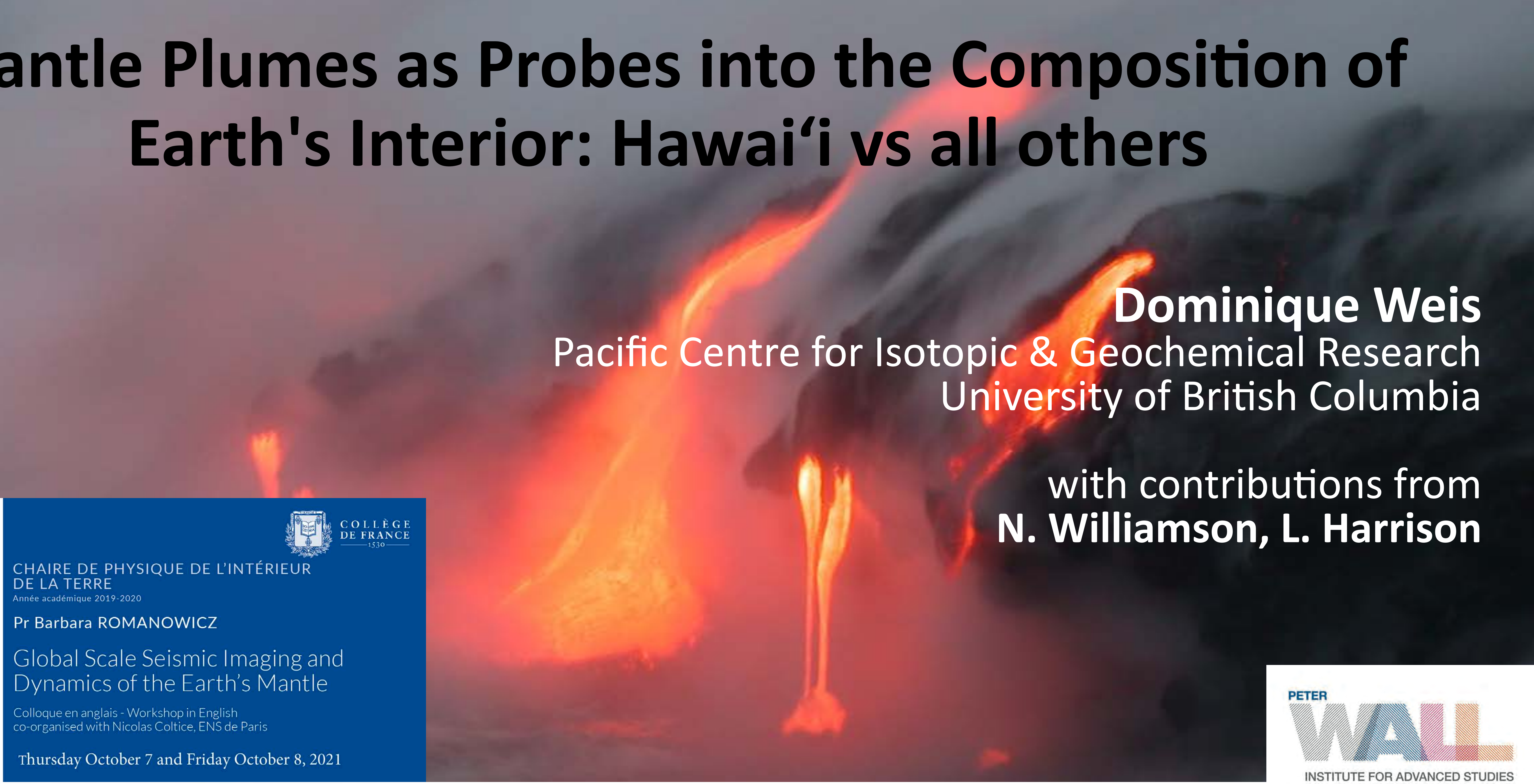
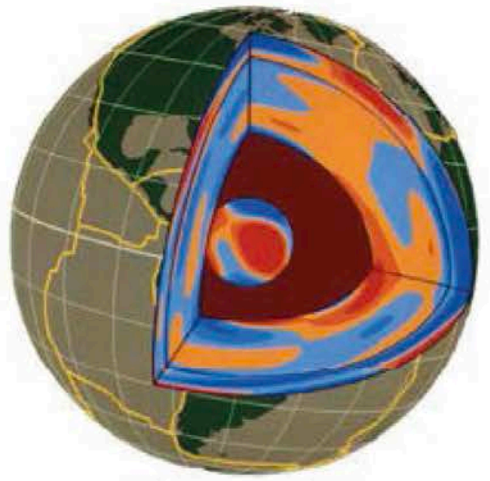


Mantle Plumes as Probes into the Composition of Earth's Interior: Hawai‘i vs all others

Dominique Weis
Pacific Centre for Isotopic & Geochemical Research
University of British Columbia

with contributions from
N. Williamson, L. Harrison



COLLÈGE DE FRANCE
1530

CHAIRE DE PHYSIQUE DE L'INTÉRIEUR DE LA TERRE
Année académique 2019-2020

Pr Barbara ROMANOWICZ

Global Scale Seismic Imaging and Dynamics of the Earth's Mantle

Colloque en anglais - Workshop in English
co-organised with Nicolas Coltice, ENS de Paris

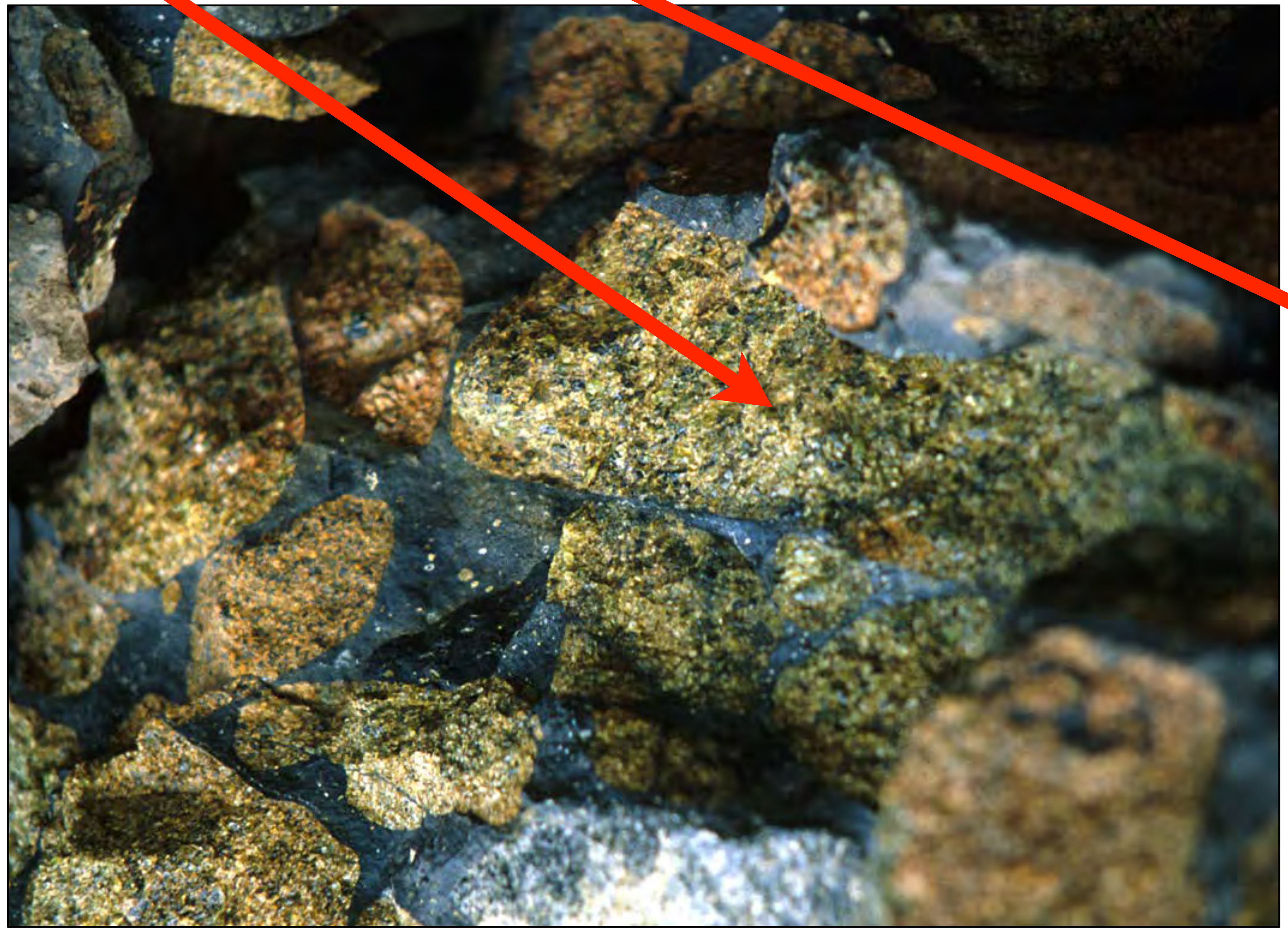
Thursday October 7 and Friday October 8, 2021

Mantle Geochemistry
Hawai‘i vs the others
Hawai‘i update

Ocean entry, Oct. 2002

Lavas as Probes of the Mantle's Composition

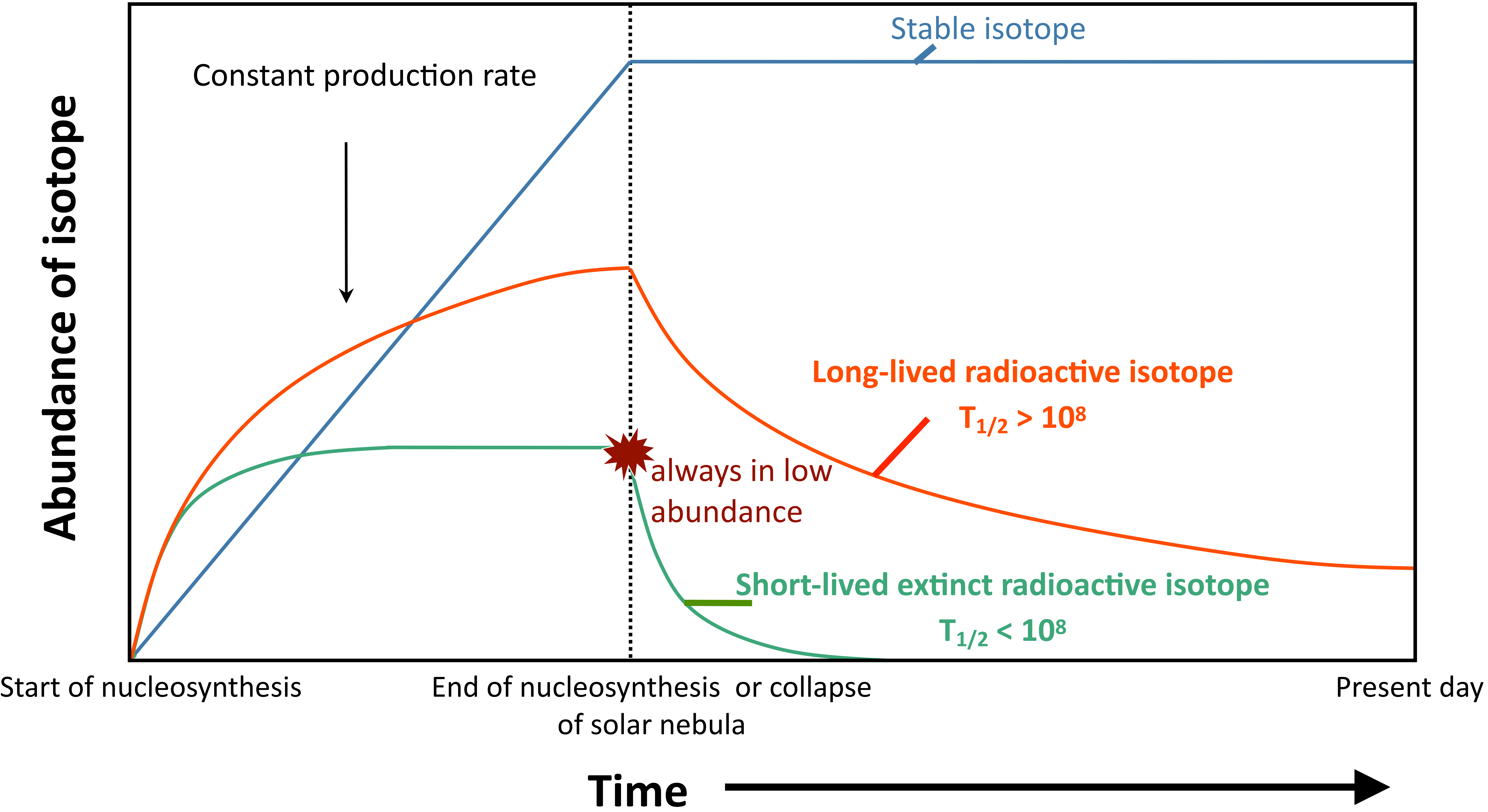
Radiogenic isotopes (e.g., ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd, ^{206}Pb/^{204}Pb) and some trace element ratios are not changed between solid and melt during partial melting.



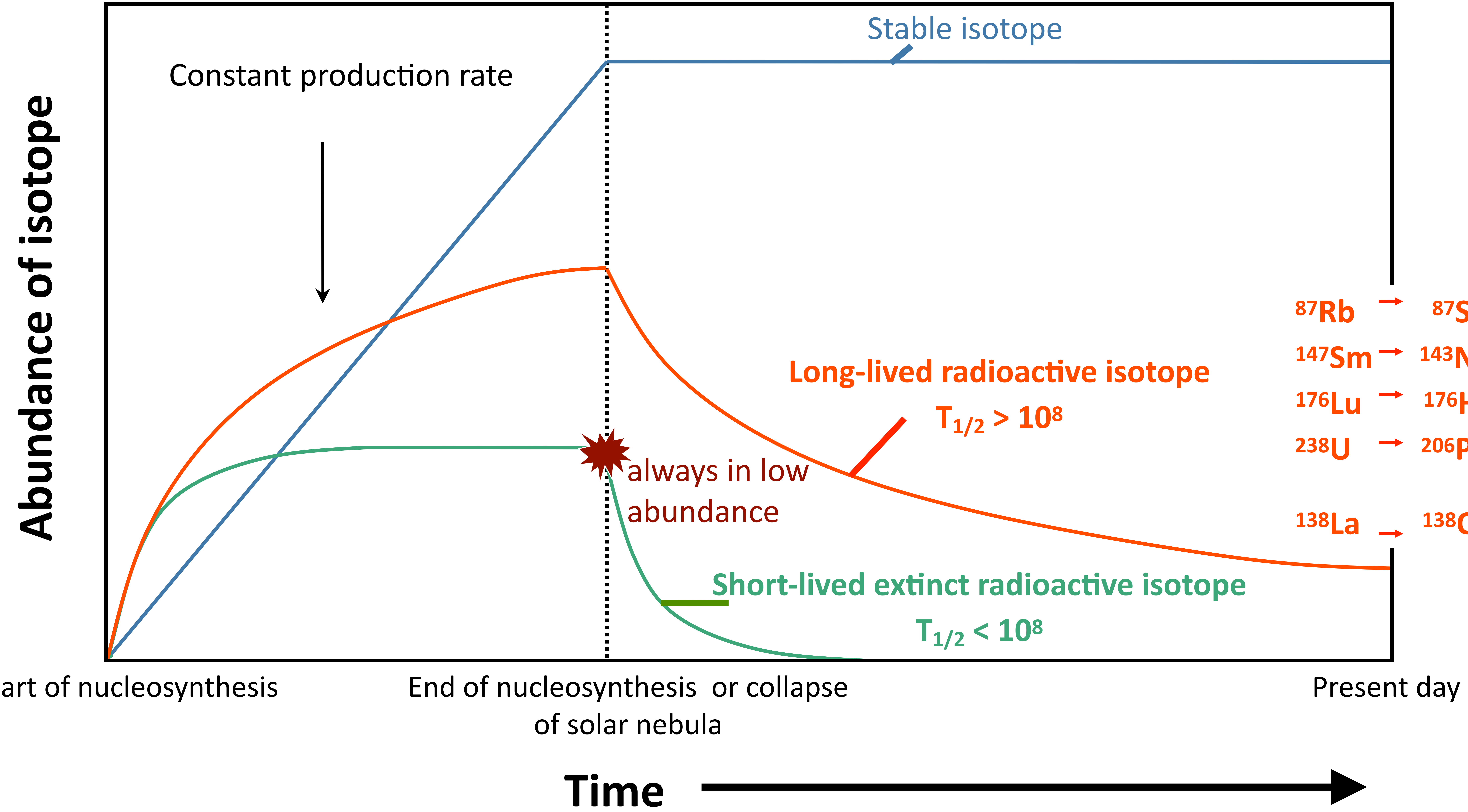
^{87}Sr/^{86}Sr solid mantle (peridotite) =

^{87}Sr/^{86}Sr melt (basalt)

Time Scales for Planetary Processes



Time Scales for Planetary Processes



^{87}Rb → ^{87}Sr $4.88*10^{10}$

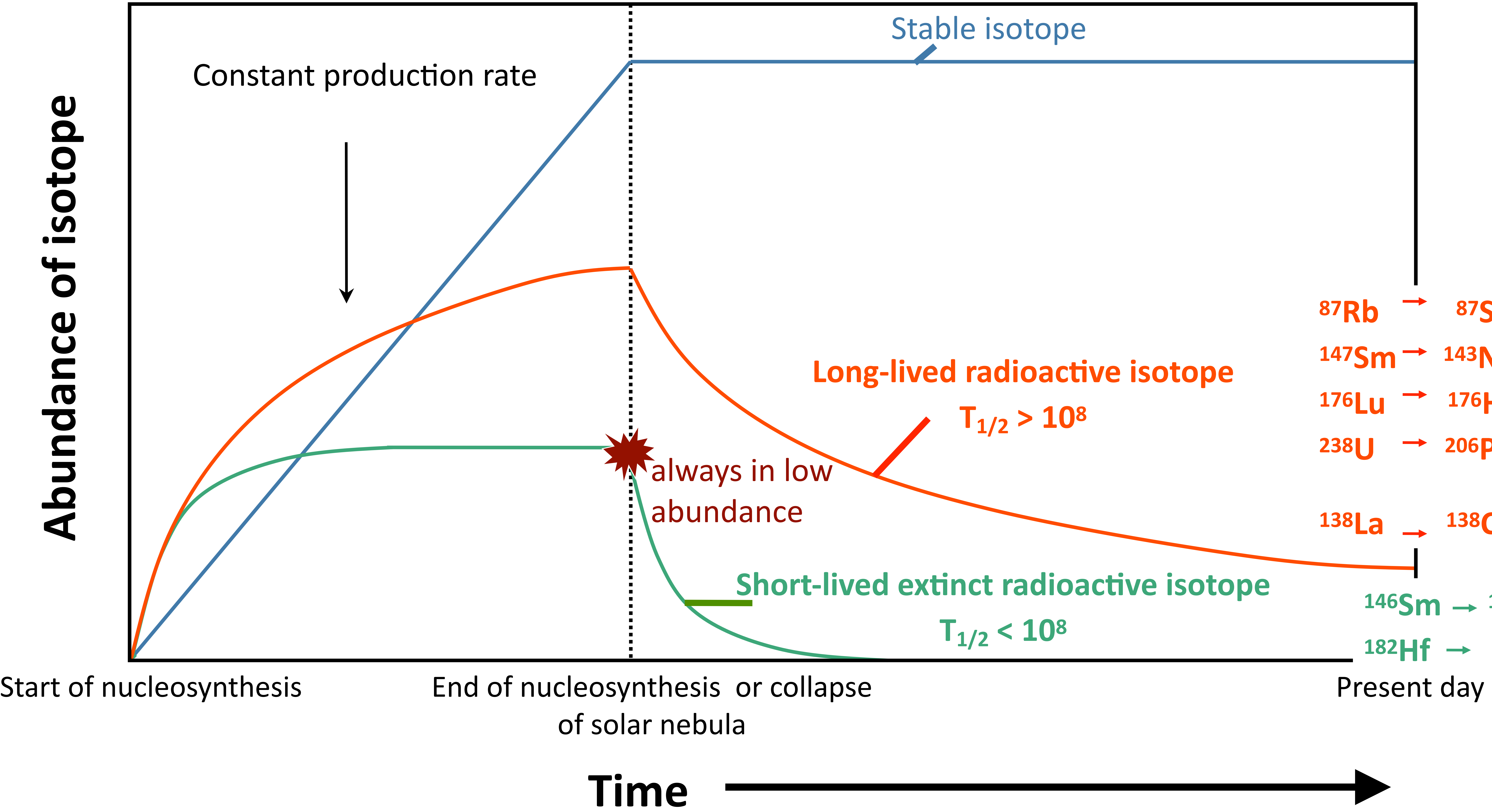
^{147}Sm → ^{143}Nd $1.06*10^{11}$

^{176}Lu → ^{176}Hf $3.57*10^{10}$

^{238}U → ^{206}Pb $4.47*10^{9}$

^{138}La → ^{138}Ce $2.59*10^{11}$

Time Scales for Planetary Processes



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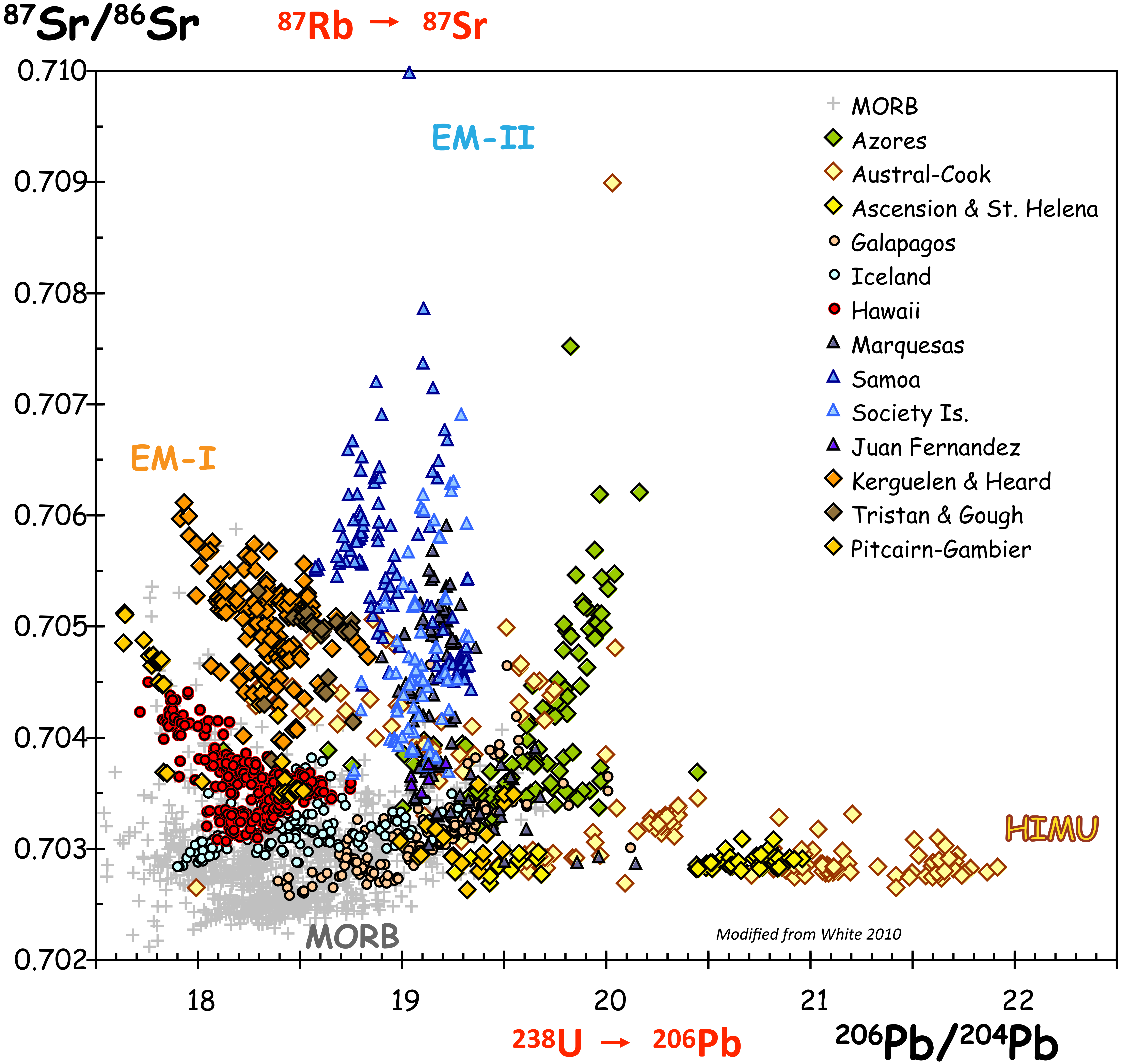
^{138}La →	^{138}Ce	$2.59*10^{11}$
^{146}Sm →	^{142}Nd	$1.03*10^{8}$
^{182}Hf →	^{182}W	$9*10^{6}$

OIB Source Components: Hawai‘i and Kerguelen both have EM-I characteristics

"fingerprinting mantle sources"



Modified from White 2010

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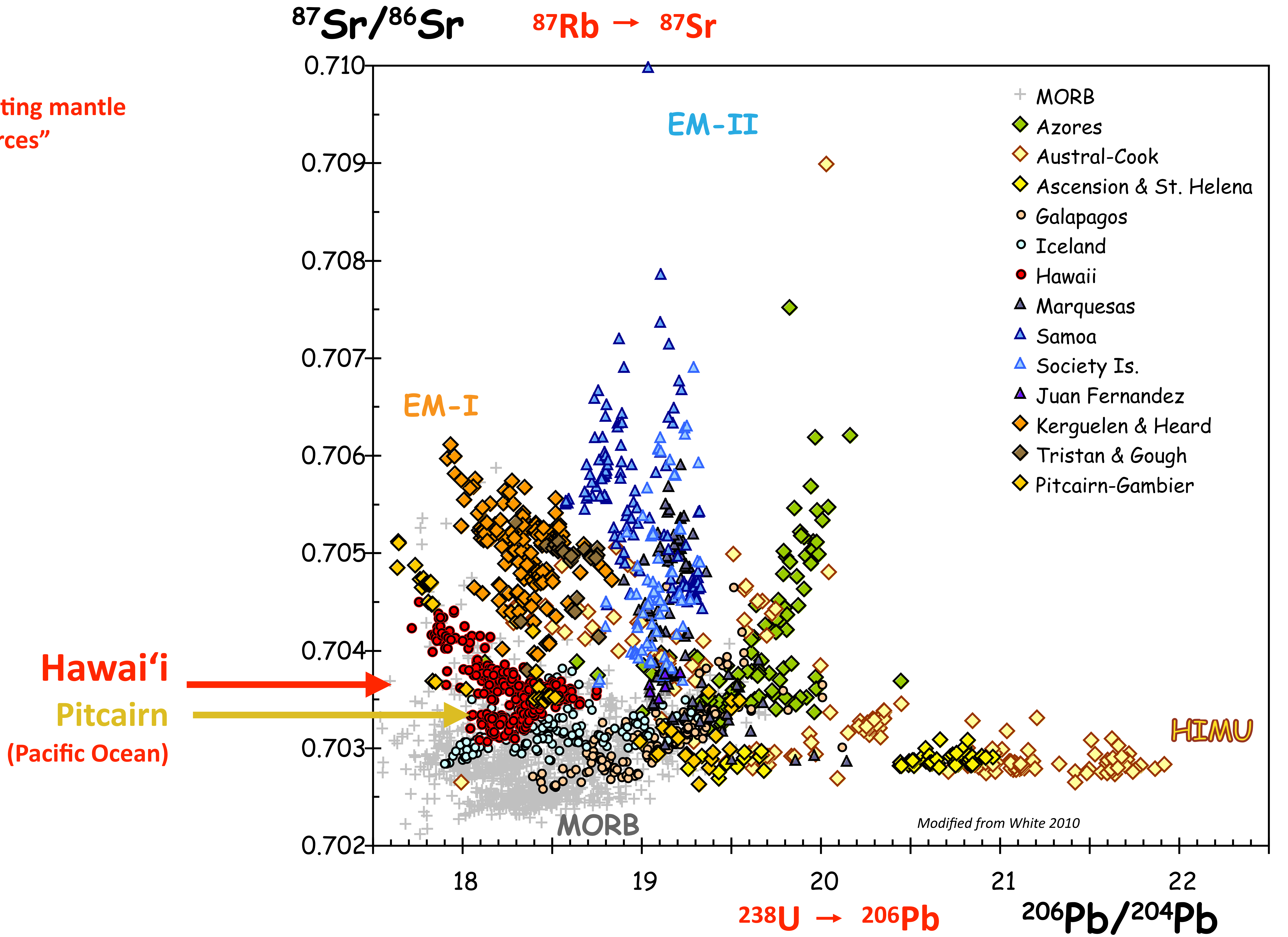

