CIDER 2018: Geochemistry Lecture #3 - Part #2, Hawaii

Radiogenic Isotope and Deep Mantle Heterogeneity

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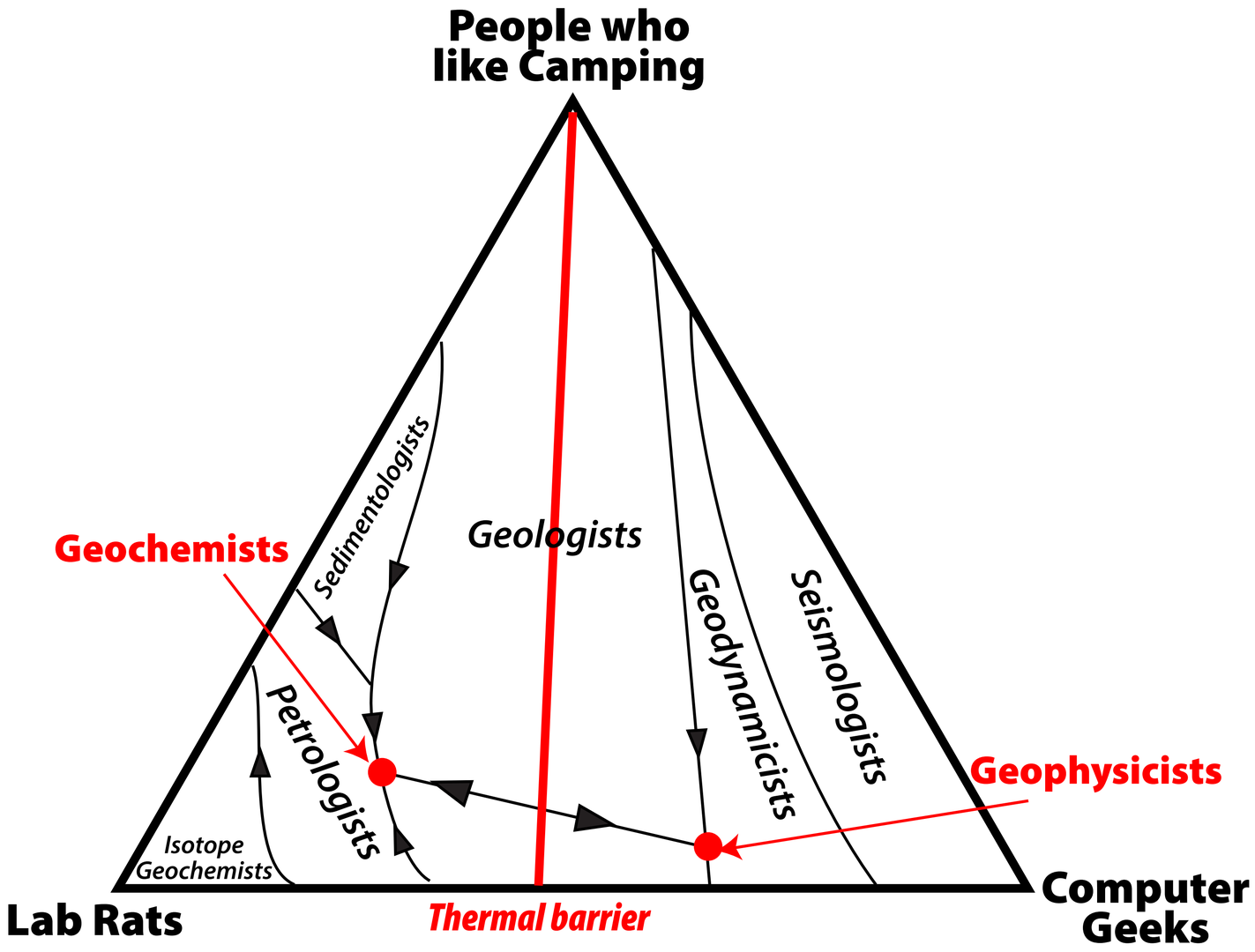
Reading materials:

Hofmann A., ToG, Chapter 2.03 (2003): Sampling Mantle Heterogeneity through Oceanic Basalts: Isotopes and Trace Elements
White, W. (2015). Probing the Earth's Deep Interior Through Geochemistry. *Geochemical Perspectives*, 95–251. http://doi.org/10.7185/geochempersp.4.2

Ocean Entry: Oct 2002

How to Move Forward?
Need to Break some Boundaries …



Experiments at 1 atm, 298 K

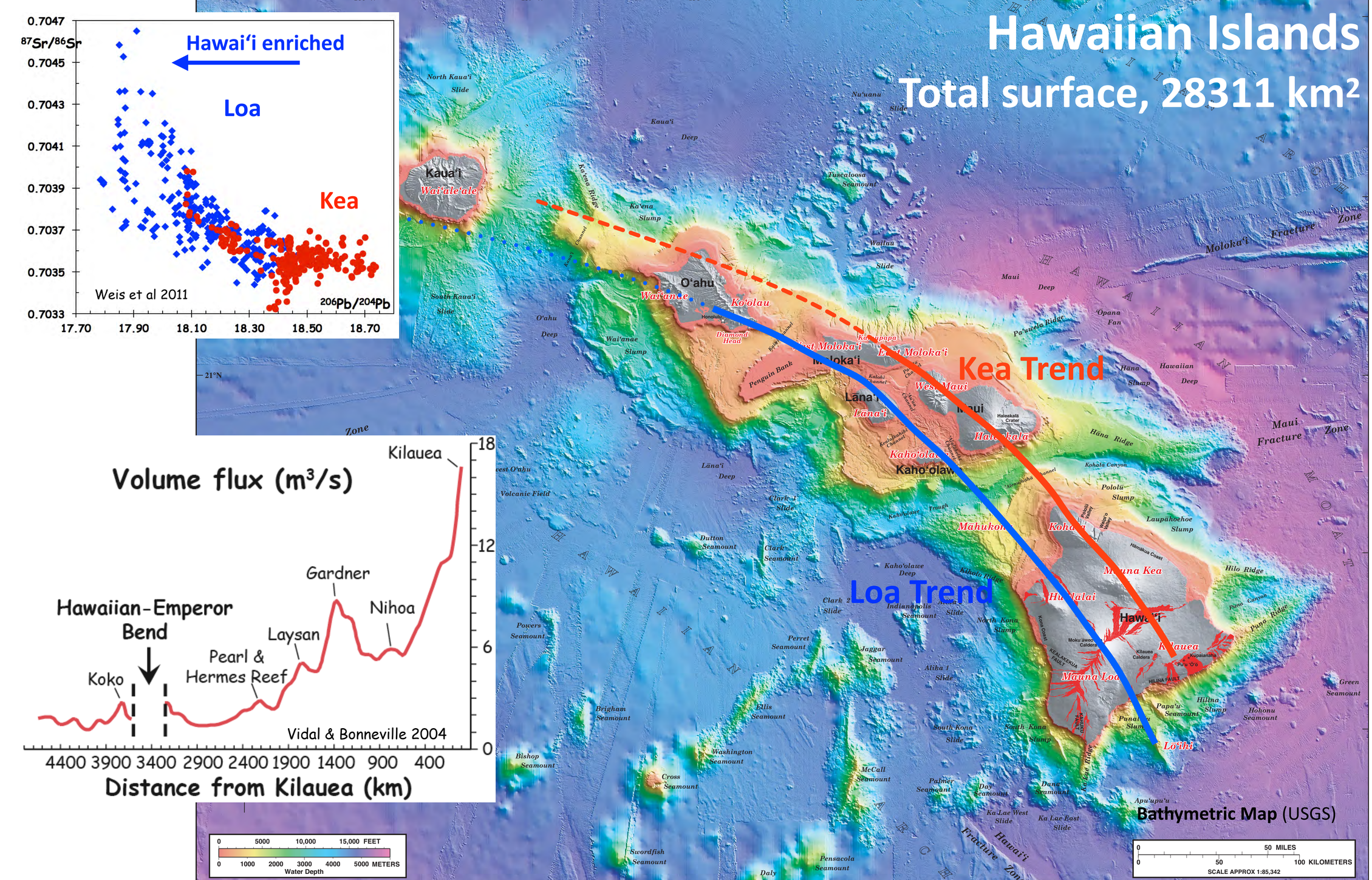
Why Hawai‘i?

Magma Flux - Largest
Best Studied - More to Know, especially crossing boundaries
Deep Mantle Origin - CMB
First Documented Occurrence of Double Chains

Kaua’i, Waimea Canyon

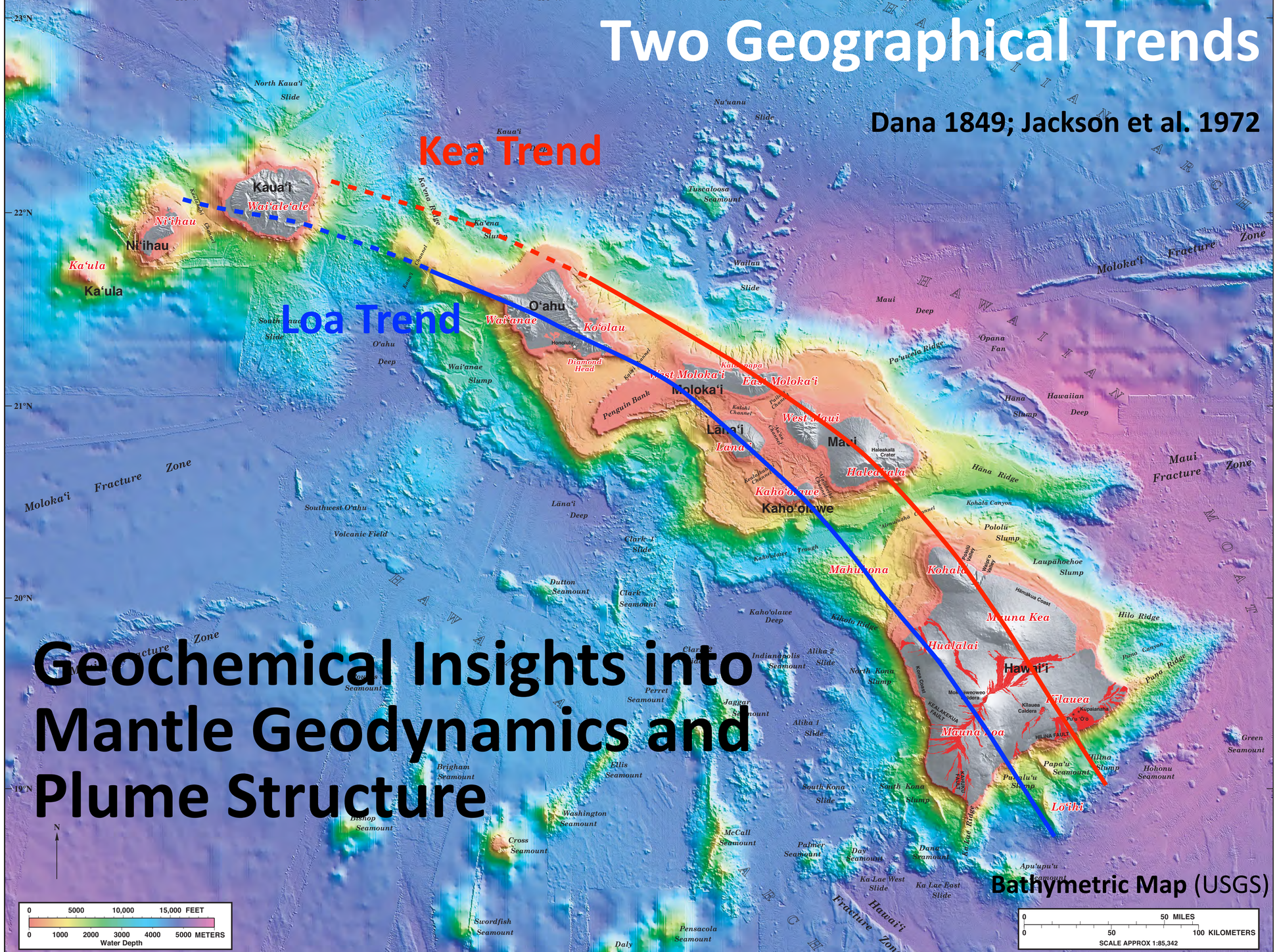
Hawaiian Islands

Total surface, 28311 km²



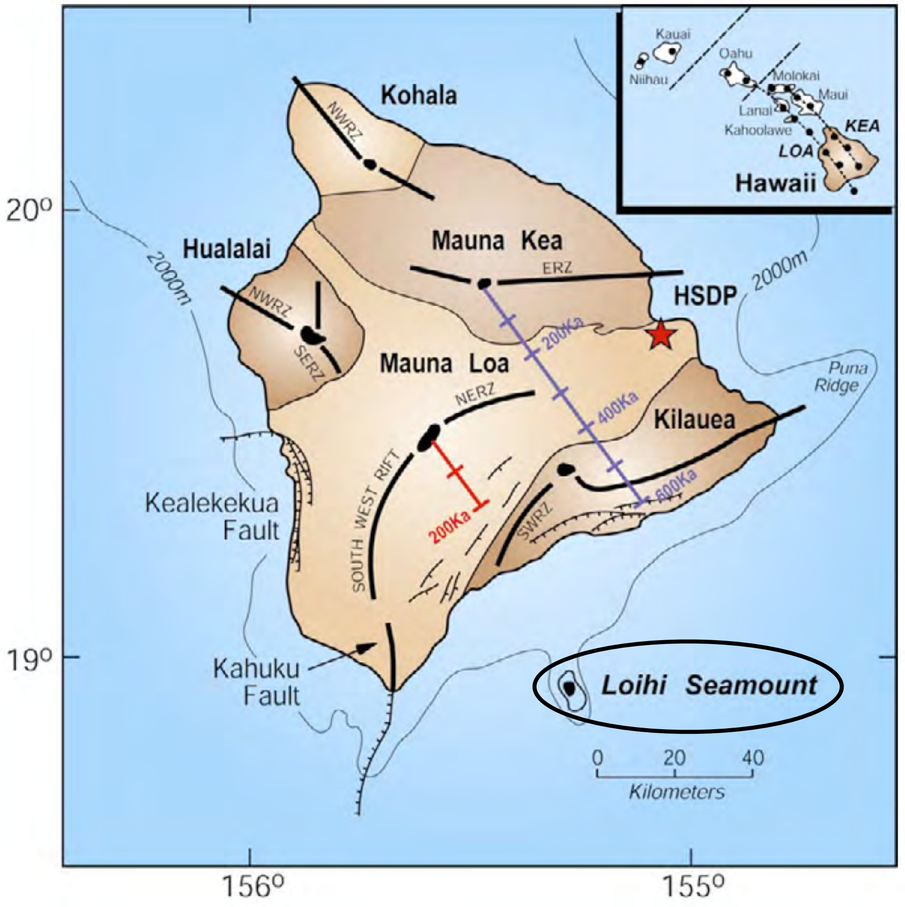
Two Geographical Trends

Dana 1849; Jackson et al. 1972



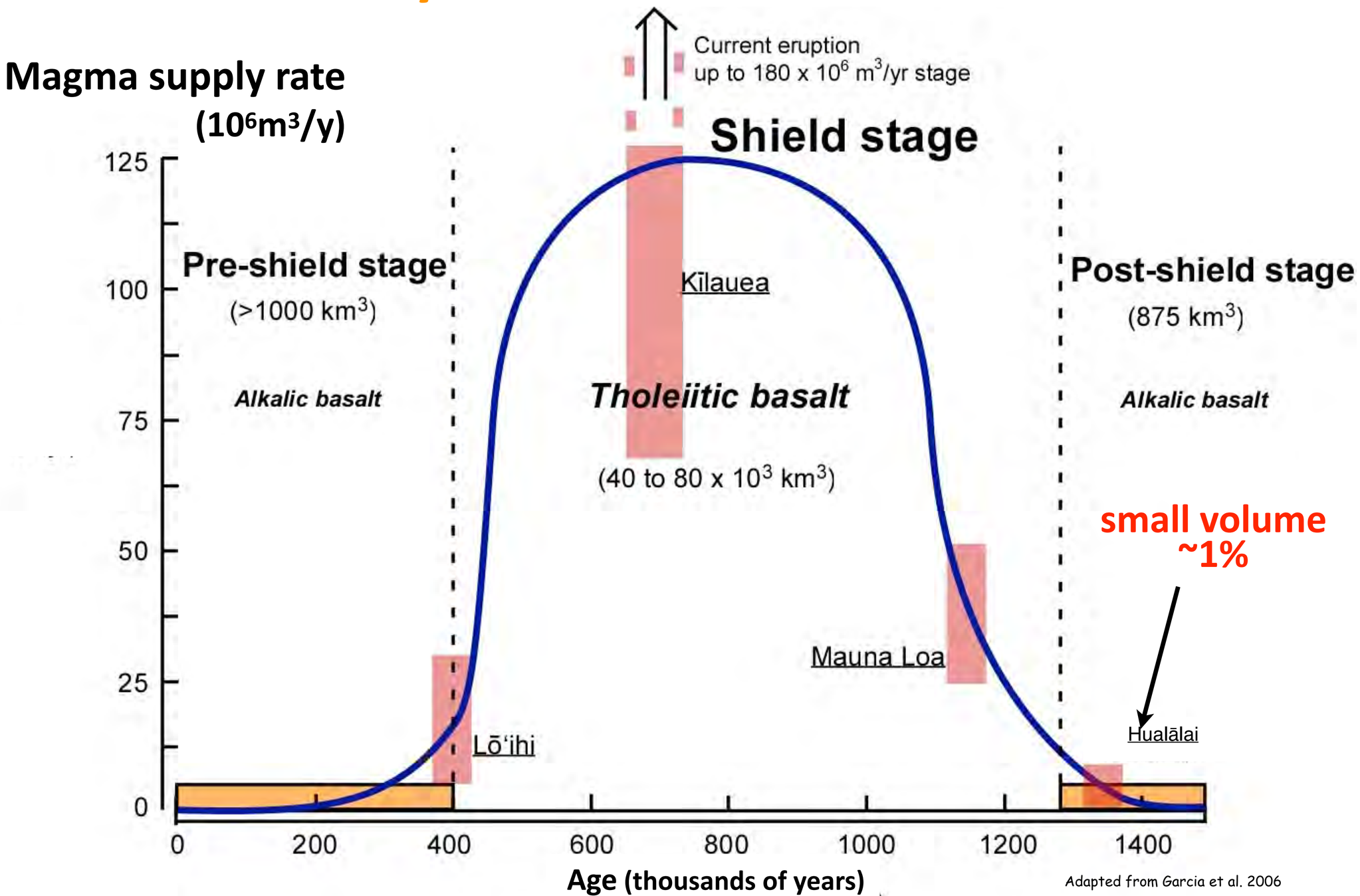
Geochemical Insights into Mantle Geodynamics and Plume Structure

Volcanoes on Hawai'i



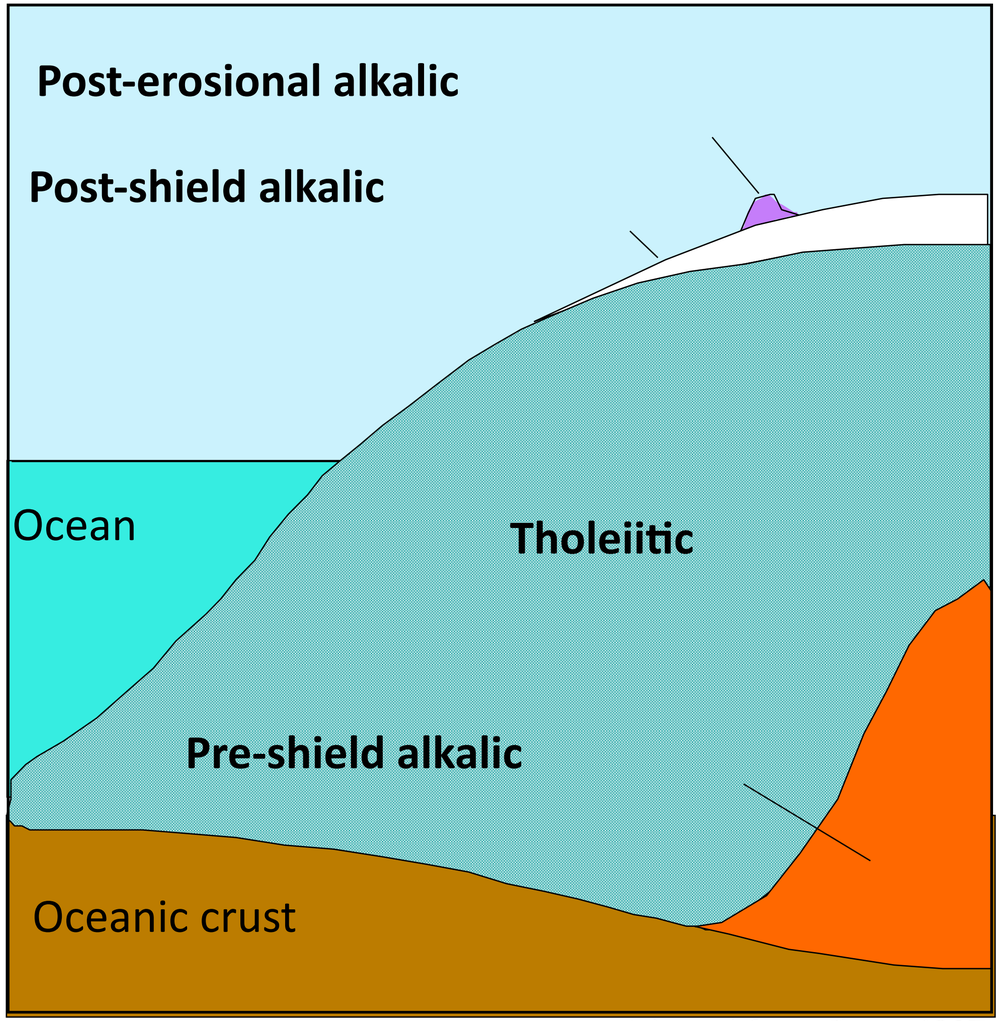
- The big island of Hawai'i contains 5 volcanoes:
  - Kohala, Hualalai, Mauna Kea, Mauna Loa, Kilauea
- The newest Hawaiian volcano, Loihi, is slowly being constructed along the SE flank of the island.
- Each volcano has a lifespan of **~1 million** years.

