マントル内物質循環の「年代」に関する二つの制約

Age of mantle reservoirs formed by slab subduction

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Outline of today’s talk

1. Introduction
   – Mantle geochemical heterogeneity and significance of HIMU

2. What we studied on HIMU ocean island basalts
   – Recent progress

3. Age of the HIMU mantle reservoir
   – Implications to crustal recycling in the mantle
Hotspot – a window to the deep mantle

Hotspots; Lower mantle

Mid-ocean ridges; Upper mantle

Subduction zones; subducted slab + upper mantle
Hotspot – a window to the deep mantle

Burke et al. (2008)

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Mantle geochemical heterogeneity

Isotopic variation of mantle derived rocks (MORB, OIB)

- Rb/Sr; $^{87}\text{Rb} \rightarrow ^{87}\text{Sr}$ (48.9 Byr; half life)
- Sm/Nd; $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$ (106 Byr)
- Lu/Hf; $^{176}\text{Lu} \rightarrow ^{176}\text{Hf}$ (37.1 Byr)
- U/Pb; $^{238}\text{U} \rightarrow ^{206}\text{Pb}$ (4.47 Byr)
- $^{235}\text{U} \rightarrow ^{207}\text{Pb}$ (0.704 Byr)
- Th/Pb; $^{232}\text{Th} \rightarrow ^{208}\text{Pb}$ (14.0 Byr)
Mantle geochemical heterogeneity

What process? When? Where?
What is HIMU?

Occurrence of “pure” HIMU basalts is limited...
**What is HIMU?**

**Isotopic variation of mantle derived rocks (MORB, OIB)**

- Low Rb/Sr, High U/Pb, Th/Pb
- (high $\mu = ^{238}U/^ {204}Pb$)

Hofmann (2003)
What is HIMU?

Proposed HIMU models

(1) Recycle model
   - Subducted dehydrated oceanic crust
     (Zindler and Hart, 1986; Chauvel et al., 1992)
   - Subducted metasomatized lithosphere
     (Niu and O’Hara, 2003; Pilet et al., 2005)

(2) Non-recycle model
   - Partial melting in the lower mantle
     (Collerson et al., 2010)
   - Interaction with core material
     (Allegre et al., 1980)
What is HIMU?

Suetsugu and Hanyu (2013)

Fluid-mobile elements

Suetsugu and Hanyu (2013)

Concentrated in melt

Concentrated in residue

Kimura and Yoshida (2006)
What is HIMU?

Hydrothermal alteration
- hydration of oceanic crust

Dehydration
Loss of fluid-mobile element

Long-term storage

Melting & mixing
Age of HIMU reservoirs

Hydrothermal alteration
- hydration of oceanic crust

Dehydration
Loss of fluid-mobile element

Long-term storage

Melting & mixing
Occurrence of “pure” HIMU basalts is limited…
Pacific HIMU vs Atlantic HIMU

Hanyu et al. (2014)
Pacific HIMU vs Atlantic HIMU

MORB glass data from Jenner and O’Neill (2012)
Age constraints (1); $^{206}\text{Pb} - ^{207}\text{Pb}$ model age

(1) Age

(2) Th/U

$^{235}\text{U}/\text{Pb}$

$^{232}\text{Th}/\text{Pb}$
Age constraints (1); $^{206}\text{Pb} - ^{207}\text{Pb}$ model age

Mantle $^{207}\text{Pb}$ evolution model

$^{238}\text{U} \rightarrow ^{206}\text{Pb}$

$^{235}\text{U} \rightarrow ^{207}\text{Pb}$

$(^{238}\text{U}/^{235}\text{U})_p = 137.88$

$\mu = \frac{^{238}\text{U}}{^{204}\text{Pb}}$
Age constraints (1); $^{206}\text{Pb}-^{207}\text{Pb}$ model age

St. Helena; 1.8 – 2.3 Ga
Austral Islands; 1.5 – 2.0 Ga

Atlantic HIMU is older than Pacific HIMU by 0.3 Ga.
Age constraints (1); \(^{206}\text{Pb}-^{207}\text{Pb}\) model age