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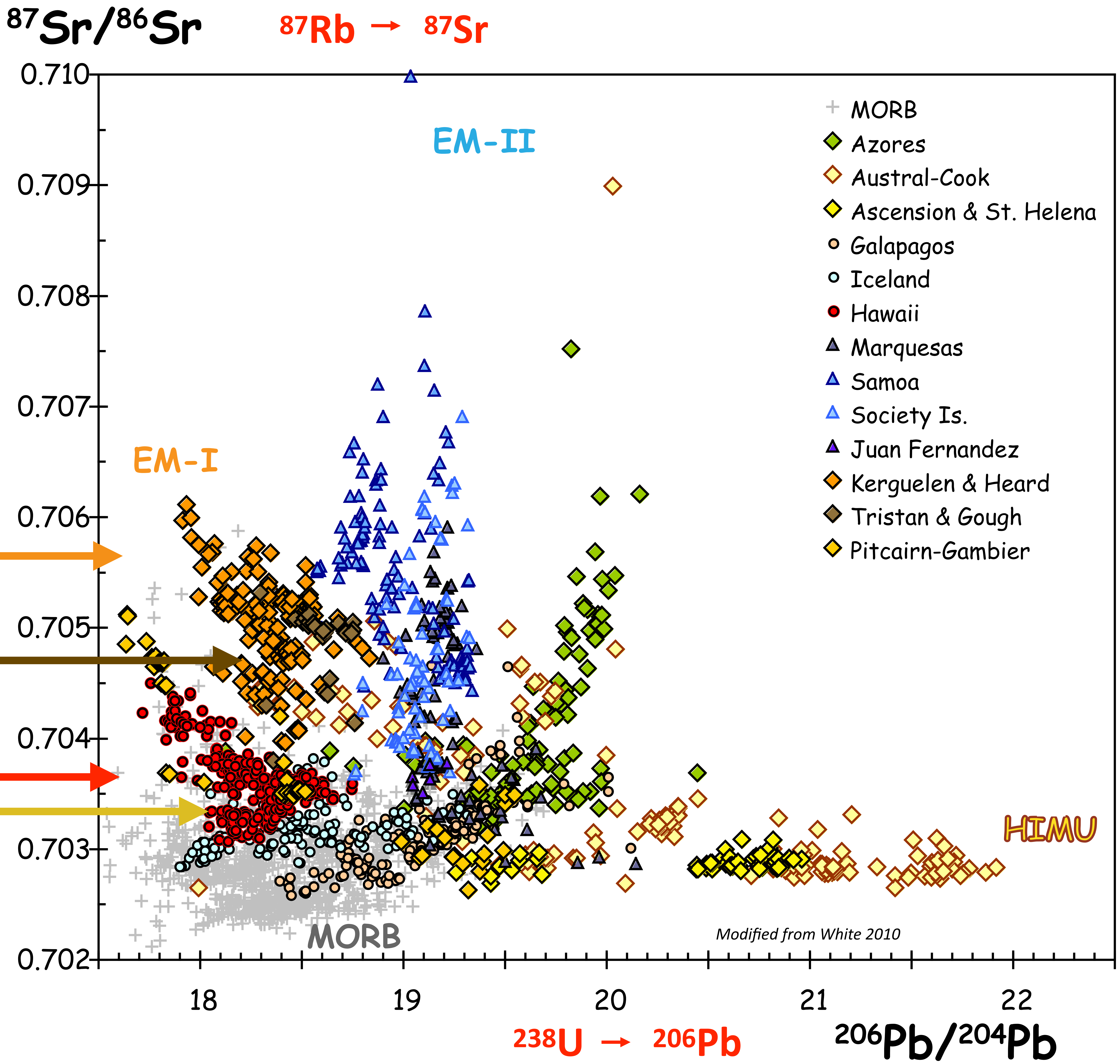


Kerguelen

(Indian Ocean)

Tristan & Gough

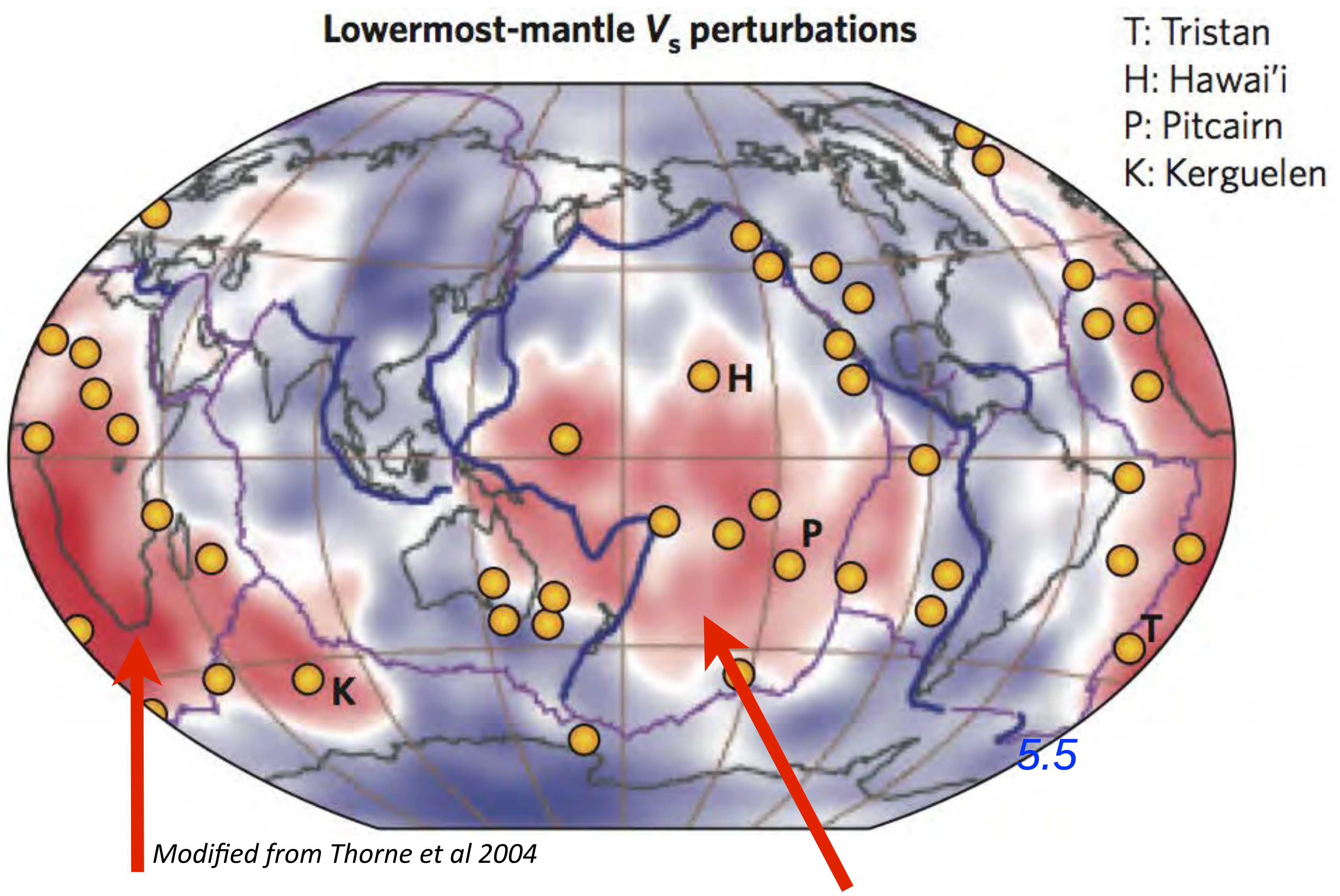
(Atlantic Ocean)

Hawai‘i

Pitcairn

(Pacific Ocean)

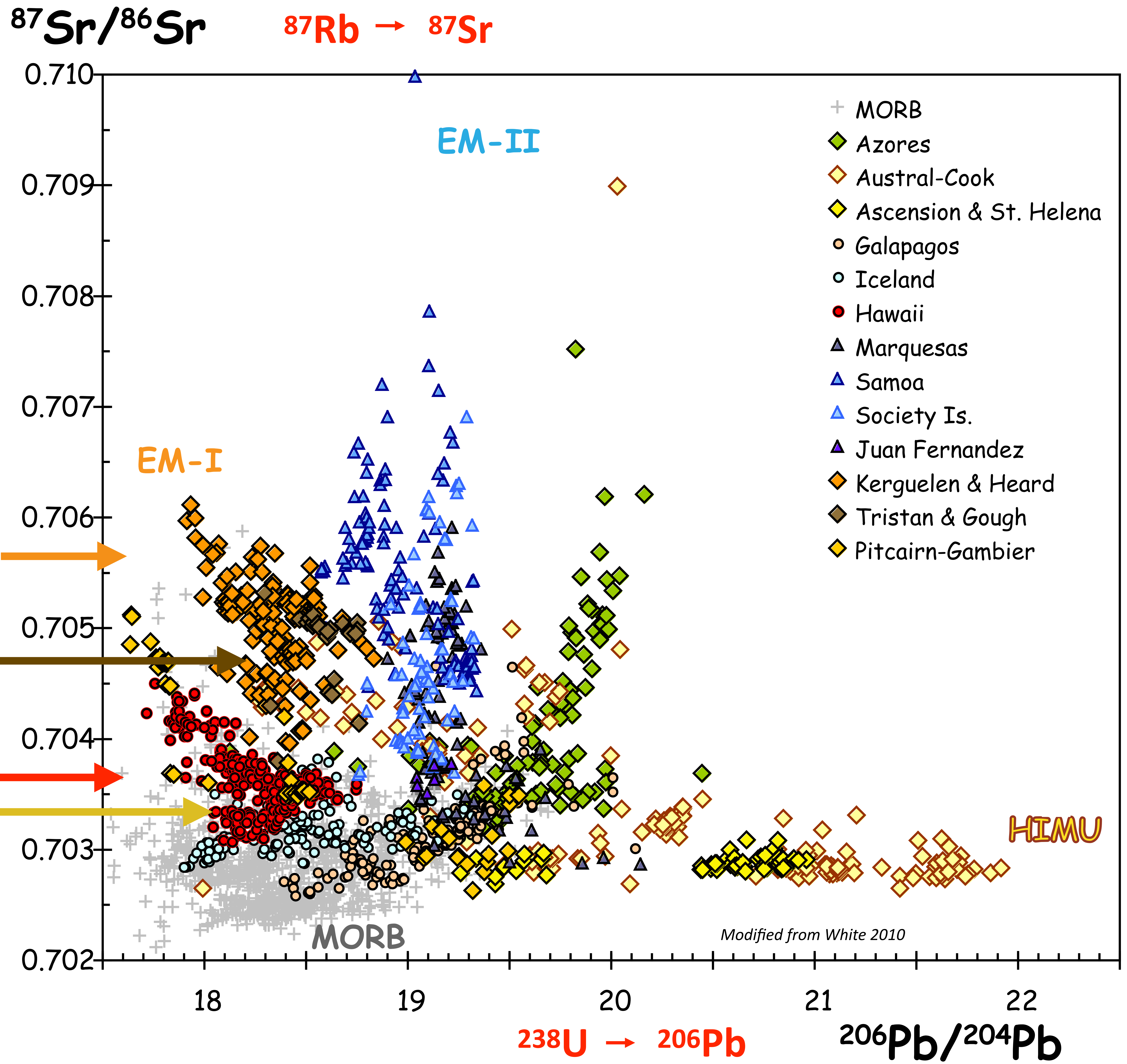
OIB Source Components: Hawai‘i and Kerguelen both have EM-I characteristics



Modified from Thorne et al 2004

African LLSVP

Pacific LLSVP



(Indian Ocean)

Tristan & Gough

(Atlantic Ocean)

Hawai‘i

Pitcairn

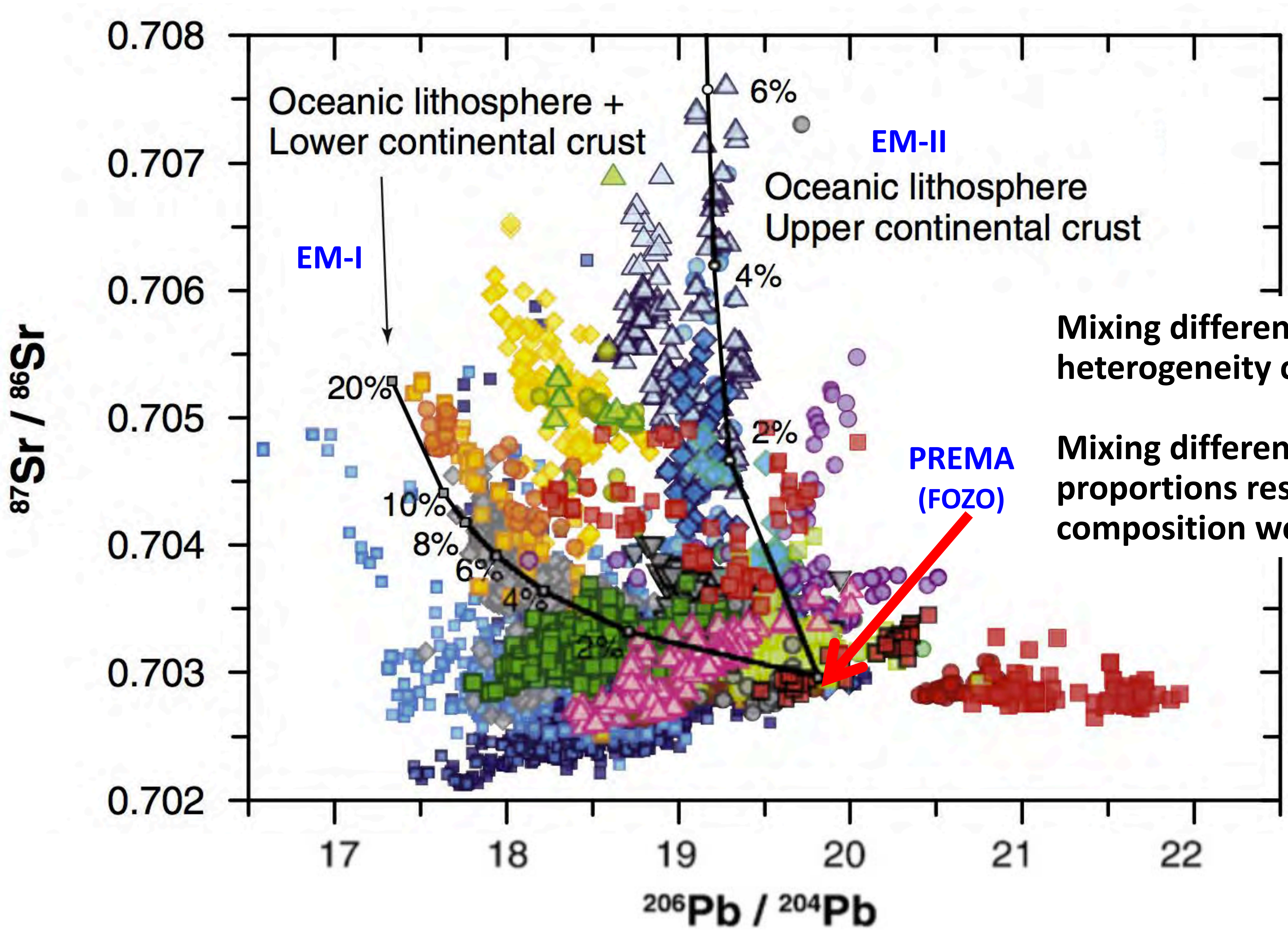
(Pacific Ocean)

Mantle Components & Reservoirs

Certain oceanic islands or groups of islands are characterized by specific isotopic compositions and can be used to “map” a series of distinct mantle components or reservoirs, which may be identifiable separate volumes in the mantle or extremes of a continuum of compositions:

- **DMM** = depleted MORB mantle, the continuously depleted upper mantle reservoir, source of mid-ocean ridge basalts.
- **EM-1** = enriched mantle 1, mantle that reflects addition of crustal materials, either recycling of delaminated subcontinental lithospheric mantle, or recycling of subducted ancient pelagic sediment.
- **EM-2** = enriched mantle 2, mantle that reflects addition of recycled oceanic crust.
- **HIMU** = high μ, where μ = U/Pb (and Th/Pb), reflecting recycling of “enriched” oceanic lithosphere that has been infiltrated by low-degree partial melts.
- A common mantle component variously referred to as:
  - PREMA = prevalent mantle
  - C = “common”’ component
  - FOZO = focal zone

Oceanic Islands, Mantle Plumes and Mantle End-Members

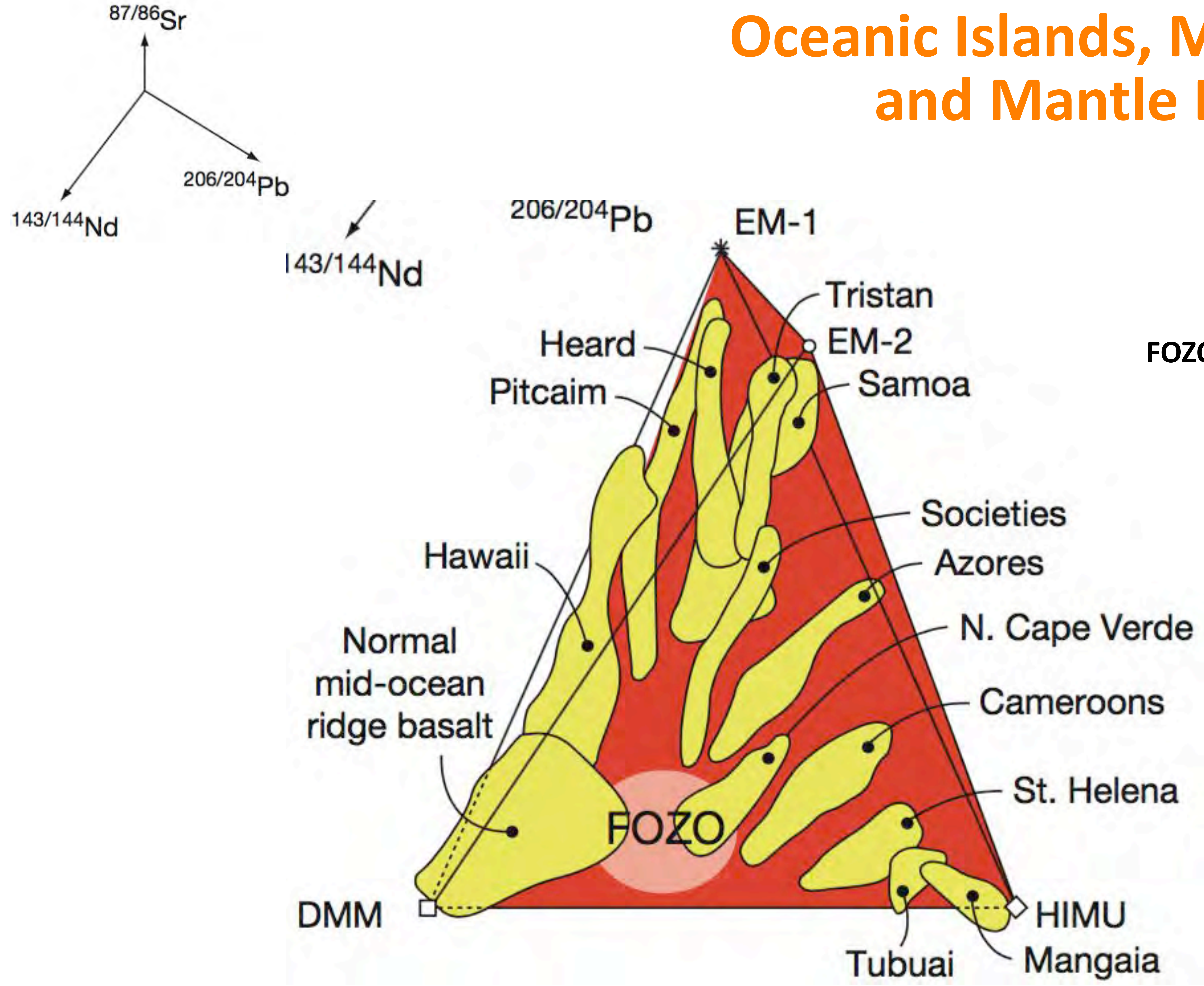


Mixing different sources of mantle heterogeneity creates different "flavors" of OIBs

Mixing different components in various proportions results in the variability in composition we observe in global OIBs

Stracke, 2012

Oceanic Islands, Mantle Plumes and Mantle End-Members



All OIBs "point" to a common mantle component FOZO (or PREMA)

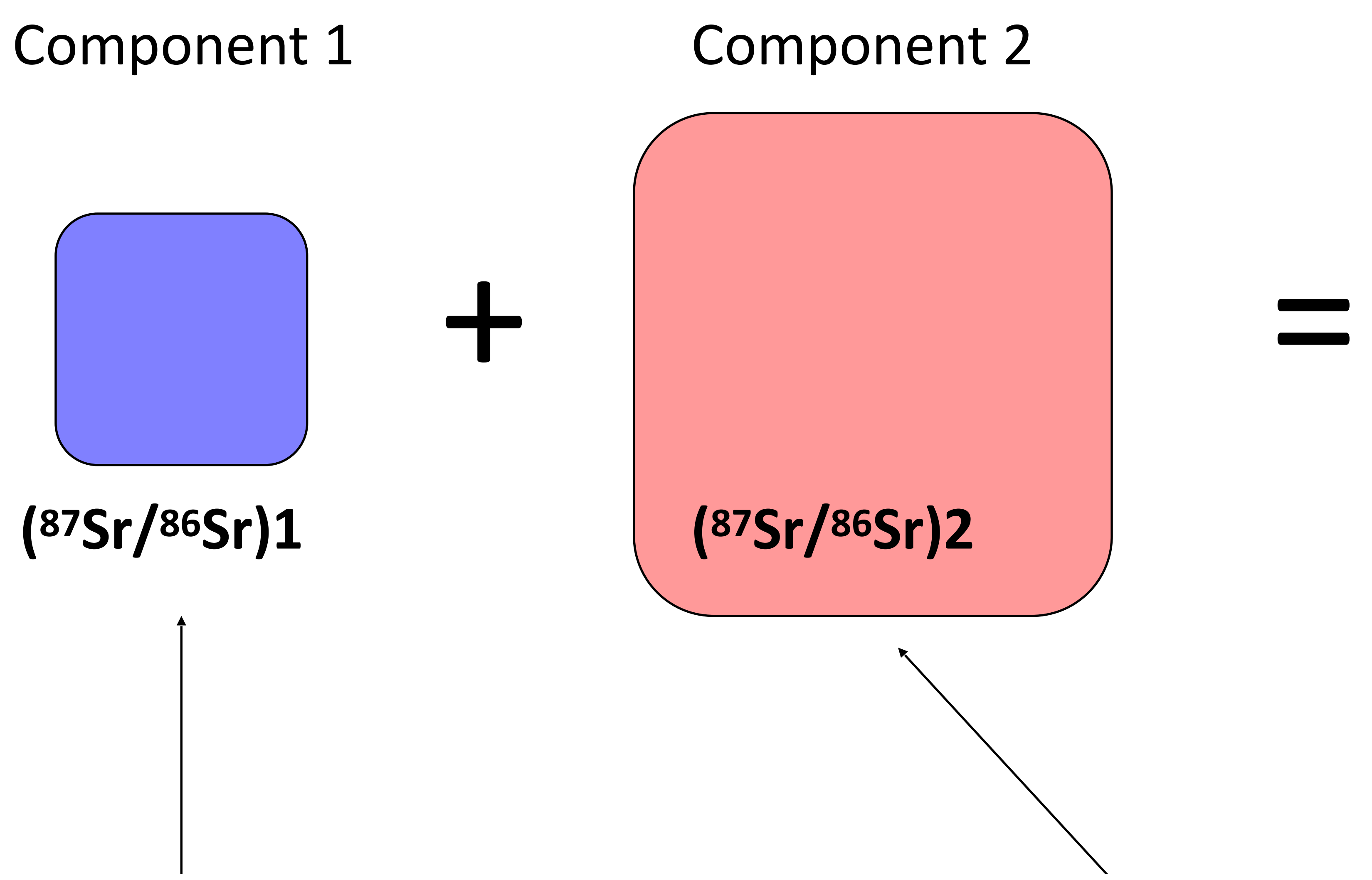
FOZO or PREMA is a ubiquitous component in all deep sourced OIBs <u>globally</u>

Ambient deep mantle, very close to bulk silicate earth composition

Hart et al, 1992
Redrawn by White.