Growth History of Hawaiian Volcanoes



Adapted from Garcia et al. 2006

Growth History of Hawaiian Volcanoes



Adapted from Clague 1987

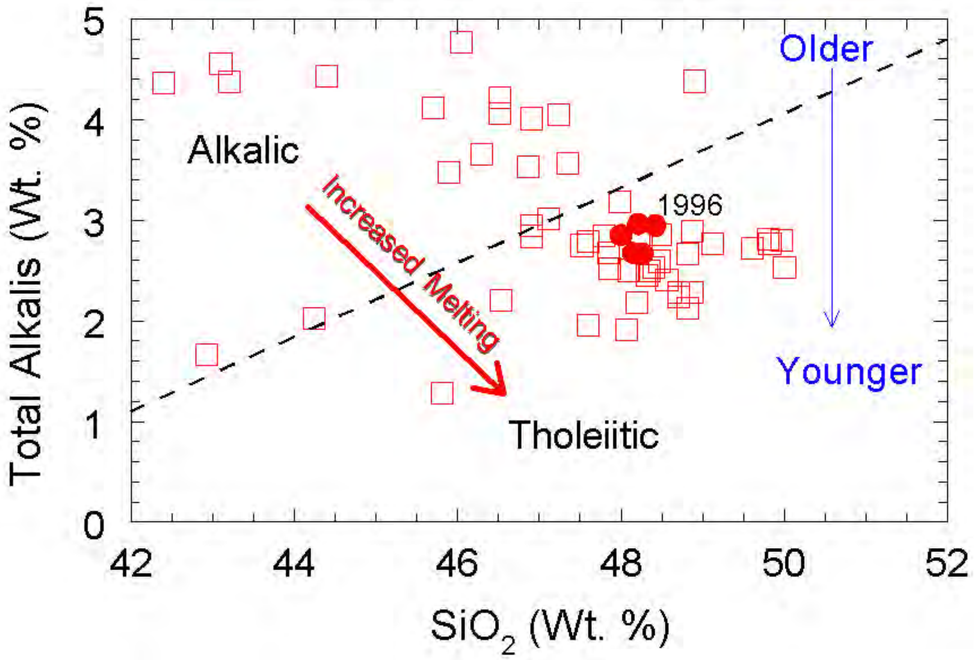
Alkalic basalt Nephelinite	<< 1 vol%	Alkalic basalt Evolved lavas	1 vol%
Tholeiites	97-98 vol%	Alkalic basalt	1-2 vol%

Hawaii: TAS Relationships

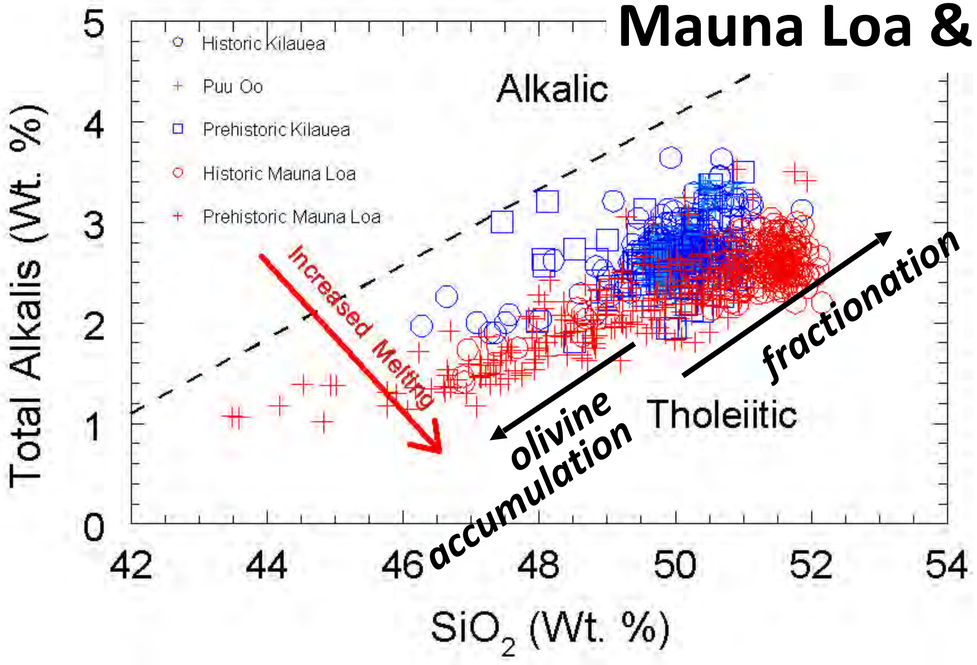
Early Stage: Submarine, Alkalic
Main Stage: Shield, Tholeiitic
Late Stage: Post-shield, Alkalic

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

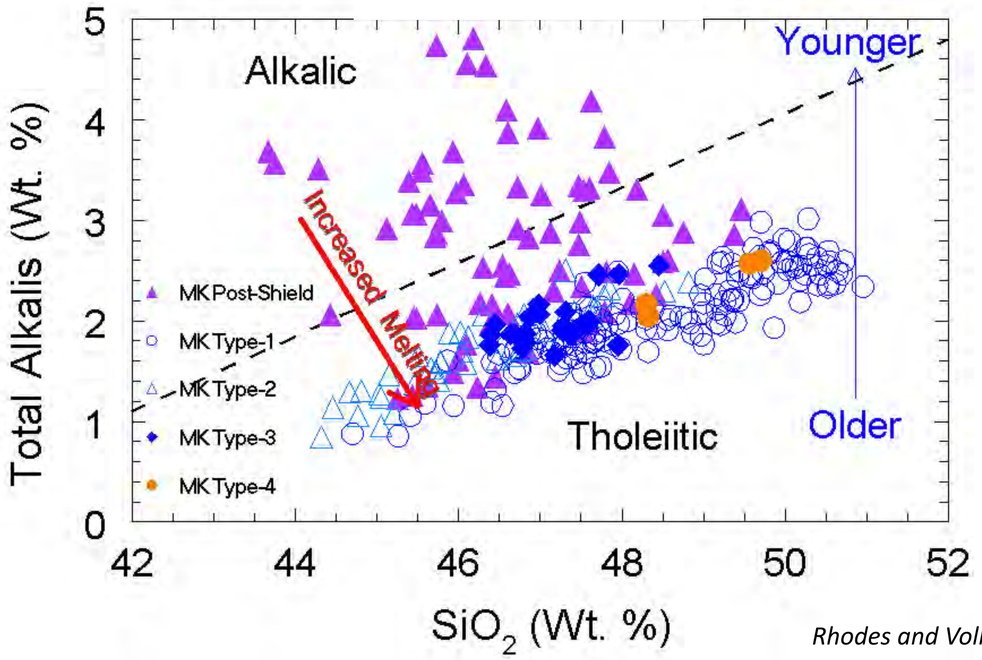
Loihi



Mauna Loa & Kilauea



Mauna Kea



Rhodes and Vollinger 2004

Shield lavas have tholeiitic compositions and represent the large majority of the volcano

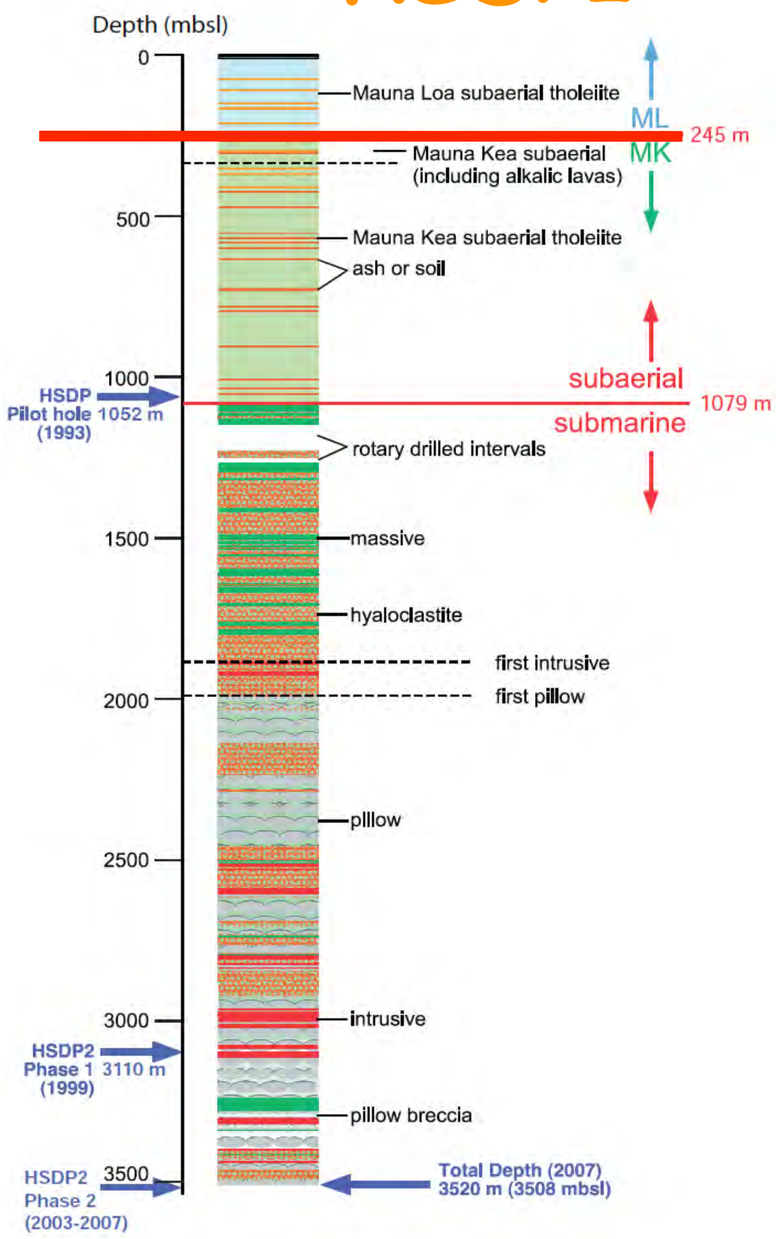
On the Slope of Mauna Loa, Big Island


Mauna Kea


Na Pali coast Kaua'i


Mauna Loa

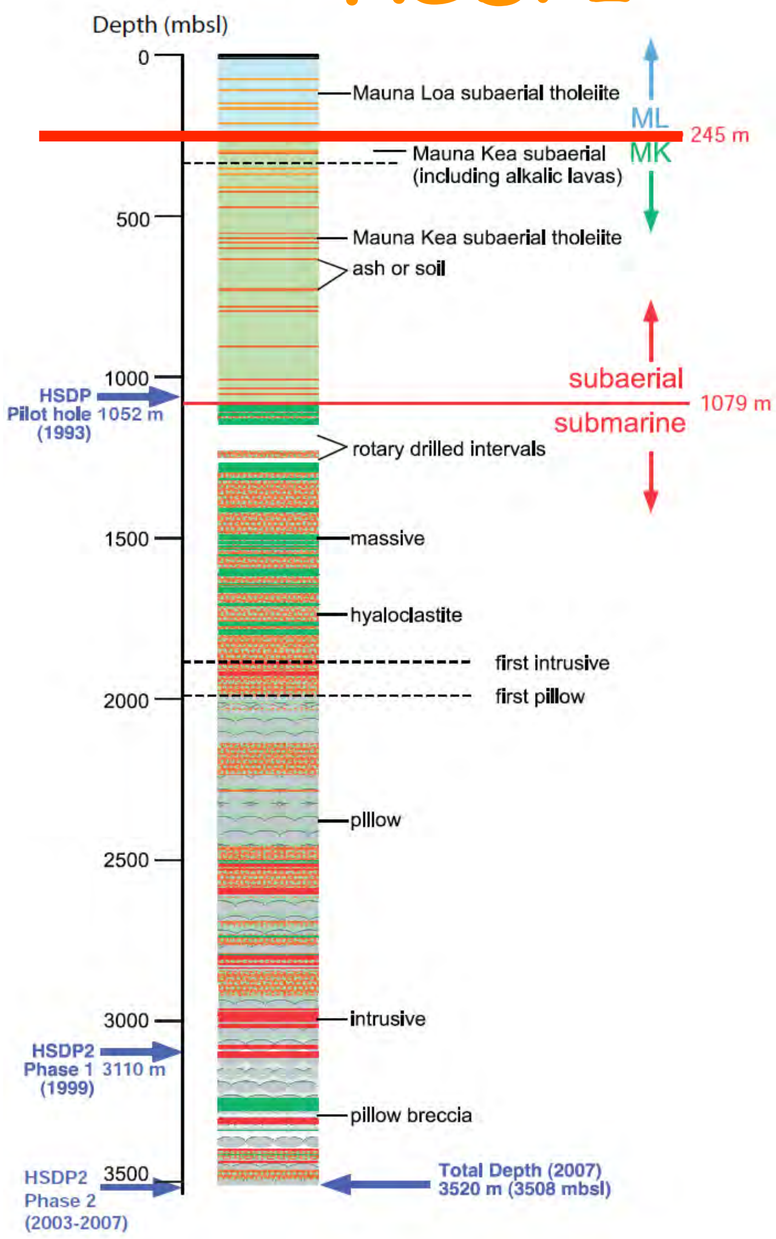
HSDP2



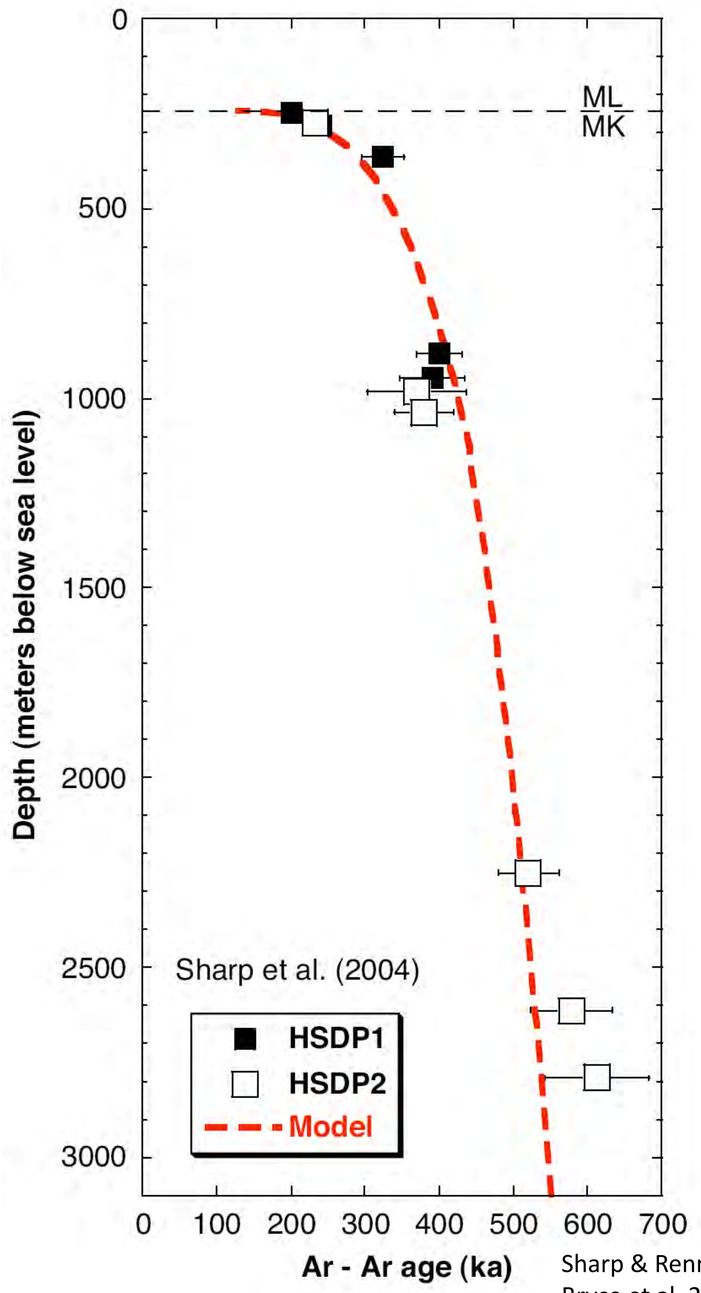
HSDP I: drilled to 1079 m in 1993 (pilot hole)

HSDP II: drilled to 3098 m in 1999 (+recent to 3508 m)

HSDP2



Age vs Depth



Sharp & Renne 2005
Bryce et al. 2005

HSDP I: drilled to 1079 m in 1993 (pilot hole)