(1) Discrete HIMU reservoir(s)  
(2) Single homogenized HIMU reservoir  
(3) Locally homogenized HIMU reservoirs
Age constraints (1); $^{206}\text{Pb}-^{207}\text{Pb}$ model age

Subducted crust; density difference = 2%

Subducted crust; density difference = 3%

Composition:
- blue; harzburgite
- green; peridotite
- red; basaltic crust

Nakagawa and Tackley (2005)
Age constraints (2); Th-U recycling

(1) Age

(2) Th/U
Age constraints (2); Th-U recycling

$$\kappa = \frac{^{232}\text{Th}}{^{238}\text{U}} \sim 1.03 \times \text{Th/U}$$

Elliott et al. (1999)
Age constraints (2); Th-U recycling

\[ \kappa = \frac{^{232}\text{Th}}{^{238}\text{U}} \sim 1.03 \times \text{Th/U} \]

\[ \kappa = 3.8 \text{ at } 2 \text{ Ga} \]

\[ \kappa = 3.6 \text{ at } 2 \text{ Ga} \]

\[ \text{HIMU: } 3.3 \text{ – } 3.7 \]

\[ \text{Chondrite (bulk Earth): } 3.8 \text{ – } 4.2 \]
Age constraints (2); Th-U recycling

![Graphs showing Th/U ratios for Fresh MORB and Altered MORB (Hole 801).](image)

Data from Arevalo and McDonough (2010) and Data from Kelley et al. (2003)

\[ \kappa = \frac{^{232} \text{Th}}{^{238} \text{U}} \approx 1.03 \times \text{Th/U} \]
Age constraints (2); Th-U recycling

κ of HIMU is too high, if the precursor of HIMU was recycled altered oceanic crust!

Altered basaltic crust is enriched in U, and hence its Th/U is lowered, by hydrothermal alteration.

Data from Kelley et al. (2003)
Age constraints (2); Th-U recycling

Archean – Late Proterozoic

- Th, U-enrich
- Th, U-deplete

U⁴⁺: less mobile with fluids like Th

U⁶⁺: mobile with fluids

Oxydation in hydrosphere

Present

- Th/U ↑
- Th/U ↓
Archean altered MORB has as high Th/U as chondritic value.

Present-day altered MORB has low Th/U.

Age constraints (2); Th-U recycling

Archean – Late Proterozoic

Th, U-enrich

Th, U-deplete

↑ Th/U

Present

Th/U ↓

U⁴⁺: less mobile with fluids like Th

U⁶⁺: mobile with fluids

Oxydation in hydrosphere
The start of Great Oxidation Event (GOE) at 2.4 Ga.

HIMU reservoir age estimated from $^{206}\text{Pb-}^{207}\text{Pb}$ systematics is:
- St. Helena: 1.8 – 2.3 Ga
- Austral Islands: 1.5 – 2.0 Ga

Oxygenation in deep water may be delayed than that in shallow water.

Holland (2006)
Age constraints (2); Th-U recycling

Mass-independent fractionation (MIF) of sulfur isotope ($\Delta^{33}$S) in HIMU basalts.

Cabral et al. (2013)
HIMU beneath Pacific and Atlantic show very similar isotopic compositions except for the $^{206}\text{Pb}-^{207}\text{Pb}$ systematics.

From the $^{206}\text{Pb}-^{207}\text{Pb}$ systematics, the reservoir age of HIMU is around 2 Ga, but that of the Atlantic HIMU is 0.3 Ga younger than that of the Pacific HIMU.

It is suggested that subducted crust form distinct HIMU reservoirs beneath Pacific and Atlantic.

$\text{Th}/\text{U}$ in HIMU estimated from $^{206}\text{Pb}-^{208}\text{Pb}$ systematics is too high than that of present-day altered oceanic crust.

The HIMU reservoir should involve subducted oceanic crust that were altered in anoxic condition in Archean or early Proterozoic.