Isotopic Mixing Modelling

We can model the mixing of melts with different concentrations and isotopic compositions using a simple equation



Component 1

Component 2

+

$(^{87}Sr/^{86}Sr)1$

$(^{87}Sr/^{86}Sr)2$

=

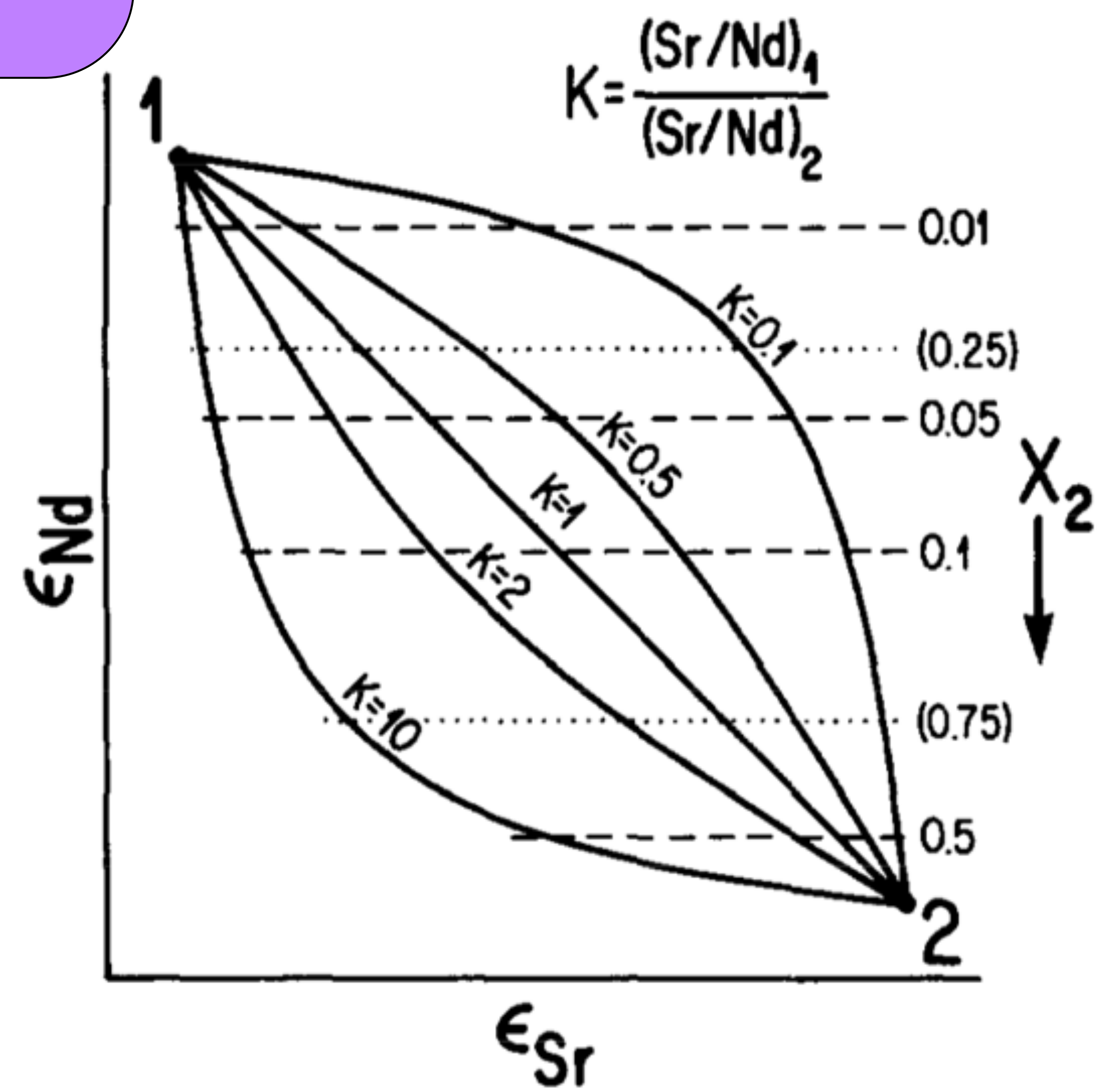
Mixture of Components 1 and 2

$(^{87}Sr/^{86}Sr)3$

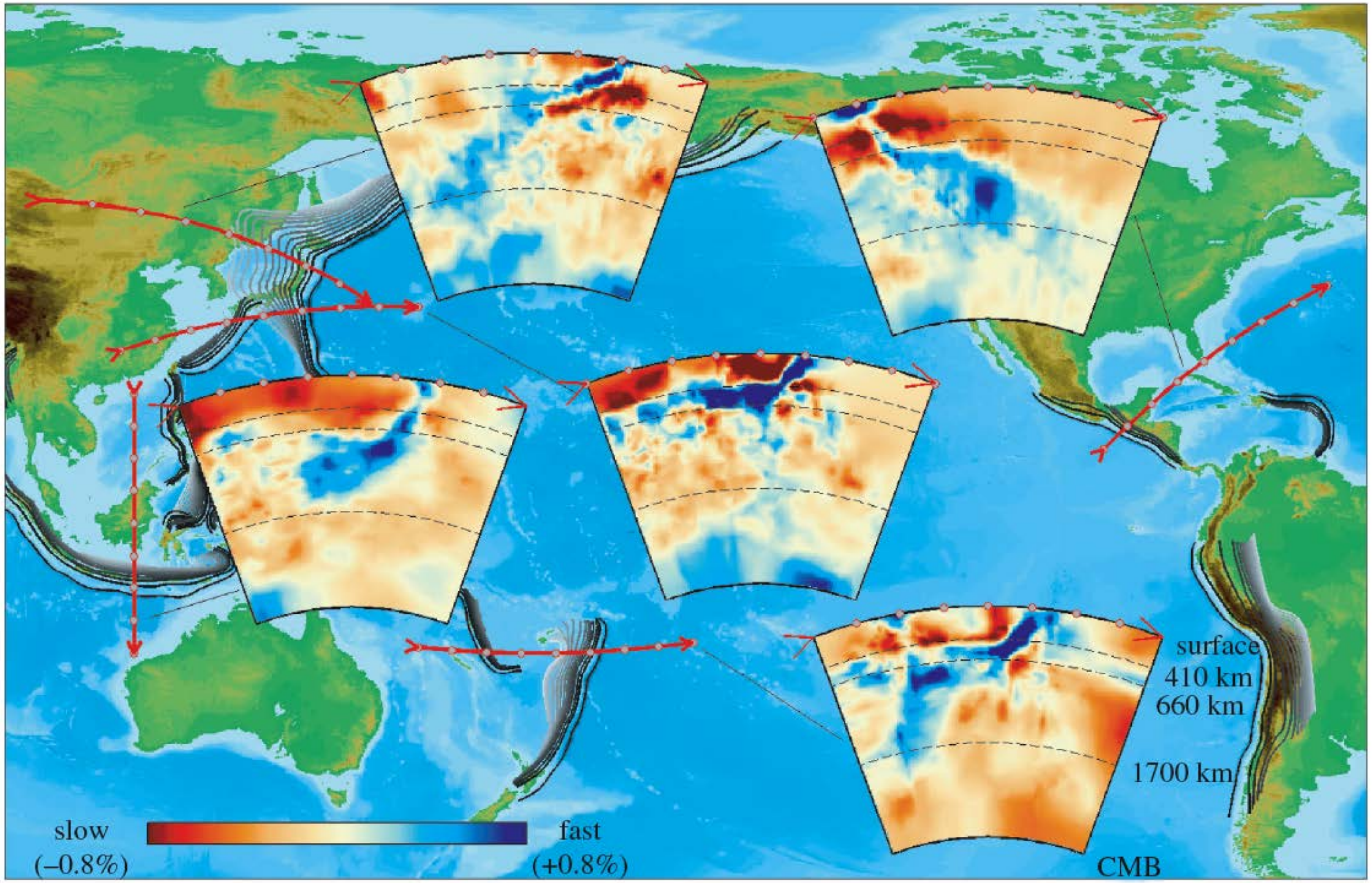
Weighed mean: intermediate in composition between $(^{87}Sr/^{86}Sr)1$ and $(^{87}Sr/^{86}Sr)2$

$$\frac{\left[(x)([Sr])_1\left(\frac{^{87}Sr}{^{86}Sr}\right)_1\right]+\left[(1-x)([Sr])_2\left(\frac{^{87}Sr}{^{86}Sr}\right)_2\right]}{\left[x([Sr])_1+(1-x)([Sr])_2\right]}$$

x = weight fraction of component 1 or 2
1 and 2 = two components being mixed



DePaolo and Wasserburg, 1979



Albarède & Van der Hilst 2002

Subducting Slabs & Recycling

– Down-going subducted oceanic lithosphere can be traced by seismic tomography using P- and S-wave variations.

– Subducted material: peridotites, harzburgites, gabbros, tholeiitic and alkali basalts, terrigenous and pelagic sediments, and lower crustal metamorphic rocks.

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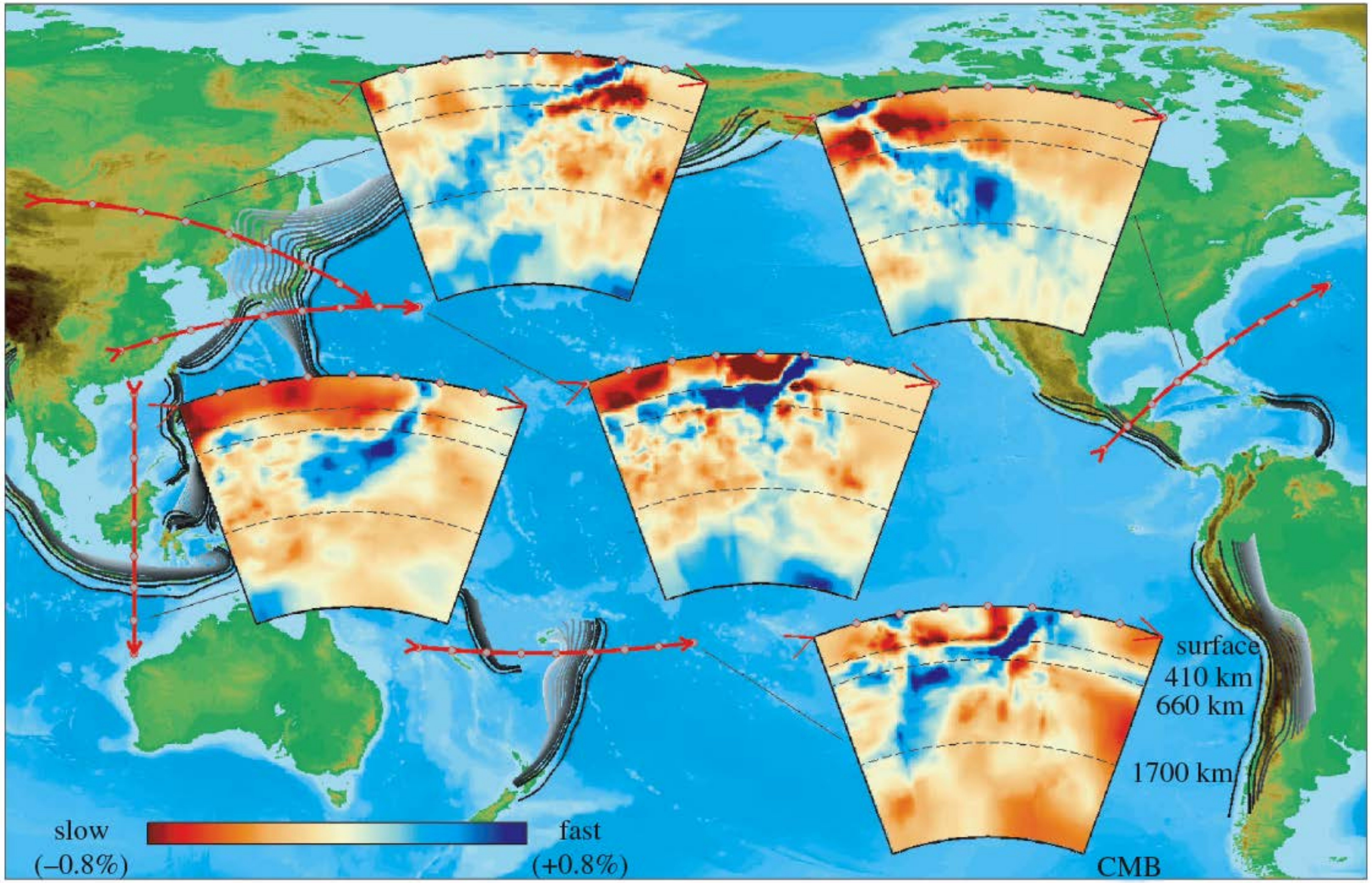


Albarède & Van der Hilst 2002

Recycled Material Mass Balance

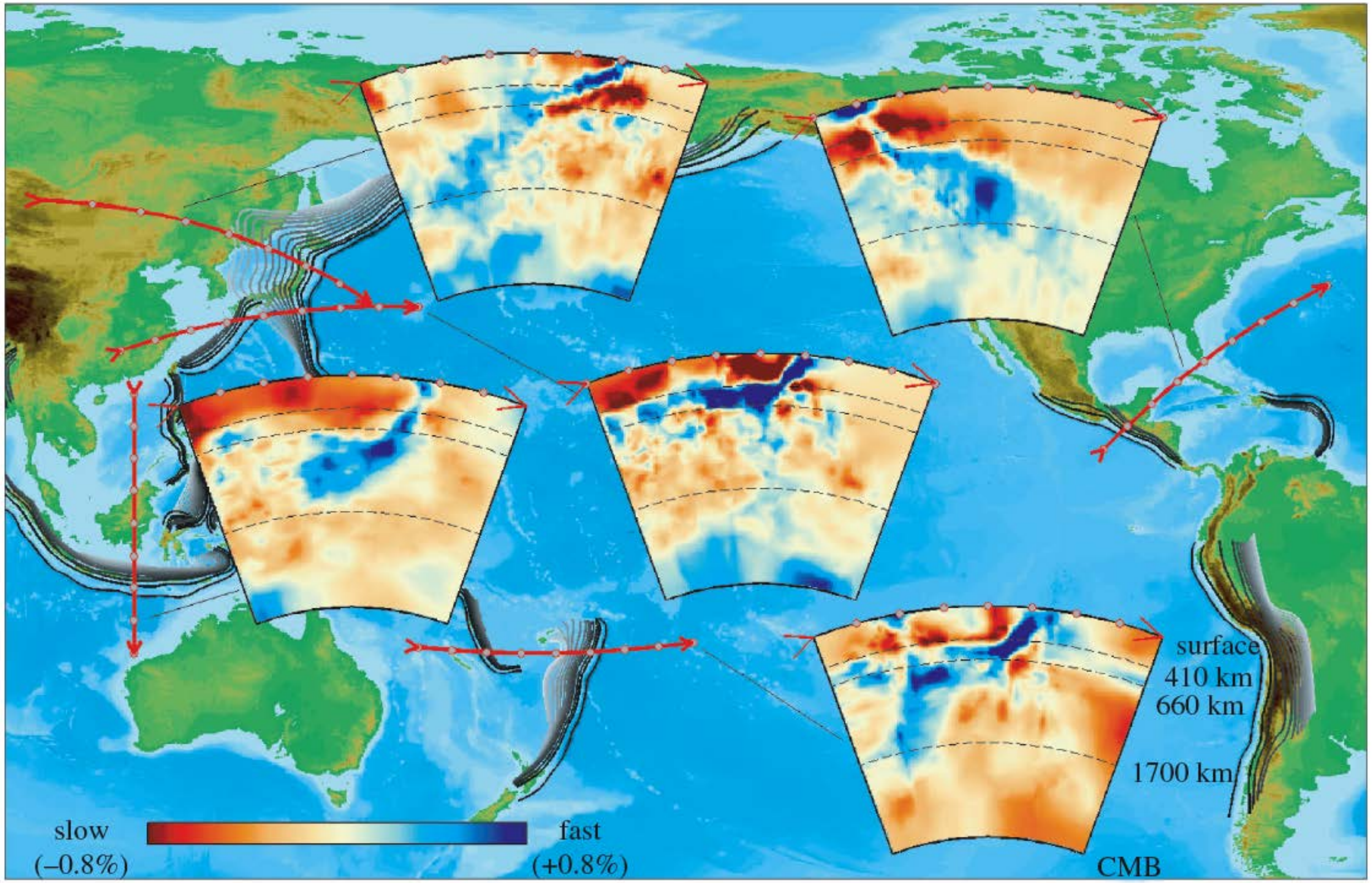
<u>Sediment</u> – 0.3-0.7 km^3/year subducts

In 3 Ga that's equal to subducting 1/3 of the modern continents

<u>Oceanic Crust</u> – 20 km^3/year subducts

In 3 Ga that's equal to ~60 billion km^3, which is 5% of the mantle's mass

Subducting Slabs & Recycling



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How could the mantle not be heterogeneous?

When projected onto the CMB, many mantle plumes plot at the edge of the LLSVPs

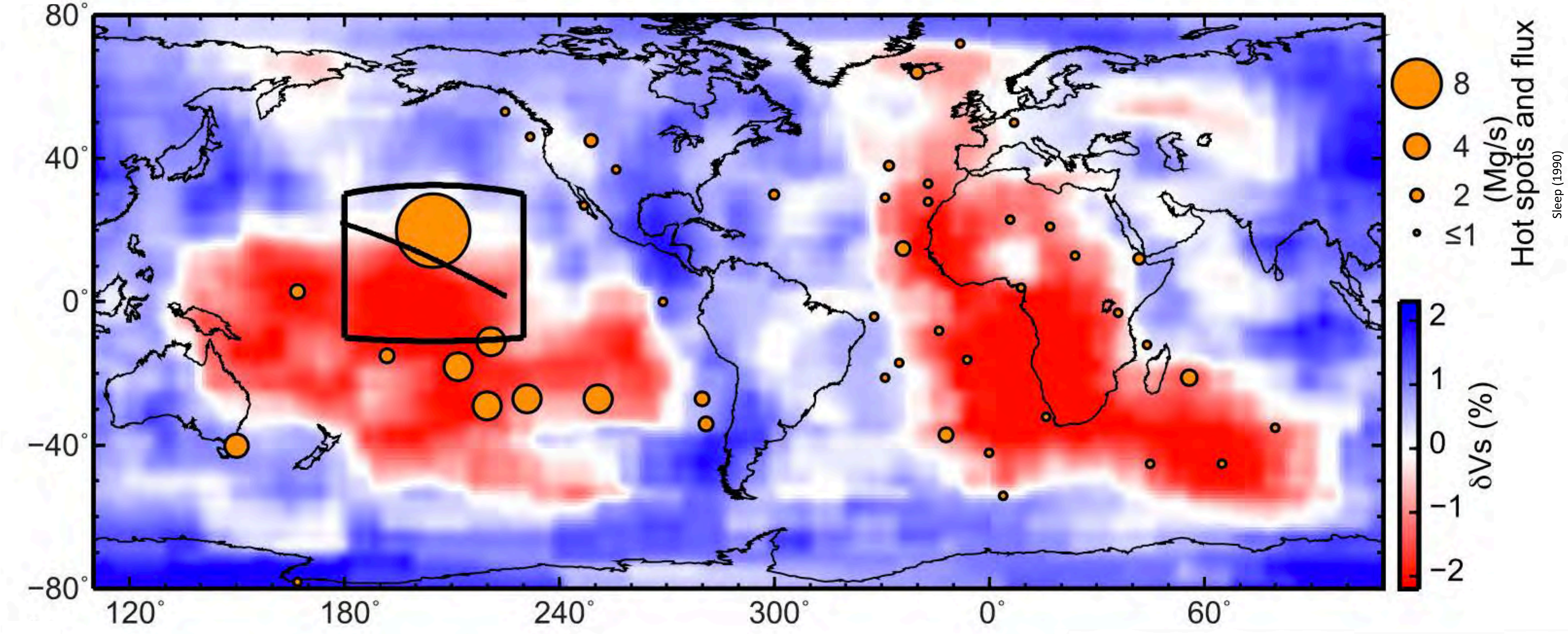
🟨 Continental flood basalts/volcanic rifted margins

🟧 Oceanic flood basalts

Modified from Thorne et al 2004

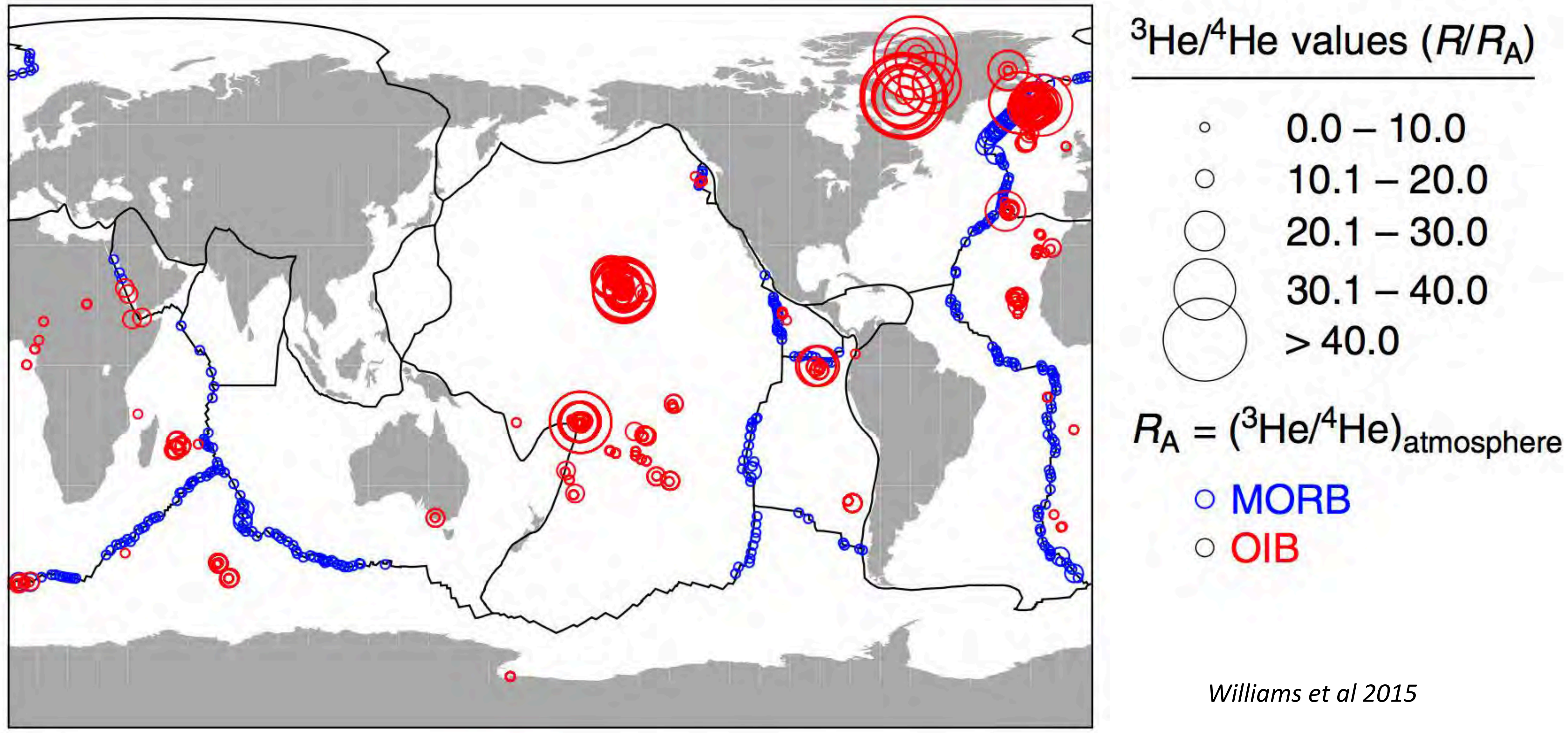
adapted from Coffin et al. 2006
**Goodliffe & Martinez 1997*
Mahoney J. J. & Coffin M. F. (eds.) 1997

Hotspot Locations on top of a Global Tomography Shear Velocity Model TXBW (Grand, 2002)



Zhao et al 2015

Global Distribution ^{3}He/^{4}He Ratios



Williams et al 2015

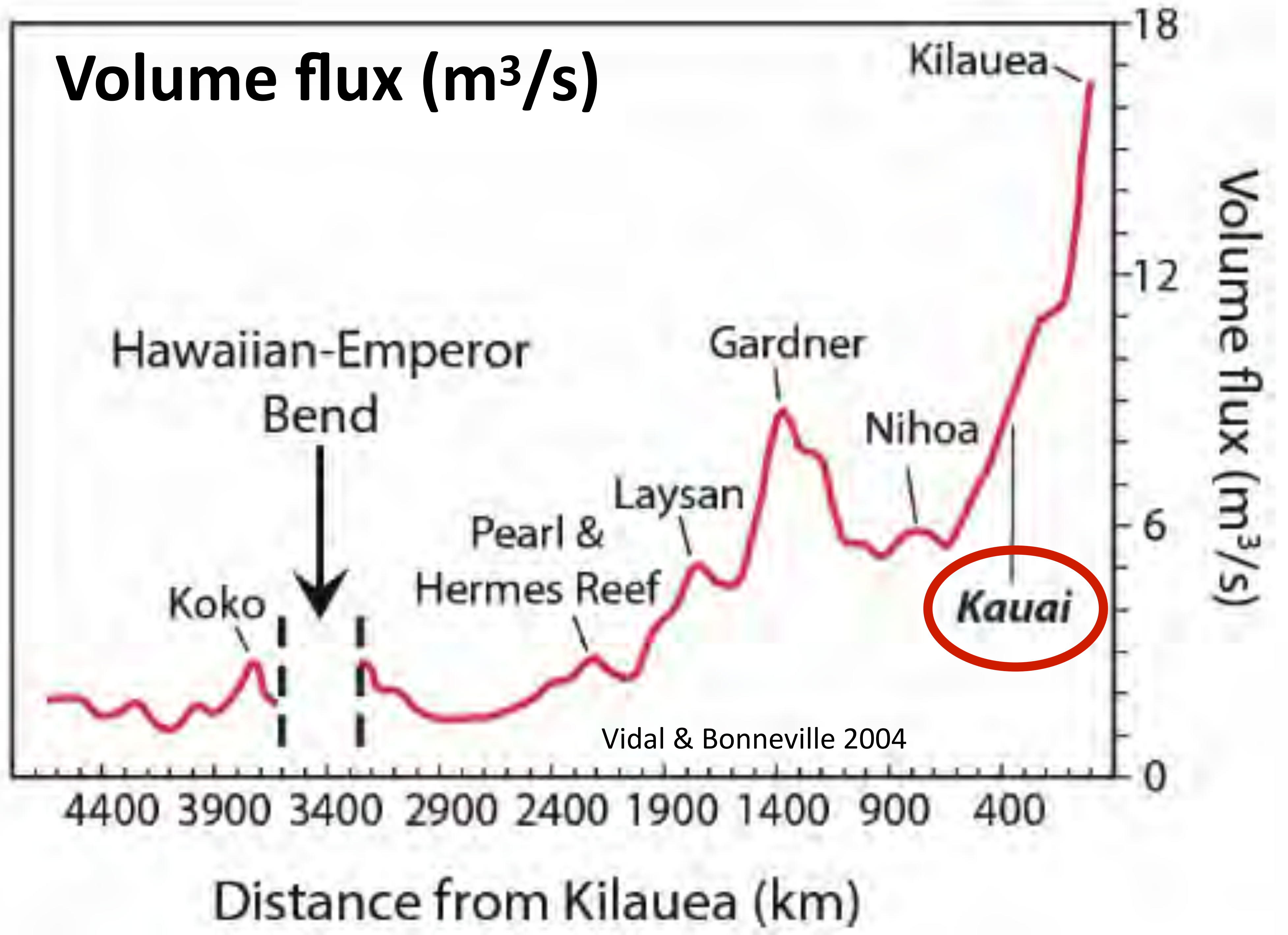
Hawai‘i?