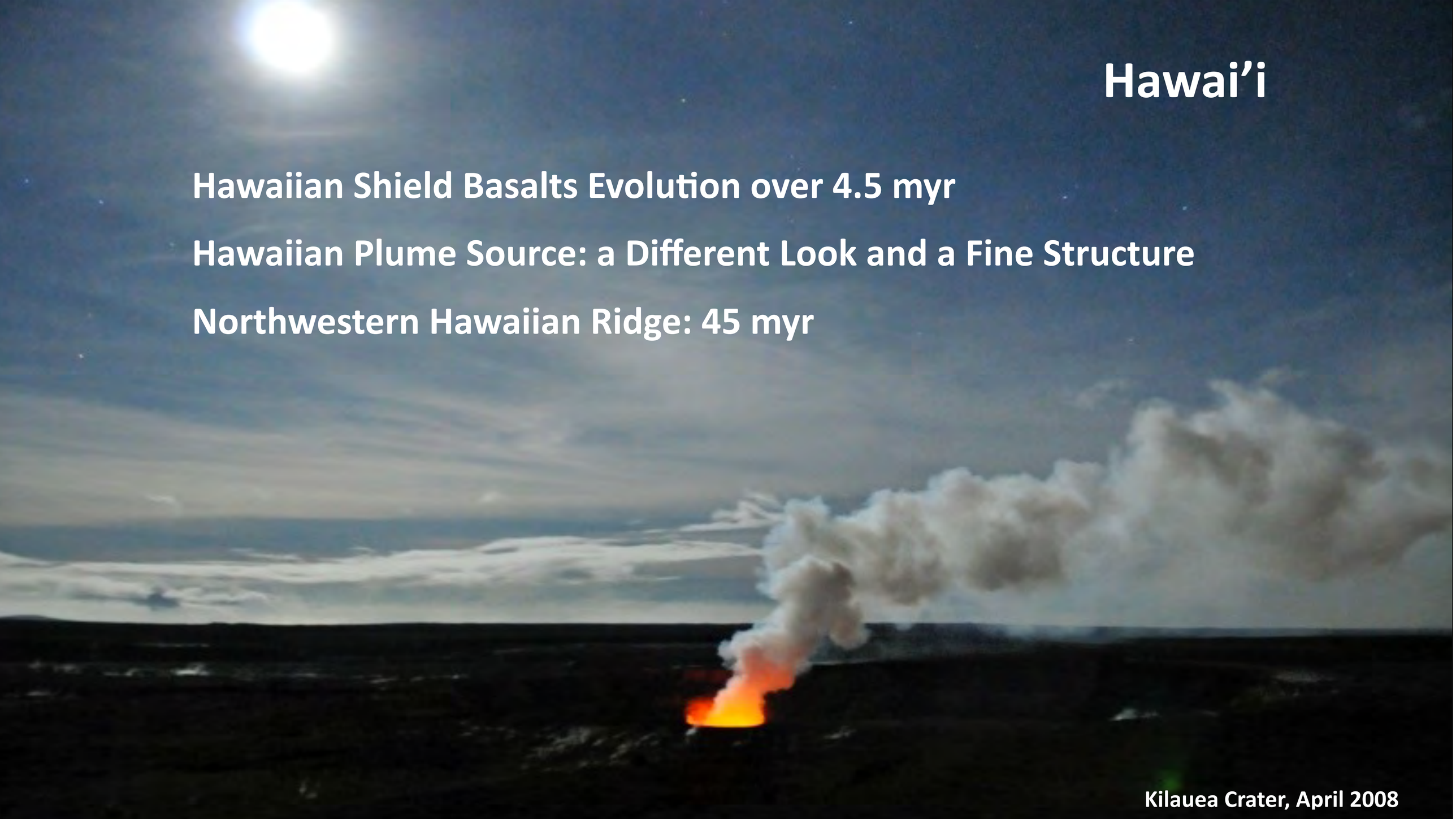
HSDP II: drilled to 3098 m in 1999 (+recent to 3508 m)

Hawai'i

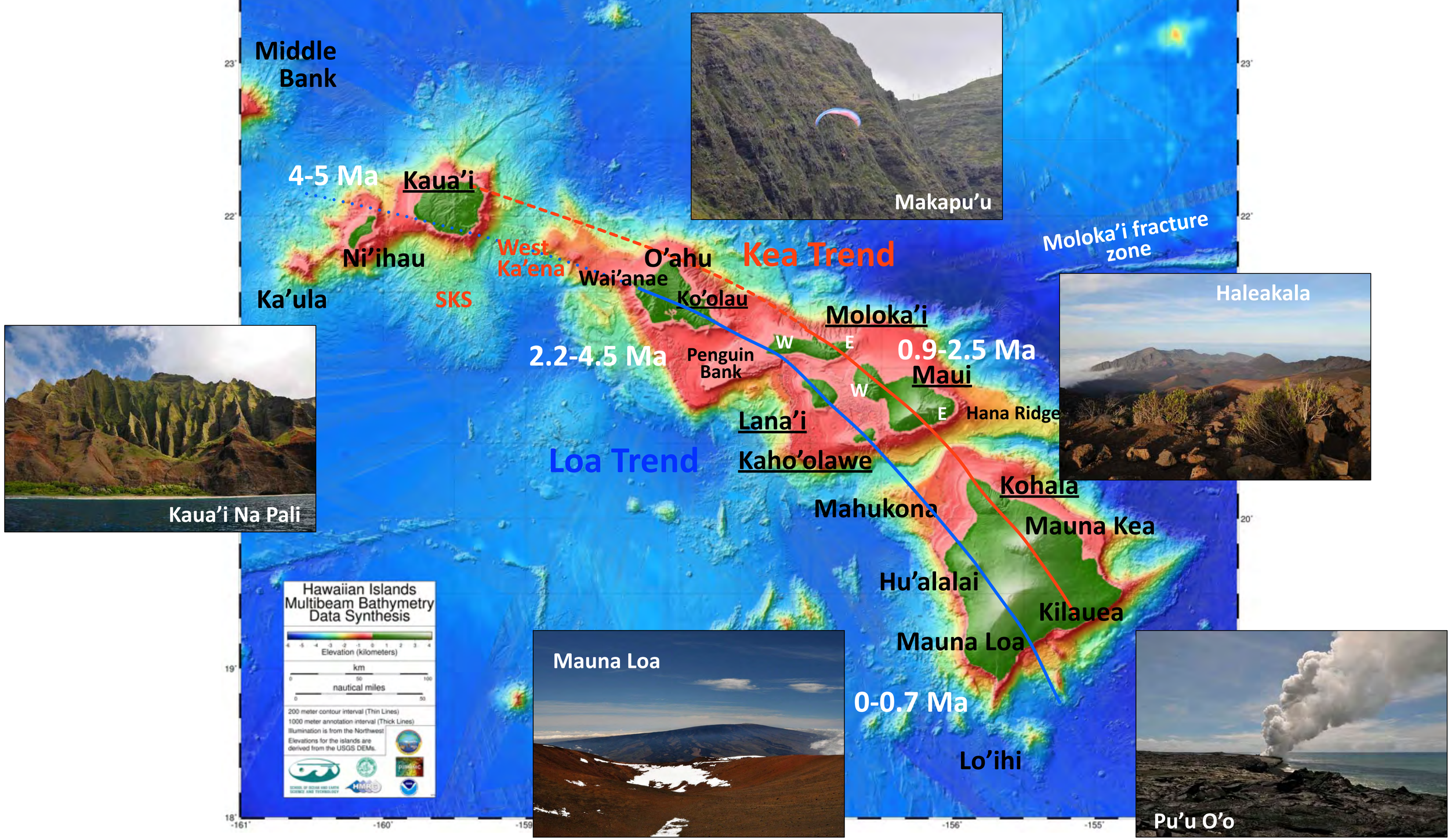
Hawaiian Shield Basalts Evolution over 4.5 myr

Hawaiian Plume Source: a Different Look and a Fine Structure

Northwestern Hawaiian Ridge: 45 myr



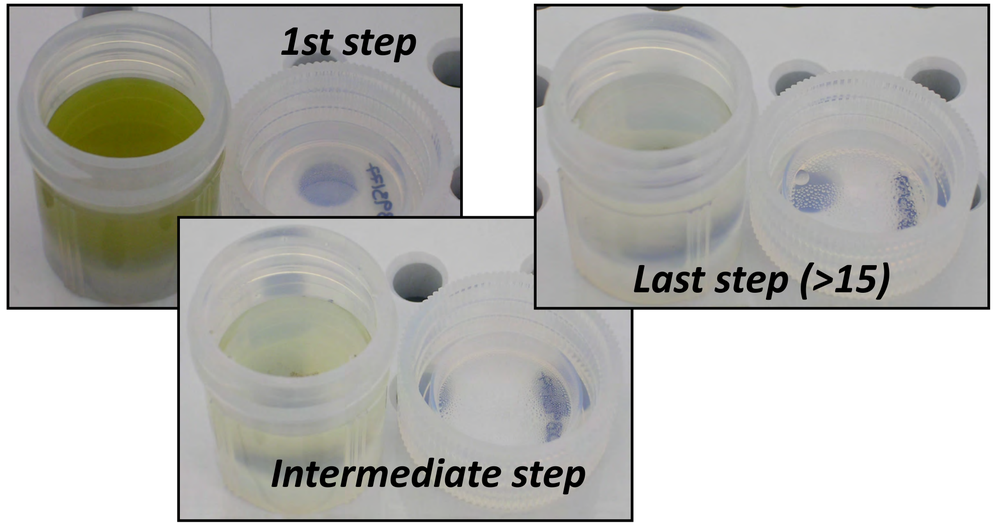
Kilauea Crater, April 2008


Middle Bank
4-5 Ma
Kaua'i
Ni'ihau
Ka'ula
SKS
West Ka'ena
Wai'anae
O'ahu
Kea Trend
Ko'olau
Moloka'i
W
E
2.2-4.5 Ma
Penguin Bank
0.9-2.5 Ma
Maui
W
E
Hana Ridge
Lana'i
Loa Trend
Kaho'olawe
Kohala
Mahukona
Mauna Kea
Hu'alalai
Kilauea
Mauna Loa
0-0.7 Ma
Lo'ihi
Moloka'i fracture zone
Makapu'u
Haleakala
Kaua'i Na Pali
Mauna Loa
Pu'u O'o
Hawaiian Islands Multibeam Bathymetry Data Synthesis
Elevation (kilometers)
km
nautical miles
200 meter contour interval (Thin Lines)
1000 meter annotation interval (Thick Lines)
Illumination is from the Northwest
Elevations for the islands are derived from the USGS DEMs.
23°
22°
20°
19°
18°
-161°
-160°
-159
-156°
-155°

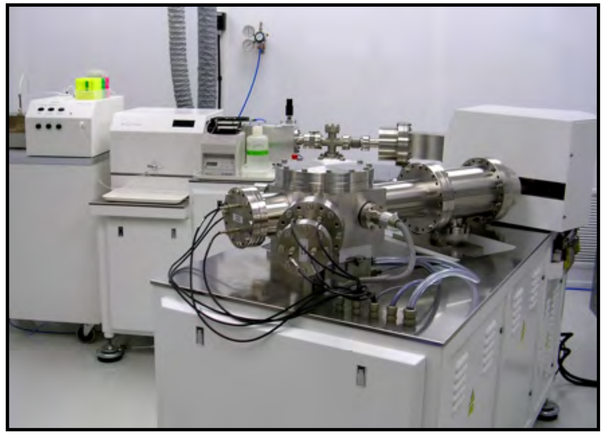
Samples, chem lab preparation and isotopic analyses

