geophysical Imaging of Mantle Plumes at Depth

Subducted components (sediment, oceanic crust, oceanic lithosphere) injected into the lower mantle have the potential to be sampled by mantle plumes.
Isotopic ratios are time-integrated signatures

"fingerprinting mantle sources"
Mantle Components & Reservoirs

Certain oceanic islands or groups of islands are characterized by specific isotopic compositions and can be used to “map” a series of distinct mantle components or reservoirs, which may be identifiable separate volumes in the mantle or extremes of a continuum of compositions:

- **DMM** = depleted MORB mantle, the continuously depleted upper mantle reservoir, source of mid-ocean ridge basalts.
- **EM-1** = enriched mantle 1, mantle that reflects addition of crustal materials, either recycling of delaminated subcontinental lithospheric mantle, or recycling of subducted ancient pelagic sediment.
- **EM-2** = enriched mantle 2, mantle that reflects addition of recycled oceanic crust.
- **HIMU** = high $\mu$, where $\mu = U/Pb$ (and Th/Pb), reflecting recycling of “enriched” oceanic lithosphere that has been infiltrated by low-degree partial melts.
- A common mantle component variously referred to as:
  - PREMA = prevalent mantle
  - C = “common” component
  - FOZO = focal zone
Mixing different sources of mantle heterogeneity creates different “flavors” of OIBs.

Mixing different components in various proportions results in the variability in composition we observe in global OIBs.
We can model the mixing of melts with different concentrations and isotopic compositions using a simple equation:

\[
\begin{align*}
(87\text{Sr}/86\text{Sr})_1 & = x(87\text{Sr}/86\text{Sr})_1 + (1-x)(87\text{Sr}/86\text{Sr})_2 \\
\end{align*}
\]

where:
- \(x\) = weight fraction of component 1 or 2
- 1 and 2 = two components being mixed

Weighed mean: intermediate in composition between \((87\text{Sr}/86\text{Sr})_1\) & \((87\text{Sr}/86\text{Sr})_2\).
Oceanic Islands, Mantle Plumes and Mantle End-Members

Step 1: solid-state mixing of two EM components

Step 2: solid-state mixing of EM with PREMA component

Step 3: solid-state mixing with DM and subsequent melting of (PREMA-EM-DM)

Stracke, 2012
Mixing can happen in steps. Mixing is more likely to occur when materials melt and are collected in a common magmatic system rather than through solid-state mechanical mixing of the mantle (very slow process).
Subducting Slabs & Recycling

- Down-going subducted oceanic lithosphere can be traced by seismic tomography using P- and S-wave variations.

- Subducted material: peridotites, harzburgites, gabbros, tholeiitic and alkali basalts, terrigenous and pelagic sediments, and lower crustal metamorphic rocks.

### Recycled Material Mass Balance

**Sediment** – 0.3-0.7 km³/year subducts

In 3 Ga that’s equal to subducting 1/3 of the modern continents

**Oceanic Crust** – 20 km³/year subducts

In 3 Ga that’s equal to ~60 billion km³, which is 5% of the mantle’s mass
Recycling Hypothesis

1) Oceanic plates (crust and sediment) enter into the mantle at subduction zones,
2) They are returned to the surface in mantle upwellings - plumes.
3) Crust and sediment are melted beneath hotspots.

Rivers contribute >85% of ocean floor sediment
Recycling Hypothesis

1) Oceanic plates (crust and sediment) enter into the mantle at subduction zones,
2) They are returned to the surface in mantle upwellings - plumes.
3) Crust and sediment are melted beneath hotspots.
Dynamic Models and Mantle Heterogeneity

Dynamic model of the mantle compositional heterogeneity after 4.65 Ga of mixing:

– Variable mixing of recycled and primordial materials

– Most of the mantle is depleted in composition, i.e. has been partially melted

Ballmer et al., 2015