Isotope Geochemistry

- Isotopes do not fractionate during partial melting or fractional crystallization processes. So they will reflect the characteristics of the mantle source.

- OIBs, which sample a great expanse of oceanic mantle in places where crustal contamination is minimal, provide incomparable evidence for the nature of the mantle.
Isotopes used as tracers in mantle geochemistry

<table>
<thead>
<tr>
<th>Parent nuclide</th>
<th>Daughter nuclide</th>
<th>Tracer ratio (radiogenic/nonradiogenic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{87}\text{Rb}$</td>
<td>$^{87}\text{Sr}$</td>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$</td>
</tr>
<tr>
<td>$^{147}\text{Sm}$</td>
<td>$^{143}\text{Nd}$</td>
<td>$^{143}\text{Nd}/^{144}\text{Nd}$</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>$^{207}\text{Pb}$</td>
<td>$^{207}\text{Pb}/^{204}\text{Pb}$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$^{206}\text{Pb}$</td>
<td>$^{206}\text{Pb}/^{204}\text{Pb}$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{208}\text{Pb}$</td>
<td>$^{208}\text{Pb}/^{204}\text{Pb}$</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$^{40}\text{Ar}$</td>
<td>$^{40}\text{Ar}/^{36}\text{Ar}$</td>
</tr>
<tr>
<td>$^{176}\text{Lu}$</td>
<td>$^{176}\text{Hf}$</td>
<td>$^{176}\text{Hf}/^{177}\text{Hf}$</td>
</tr>
<tr>
<td>$^{187}\text{Re}$</td>
<td>$^{187}\text{Os}$</td>
<td>$^{187}\text{Os}/^{188}\text{Os}$</td>
</tr>
</tbody>
</table>
Mantle Reservoirs

Mantle Reservoirs

DM (Depleted Mantle) = N-MORB source

PREMA (PREvalent MAntle)

BSE (Bulk Silicate Earth) or the Primary Uniform Reservoir

HIMU (high-μ, μ = 238U/204Pb)

The high Sr ratios in EM I and EM II also require a high Rb content and a similarly long time to produce the excess \( \text{Sr} \). This signature correlates well with continental crust (or sediments derived from it). Oceanic crust and sediment are other likely candidates for these reservoirs.

\( \text{EM-II} = \) enriched mantle-2

\( \text{EM I} = \) enriched mantle-1 has low \( \text{Sr} \) (near primordial) and very low \( \text{Nd} \)
### Binary mixtures

<table>
<thead>
<tr>
<th>Component</th>
<th>Sr Concentration</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component A</td>
<td>500 ppm</td>
<td>0.7</td>
</tr>
<tr>
<td>Component B</td>
<td>100 ppm</td>
<td>0.8</td>
</tr>
</tbody>
</table>

\[
\left( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \right)_M = \frac{0.8 \times 100 \times 0.9 + 0.7 \times 500(1 - 0.9)}{100 \times 0.9 + 500(1 - 0.9)} = 0.764
\]

The isotope geology of Pb

Pb produced by radioactive decay of U & Th

\[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} \]
\[ ^{235}\text{U} \rightarrow ^{207}\text{Pb} \]
\[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} \]

\[^{204}\text{Pb}\] is non-radiogenic

so, increase of \[^{208}\text{Pb}/^{204}\text{Pb}, ^{207}\text{Pb}/^{204}\text{Pb},\]
due to U and Th decay
The isotope geology of Pb

Primeval lead
(Isotope ratios of Pb in troilite of the iron meteorite Canyon Diablo)

\[ \left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_t = a_0 + \mu (e^{\lambda_1 T} - e^{\lambda_2 t}) \]

\[ \left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_t = b_0 + \frac{\mu}{137.88} (e^{\lambda_2 T} - e^{\lambda_2 t}) \]

\[ \left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_i = a_0 = 9.30 \]

\[ \left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_i = b_0 = 10.29 \]
The isotope geology of Pb

The straight lines are isochrons for selected values of t. Point P: $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of a lead mineral (e.g. galena that was withdrawn $3 \times 10^9$ years ago from a source region with a present $\mu$-value of 9.

\[
\left( \frac{^{206}\text{Pb}}{^{204}\text{Pb}} \right)_t = a_0 + \mu (e^{\lambda_1 t} - e^{\lambda_{1t}})
\]

\[
\left( \frac{^{207}\text{Pb}}{^{204}\text{Pb}} \right)_t = b_0 + \frac{\mu}{137.88} (e^{\lambda_2 t} - e^{\lambda_{2t}})
\]
The isotope geology of Pb

Two-stage Pb evolution model of Stacey & Kramers (1975)
In this model Pb evolves from primordial isotope ratios between 4.6 and 3.7 Ga in a reservoir with a \( \mu-(^{238}\text{U}/^{204}\text{Pb}) \) value of 7.2. At 3.7 Ga the \( \mu \)-value of the reservoir was changed by geochemical differentiation to 9.7.

HIMU: requires mantle sources with exceptionally high U/Pb and Th/Pb ratios.

EM-1: requires mantle sources with high Th/U ratios.
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)
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**Mantle reservoirs/flavors**

- Isotopically enriched reservoirs (EM-1, EM-2, and HIMU) are too enriched for any known mantle process, and they correspond to crustal rocks and/or sediments

- **HIMU** – (enriched in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, depleted in $^{87}\text{Sr}/^{86}\text{Sr}$)
  
  *Origin:* a) recycled oceanic crust, which has lost alkalis (Rb) and Pb during alteration and subduction
  b) metasomatically enriched oceanic lithosphere

- **EM-1** (slightly enriched in $^{87}\text{Sr}/^{86}\text{Sr}$, but not in Pb, very low $^{143}\text{Nd}/^{143}\text{Nd}$)
  
  *Origin:* a) recycling of delaminated subcontinental lithosphere
  b) recycling of subducted ancient pelagic sediment (because of their high Th/U and low (U,Th)/Pb ratios)

- **EM-2** (more enriched, especially in $^{87}\text{Sr}/^{86}\text{Sr}$ and radiogenic Pb)
  
  *Origin:* a) recycled ocean crust and small amount of subducted sediment
  b) recycling of melt-impregnated oceanic lithosphere
The isotope geology of Pb

- U, Pb, and Th are concentrated in continental crust (high radiogenic daughter Pb isotopes)
- Oceanic crust has elevated U and Th content (compared to the mantle) as well as sediments derived from oceanic and continental crust
- Pb isotopes are a sensitive measure of crustal (including sediment) components in mantle isotopic systems
The lead paradox

Kruste und Mantel:
komplementär bzgl. Pb-
Konzentration – nicht aber
bzgl. Isotopie!

The fact that MORBs do not plot to the left of the
geochron is called the “First Lead Paradox”

Hofmann (2003) : Treatise on Geochemistry
The lead paradox

hidden reservoir with Pb isotopes to the left of the geochron

• uptake of lead by the core (“core pumping”)?
• storage of unradiogenic lead in the lower cont. crust or subcont. lithosphere?

Ave. oceanic and cont. crust close to geochron
→ little net fractionation of U/Pb during crust-mantle differentiation
Wilson (1989) The $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ 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)

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

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

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

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

DUPAL = DUPre & ALlegre
SOPITA = SOuth Pacific Isotopic and Thermal Anomaly

Hart (1984)