Sample Collection

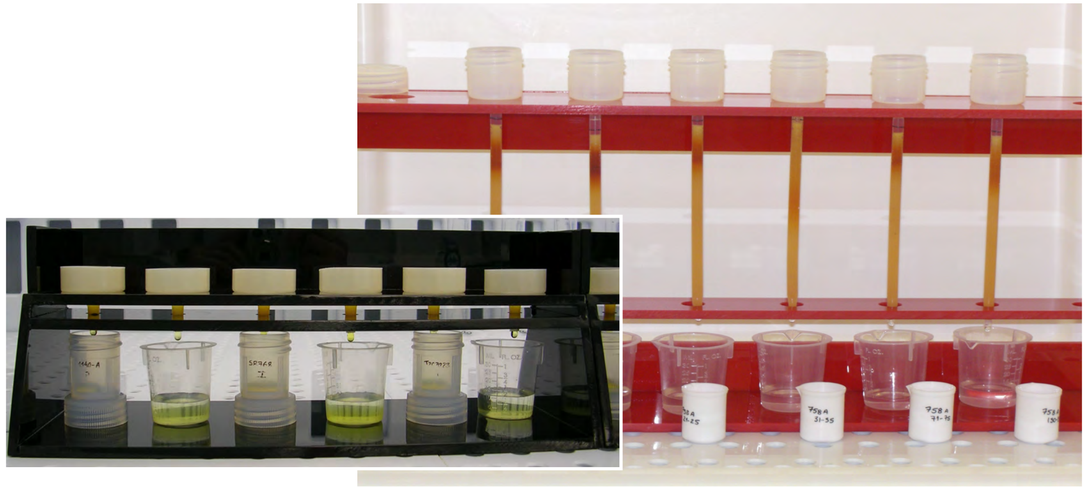
Sequential Acid Leaching



High-Precision Isotopic Analyses



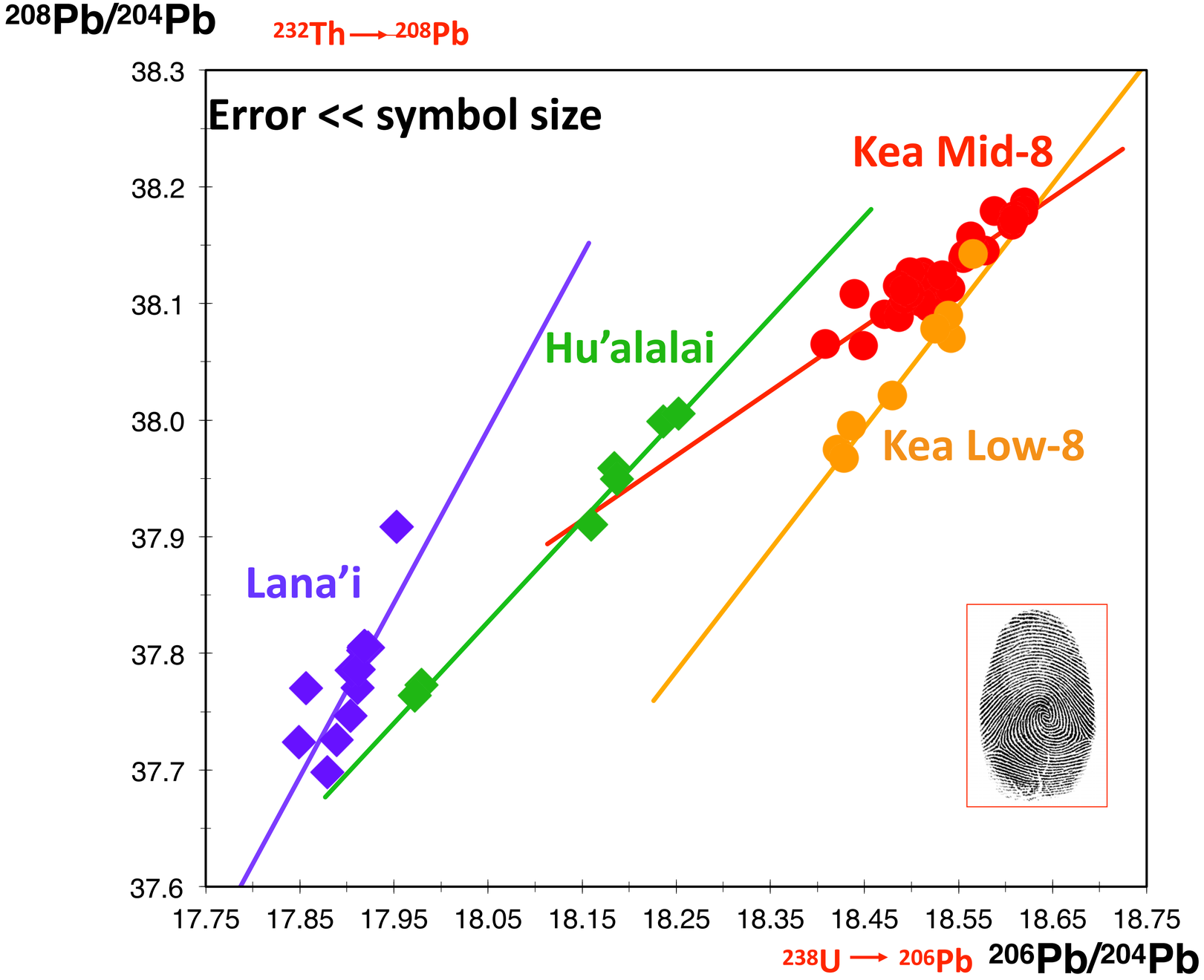
Chemical Separation

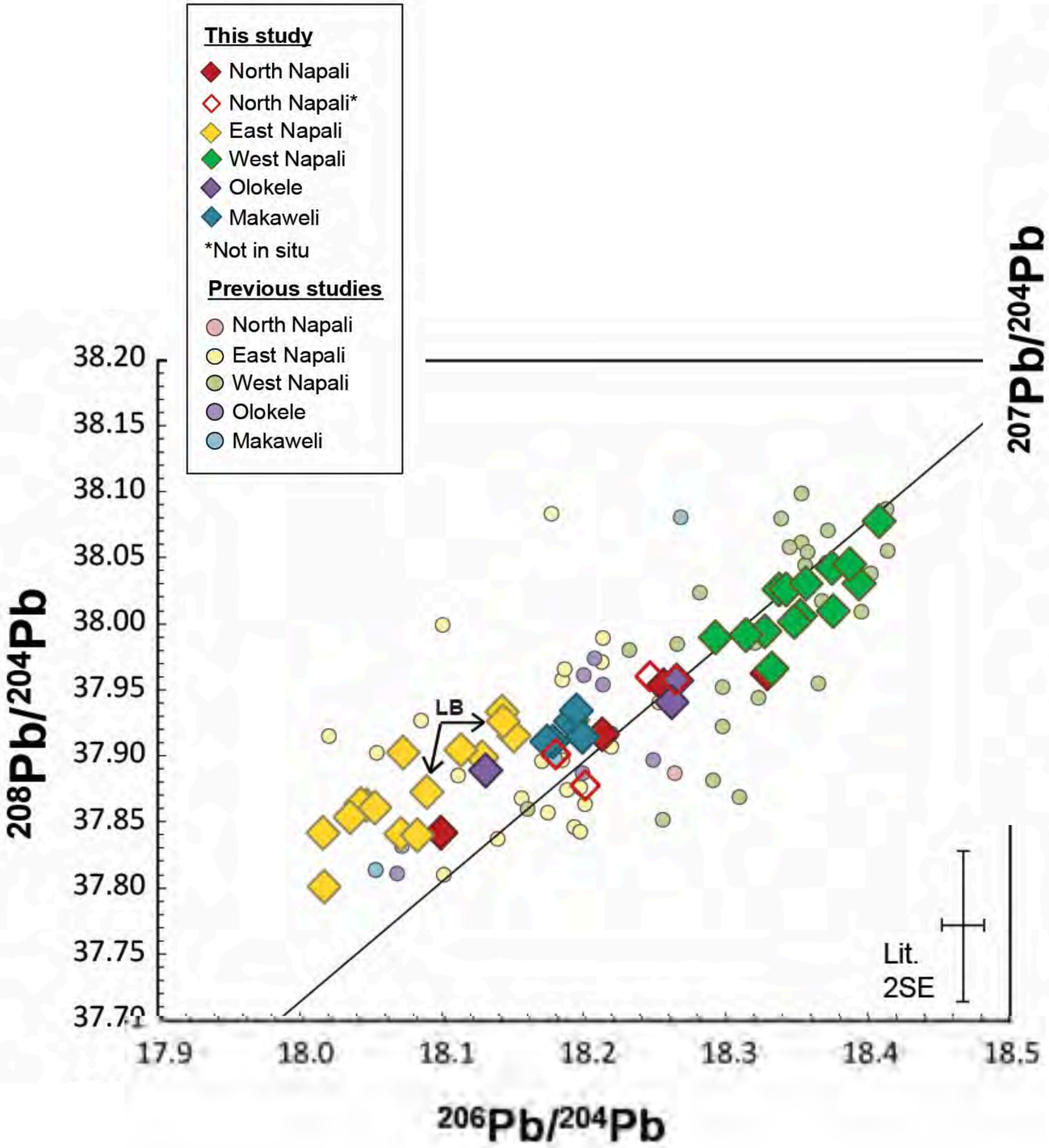


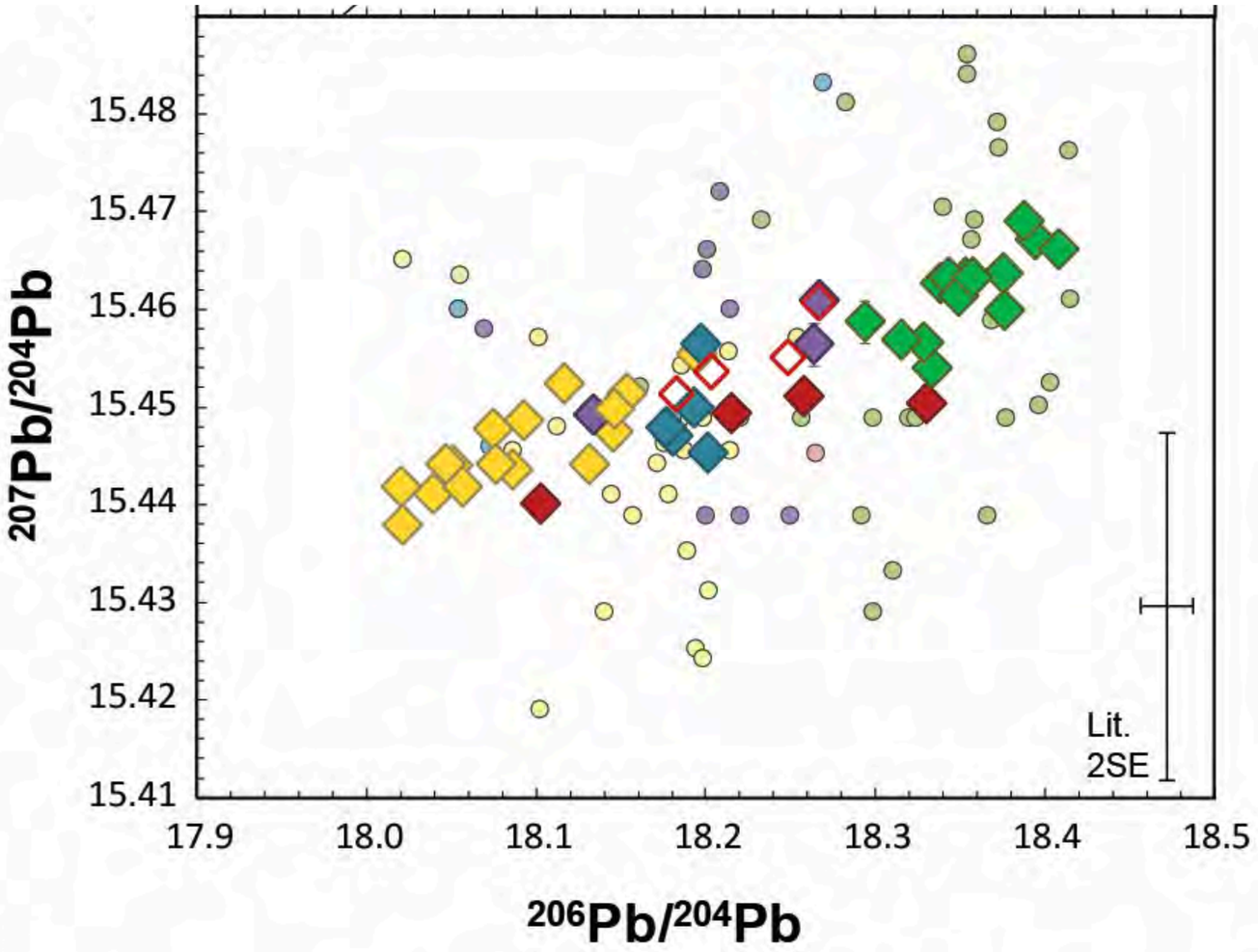

KIMTECH
KIMTECH
PARAFILM


nu instruments
SWL 5 t
pcigr

Pb-Pb Isotope Systematics: Improved Resolution



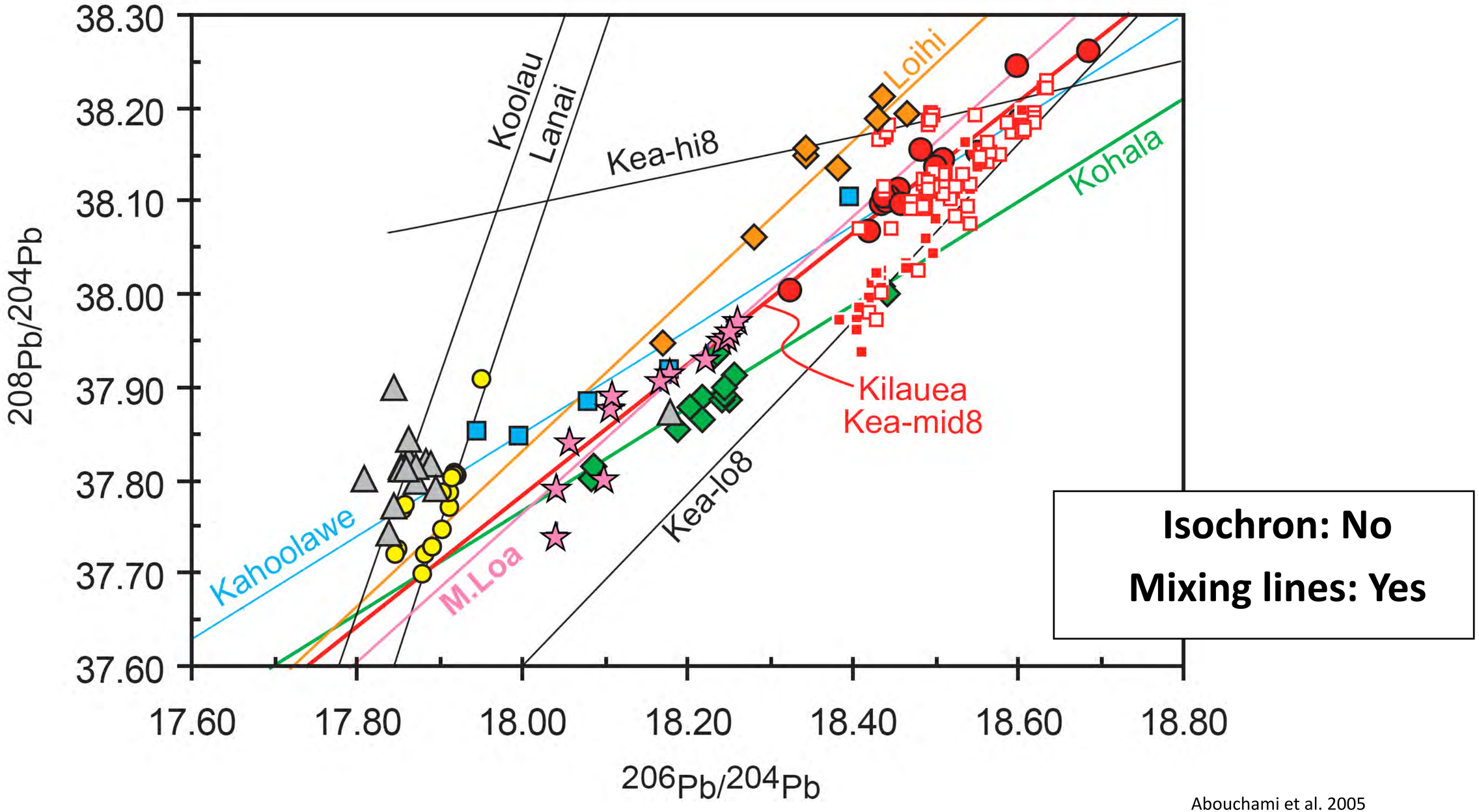




Pb-Pb Isotope Systematics Improved Resolution

Example of Kauai

Triple Spike Pb Isotope Data: Shield Stage Lavas



Abouchami et al. 2005

What do Pb Isotope Lines Mean?

✓ **Isochron:**

$$(^{206}Pb/^{204}Pb)_t = (^{206}Pb/^{204}Pb)_0 + (^{238}U/^{204}Pb)_t * (e^{\lambda t} - 1)$$

Same equation for $^{207}Pb/^{204}Pb$; by combining the two:

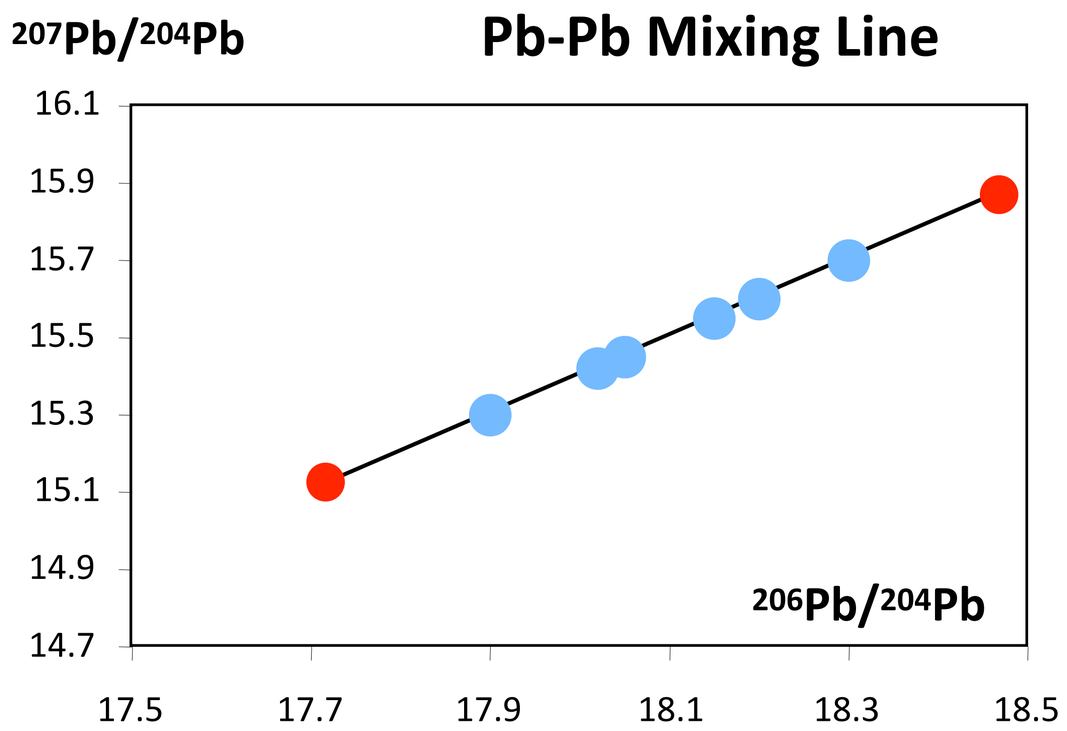
$$M = \frac{1}{137.88} * \frac{e^{\lambda_{235} * t} - 1}{e^{\lambda_{238} * t} - 1}$$

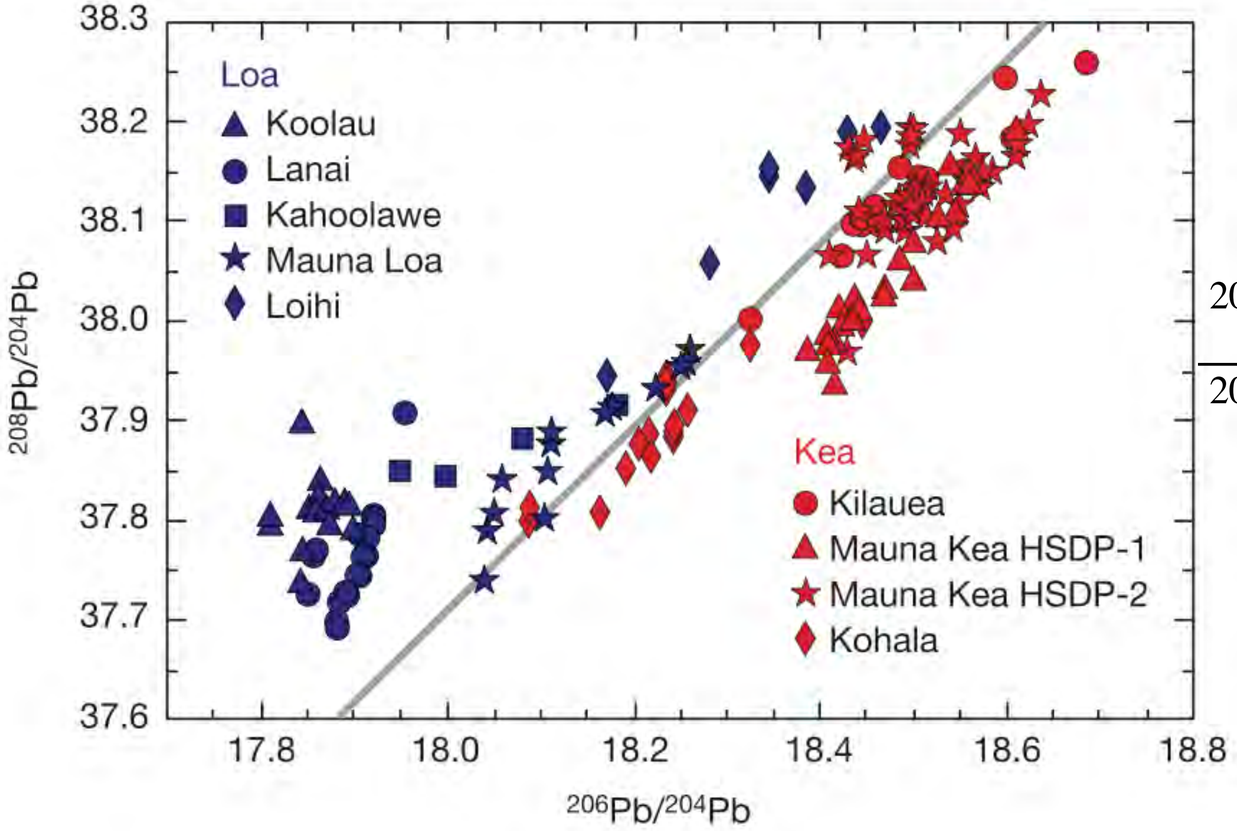
the slope in a ^{7}Pb-^{6}Pb diagram is directly a function of the age, or ...

✓ **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?

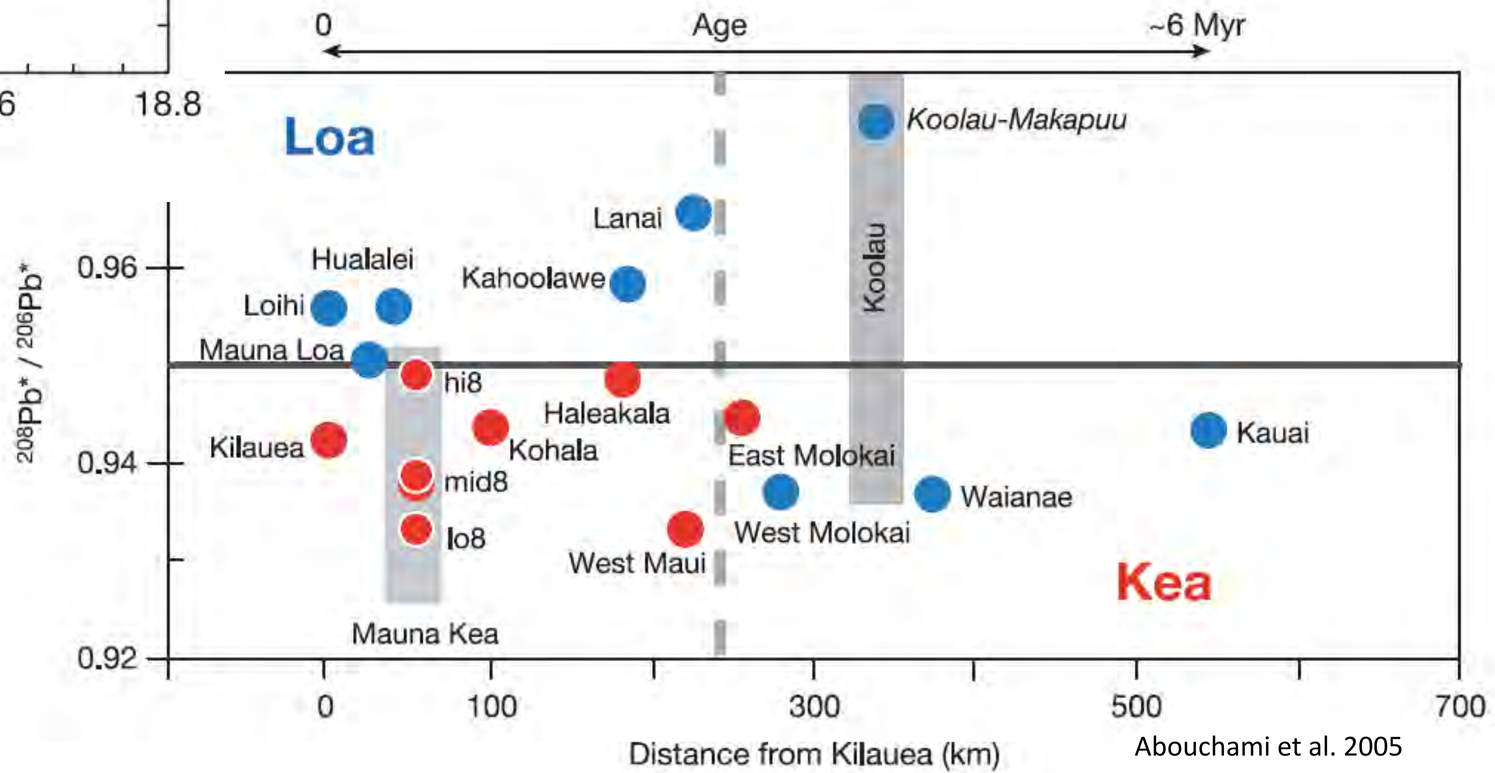




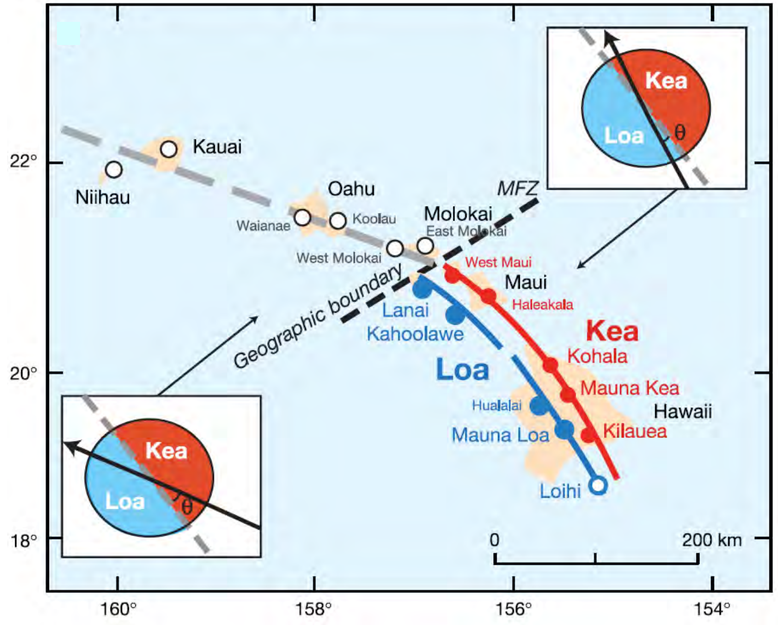
$$\frac{^{208*}Pb}{^{206*}Pb} = \frac{\left(^{208}Pb/^{204}Pb\right)_{sample} - \left(^{208}Pb/^{204}Pb\right)_{init}}{\left(^{206}Pb/^{204}Pb\right)_{sample} - \left(^{206}Pb/^{204}Pb\right)_{init}} \approx \frac{Th}{U}$$

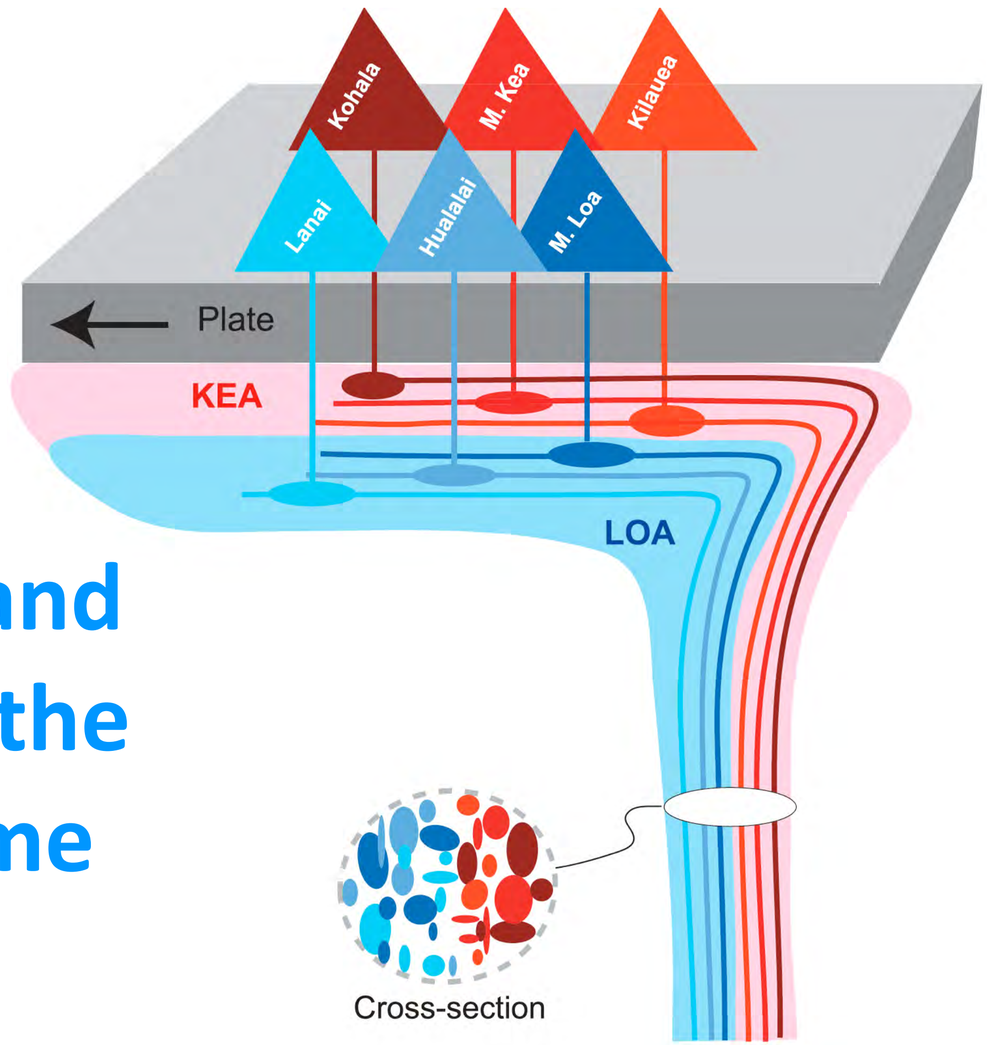
where init stands for Earth's primordial Pb isotopic composition

High-Precision Pb Hawai'i
Where did it start?