I - Largest buoyancy flux and erupted volume of lavas
II - The Hawai‘i mantle plume flux has become stronger with time
III - Volcanoes arranged in 2 parallel geographical chains, geochemically distinct
IV - Dominated by tholeiitic shield compositions
VI - Deep Mantle Origin - CMB, where
VII - the Loa trend samples enriched (EM-I) compositions

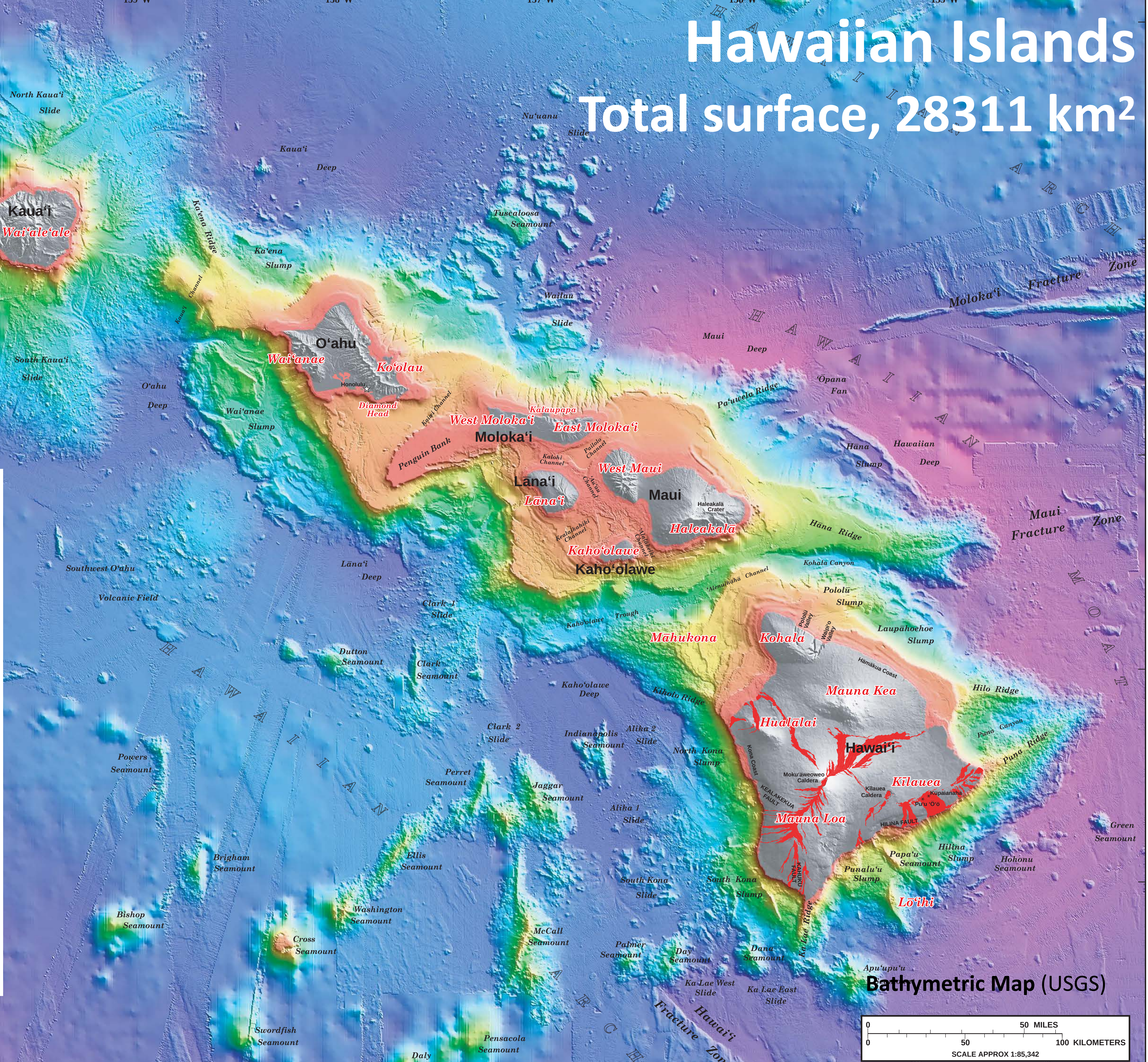
Kaua‘i, Waimea Canyon

Hawaiian Islands

Total surface, 28311 km²



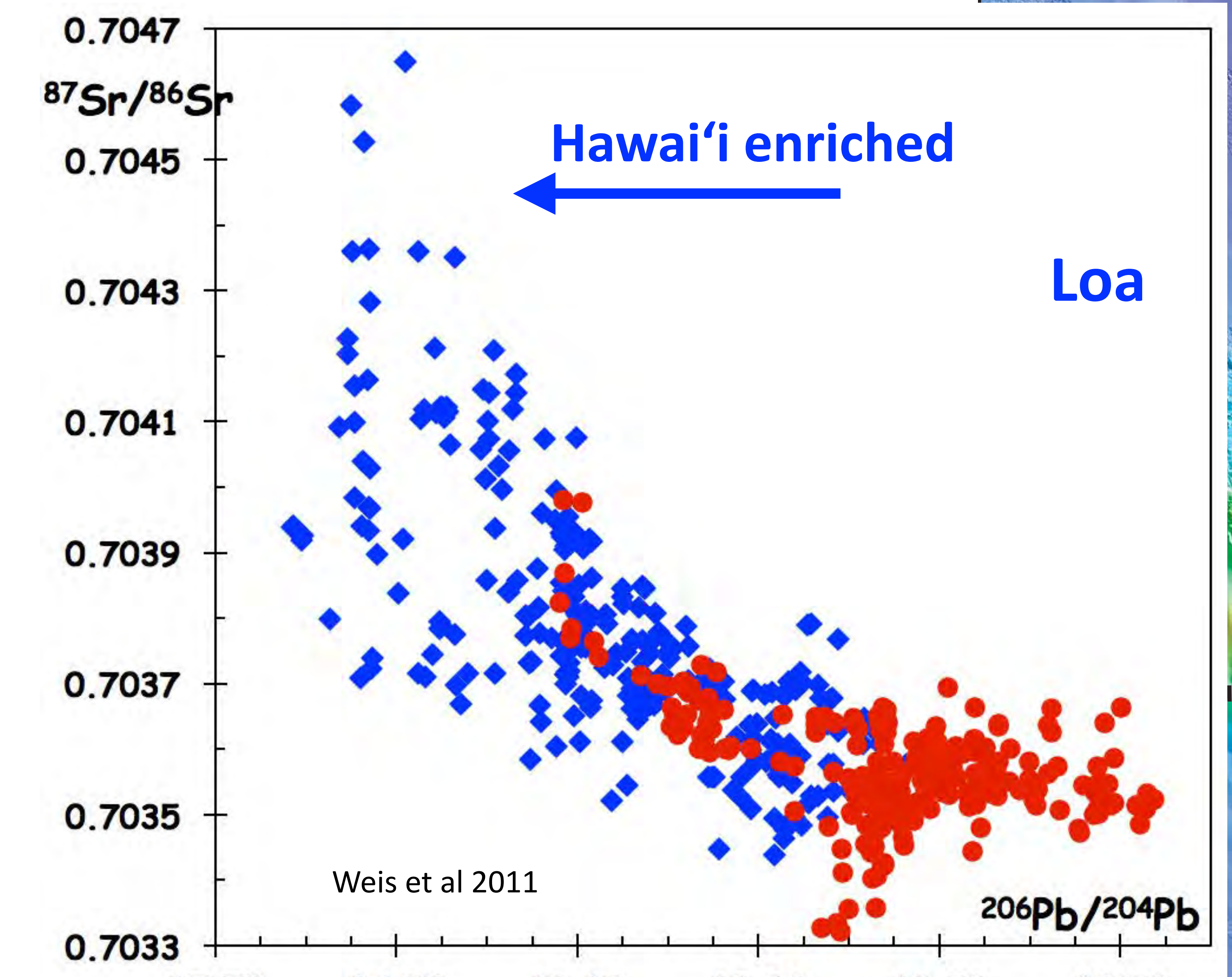
Vidal & Bonneville 2004



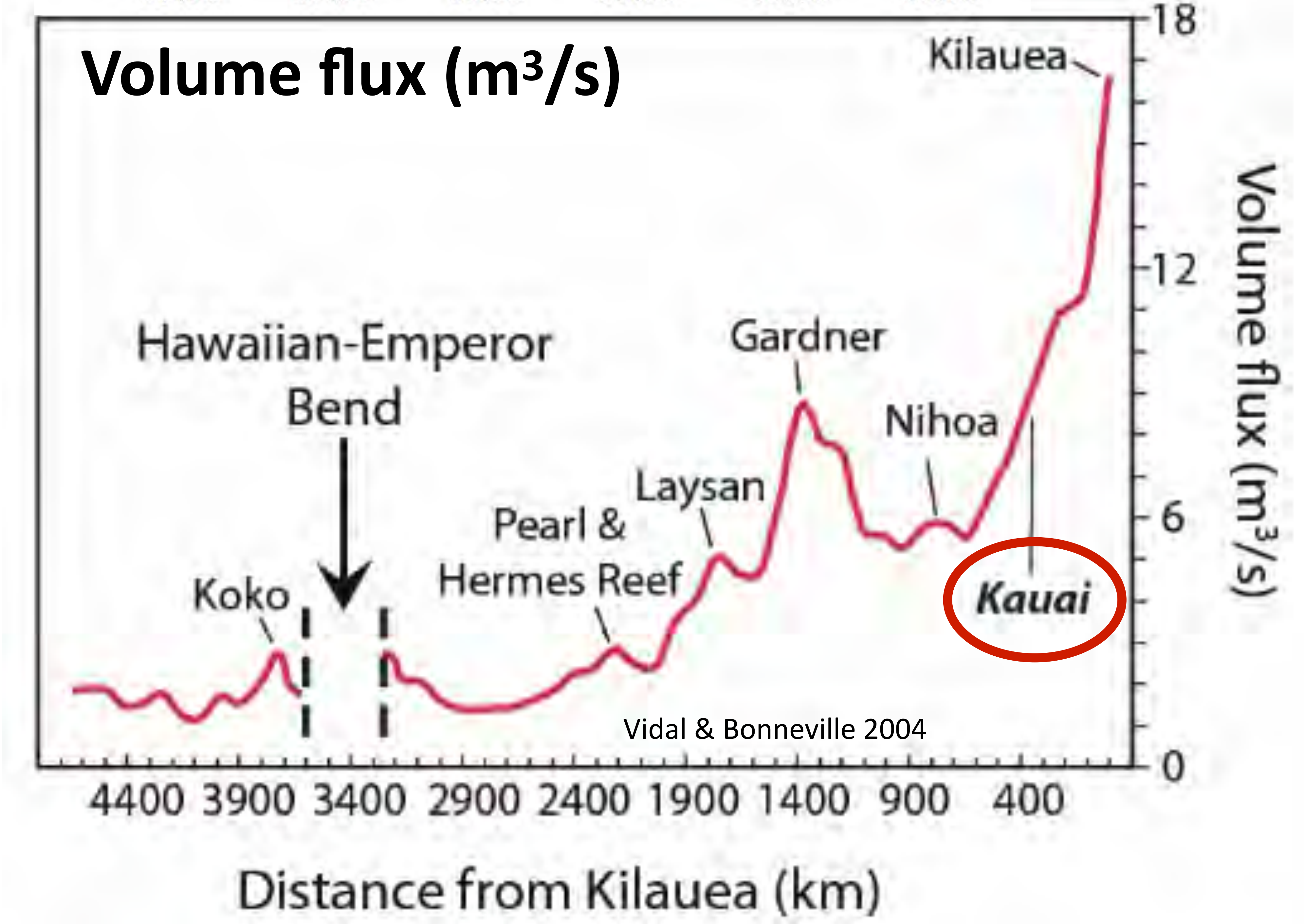
Bathymetric Map (USGS)

Hawaiian Islands

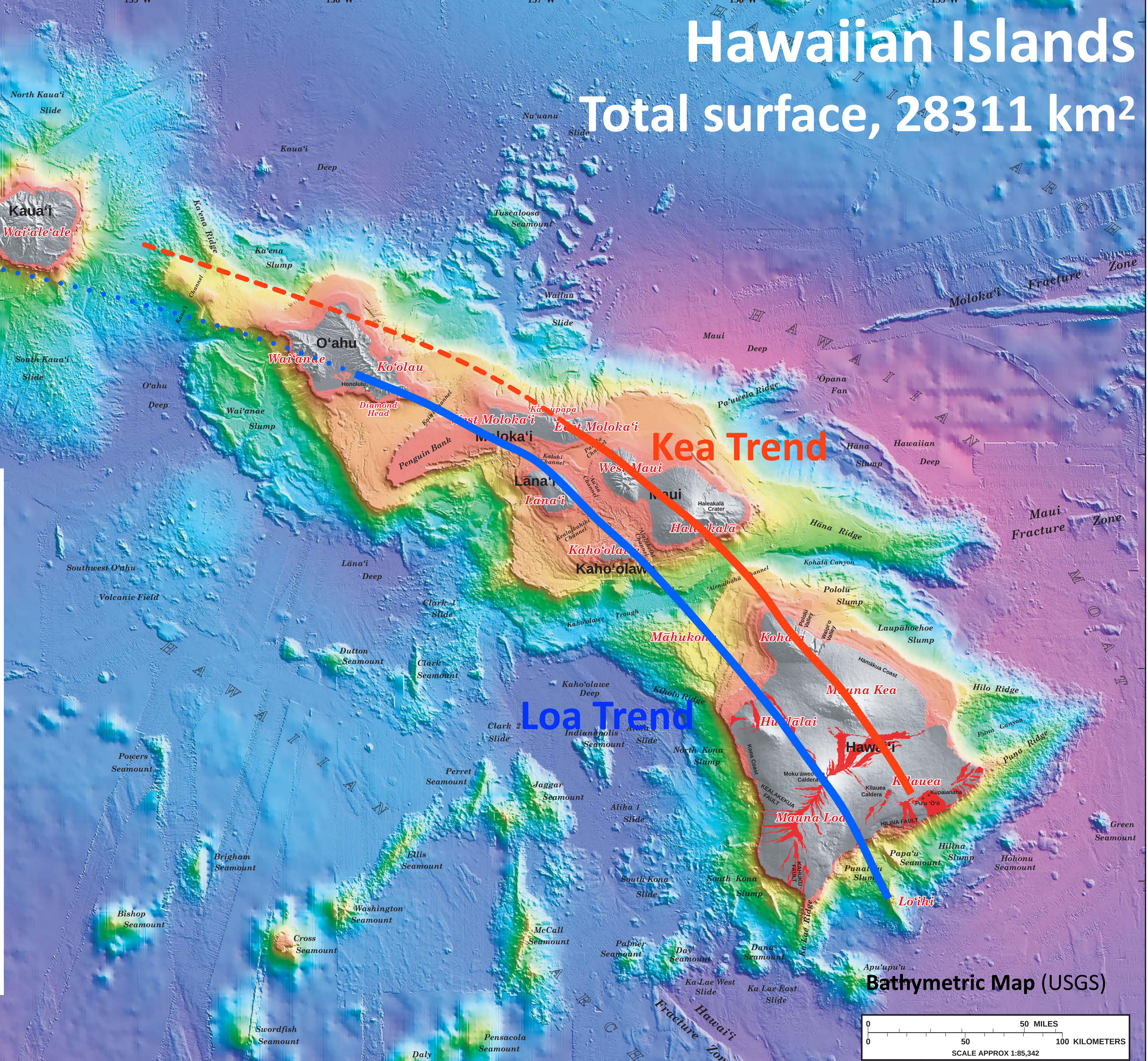
Total surface, 28311 km²



Weis et al 2011



Vidal & Bonneville 2004



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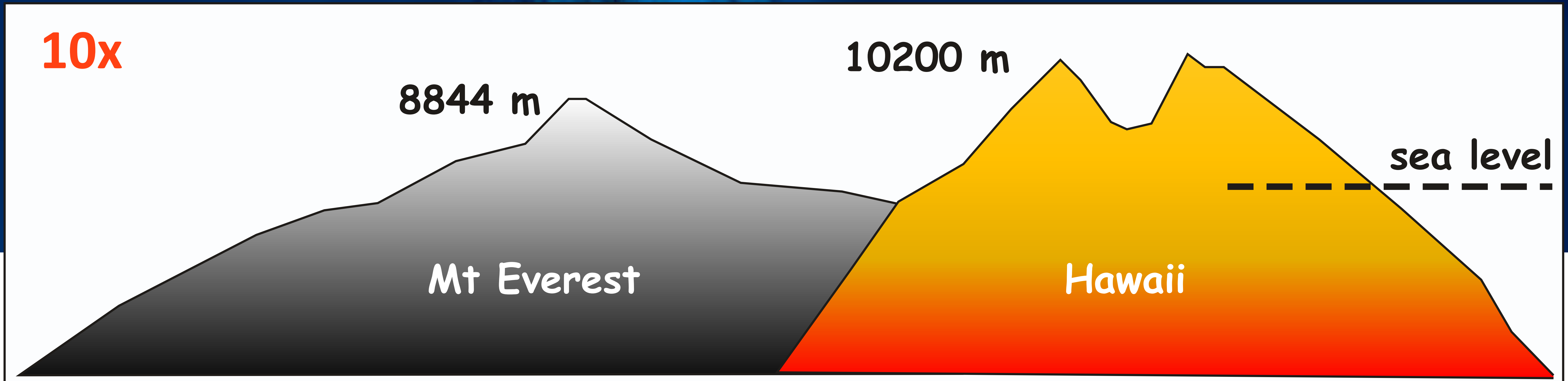
Mountains from Space



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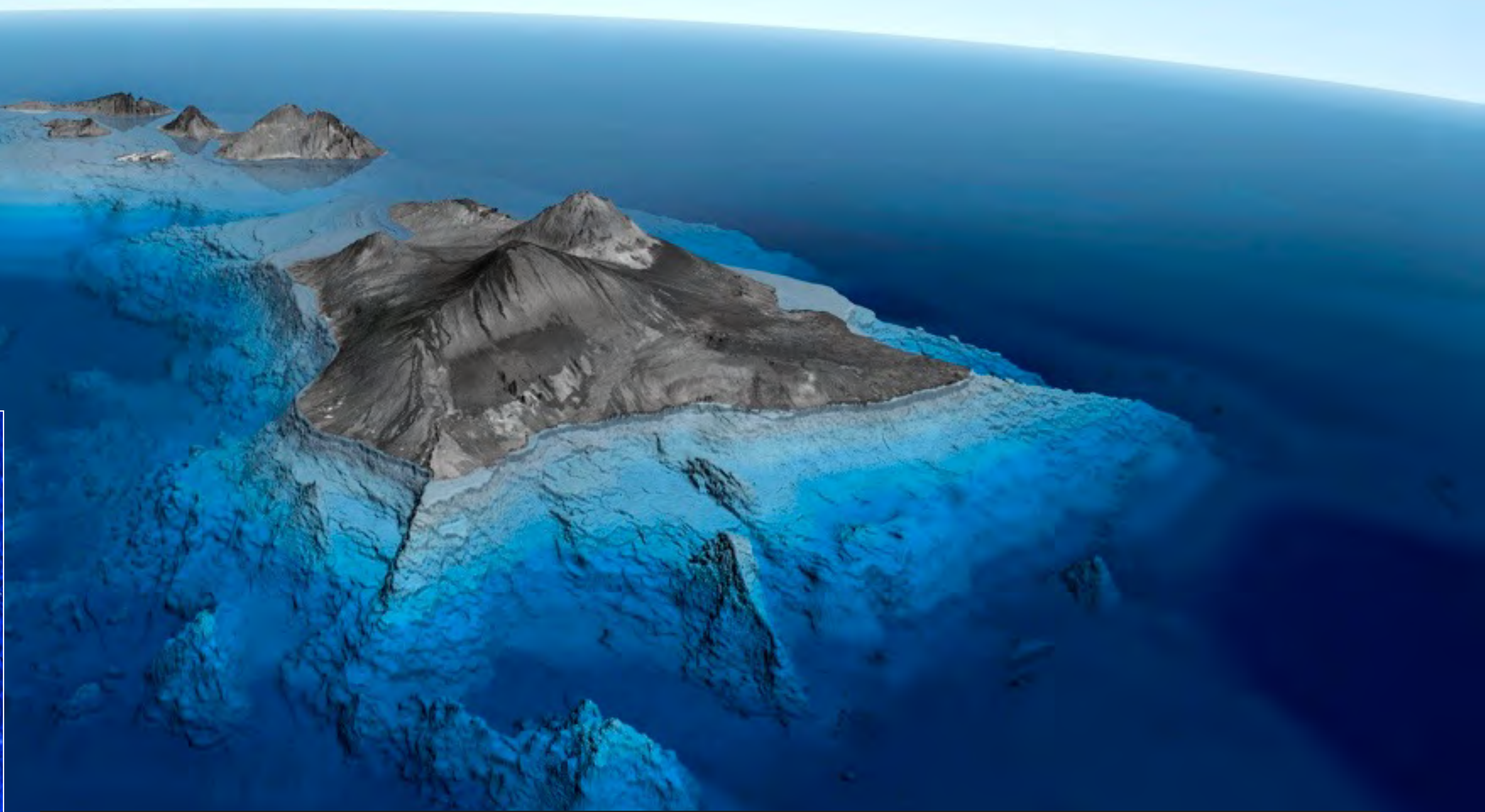


Hawaiian Swell - seafloor bulge:
1 km high & 1000 km wide

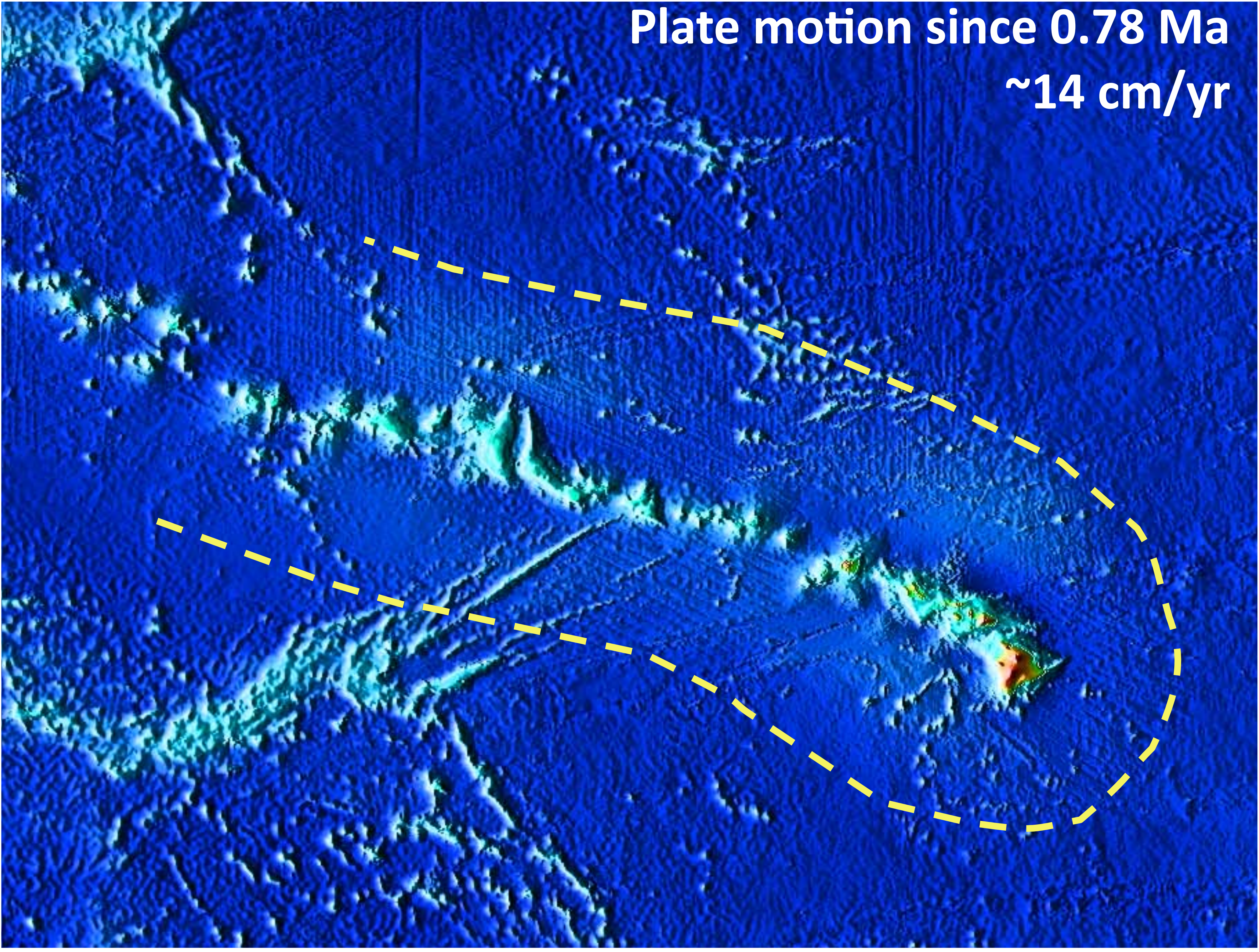
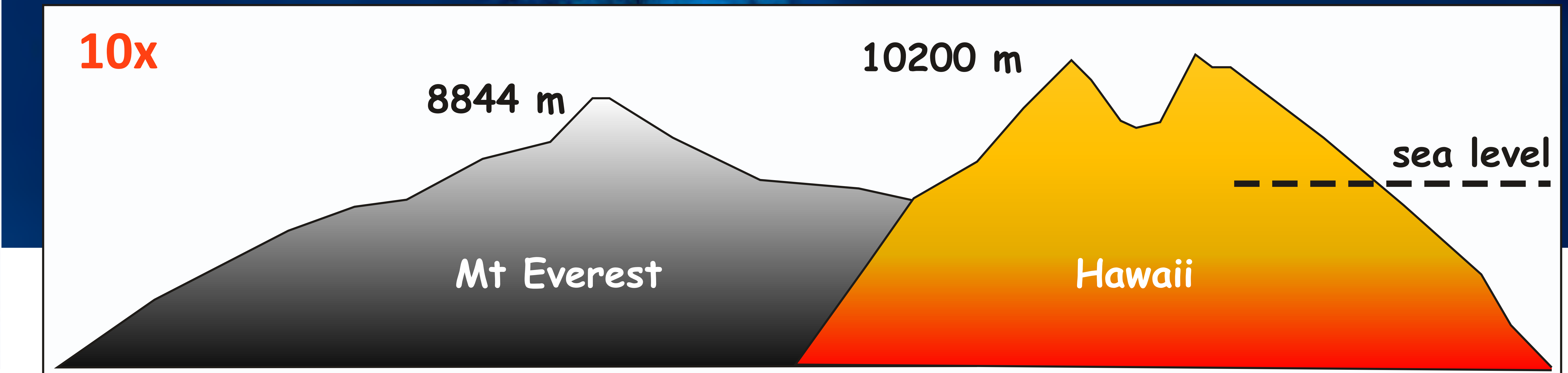


