Radiogenic Isotope and Deep Mantle Heterogeneity

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Reading materials:

How to Move Forward?
Need to Break some Boundaries ...
Why Hawai‘i?

Magma Flux - Largest
Best Studied - More to Know, especially crossing boundaries
Deep Mantle Origin - CMB
First Documented Occurrence of Double Chains
volcanism waxes and wanes: (1) capped by drowned coral reefs. Many of which are submerge, while erosion incises deep river valleys, such as landslides and tsunami, or fail more gradually, forming upper submarine slopes. Above sea level then, the volcanoes following a lengthy period of erosion and volcanic quiescence. During the early alkalic and shield stages, two or more ... rift-zone eruption. The rift zones commonly extend deep underwater, producing submarine eruptions of bulbous pillow lava.

Kuril Trench

Hawaiian volcanoes typically evolve in four stages as once a volcano has grown above sea level, subaerial...
volcanism waxes and wanes: (1) are now as much as 2,000 m underwater, many of which are those on the Island of Kaua’i. The edges of the submarine submerge, while erosion incises deep river valleys, such as flows no longer reach the ocean, the volcano continues to the base of the volcanoes. Once volcanism wanes and lava the upper submarine slopes. Above sea level then, the volcanoes steep blanket of unstable volcanic sediment that mantles the rejuvenated scattered cones that thinly cap the shield-stage lavas; and (4) roughly 95 percent of a volcano’s volume is emplaced; (3)
The big island of Hawai‘i contains 5 volcanoes:
- Kohala, Hualalai, Mauna Kea, Mauna Loa, Kilauea

The newest Hawaiian volcano, Loihi, is slowly being constructed along the SE flank of the island.

Each volcano has a lifespan of ~1 million years.
Growth History of Hawaiian Volcanoes

Magma supply rate
(10^6 m^3/y)

Pre-shield stage
(>1000 km^3)

Kilauea
(40 to 80 x 10^3 km^3)

Tholeiitic basalt

Post-shield stage
(875 km^3)

Mauna Loa

small volume
~1%

Hualalai

Adapted from Garcia et al. 2006
Growth History of Hawaiian Volcanoes

Post-erosional alkalic
Post-shield alkalic

Pre-shield alkalic
Oceanic crust

Ocean

Tholeiitic

Adapted from Clague 1987

Alkaline basalt
Nephelinite << 1 vol%
Tholeiites 97-98 vol%

Alkaline basalt 1 vol%
Evolved lavas 1-2 vol%

Diamond Head
Haleakala
MK alkalic
Kilauea lavas
**Mauna Loa & Kilauea**

- **Today’s magma production rates:**
  - Kilauea: 0.10 to 0.18 km³/yr
  - Mauna Loa: 0.03 km³/yr
  - Loihi: <<

**Total production:** 0.15 to 0.2 km³/yr

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**Hawaii: TAS Relationships**

- **Early Stage:** Submarine, Alkalic
- **Main Stage:** Shield, Tholeiitic
- **Late Stage:** Post-shield, Alkalic

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**Rhodes and Vollinger 2004**
Shield lavas have tholeiitic compositions and represent the large majority of the volcano.
HSDP I: drilled to 1079 m in 1993 (pilot hole)
HSDP II: drilled to 3098 m in 1999 (+recent to 3508 m)
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Hawaiian Shield Basalts Evolution over 4.5 myr
Hawaiian Plume Source: a Different Look and a Fine Structure
Northwestern Hawaiian Ridge: 45 myr
Samples, chem lab preparation and isotopic analyses

Sequential Acid Leaching

Sample Collection

1st step

Intermediate step

Last step (>15)

High-Precision Isotopic Analyses

Chemical Separation
Pb-Pb Isotope Systematics: Improved Resolution

$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$ vs $\frac{^{232}\text{Th}}{^{208}\text{Pb}}$

Error $\ll$ symbol size

- Lana'i
- Hu'alalai
- Kea Mid-8
- Kea Low-8
Pb-Pb Isotope Systematics
Improved Resolution
Example of Kauai
Triple Spike Pb Isotope Data: **Shield Stage** Lavas

Isochron: No
Mixing lines: Yes
What do Pb Isotope Lines Mean?

**Isochron:**

\[
\left( \frac{206\, \text{Pb}}{204\, \text{Pb}} \right)_t = \left( \frac{206\, \text{Pb}}{204\, \text{Pb}} \right)_0 + \left( \frac{238\, \text{U}}{204\, \text{Pb}} \right)_t \left( e^{\lambda t} - 1 \right)
\]

Same equation for \( \frac{207\, \text{Pb}}{204\, \text{Pb}} \); by combining the two:

\[
M = \frac{1}{137.88} \left( e^{\lambda_{235} t} - 1 \right)
\]

the slope in a \( \frac{7\, \text{Pb}}{6\, \text{Pb}} \) diagram is directly a function of the age, or …

**Mixing lines:**

In a Pb-Pb diagram because it involves the same element, mixing is always a line.