Abouchami et al. 2005

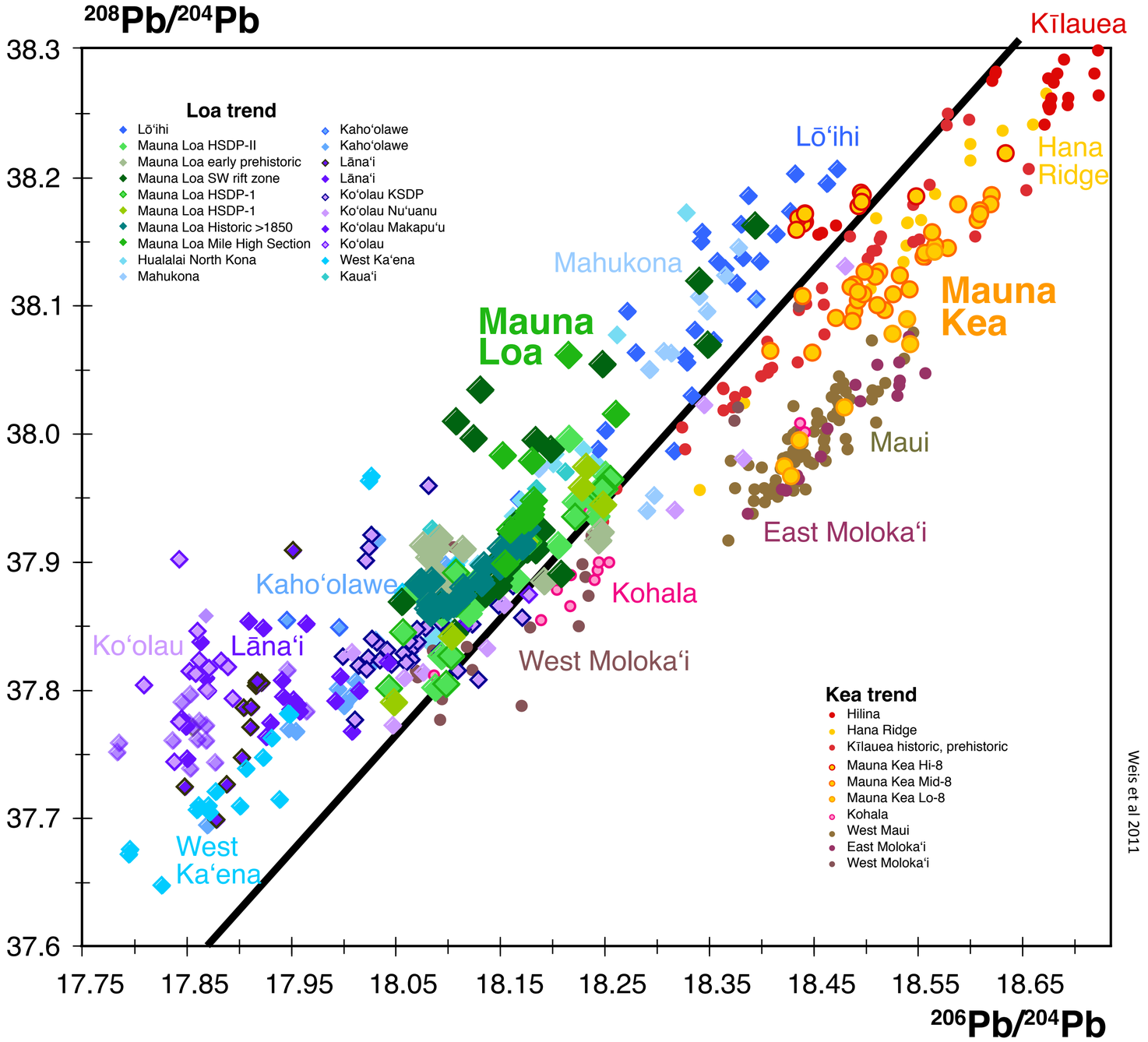




Bilateral Asymmetry and Vertical Continuity in the Hawaiian Mantle Plume

Abouchami et al. 2005

High-Precision Pb Isotope Data: Hawai‘i Shield Lavas

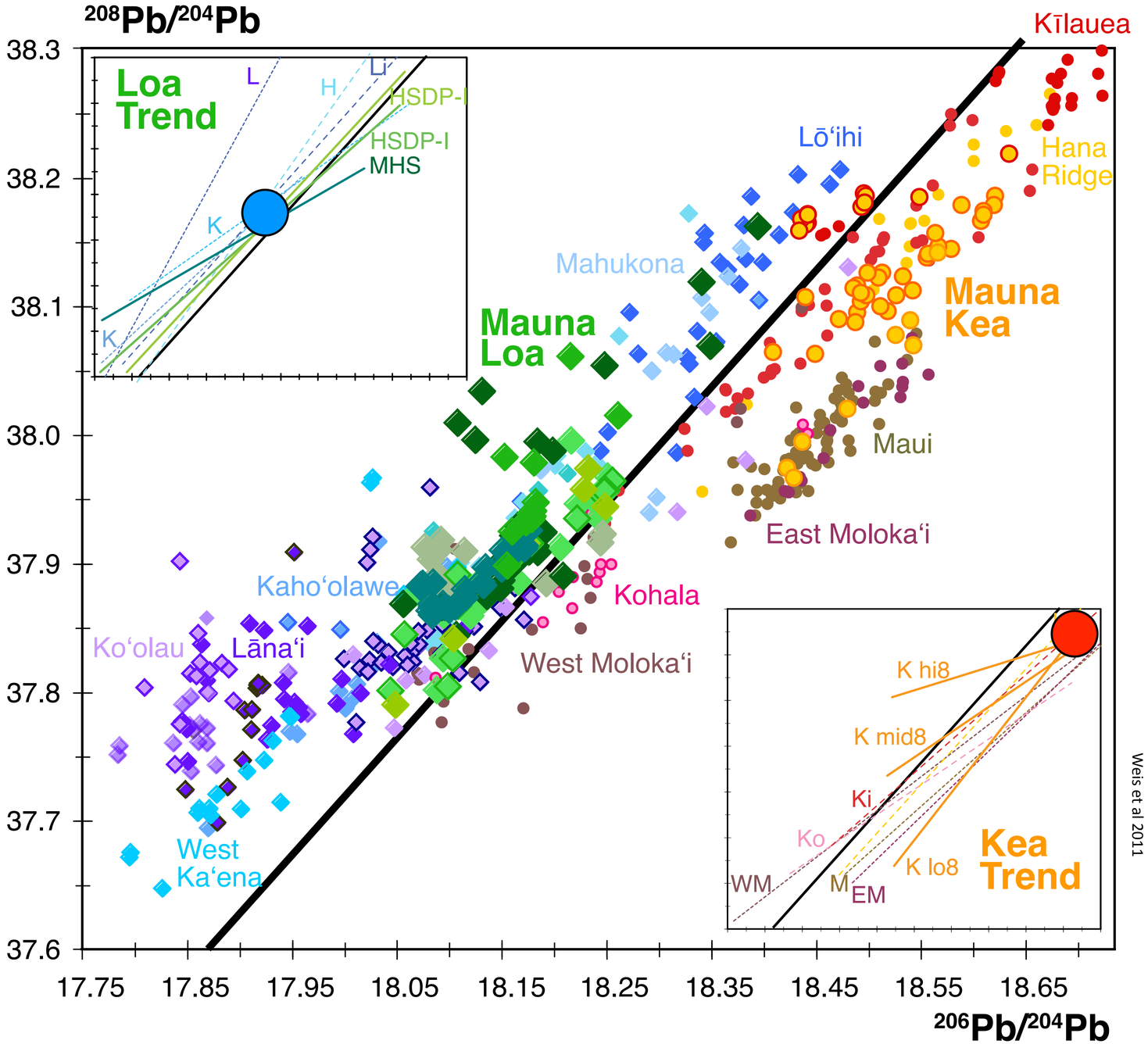


Only shield lavas

>700 samples

(MC-ICP-MS or TS)/NORM

High-Precision Pb Isotope Data: Hawai‘i Shield Lavas



Weis et al 2011

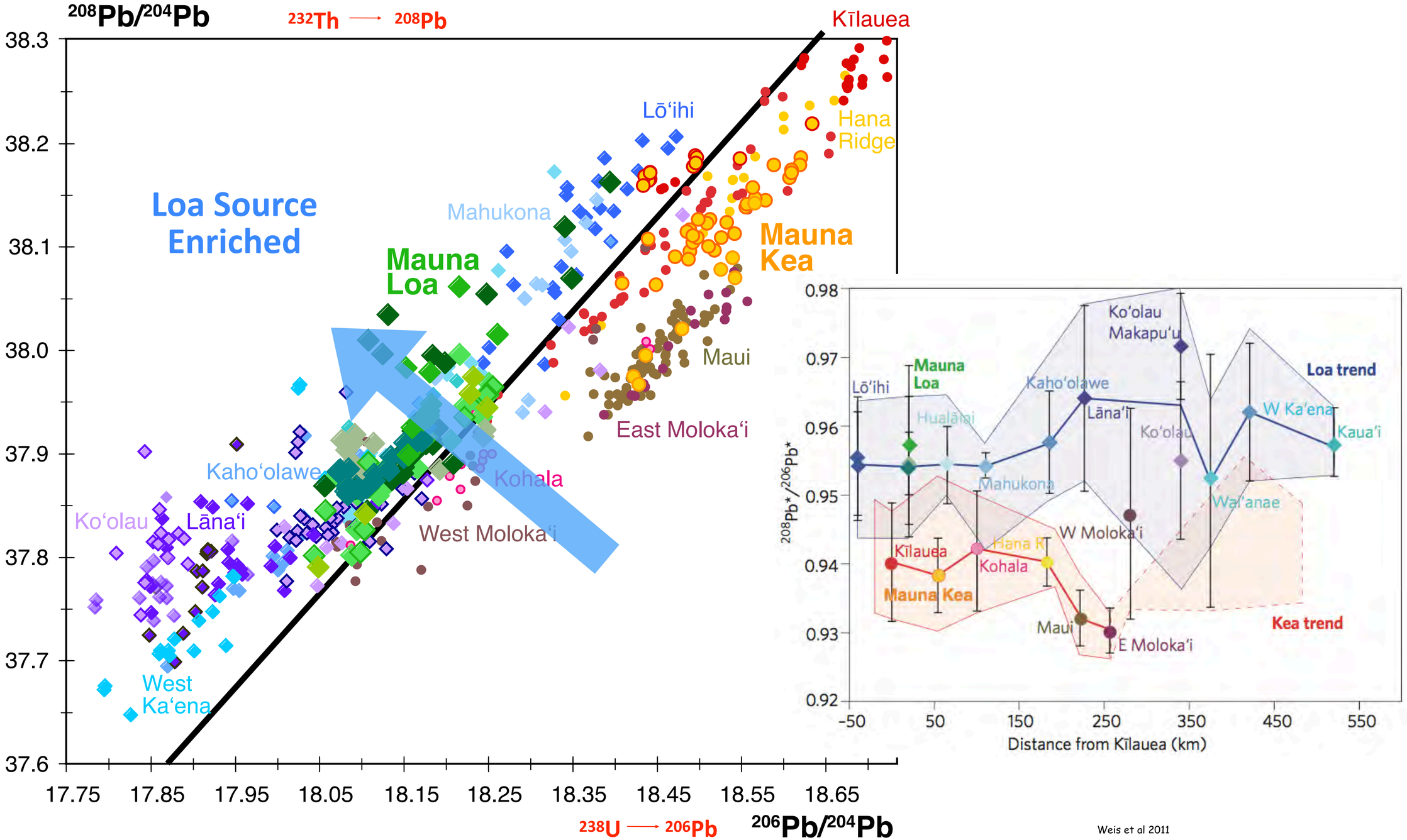
Kea end-member:

- common to many Pacific islands
- similar to “c” or super chondritic BSE

Loa trend volcanoes:

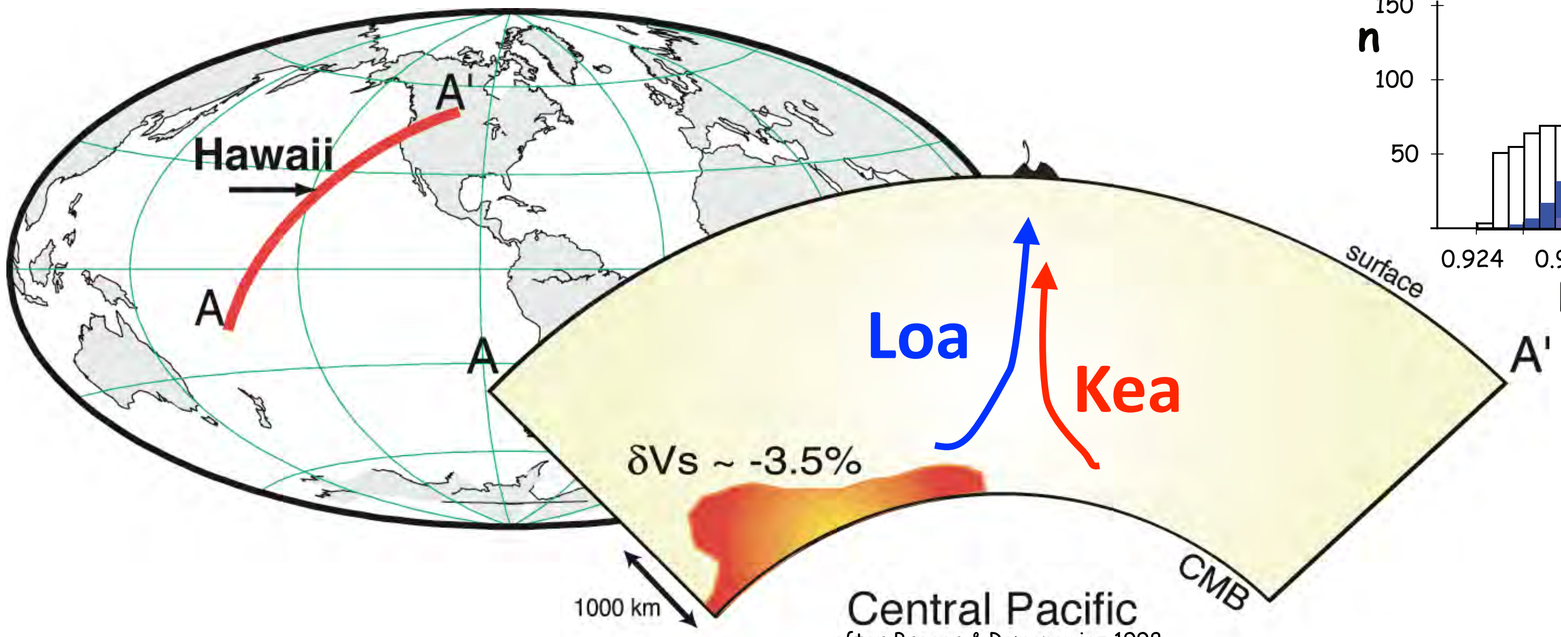
- higher $^{208}Pb/^{204}Pb$ ratios for a given $^{206}Pb/^{204}Pb$, higher $^{87}Sr/^{86}Sr$ and lower ε_{Nd} and ε_{Hf}
- **more heterogeneous**