Plate motion since 0.78 Ma
~14 cm/yr



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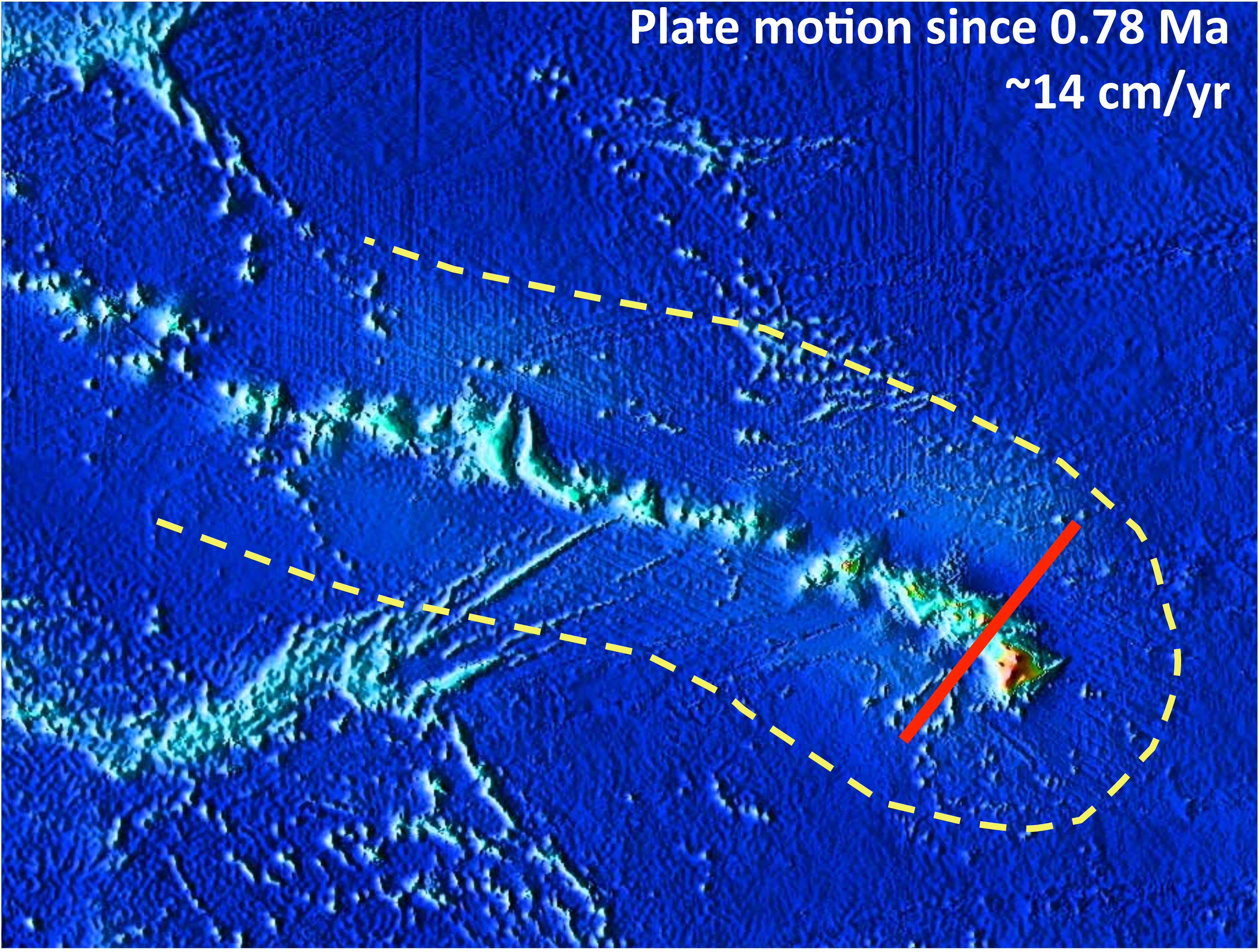

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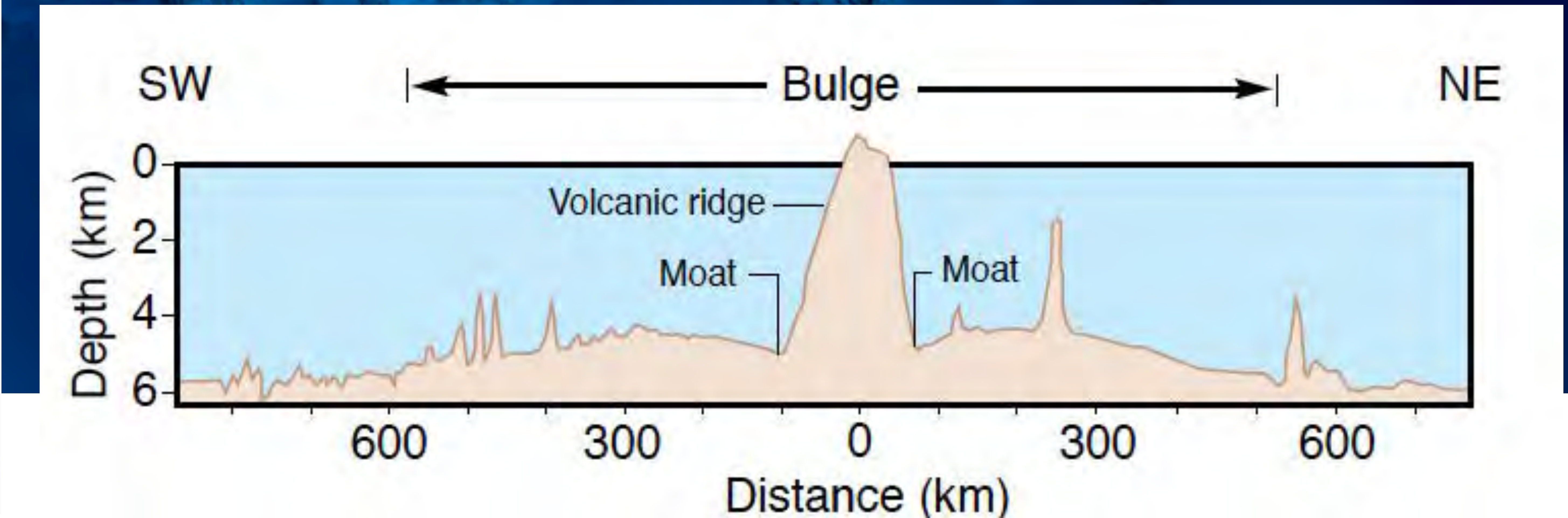
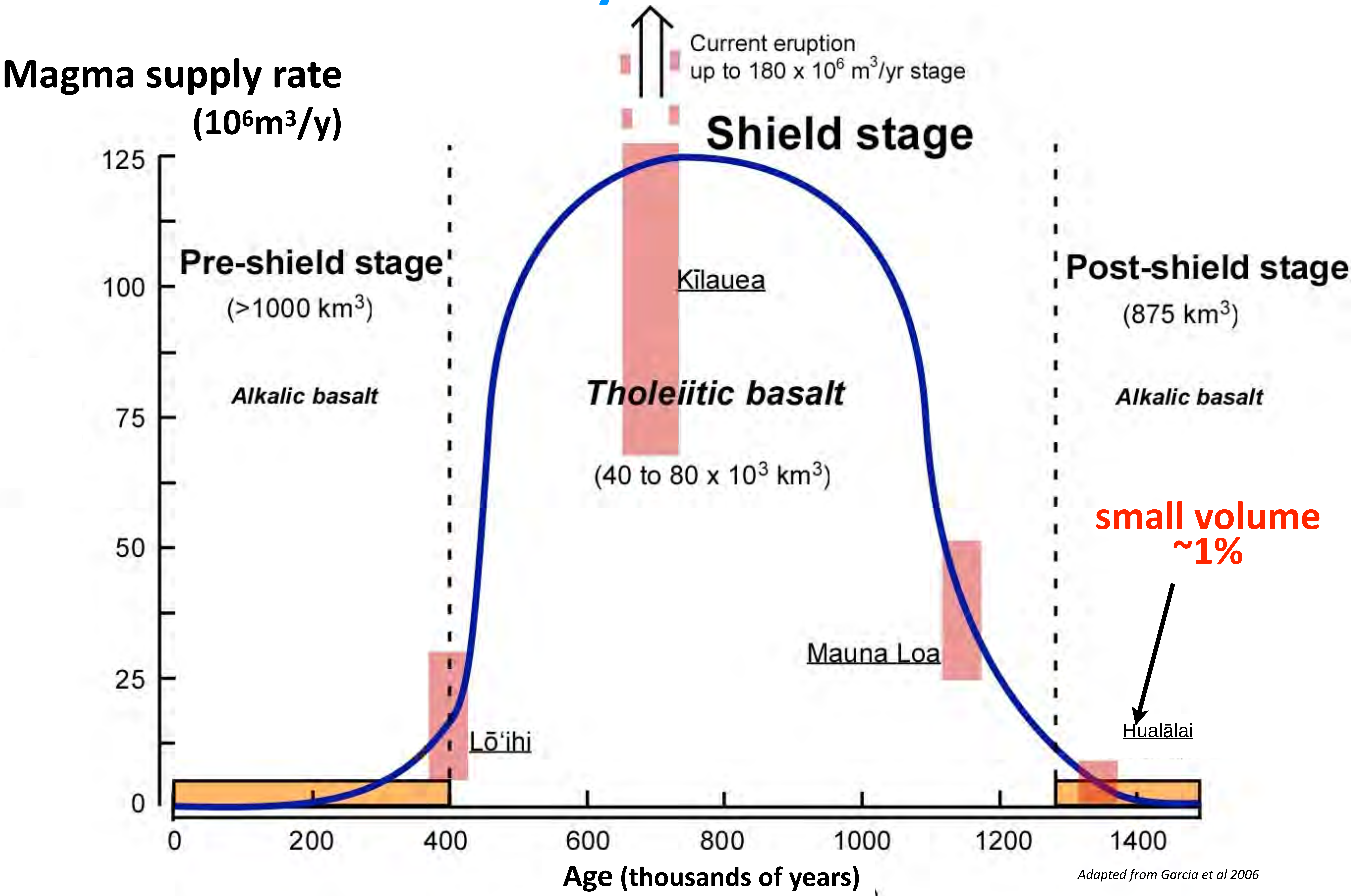


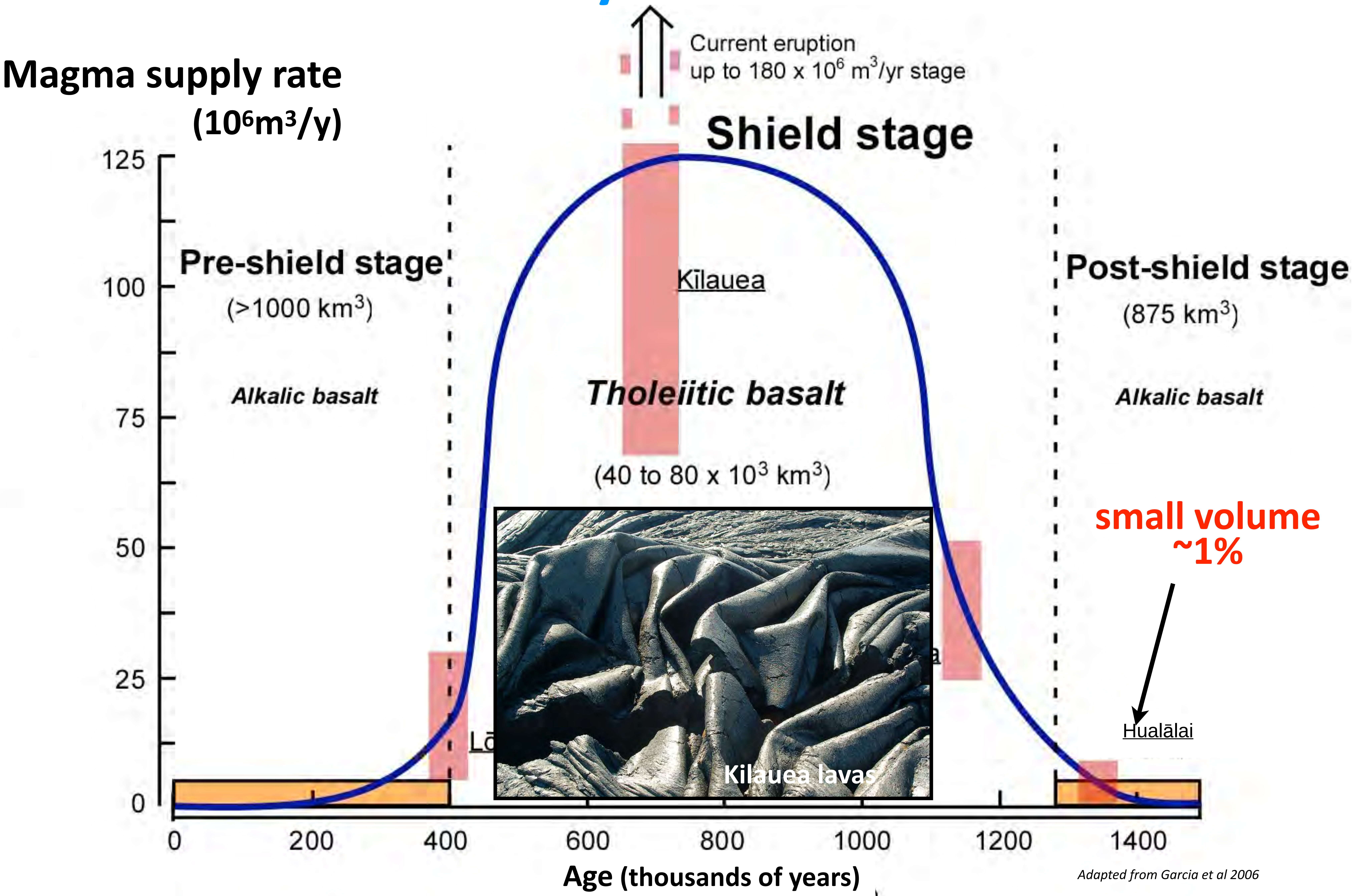
Growth History of Hawaiian Volcanoes



small volume
~1%

Adapted from Garcia et al 2006

Growth History of Hawaiian Volcanoes



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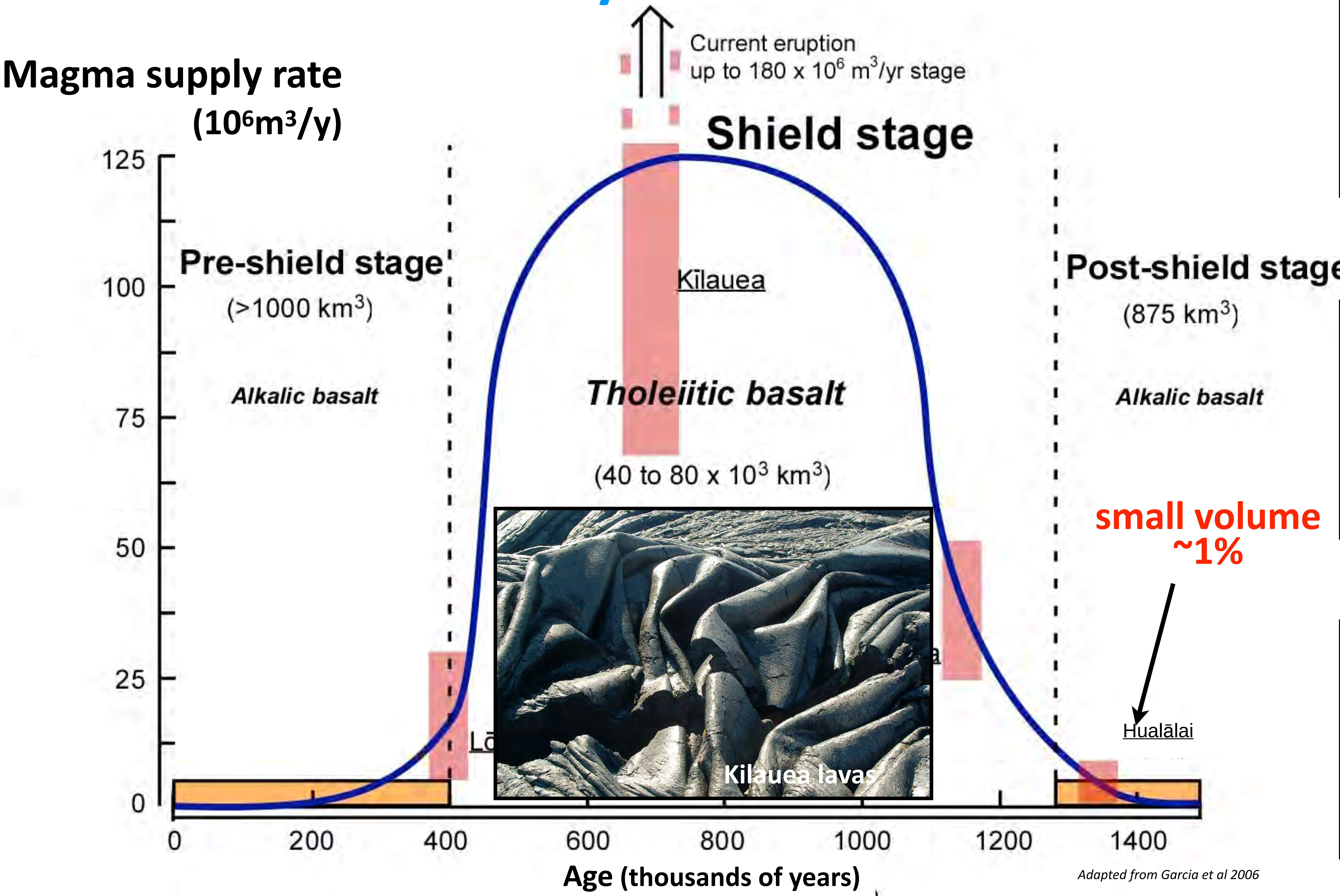

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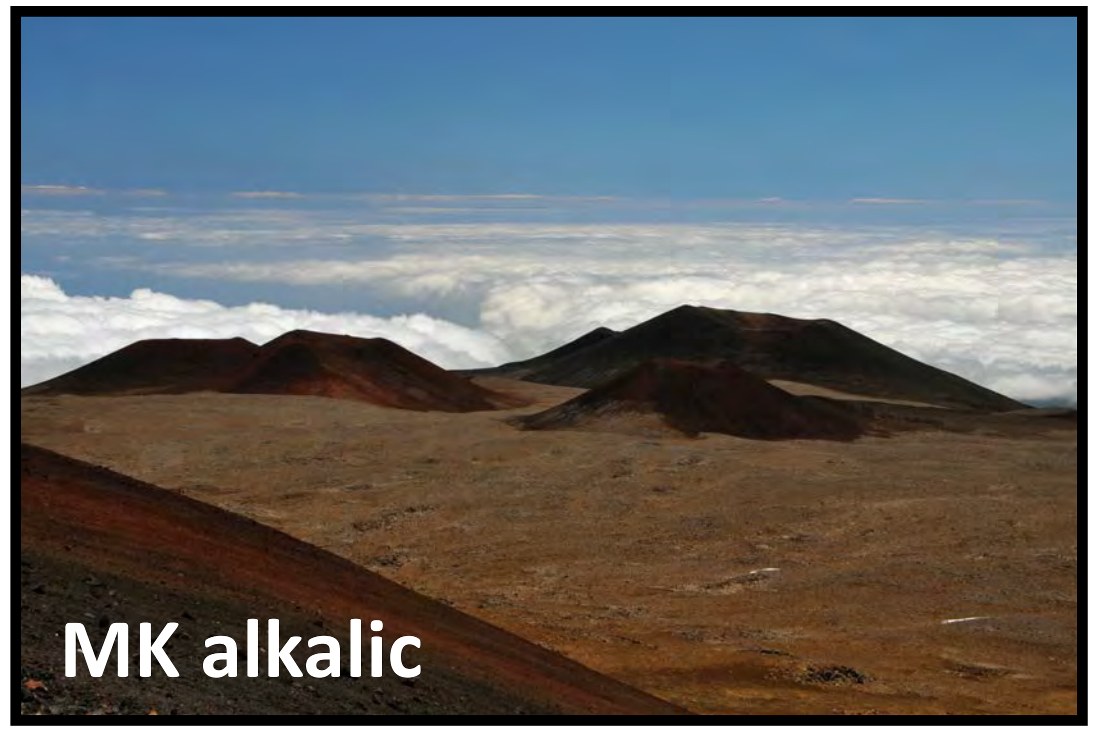
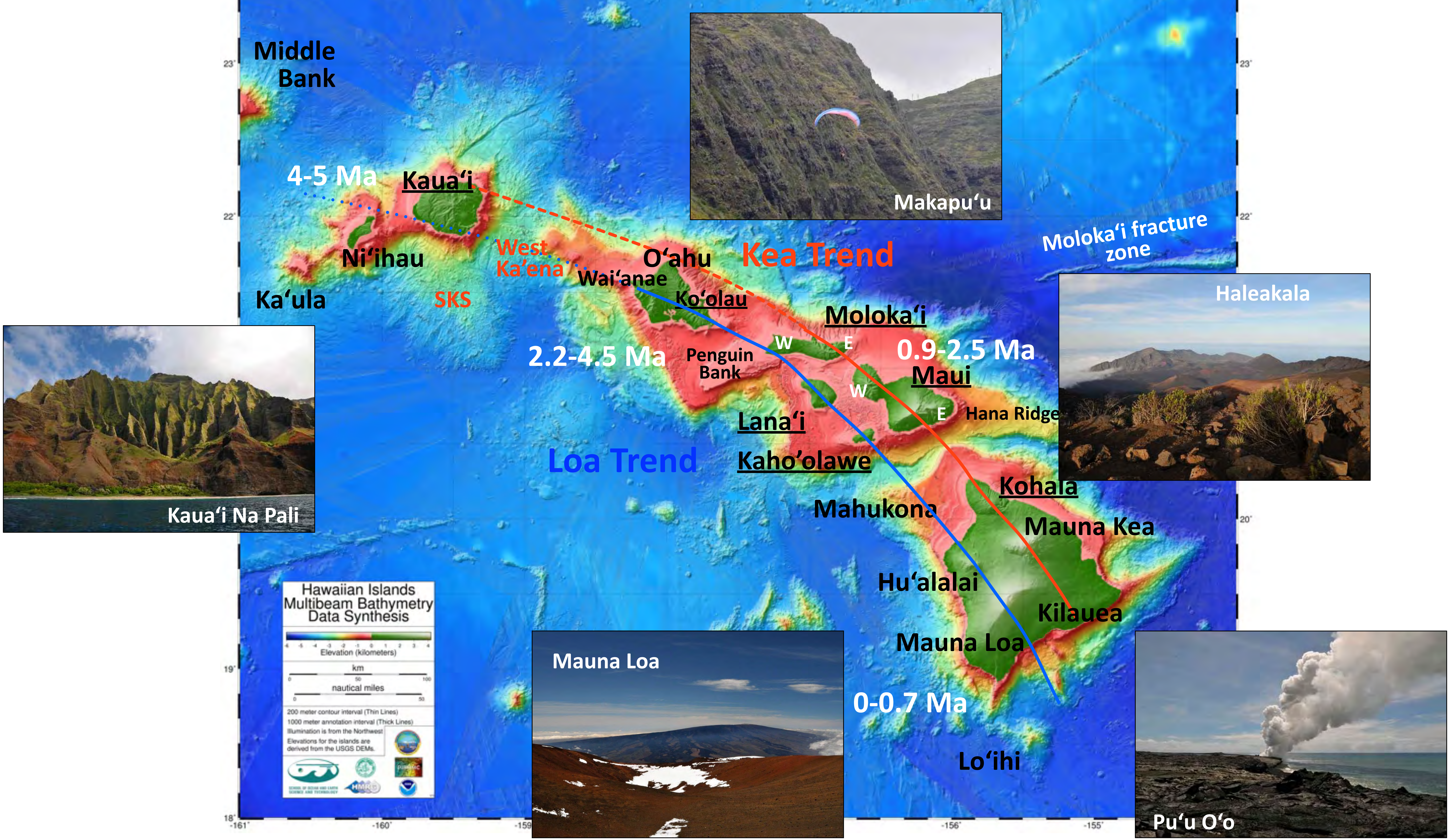


Hawaiʻi

Hawaiian Shield Basalts Evolution over 4.5 myr

Northwestern Hawaiian Ridge: 45 myr

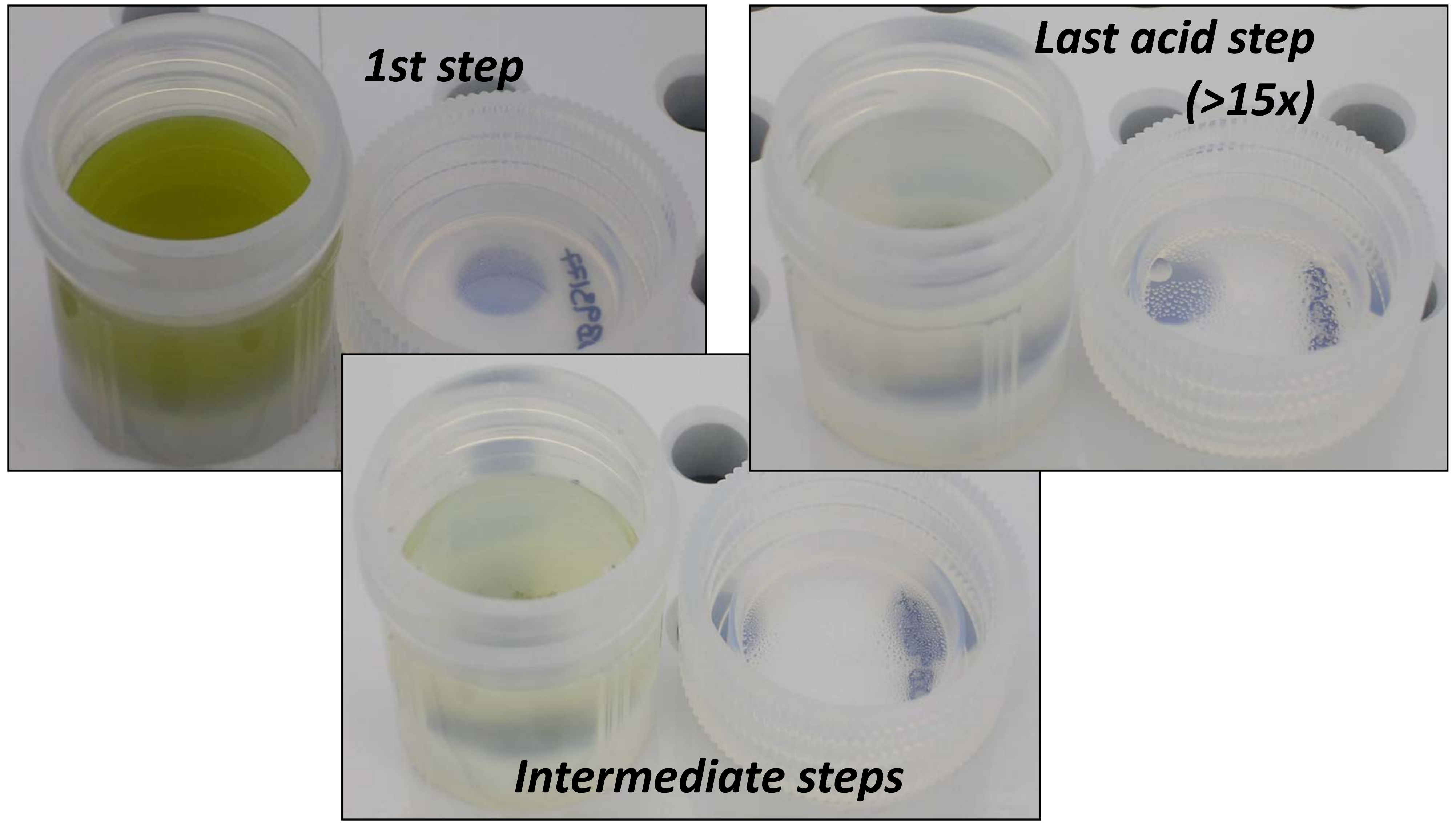
Kilauea Crater, April 2008


Middle Bank
4-5 Ma
Kauaʻi
Niʻihau
Kaʻula
West Kaʻena
SKS
Oʻahu
Waiʻanae
Koʻolau
Kea Trend
Molokaʻi
W
E
0.9-2.5 Ma
Maui
W
E
Hana Ridge
2.2-4.5 Ma
Penguin Bank
Lanaʻi
Kahoʻolawe
Loa Trend
Kohala
Mahukona
Mauna Kea
Huʻalalai
Kilauea
Mauna Loa
0-0.7 Ma
Loʻihi
Molokaʻi fracture zone
Makapuʻu
Haleakala
Kauaʻi Na Pali
Mauna Loa
Puʻu Oʻo
Hawaiian Islands Multibeam Bathymetry Data Synthesis
-6 -5 -4 -3 -2 -1 0 1 2 3 4
Elevation (kilometers)
km
0 50 100
nautical miles
0 50
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.
SCHOOL OF OCEAN AND EARTH SCIENCE AND TECHNOLOGY
HMRG
23°
22°
20°
19°
18°
-161°
-160°
-159°
-156°
-155°