- Significance?
- Physical existence of the end-members?
where \( \text{init} \) stands for Earth's primordial Pb isotopic composition.

\[
\frac{208^{*}Pb}{206^{*}Pb} = \left( \frac{208^{*}Pb/204^{*}Pb}{206^{*}Pb/204^{*}Pb} \right)_{\text{sample}} - \left( \frac{208^{*}Pb/204^{*}Pb}{206^{*}Pb/204^{*}Pb} \right)_{\text{init}} \approx \frac{\text{Th}}{U}
\]

High-Precision Pb Hawai‘i
Where did it start?
Bilateral Asymmetry and Vertical Continuity in the Hawaiian Mantle Plume

Abouchami et al. 2005
High-Precision Pb Isotope Data: Hawai‘i Shield Lavas

Only shield lavas
>700 samples

(MC-ICP-MS or TS)/NORM

Weis et al. 2011
High-Precision Pb Isotope Data: Hawai‘i Shield Lavas

Kea end-member:
- common to many Pacific islands
- similar to “c” or super chondritic BSE

Loa trend volcanoes:
- higher $^{208}\text{Pb}/^{204}\text{Pb}$ ratios for a given $^{206}\text{Pb}/^{204}\text{Pb}$, higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $\varepsilon_{\text{Nd}}$ and $\varepsilon_{\text{Hf}}$
- more heterogeneous
volcanism originates on the deep sea floor; (2) rejuvenated scattered cones that thinly cap the shield-stage lavas; and (4) following a lengthy period of erosion and volcanic quiescence. During the early alkalic and shield stages, two or more volcanoes may erupt simultaneously, extending the rift zone. These subaerial eruptions may be...
A Simple Bilateral Source? Some Challenges

- Simple Bilateral Source?
- Some Challenges
- Only shield lavas
- Only modern, high-precision data
- ~800 samples
Kea vs Loa: 95% Accuracy

Kea Volcanoes
Canonical Scores Plot

Group Frequencies
Kea vs Loa:

Group Frequencies
Enriched Loa Loa Loihi
71 366 35

Loa Volcanoes
Canonical Scores Plot

Rhy McMillan, PCIGR
Hawaii Shield Lavas
Canonical Scores Plot

FACTOR(1)  FACTOR(2)  FACTOR(3)

FACTOR(1)  FACTOR(2)  FACTOR(3)

FACTOR(2)  FACTOR(2)  FACTOR(2)

FACTOR(3)  FACTOR(3)  FACTOR(3)

Pb Isotopes

Group Frequencies

- Enriched Loa: 74
- Kea: 136
- Loa1: 72
- Loa2: 294
- Loihi: 35
- WMauiEMolokai: 120

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Canonical Scores Plot

FACTOR(1)
FACTOR(2)
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Rhy McMillan, PCIGR
Back in Time: Hawaiian Ridge-Emperor Seamounts 85 myr

[Map of the Pacific Ocean showing the Hawaiian Ridge and Emperor Seamounts, with labels for various locations such as Gardner, Nihoa, Pearl & Hermes Reef, Koko, and others.]

Volume flux (m³/s) vs. Distance from Kilauea (km)

Hawaiian-Emperor Bend

Kilauea

Turnif & Academician Berg Seamounts

R/V Falkor Mapping, Schmidt Ocean Institute 2013

Midway Area

Vidal & Bonneville 2004
Northwestern Hawaiian Ridge

42 myr from the bend to the islands
24 shield-stage samples from 13 volcanoes

L. Harrison PhD Thesis
NWHR: Pb Isotope Systematics

Harrison et al
EPSL 2017

Garcia et al 2015
NWHR Pb Isotope Variations vs Plume Magmatic Flux and Distance from Kilauea

Northwest Hawaiian Ridge

NWHR: Dramatic Increase Last 30 myr

Emperor Seamounts

Emperor: Low Output Small Variation

Estimated Volume Flux (m³/sec) vs Age (Ma)

Harrison et al. EPSL 2017
Evolution of the Hawaiian Plume Source at the CMB since inception

A. Pacific LLSVP core lower mantle

B. Hawaiian Plume Formation

C. Emperor Seamounts ~82 - 47 Ma

D. Intermittent Loa

E. Hawaiian Islands ~6.5 - 0 Ma

Harrison et al. EPSL 2017
There is a clear difference between Loa and Kea trend volcanoes:
- Kea Volcanoes ≈ Ambient Pacific Mantle
  The Kea trend samples the Pacific deep mantle.
- Loa Compositions ≈ LLSVP or ULVZ.

Statistically, six groups can be identified on Hawaii:
- two major ones: Kea and Loa, and,
- four minor ones, finite in time/space: (WMau‘i-EMoloka‘i, Kohala), (Lō‘ihi, Enriched Loa).

The Loa trend is heterogeneous and composed of multiple compositional components.
EM-I type mantle plumes: Hawai‘i and Pitcairn from the edge of the Pacific LLSVP and, Kerguelen and Tristan of the African LLSVP

Modified from Thorne et al. 2004
Weis et al. 2011
Mantle plume tails are dynamic and can change compositionally with time.

Hawaiian plume drift samples multiple mantle domains which has impact on:
- Geochemistry, spatial organization and timing
- Magmatic Flux
- Volcanic Propagation Rate

The EM-I geochemical signatures are related to the presence of enriched, recycled continental material in these anomalous velocity zones at the CMB - each with a different composition (African LLSVP, slightly more enriched - older?).

The appearance of Loa signatures early on the NWHR indicates that LLSVP are long-lived features of the deep mantle that also play a significant role in the geochemical signature of strong mantle plumes.