Radiogenic Pb: $^{208}Pb^*/^{206}Pb^*$: Th/U Proxy

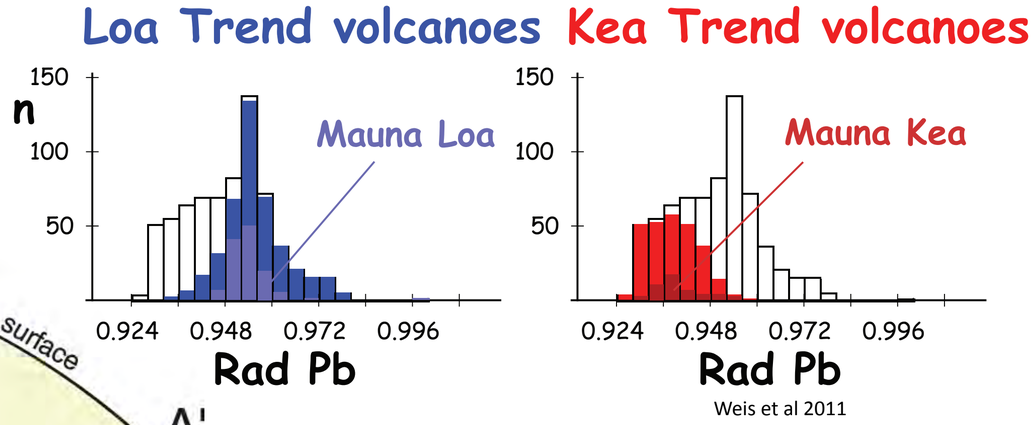


Weis et al 2011

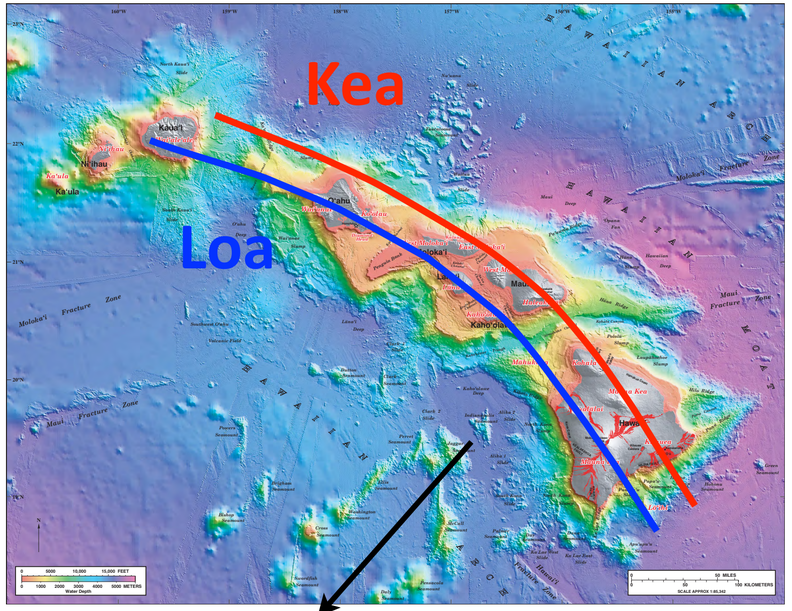
Possible plume location cross-section



Central Pacific
after Breger & Romanowicz 1998

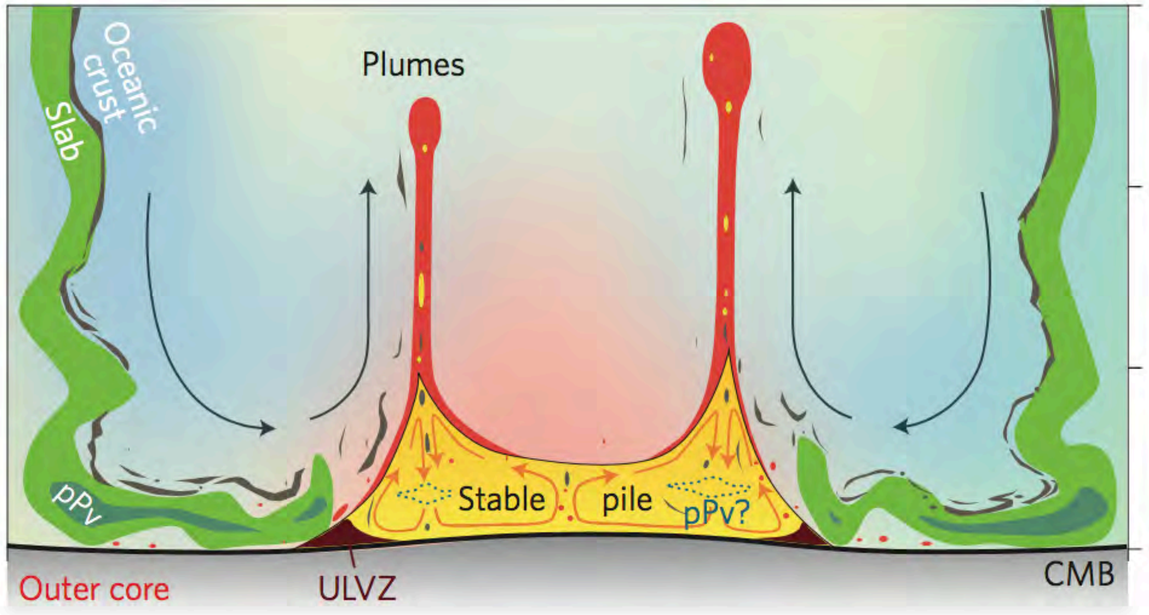


Weis et al 2011



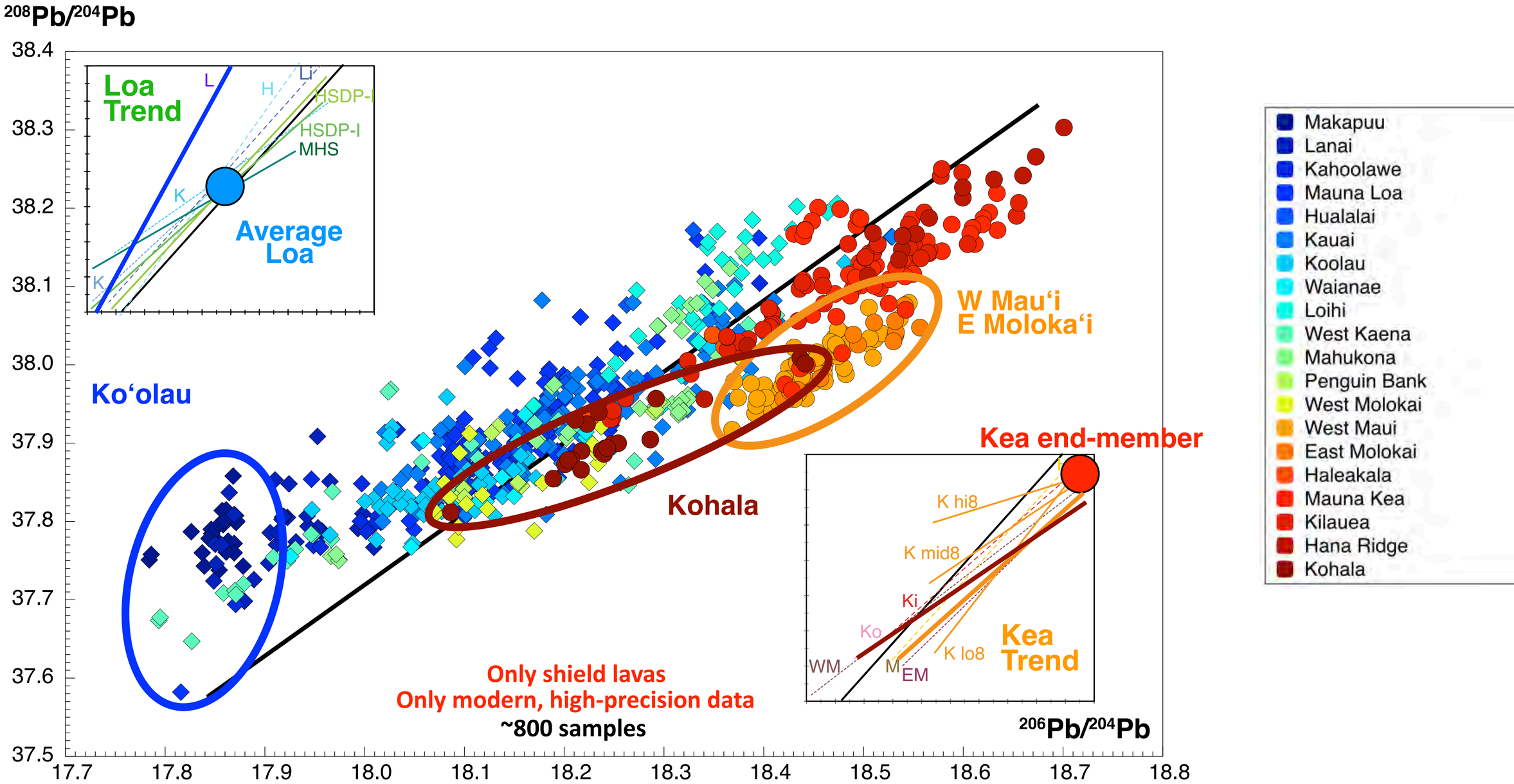
Pacific ULVZ

Complex CMB



Garnero et al 2016

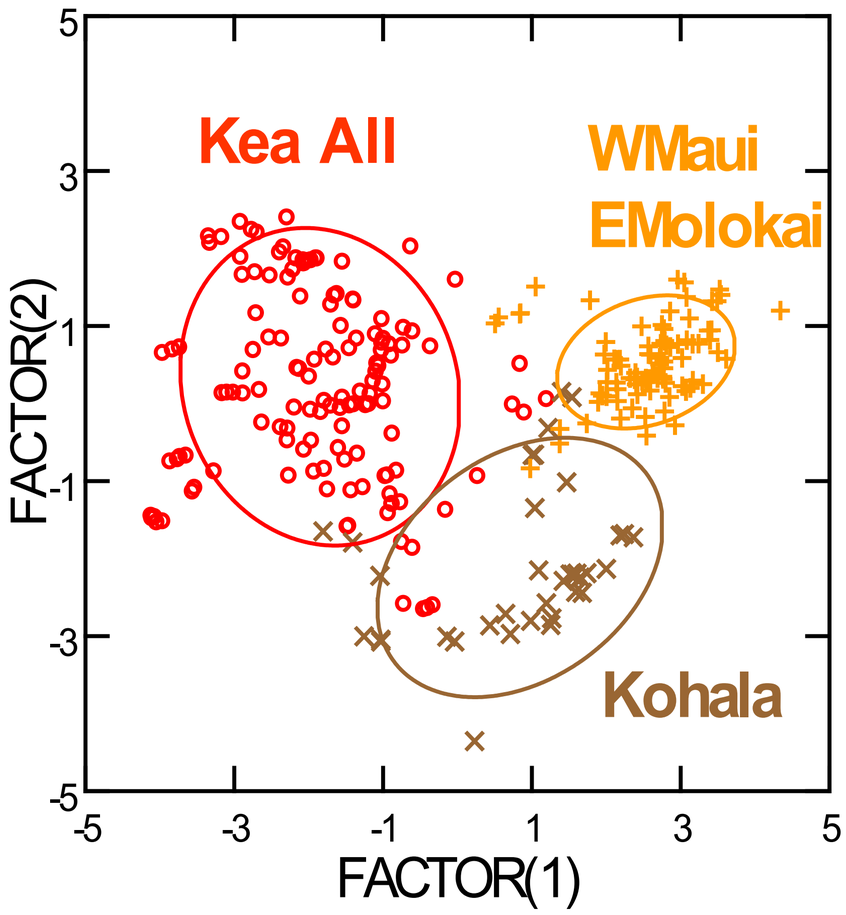
A Simple Bilateral Source? Some Challenges



Kea vs Loa: 95% Accuracy

Kea Volcanoes

Canonical Scores Plot



Group Frequencies

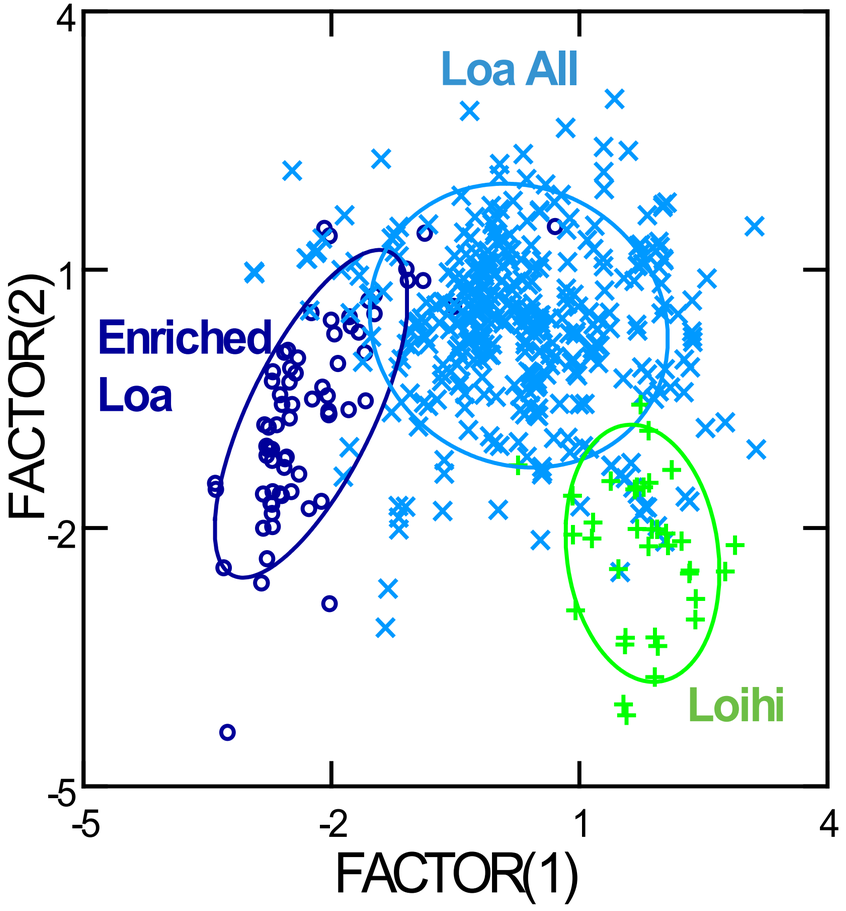
Kea	***Kohala***	***WMaui EMolokai***
136	***36***	***87***