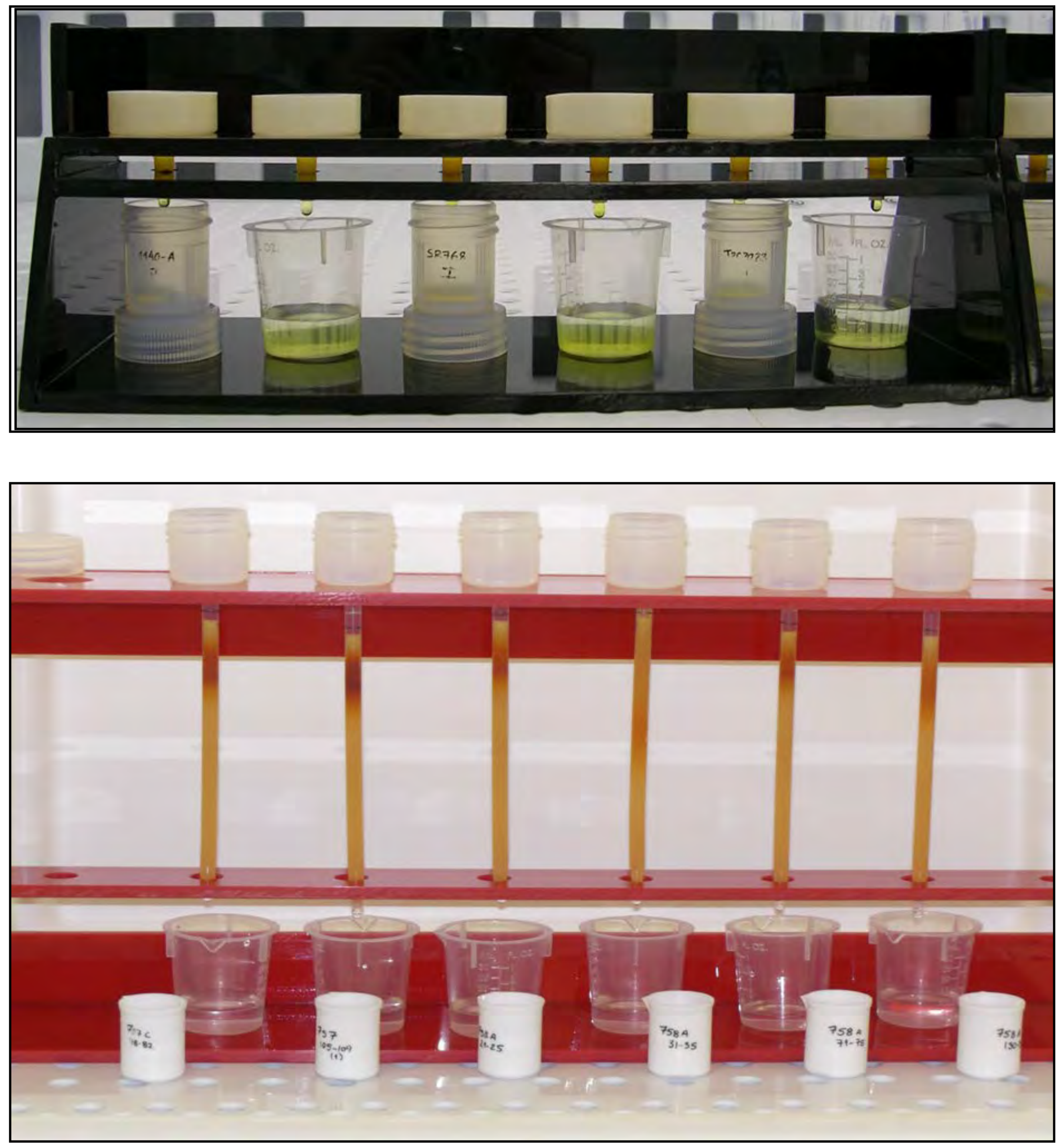
Samples, Chem Lab Preparation and Isotopic Analyses

1) Sample Collection

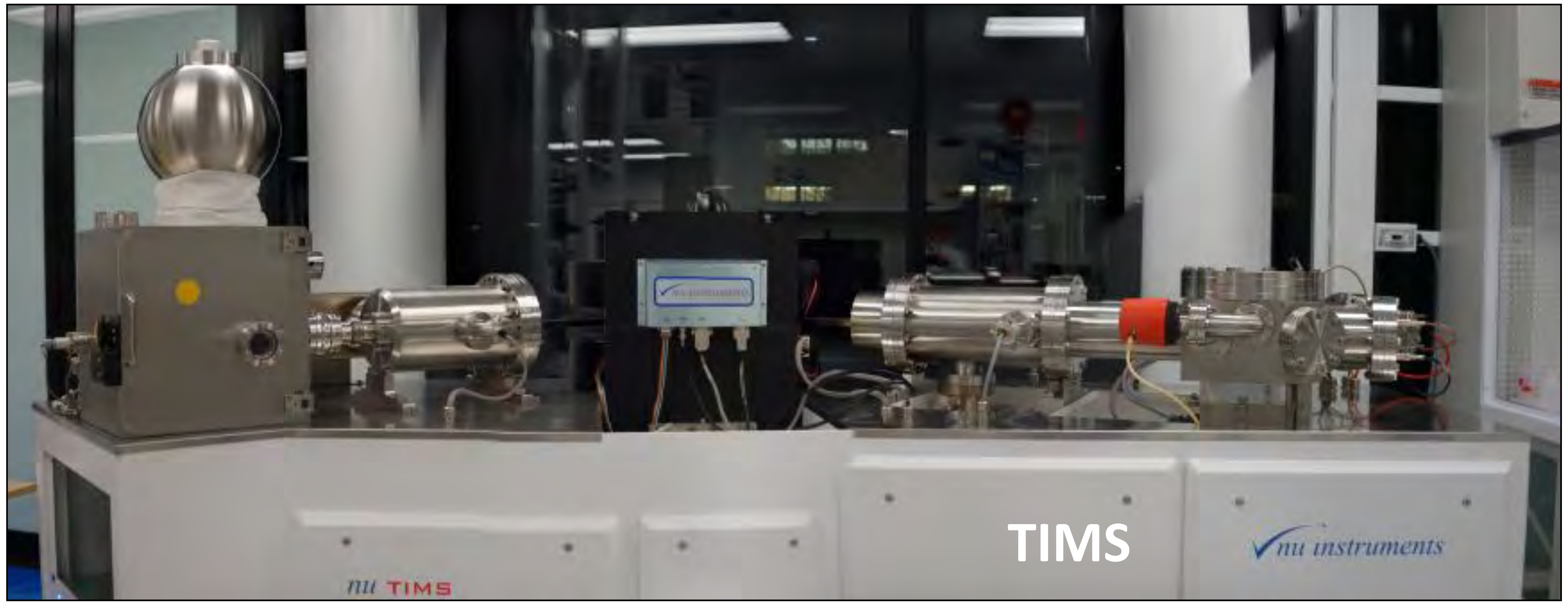
2) Sequential Acid Leaching



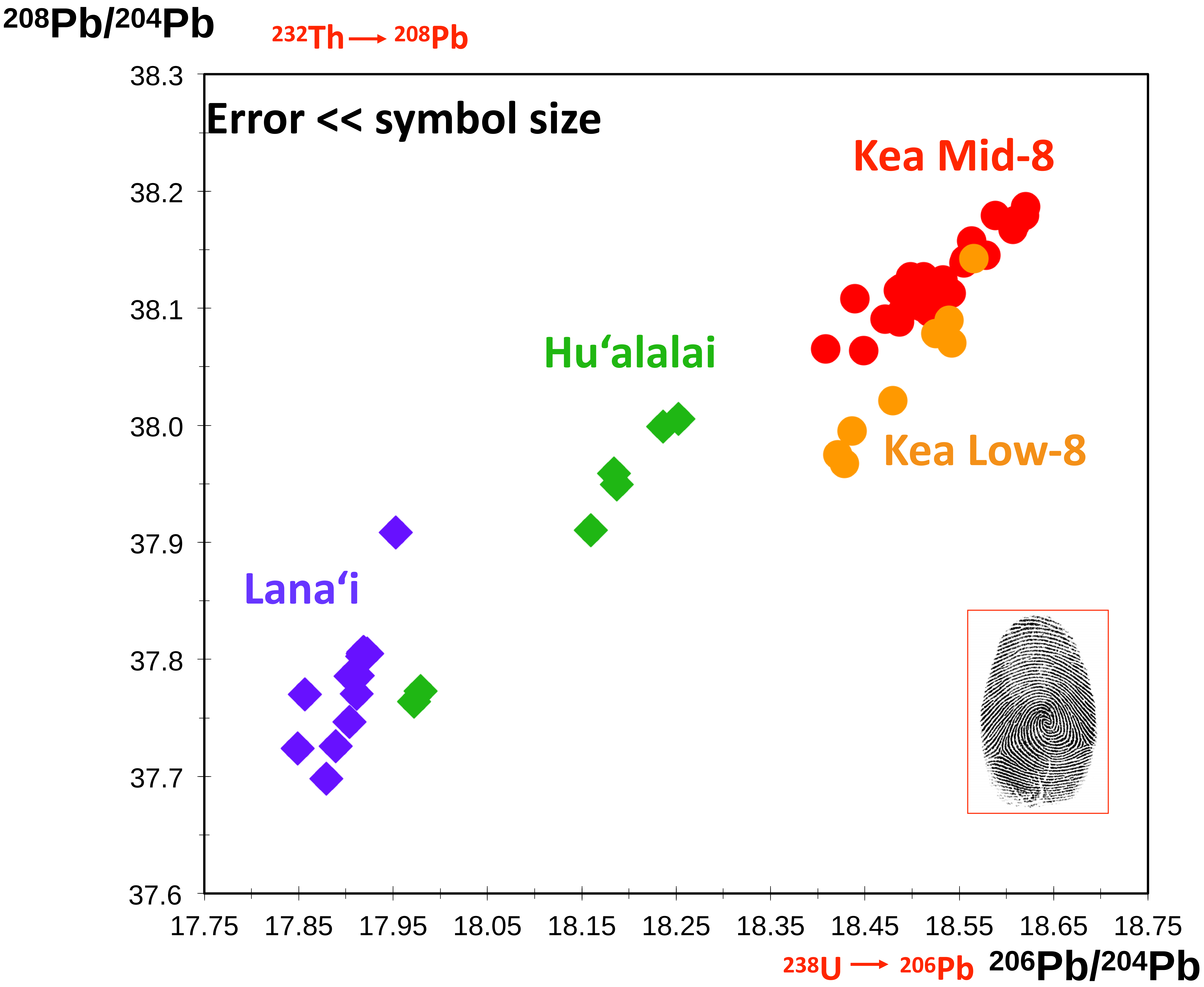
3) Chemical Separation



4) High-Precision Isotopic Analyses



Pb-Pb Isotope Systematics: Improved Resolution: Mixing lines



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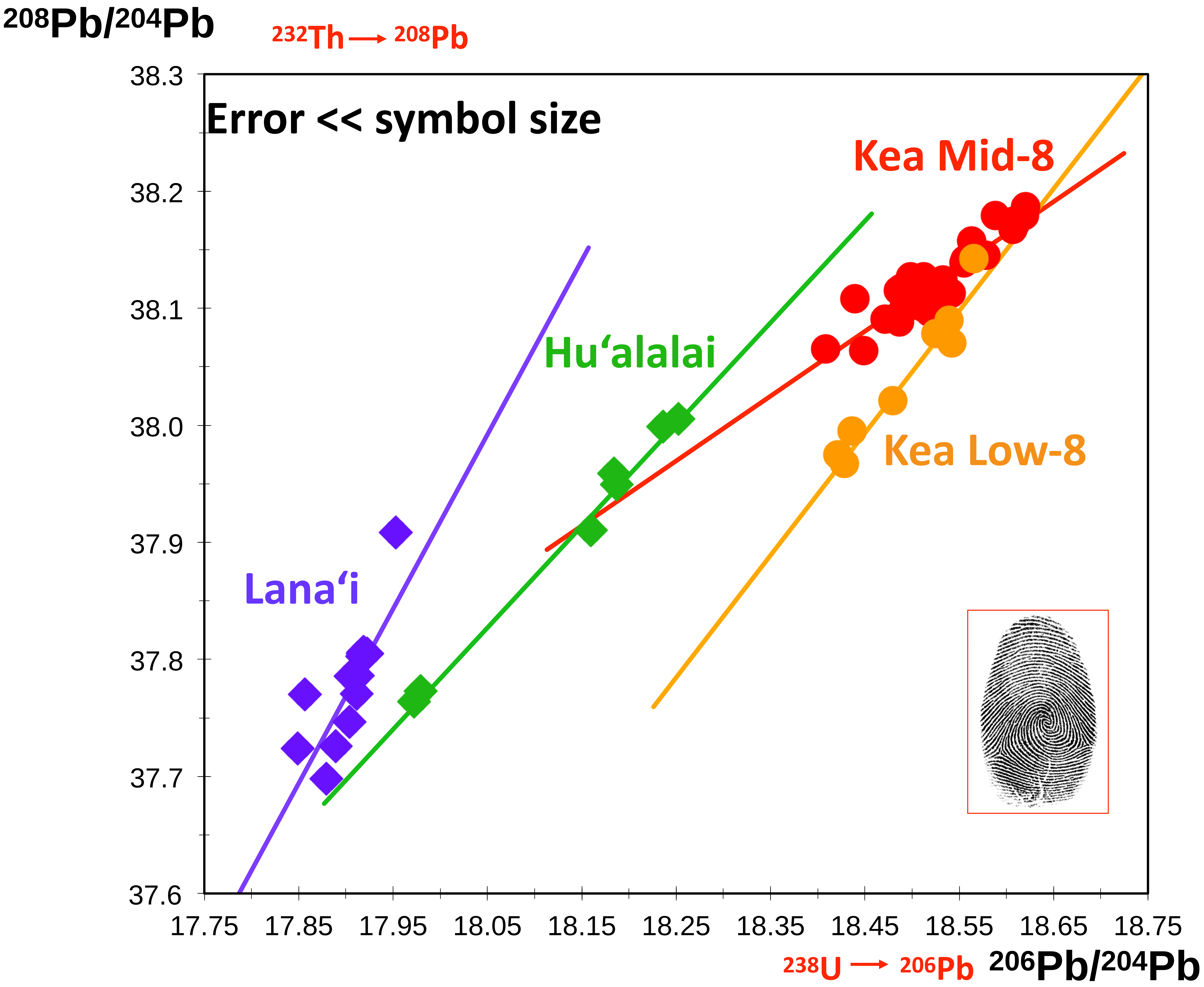
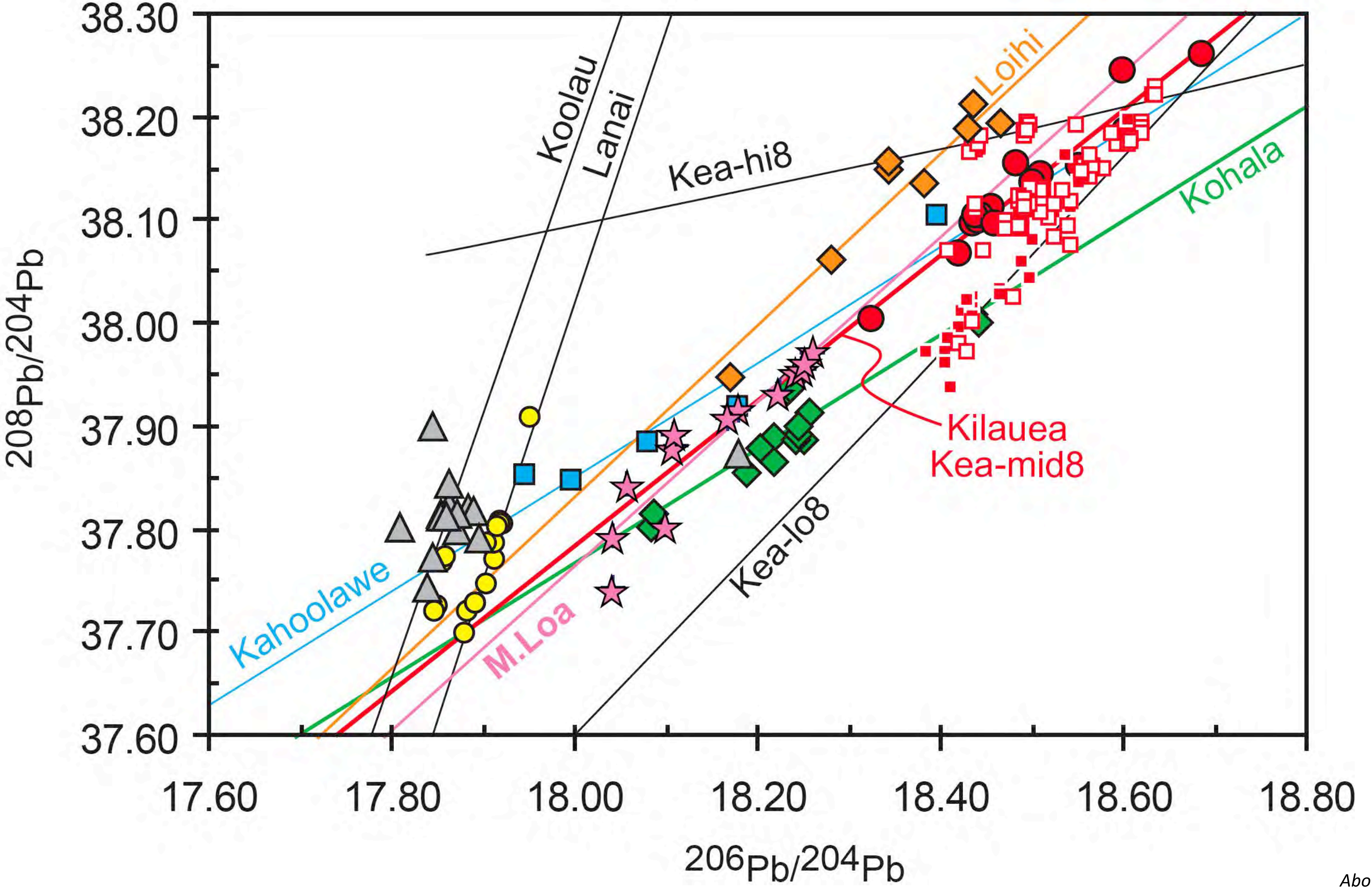


Triple Spike Pb Isotope Data: Shield Stage Lavas



Abouchami et al. 2005

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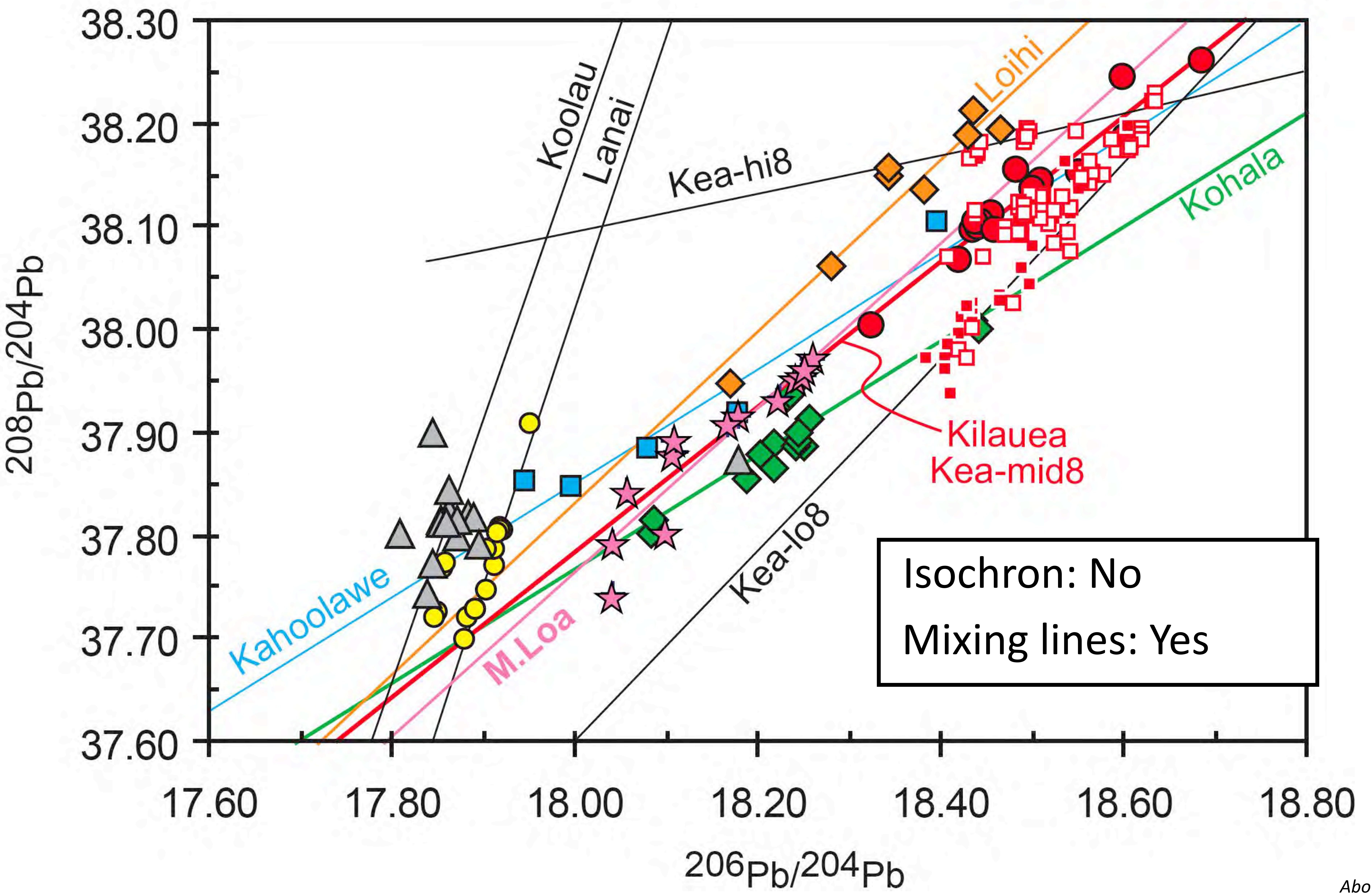

Isochron: No

Mixing lines: Yes

Abouchami et al. 2005

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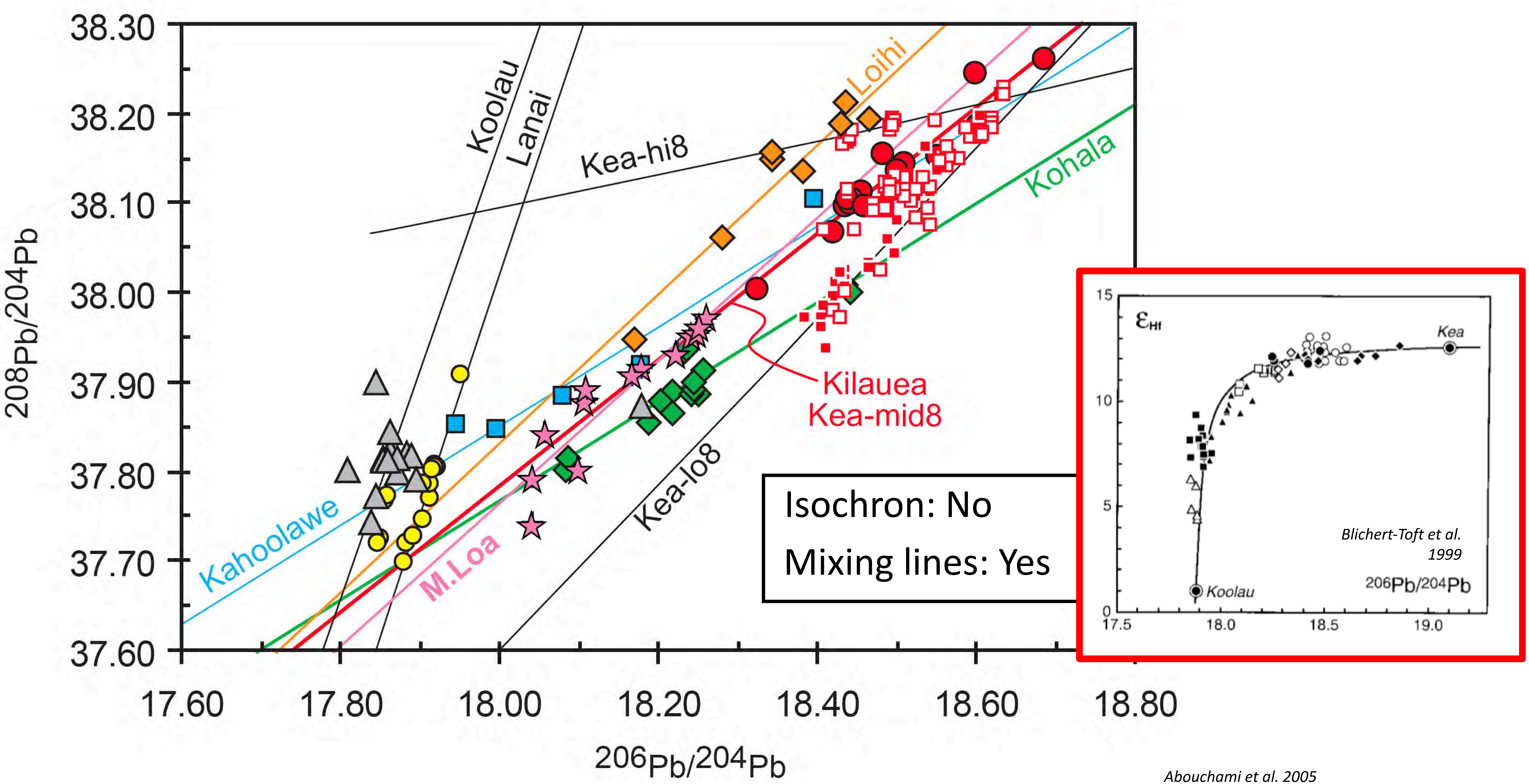
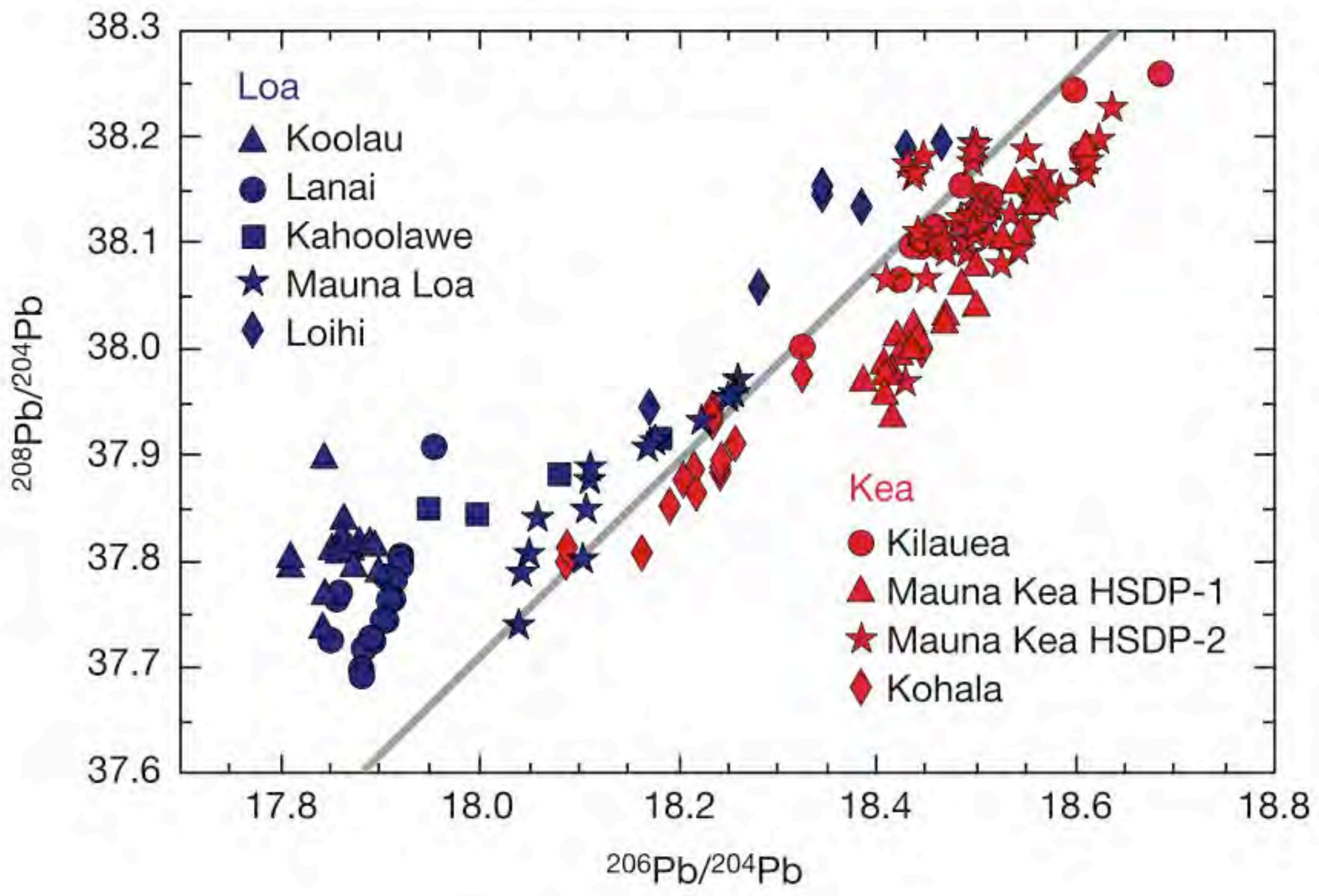


