Uranium-series Disequilibrium in Subduction Zone Volcanic Rocks

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Subduction zone magmatism

- Subducting slabs release fluid components due to mineralogical reactions during progressive metamorphic dehydration.
- The fluid released from the slab subsequently induces mantle melting as it ascends, resulting in subduction zone magmatism.
Secular equilibrium and U-series disequilibrium

- \( ^{238}\text{U} \rightarrow \ldots \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow \ldots \rightarrow ^{206}\text{Pb} \)
- \( T_{1/2} \) (yr) \( 4.5 \times 10^9 \)
- \( 7.5 \times 10^4 \)
- \( 1600 \)
- Stable

- \( \lambda_{^{238}\text{U}}N_{^{238}\text{U}} = \lambda_{^{230}\text{Th}}N_{^{230}\text{Th}} \) (Radioactive equilibrium
  \( \lambda \) : decay constant)
- \( 5 \times T_{1/2} \)
- \( \lambda_{^{238}\text{U}}N_{^{238}\text{U}} \neq \lambda_{^{230}\text{Th}}N_{^{230}\text{Th}} \) (Radioactive disequilibrium)
- Elemental fractionation

- After Bourdon et al. (2003)

- \( ^{238}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow \ldots \rightarrow ^{206}\text{Pb} \)

- \( ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \)

- \( ^{238}\text{U} - ^{230}\text{Th} \) disequilibrium: fractionation within the last 350 kyr
- \( ^{230}\text{Th} - ^{226}\text{Ra} \) disequilibrium fractionation within the last 8 kyr
$^{238}\text{U} - ^{230}\text{Th}$ equiline diagram

Equiline

$\lambda_{^{238}\text{U}N_{^{238}\text{U}}} = \lambda_{^{230}\text{Th}N_{^{230}\text{Th}}}$ (Activity)

$$\left(\frac{^{230}\text{Th}}{^{232}\text{Th}}\right) = \left(\frac{^{238}\text{U}}{^{232}\text{Th}}\right)^0 \cdot (1 - e^{-\lambda_{^{230}\text{Th}}t}) + \left(\frac{^{230}\text{Th}}{^{232}\text{Th}}\right)^0 \cdot e^{-\lambda_{^{230}\text{Th}}t}$$

slope  \hspace{3cm} intercept
238U-230Th disequilibrium and tectonic settings

MORB, OIB

Subduction zone

Garnet: $D_U/D_{Th} > 1$
Pyroxene: $D_U/D_{Th} < 1$

MORB and OIB melts originated from garnet stability fields

U is more fluid mobile than Th.
Slab derived fluid preferentially transfers U than Th.

Cl chonrite (U/Th = 0.26)
<table>
<thead>
<tr>
<th></th>
<th>Iwate</th>
<th>Akitakoma</th>
<th>Hachimantai</th>
<th>Yakeyama</th>
<th>Kampu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample#</td>
<td>IW1</td>
<td>IW4</td>
<td>IW7</td>
<td></td>
<td></td>
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<tr>
<td>SiO2 (%)</td>
<td>53.6</td>
<td>50.9</td>
<td>52.8</td>
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<td>MgO (%)</td>
<td>6.50</td>
<td>5.80</td>
<td>7.24</td>
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<td>Age</td>
<td>1732</td>
<td>&lt;10ka</td>
<td>&lt;10ka</td>
<td>5–10ka</td>
<td>2ka</td>
</tr>
</tbody>
</table>

Hasegawa et al. (2009)
Analytical techniques

- Chemical separation: U/TEVA spec (Eichrom)
- Th and U isotopes: TIMS (TRITON plus)
- Th and U abundances: ID-ICP-MS (X-series II)
U-Th disequilibrium of NEJ volcanic rocks

- Fore arc lavas: \(^{238}\text{U}\)-excesses
- Rear arc lavas: \(^{230}\text{Th}\)-excesses
- The extent of \(^{238}\text{U}\) enrichment decreases as the slab depth increases.

Gradual decrease of the amount of slab derived fluid mixed into the wedge mantle.
Rear arc samples

- Dynamic melting of garnet-bearing upwelling DMM-like mantle?
  - No. \(\frac{^{230}\text{Th}}{^{232}\text{Th}}\) and \(\frac{^{238}\text{U}}{^{232}\text{Th}}\) ratios are too small.

- Model 1) Dynamic melting of enriched mantle

- Model 2) Flux melting of enriched mantle induced by the addition of \(^{230}\text{Th}\)-rich slab-derived fluid.
\( ^{238} \text{U} - ^{230} \text{Th} \) age and eruption age are decoupled.

- A long (>80 kyr) residence time before eruption? \( \rightarrow \) NO
- Assimilation and fractional crystallization? \( \rightarrow \) NO
- Mixing line produced by the addition of Th enriched slab-derived fluid w/o age significance.

Kampu
Eruption age: <20 ka

Mantle wedge \( (^{230} \text{Th} / ^{232} \text{Th})_{\text{ini}} = 0.91 \)

Slab derived fluid

No correlation between U-Th fractionation and magma differentiation
Frontal-arc samples (NE Japan and Izu arc)

- Miyakejima: DMM-like source mantle
- Fuji+Oshima+Komagatake: E-DMM source mantle
- Iwate: More enriched source mantle?
238U-230Th age and eruption age are decoupled.

- A long (>90 kyr) residence time before eruption? → NO
- Addition of slab derived fluid to extremely enriched mantle wedge
Summary

- Rear arc samples have $^{230}$Th excesses due either to the dynamic melting of enriched source mantle or flux melting by the addition of Th-rich slab-derived fluid.

- Frontal arc samples have $^{238}$U excesses due to the addition of U-rich slab-derived fluid to the mantle wedge that is more enriched than E-DMM.

- Wedge mantle beneath NE Japan can be heterogeneous regarding U/Th and Th isotope ratios due to ancient mantle metasomatism.