Group Frequencies

Enriched Loa	***Loa***	***Loihi***
71	***366***	***35***

Loa Volcanoes

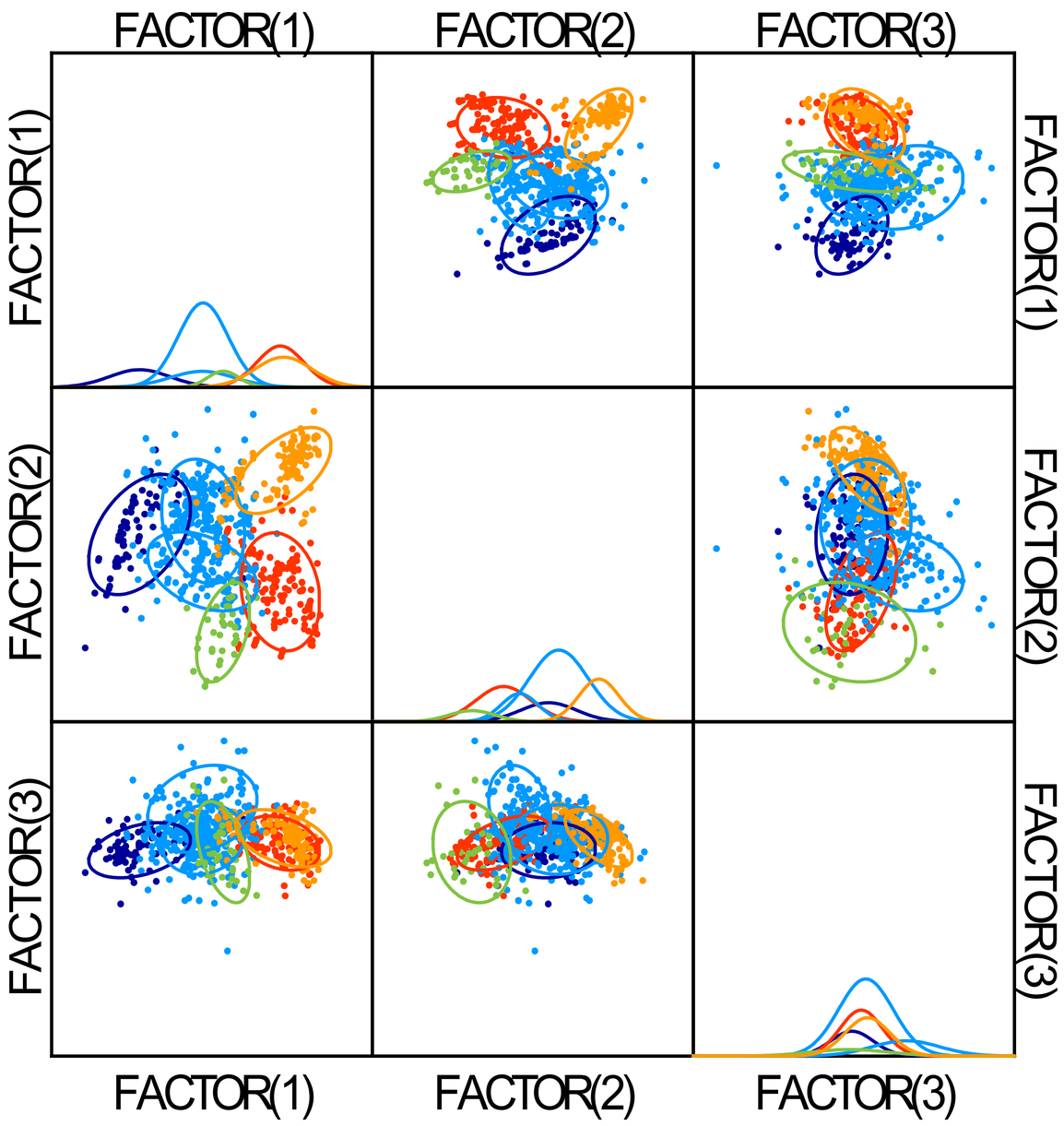
Canonical Scores Plot



Rhy McMillan, PCIGR

Hawaii Shield Lavas

Canonical Scores Plot



Pb Isotopes

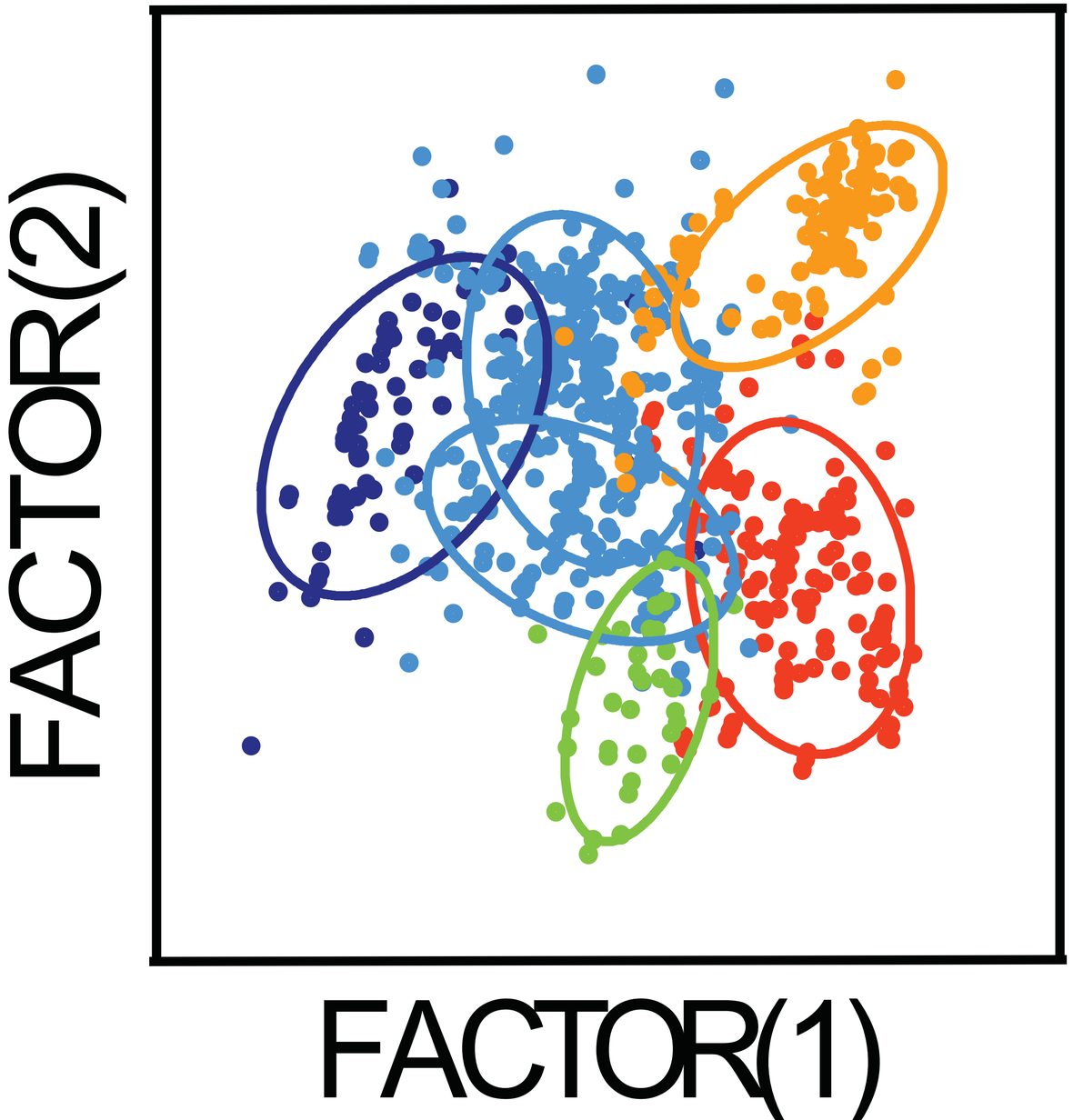
Group Frequencies

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

Rhy McMillan, PCIGR

Hawaii Shield Lavas

Canonical Scores Plot



Pb Isotopes

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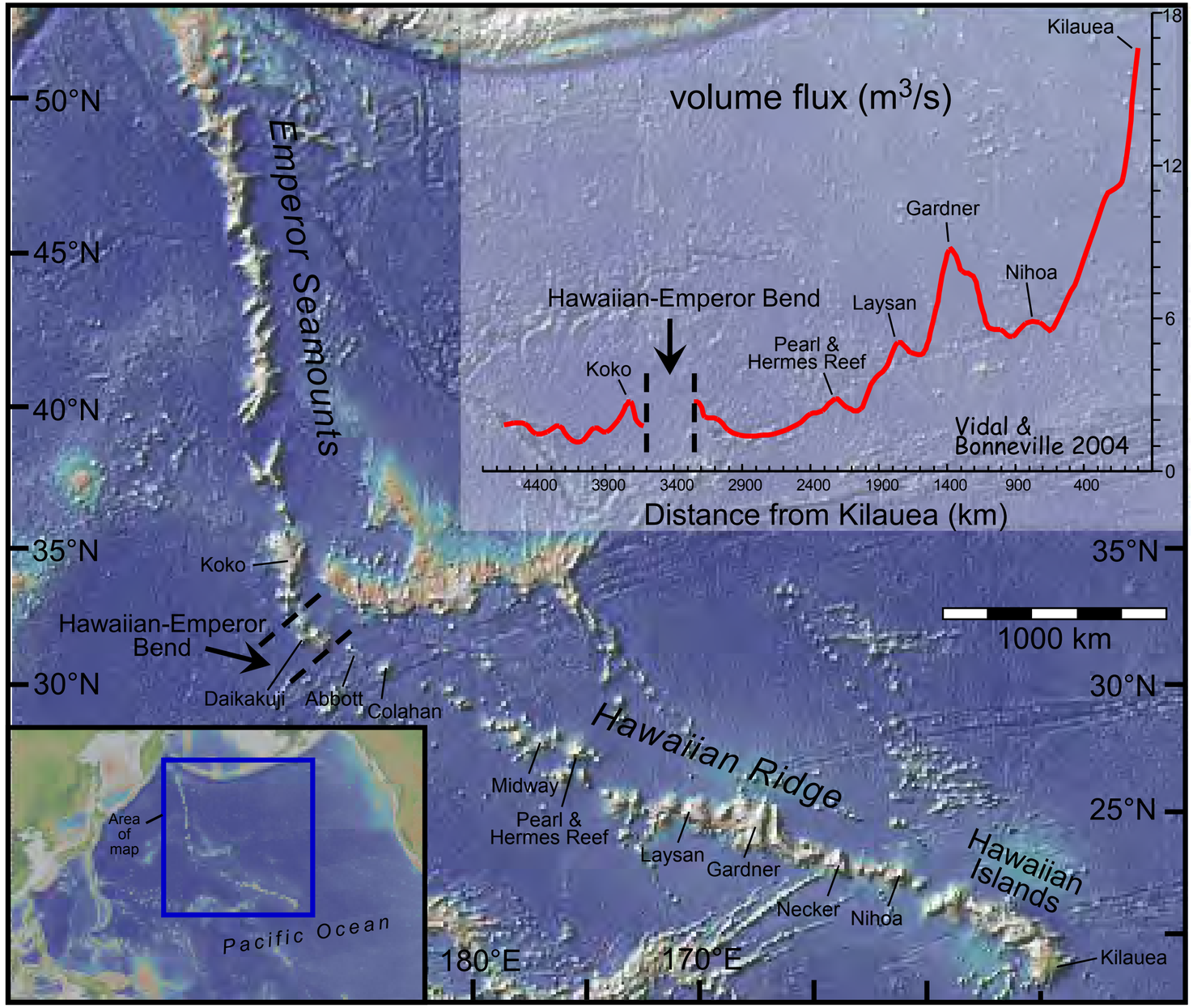
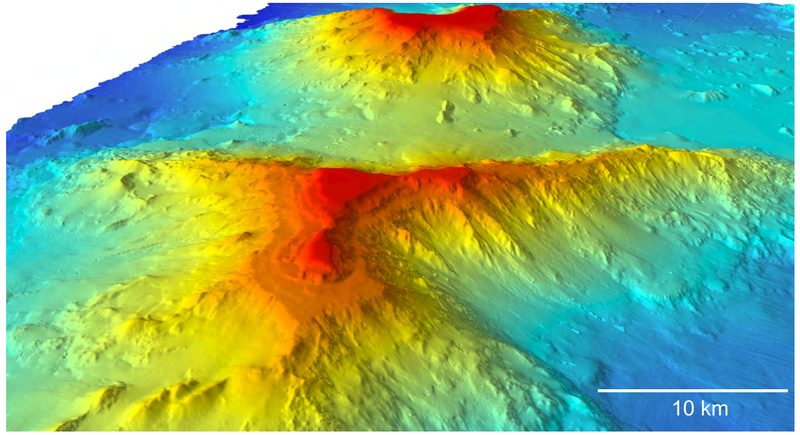
Rhy McMillan, PCIGR

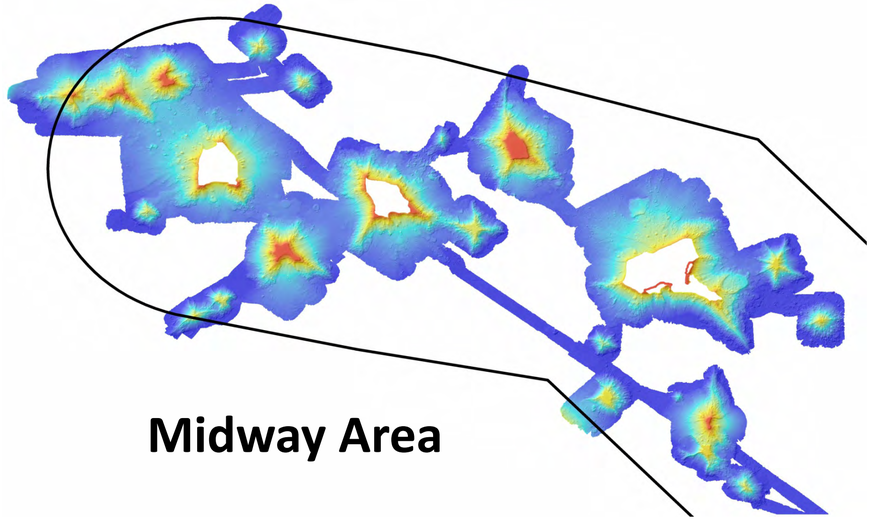
Back in Time: Hawaiian Ridge-Emperor Seamounts 85 myr