Isochron: No

Mixing lines: Yes

Abouchami et al. 2005

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

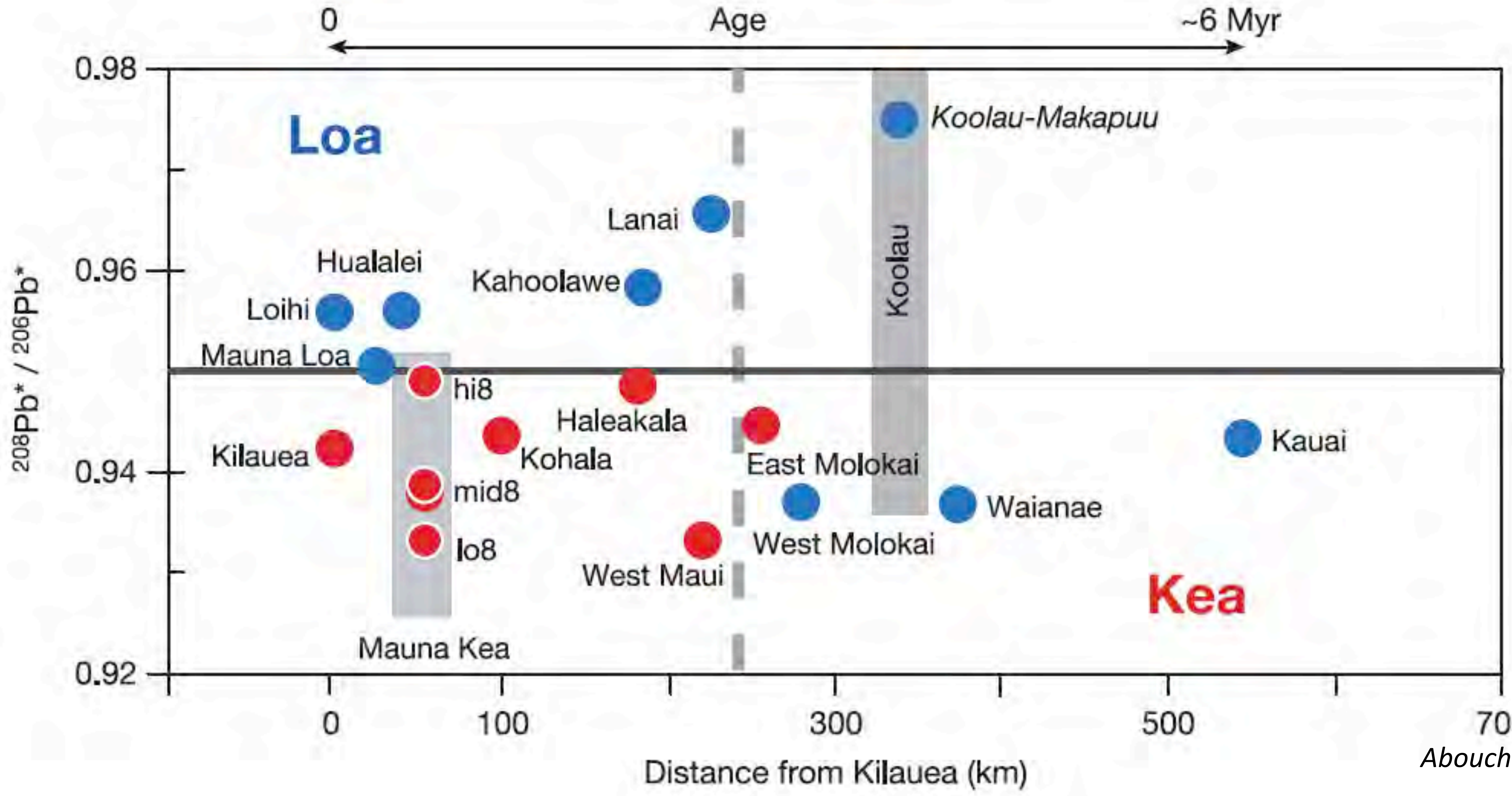


$$\frac{^{208*}Pb}{^{206*}Pb} = \frac{\left(^{208}Pb/^{204}Pb\right)_{sample} - \left(^{208}Pb/^{204}Pb\right)_{init}}{\left(^{206}Pb/^{204}Pb\right)_{sample} - \left(^{206}Pb/^{204}Pb\right)_{init}} \approx \frac{Th}{U}$$

where init stands for Earth's primordial Pb isotopic composition

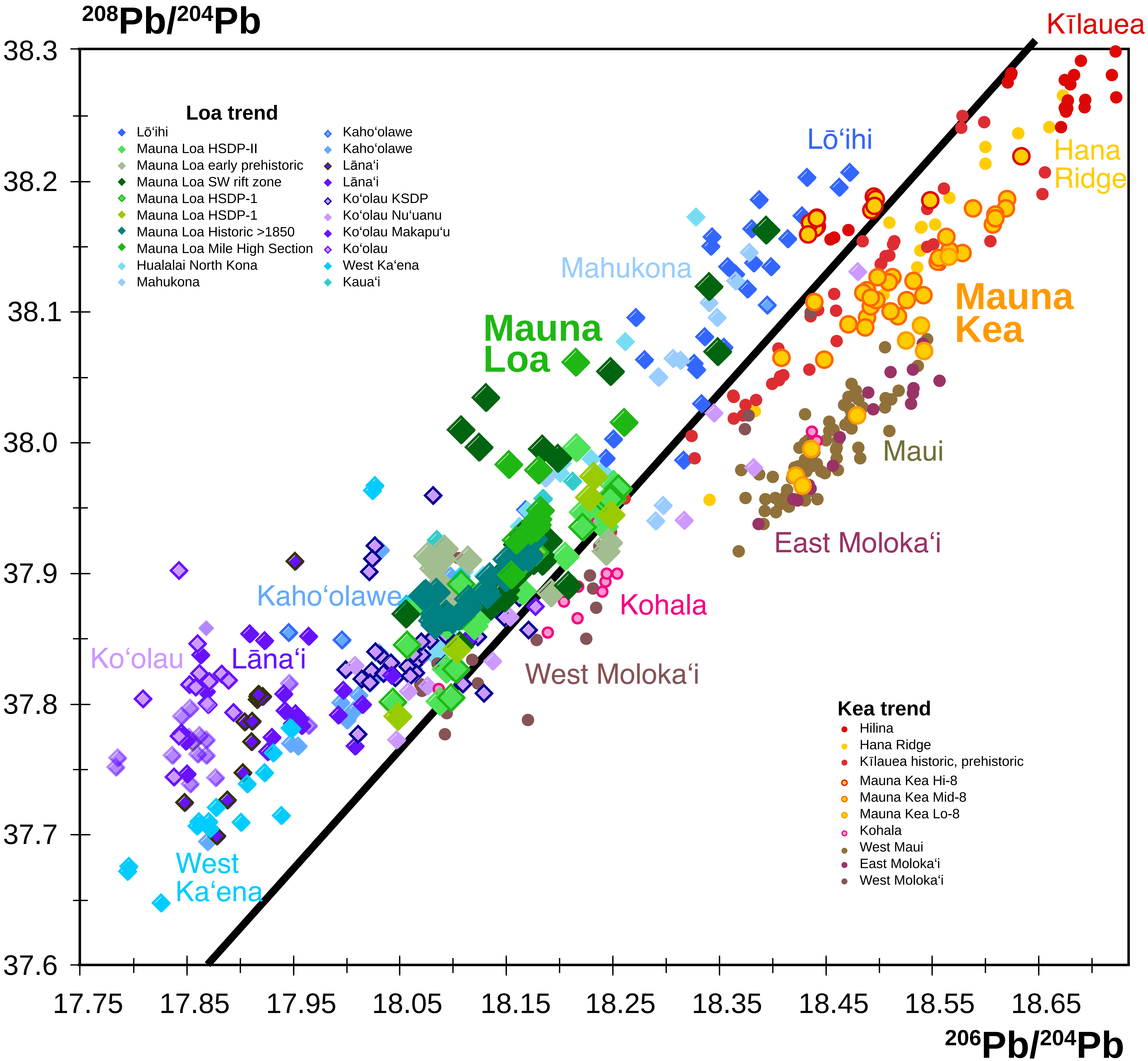
$^{232}Th \longrightarrow {}^{208}Pb$

$^{238}U \longrightarrow {}^{206}Pb$



Abouchami et al. 2005

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



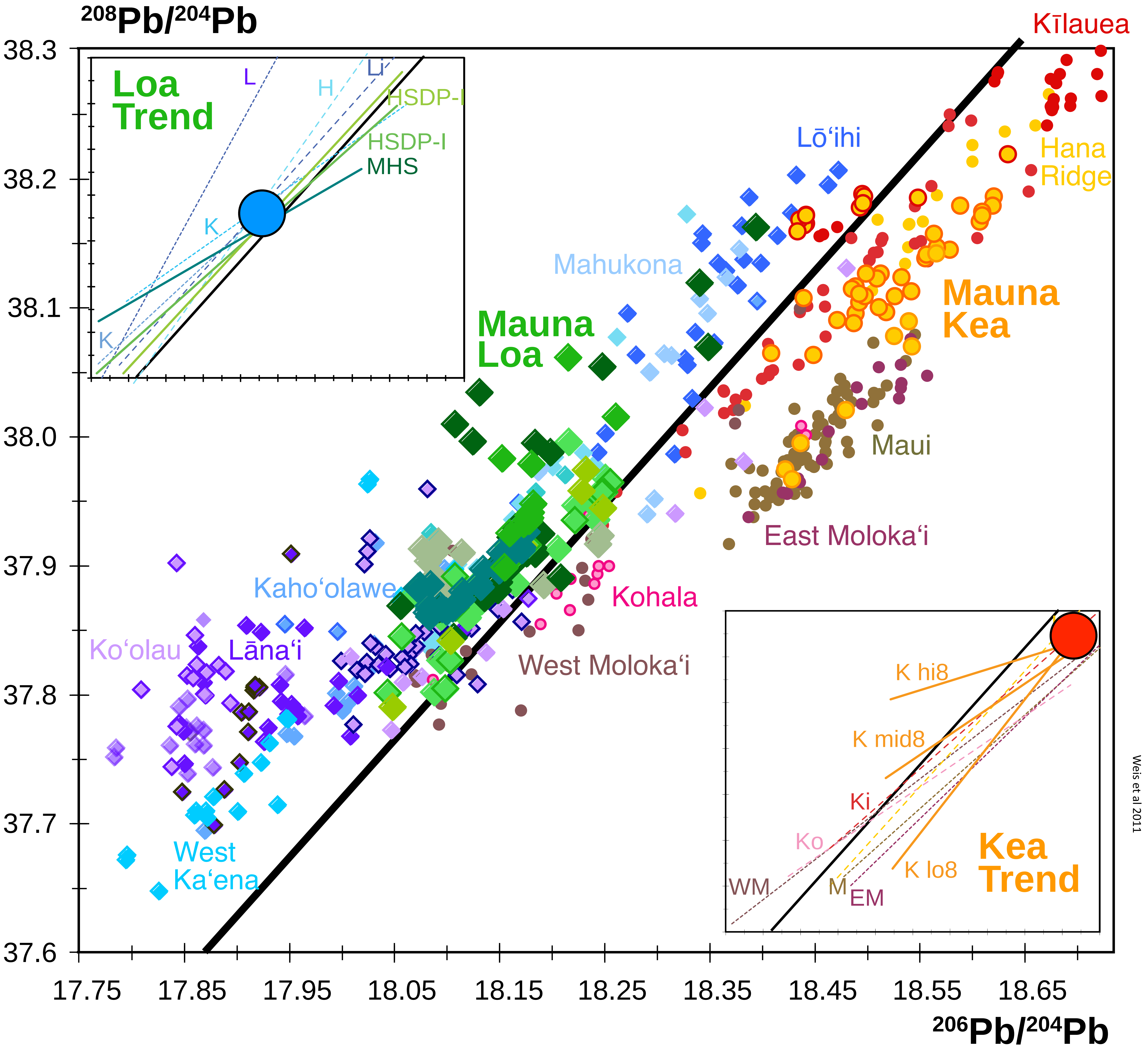
Weis et al 2011

Only shield lavas

>700 samples

(MC-ICP-MS or TS)/NORM

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



Weis et al 2011

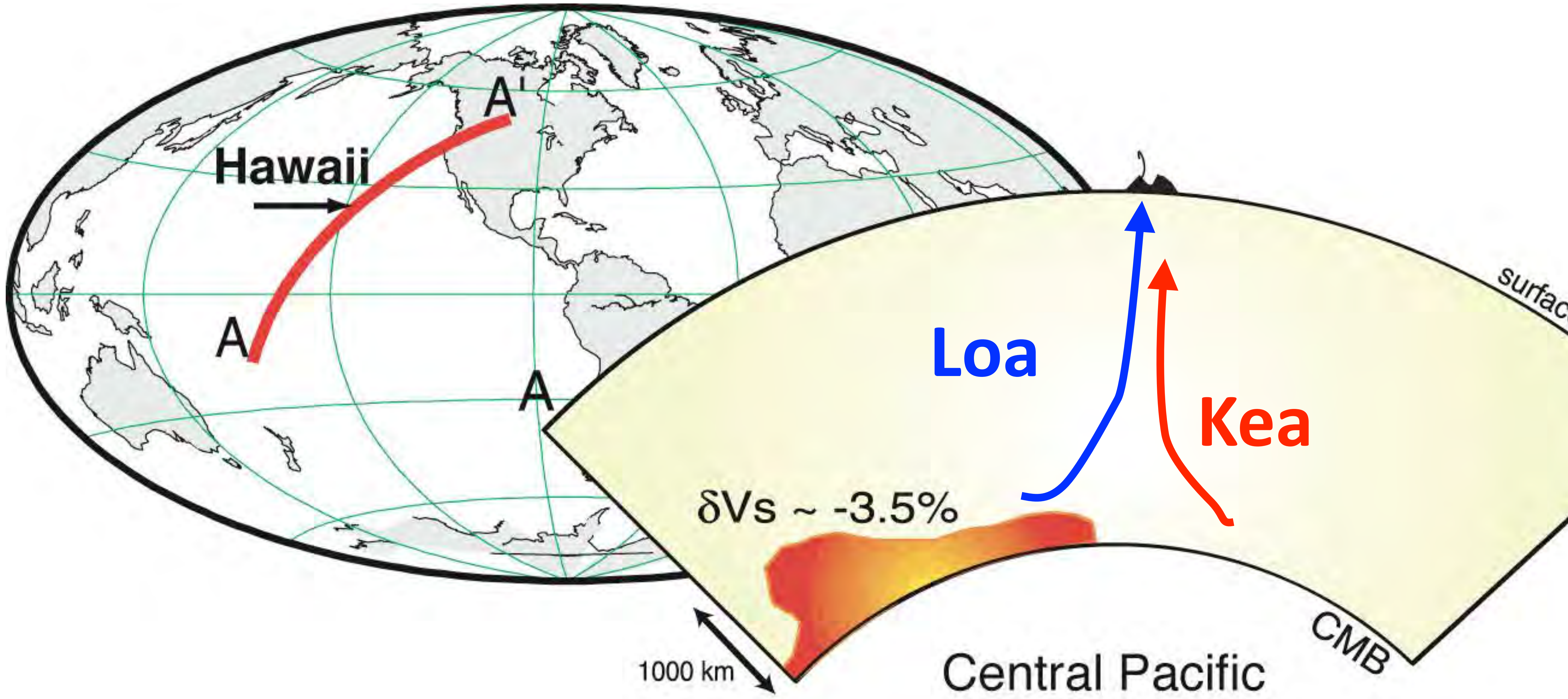
Kea end-member:

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

Loa trend volcanoes:

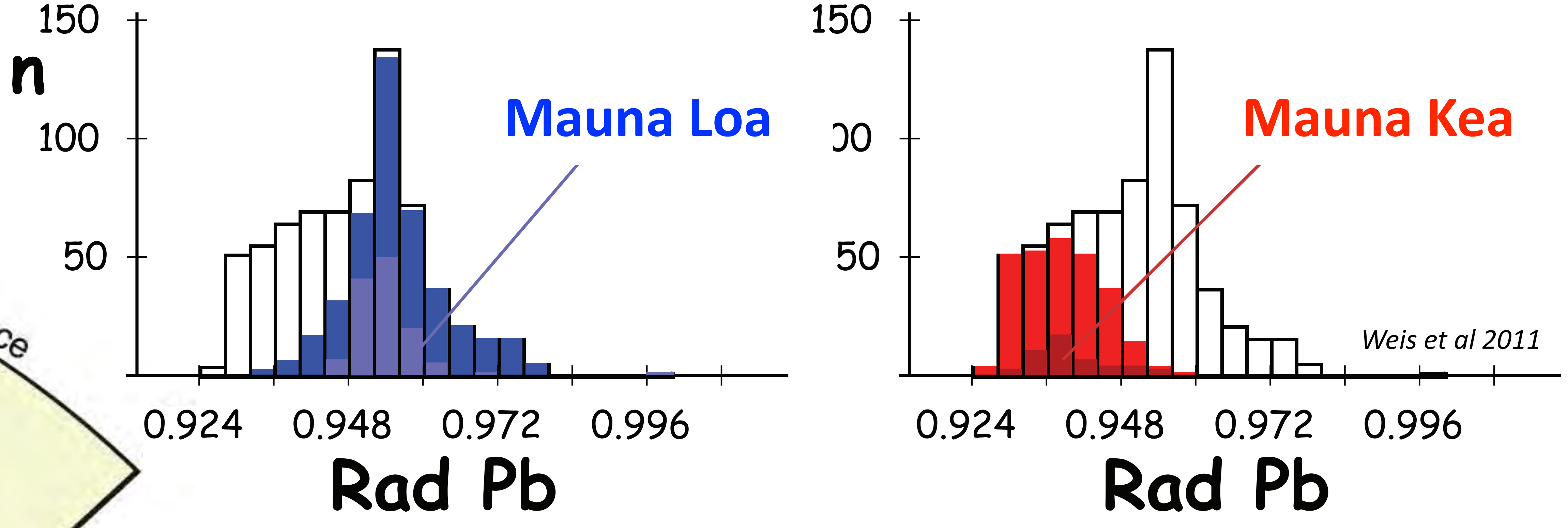
- higher ^{208}Pb/^{204}Pb ratios for a given ^{206}Pb/^{204}Pb, higher ^{87}Sr/^{86}Sr and lower ε_{Nd} and ε_{Hf}
- **more heterogeneous**