R/V Falkor Mapping,
Schmidt Ocean Institute 2013

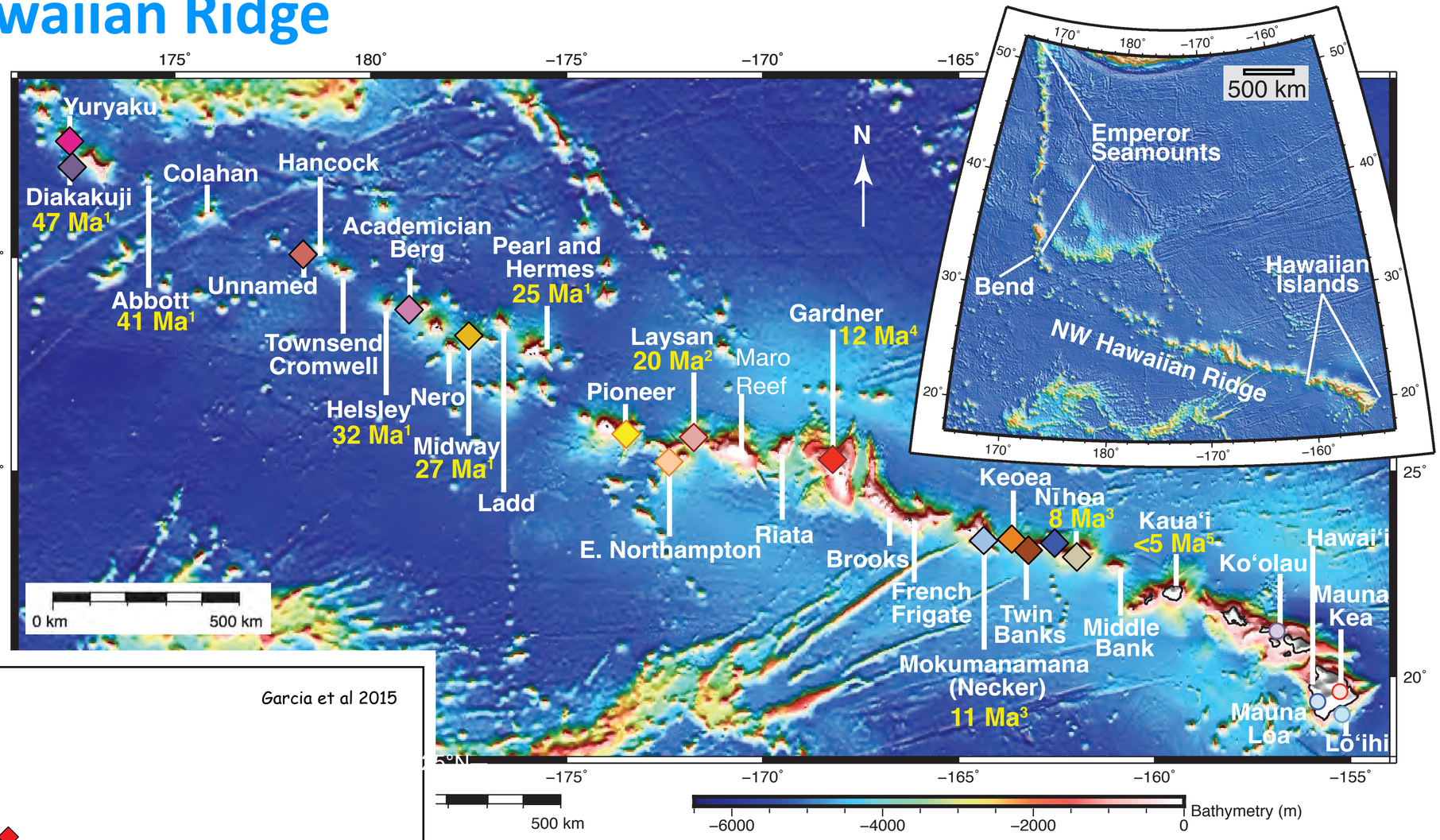


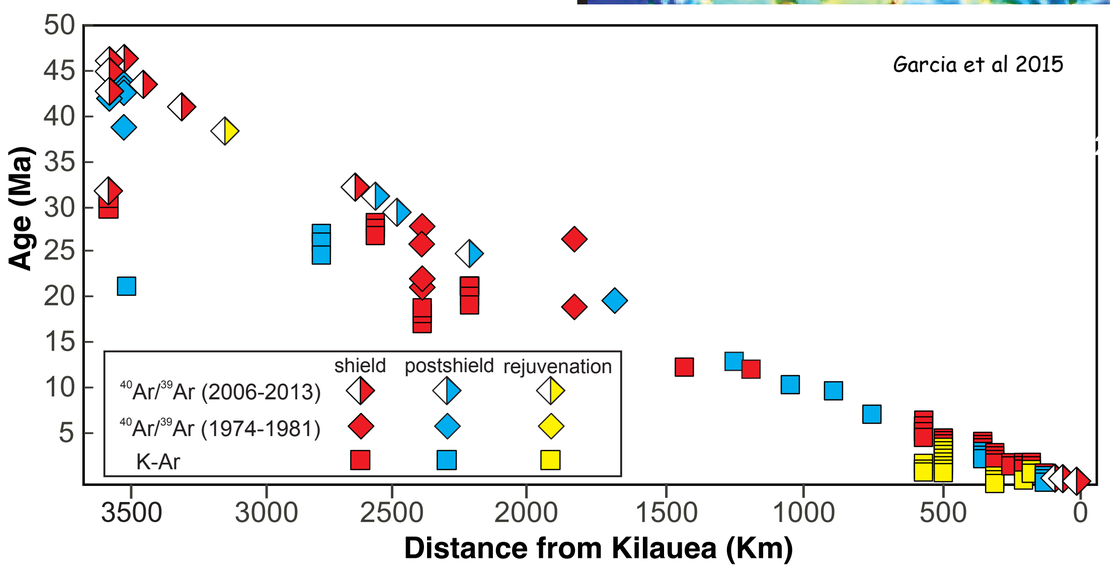
Turnif & Academician Berg Seamounts



Midway Area

Northwestern Hawaiian Ridge

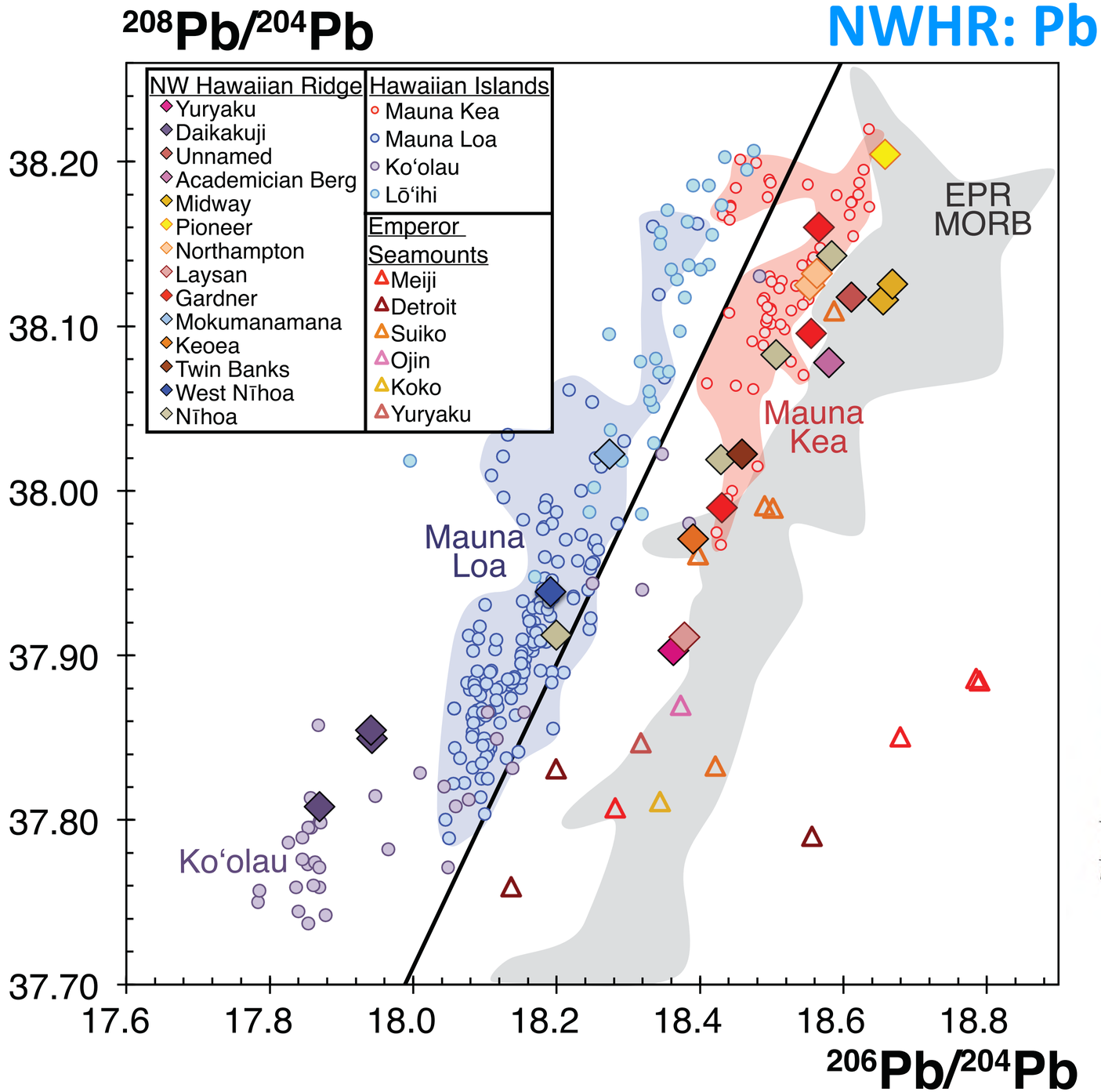


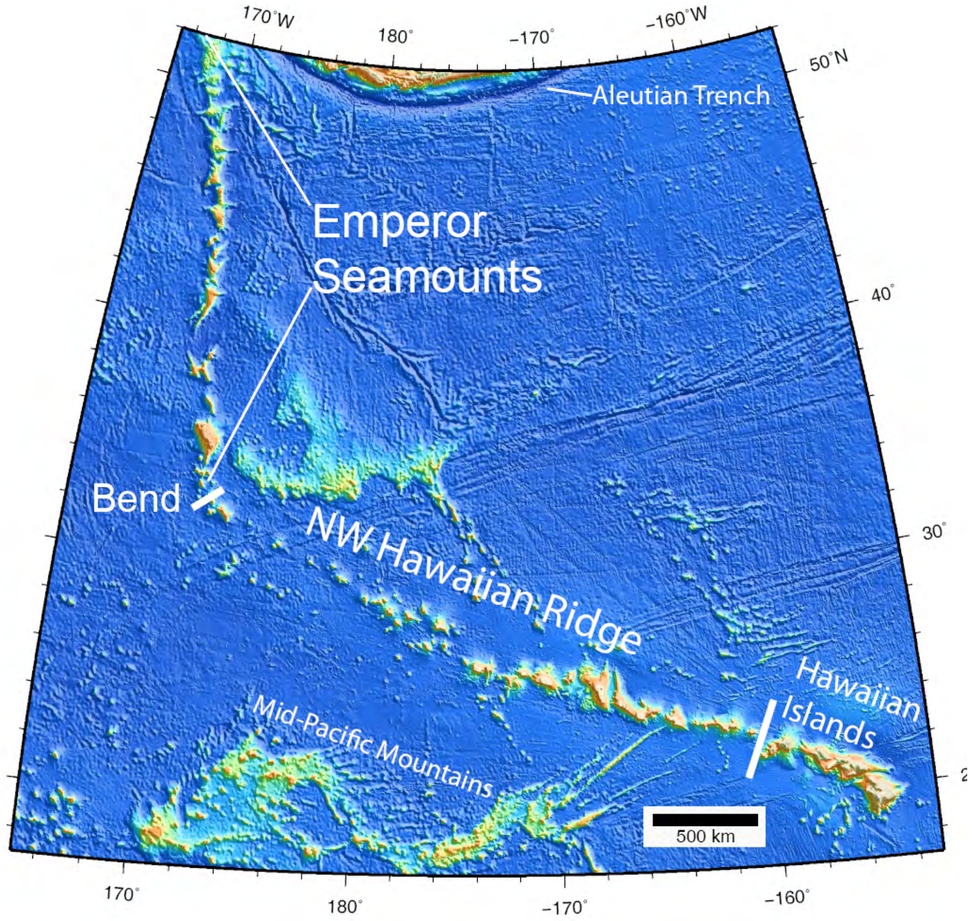


42 myr from the bend to the islands
24 shield-stage samples from
13 volcanoes

L. Harrison PhD Thesis

NWHR: Pb Isotope Systematics

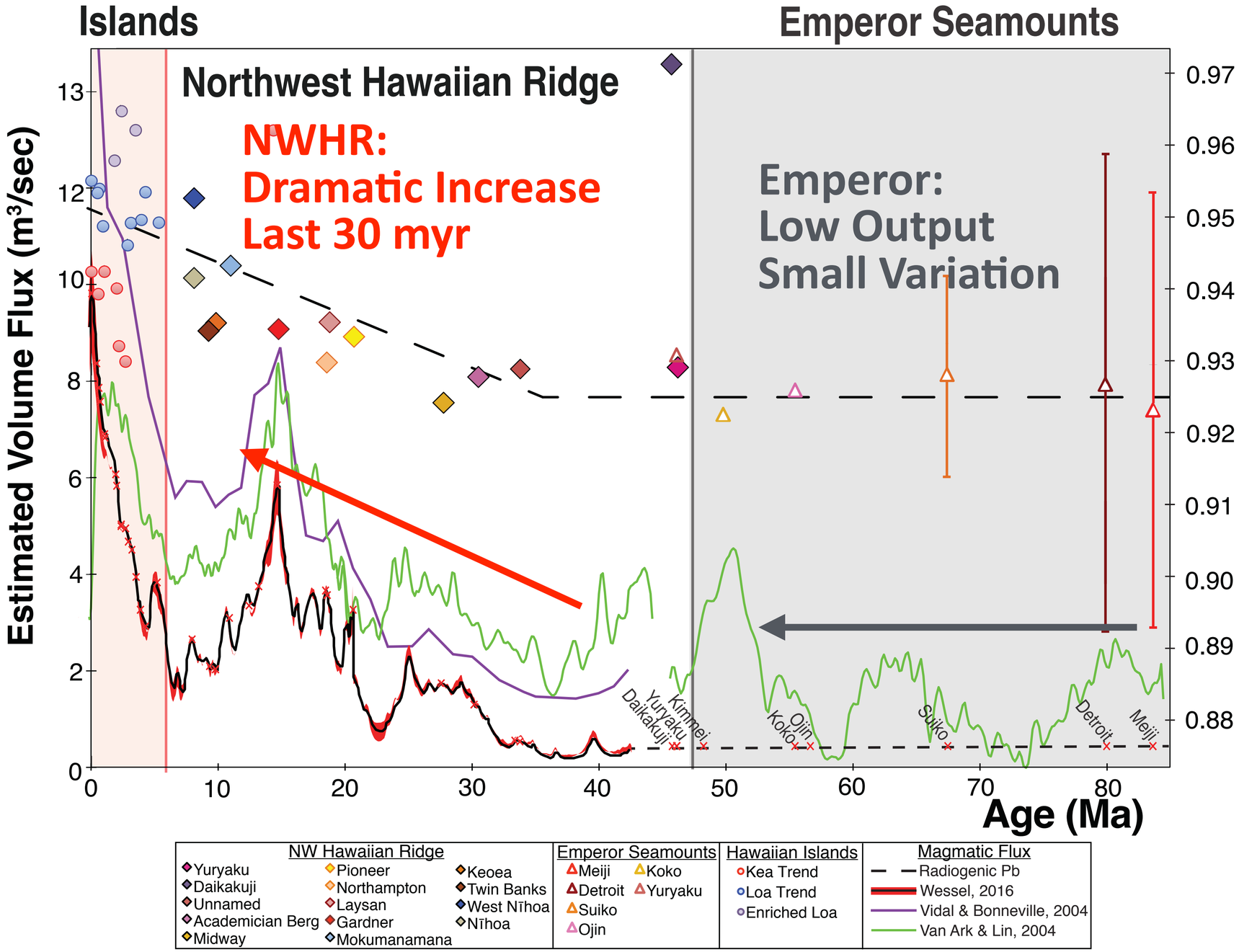


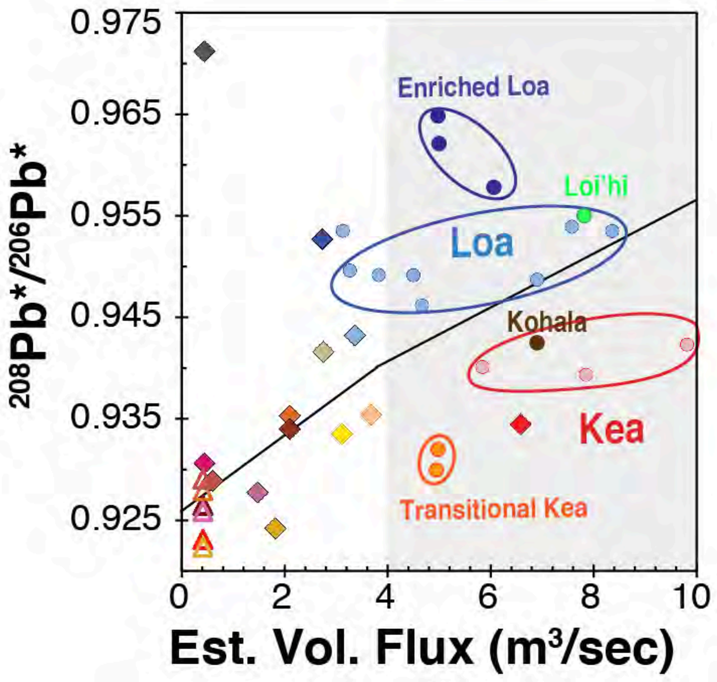


Garcia et al 2015

Harrison et al
EPSL 2017

NWHR Pb Isotope Variations vs Plume Magmatic Flux and Distance from Kilauea





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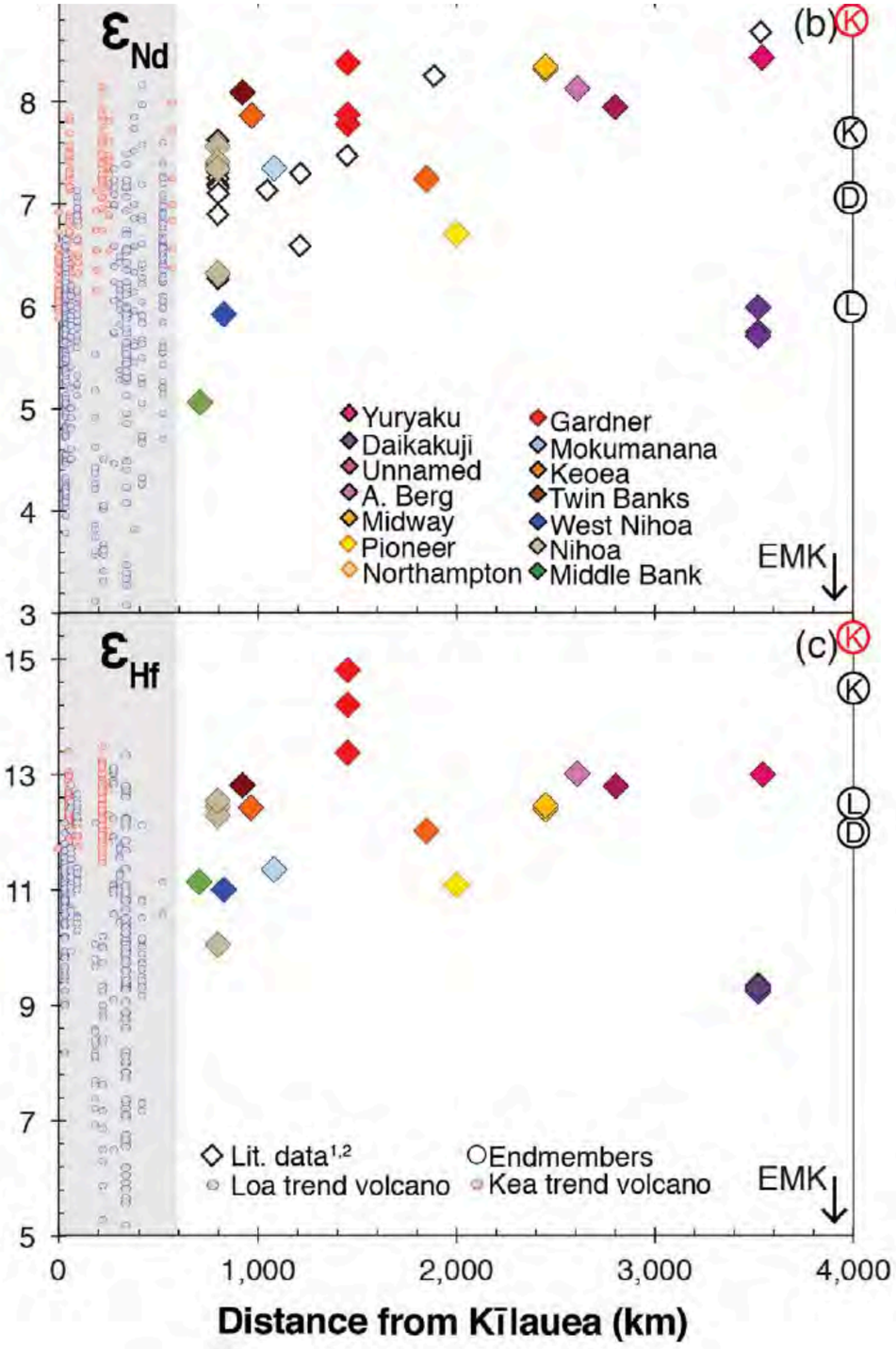
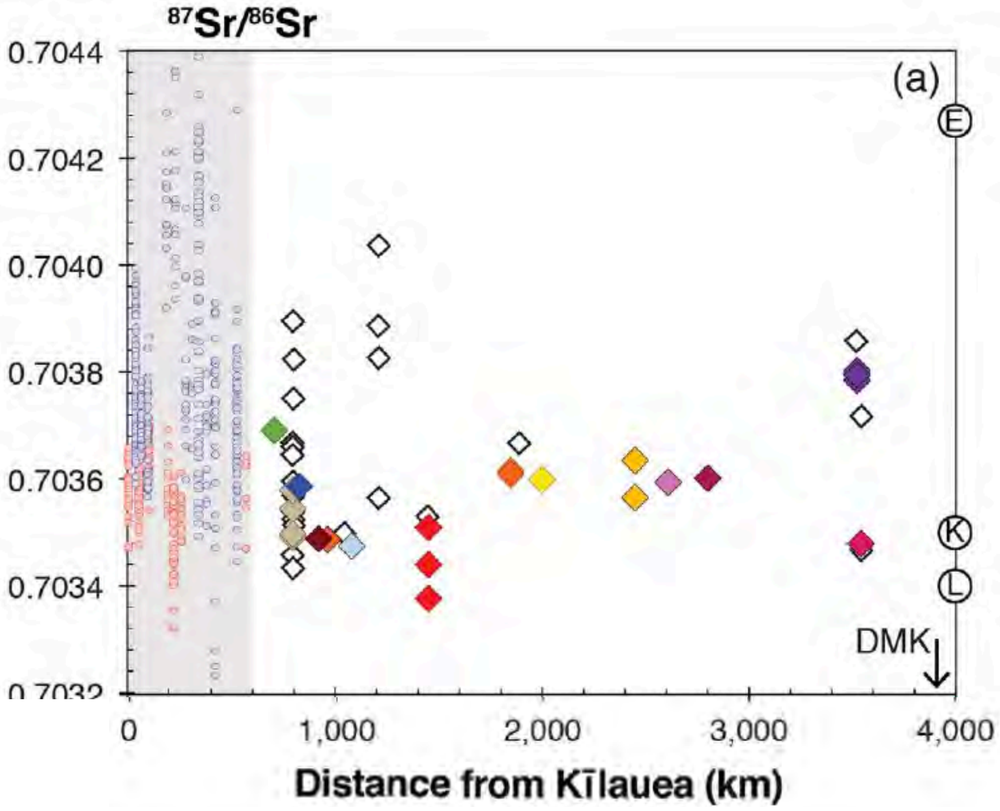
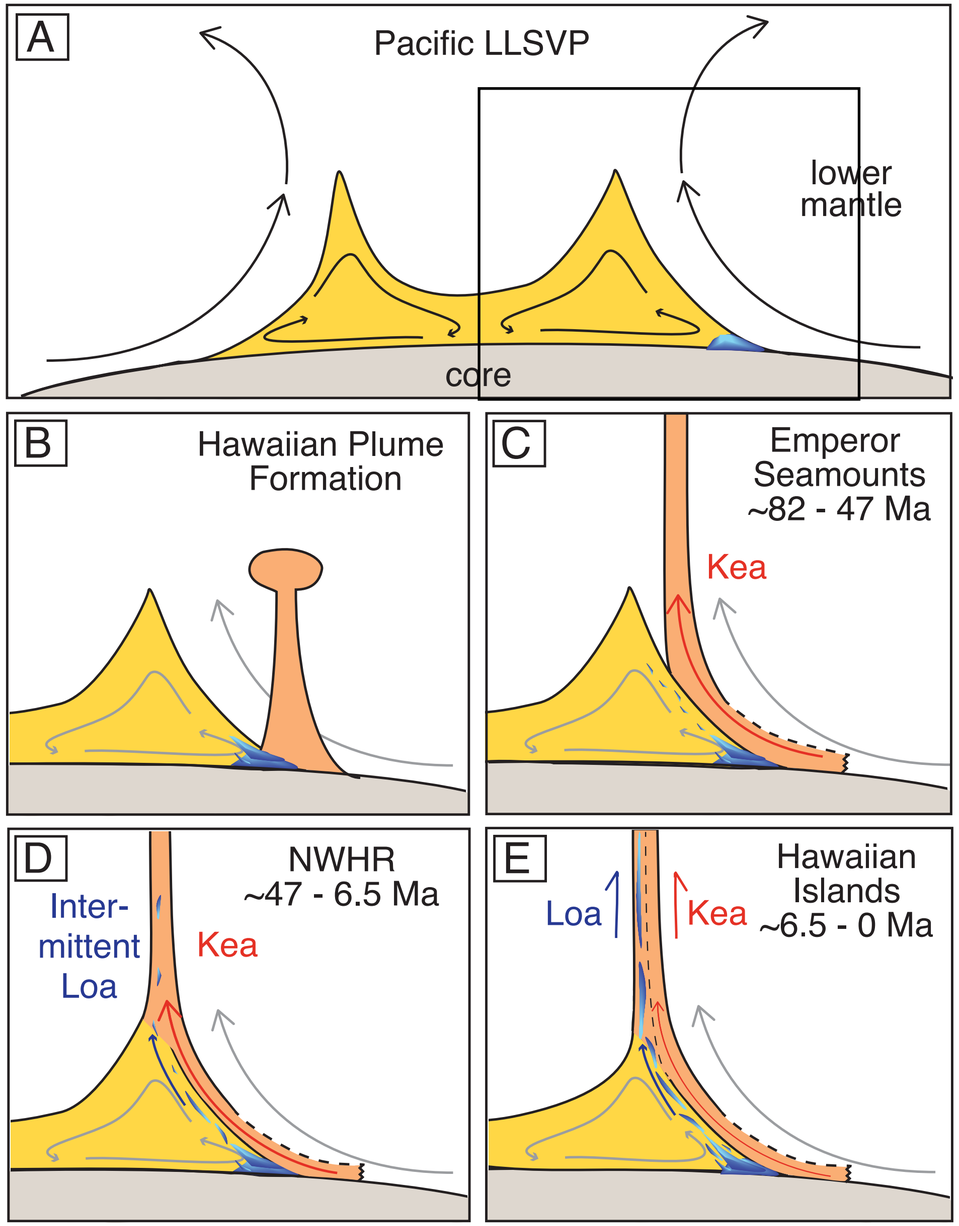




Harrison & Weis
in press G3

Evolution of the Hawaiian Plume Source at the CMB since inception



Harrison et al
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Hawaiian Islands Geochemistry

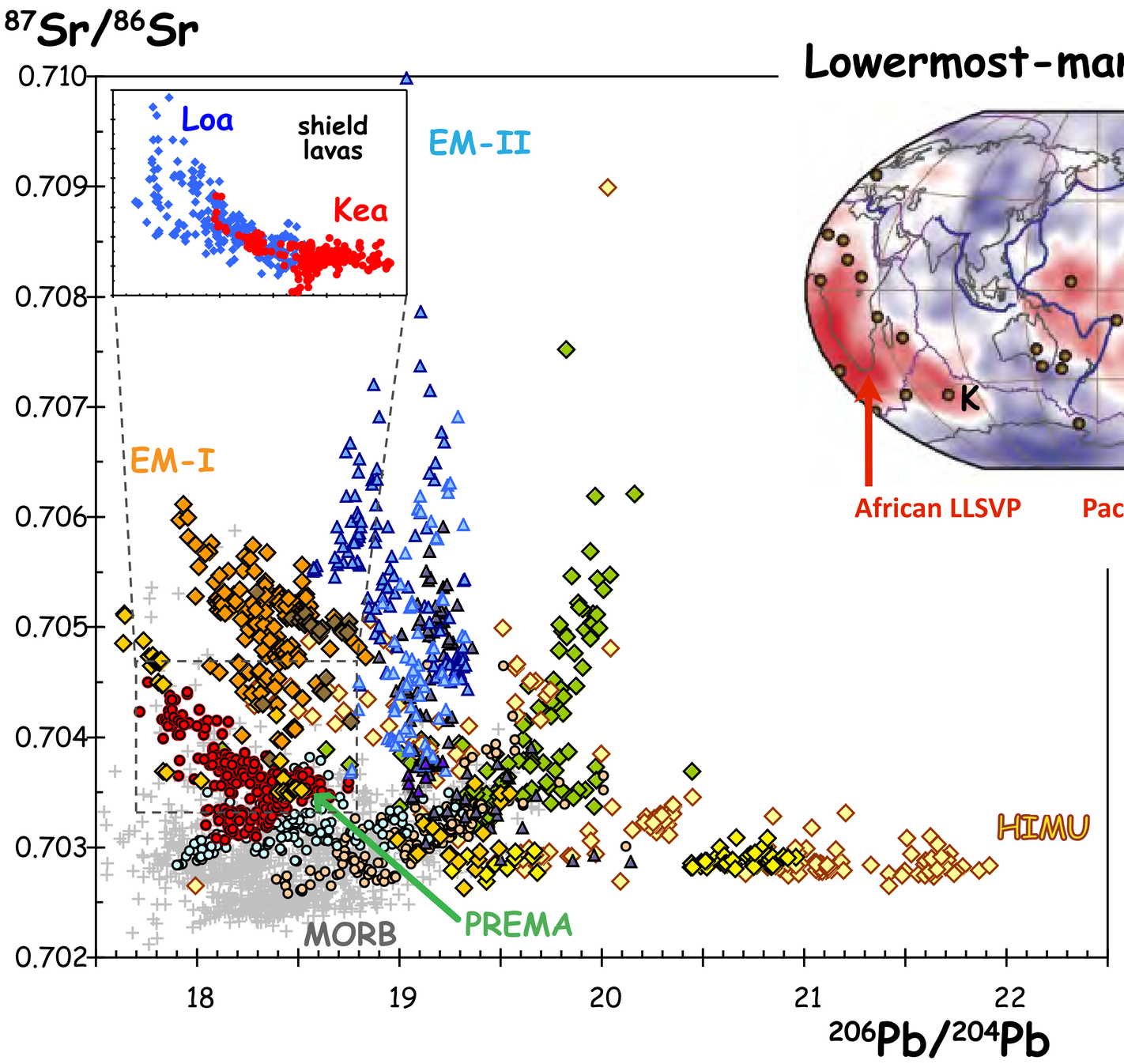
- There is a clear difference between Loa and Kea trend volcanoes:
  - Kea Volcanoes ≈ Ambient Pacific Mantle

    The Kea trend samples the Pacific deep mantle.
  - Loa Compositions ≈ LLSVP or ULVZ.

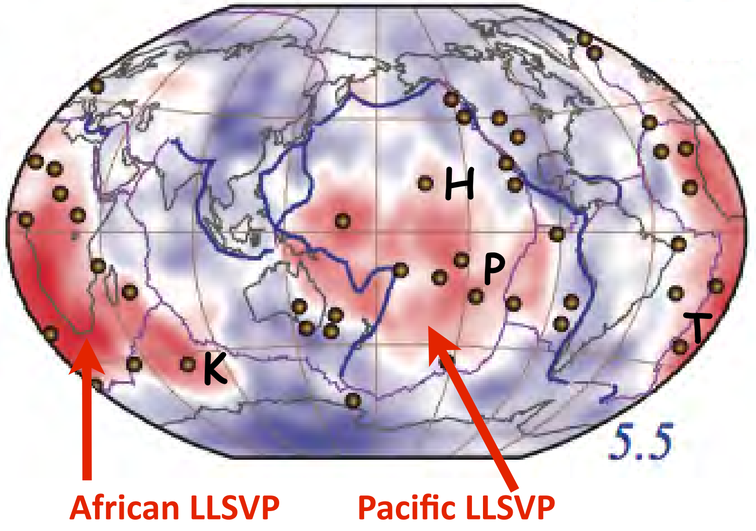
- Statistically, **six groups** can be identified on Hawaii:
  - two major ones: **Kea and Loa**, and,
  - four minor ones, **finite** in time/space: (WMauʻi-EMolokaʻi, Kohala), (Lōʻihi, Enriched Loa).

- The Loa trend is *heterogeneous* and composed of multiple compositional components.

Mauna Kea post-shield cones



Lowermost-mantle V_s perturbations



H: Hawai'i
K: Kerguelen
P: Pitcairn
T: Tristan

Modified from Thorne et al. 2004

Weis et al. 2011

EM-I type mantle plumes: Hawai'i and Pitcairn from the edge of the Pacific LLSVP and, Kerguelen and Tristan of the African LLSVP

Implications for the Deep Mantle and LLSVPs

- 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.

Kaua'i, NaPali coast