Possible plume location cross-section

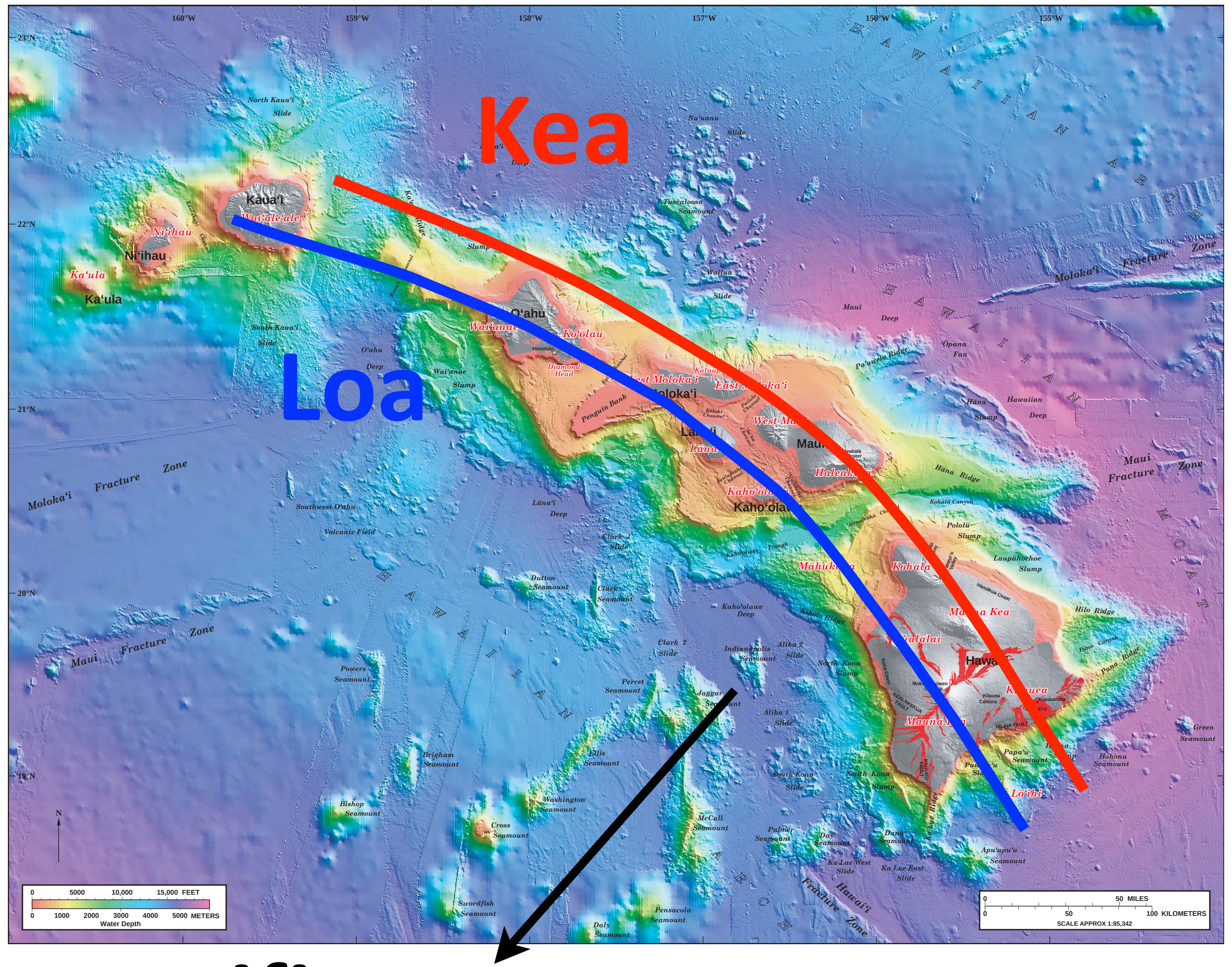


after Breger & Romanowicz 1998

Loa Trend volcanoes **Kea Trend volcanoes**

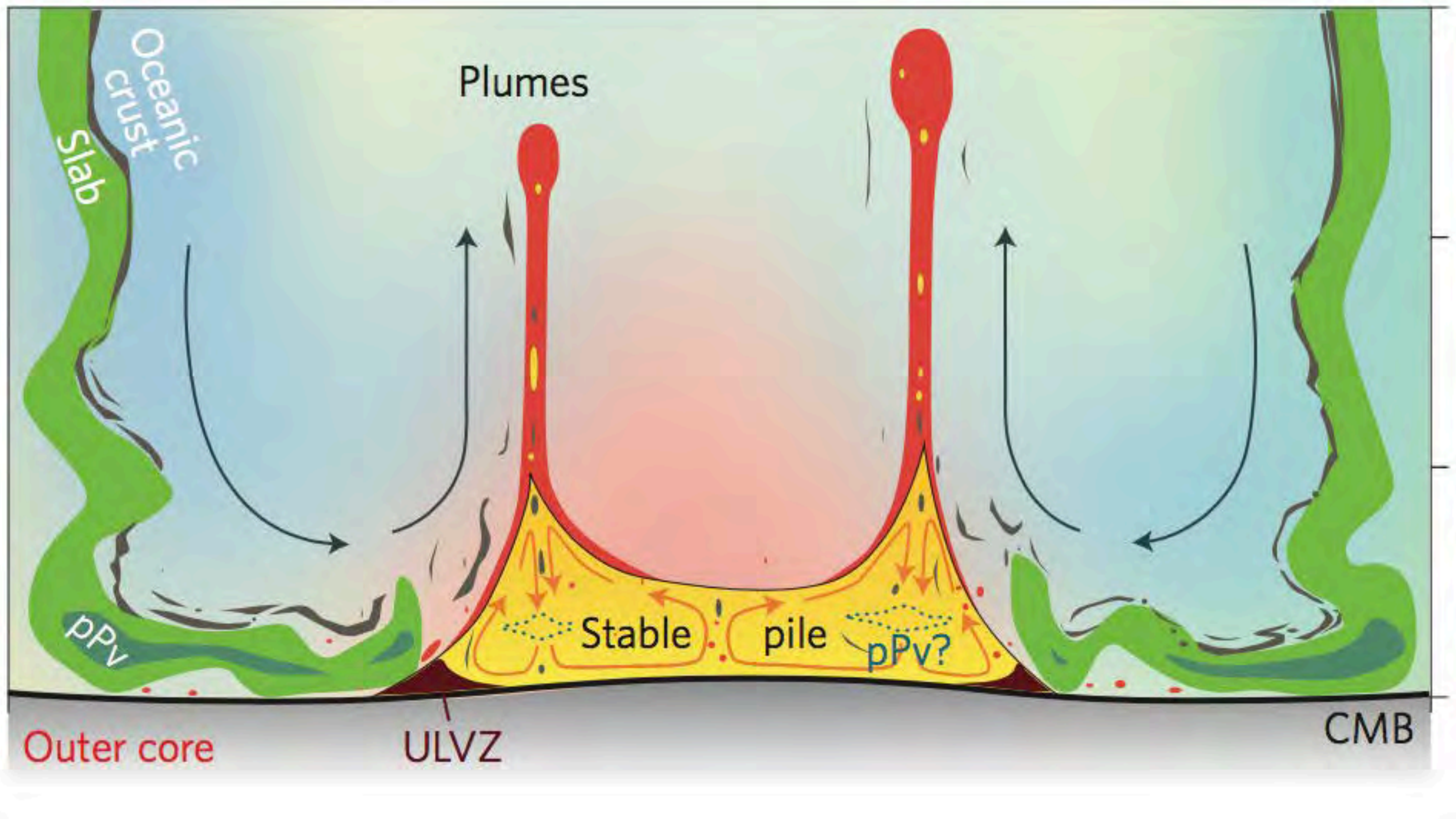


Weis et al 2011



Pacific ULVZ

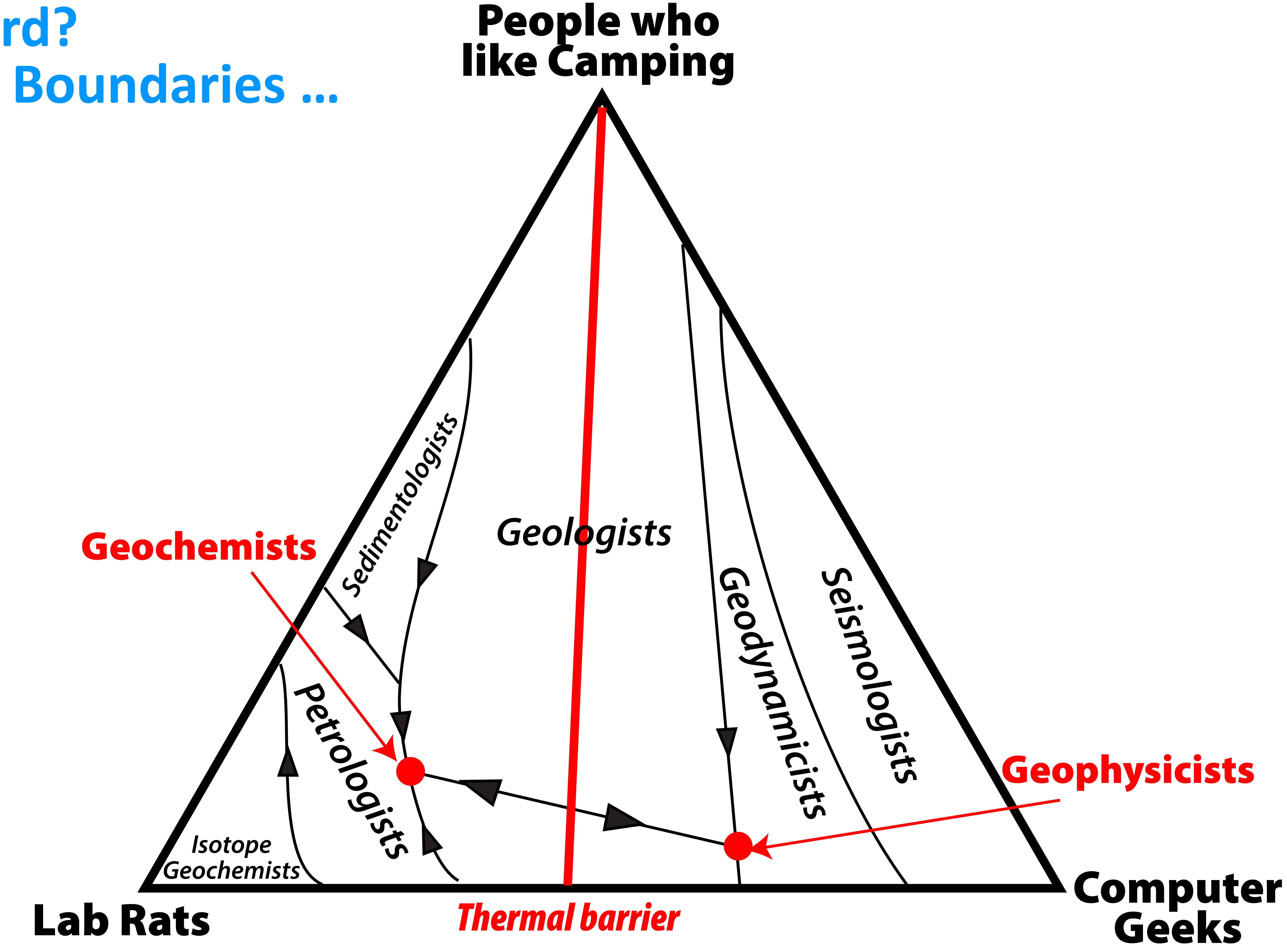
Complex CMB



Garnero et al 2016

How to Move Forward?
Need to Break some Boundaries …

How to Move Forward?
Need to Break some Boundaries …

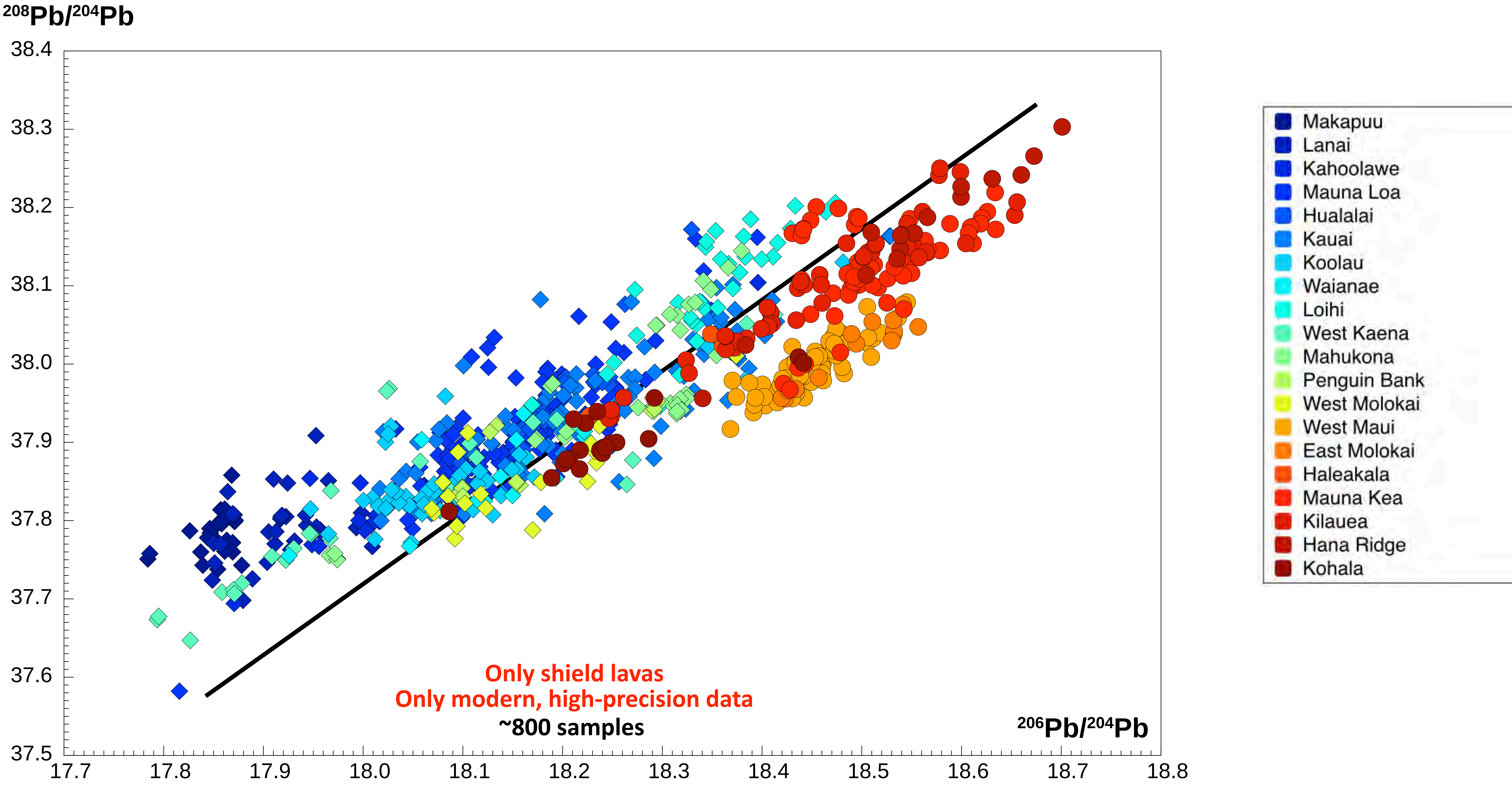


Experiments at 1 atm, 298 K

Back to Hawaiʻi
Shield Lavas

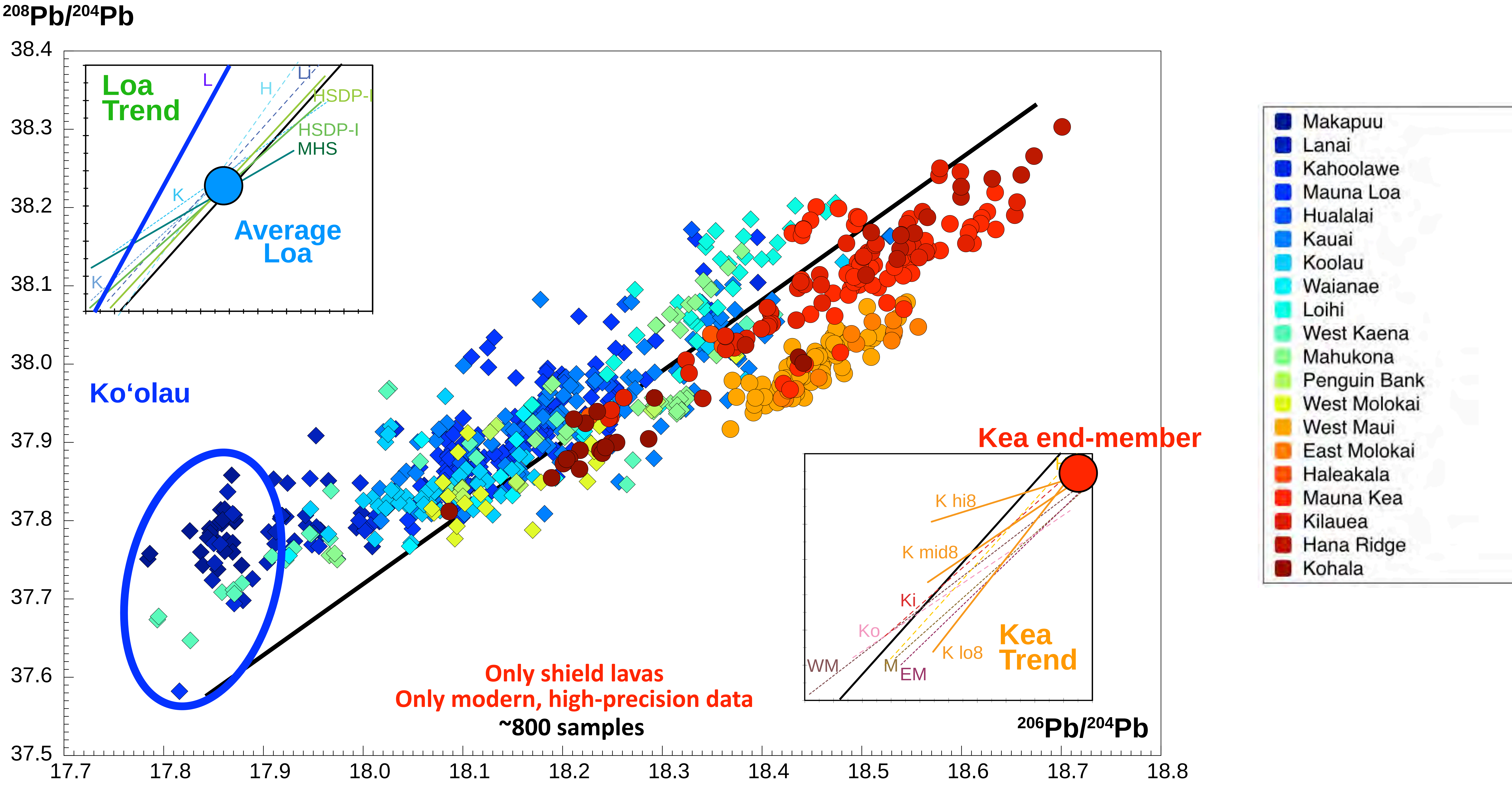
Kauaʻi, Kalalau Valley

A Simple Bilateral Source? Some Challenges



Only shield lavas
Only modern, high-precision data
~800 samples

A Simple Bilateral Source? Some Challenges



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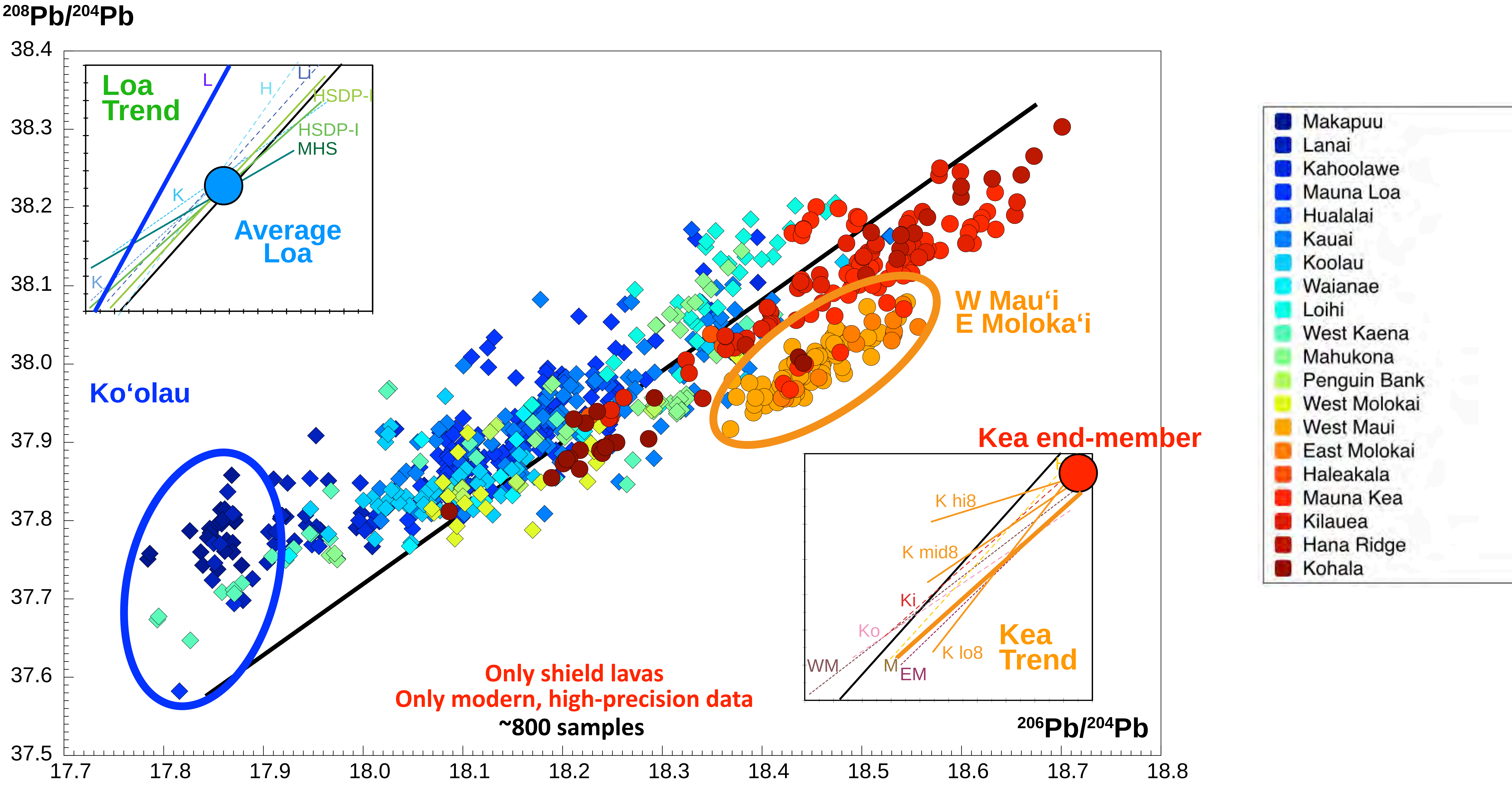
A Simple Bilateral Source? Some Challenges



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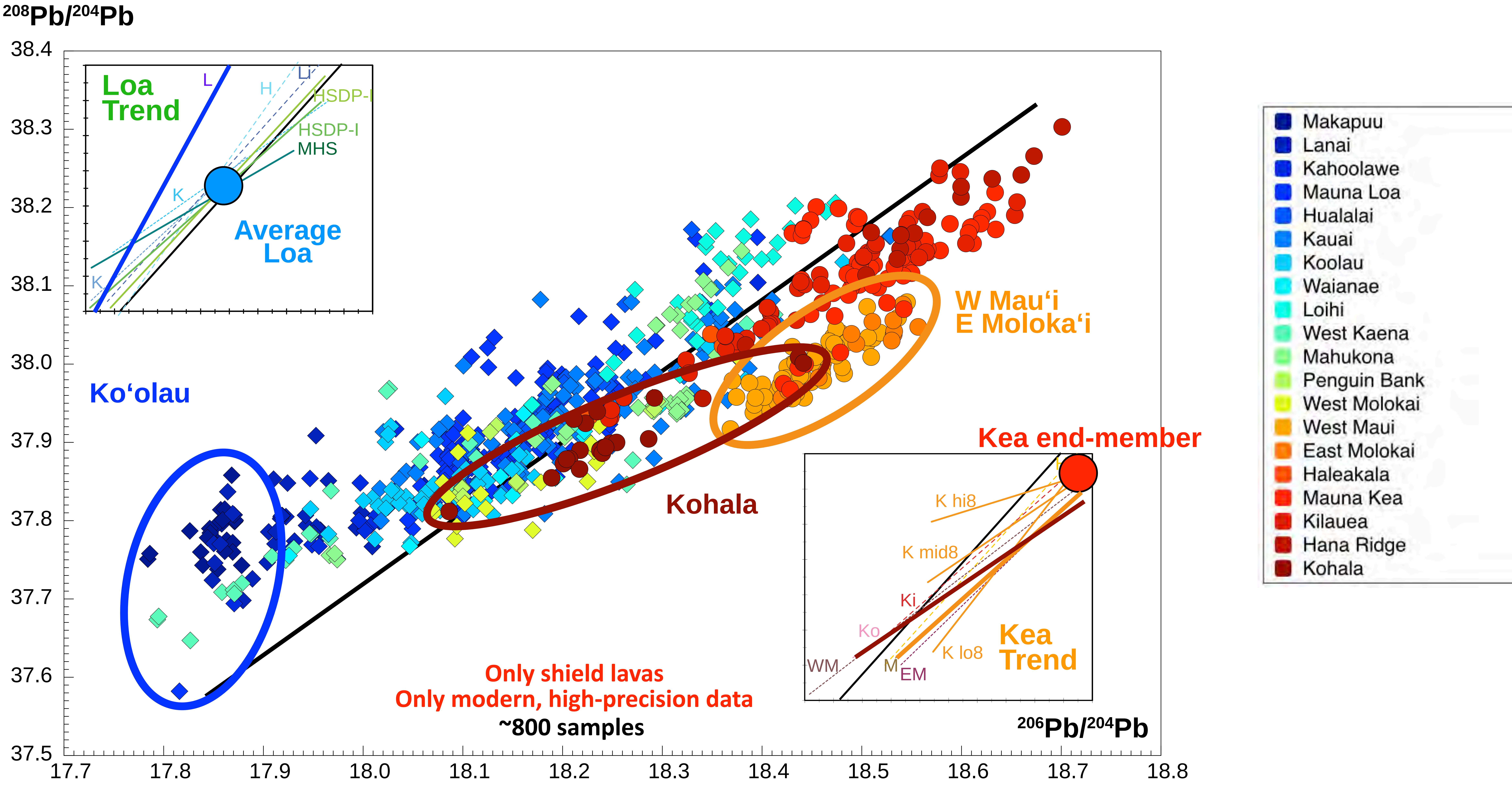
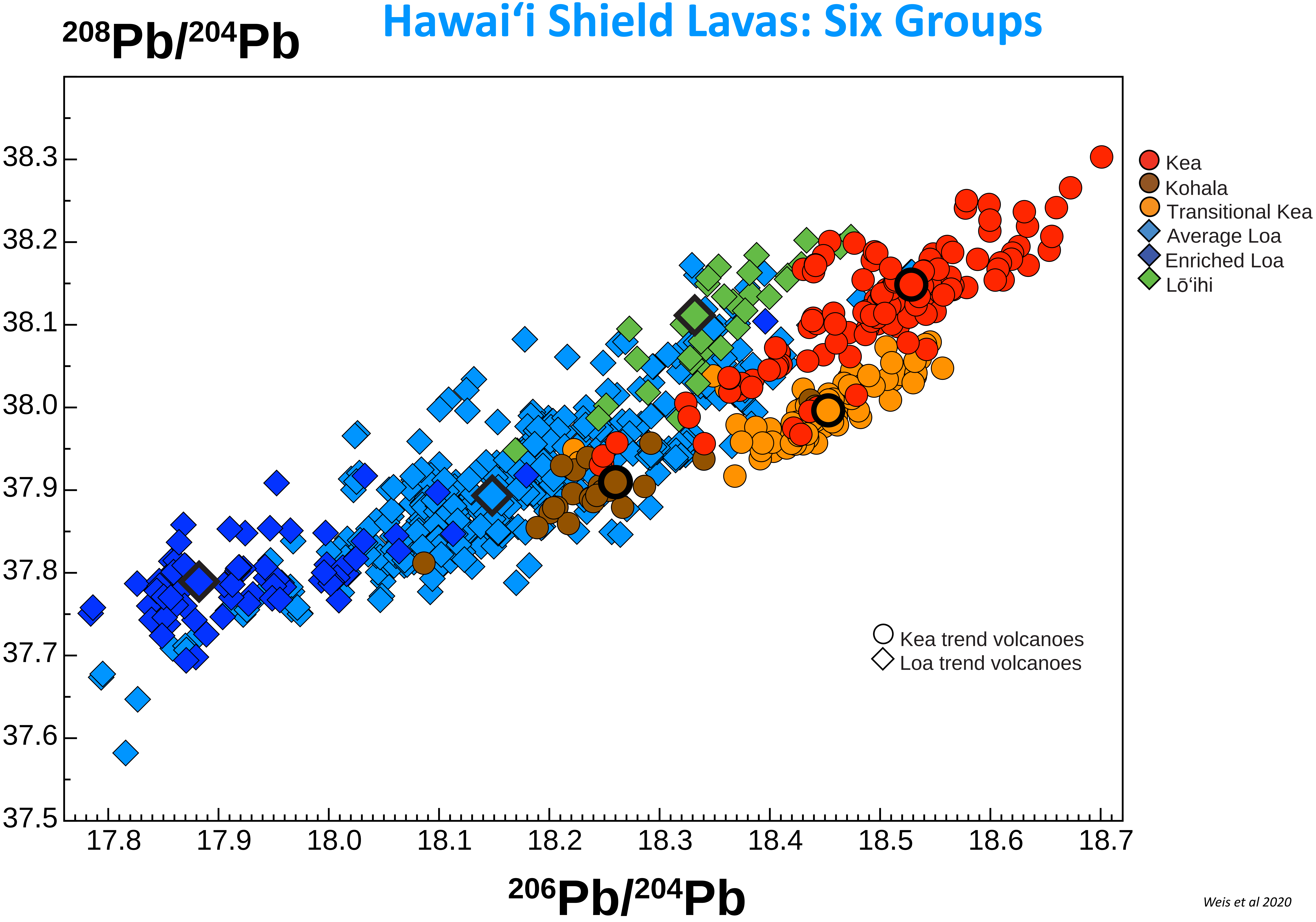
A Simple Bilateral Source? Some Challenges



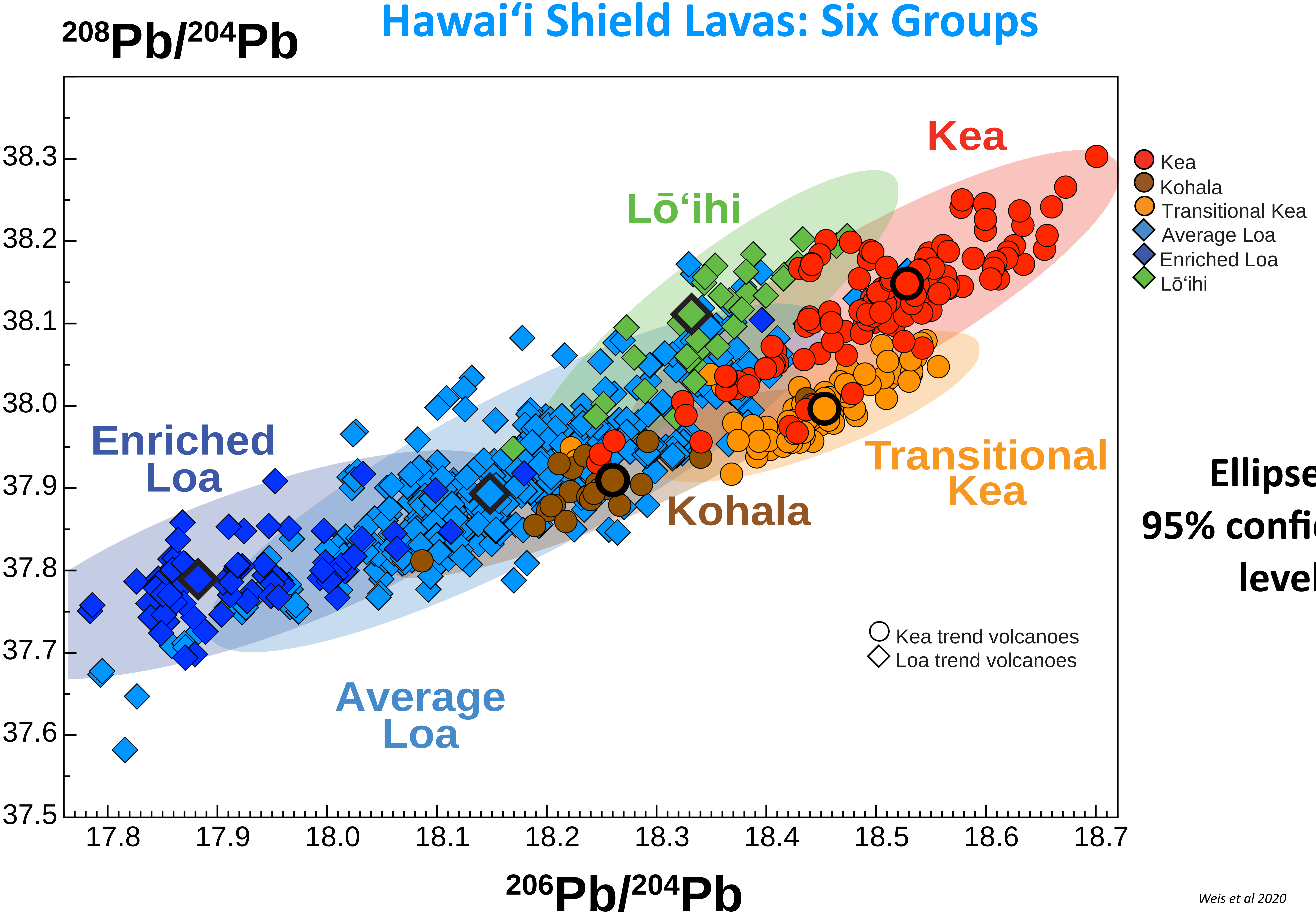
Only shield lavas
Only modern, high-precision data
~800 samples

Hawai‘i Shield Lavas: Six Groups



Weis et al 2020

Hawaiʻi Shield Lavas: Six Groups

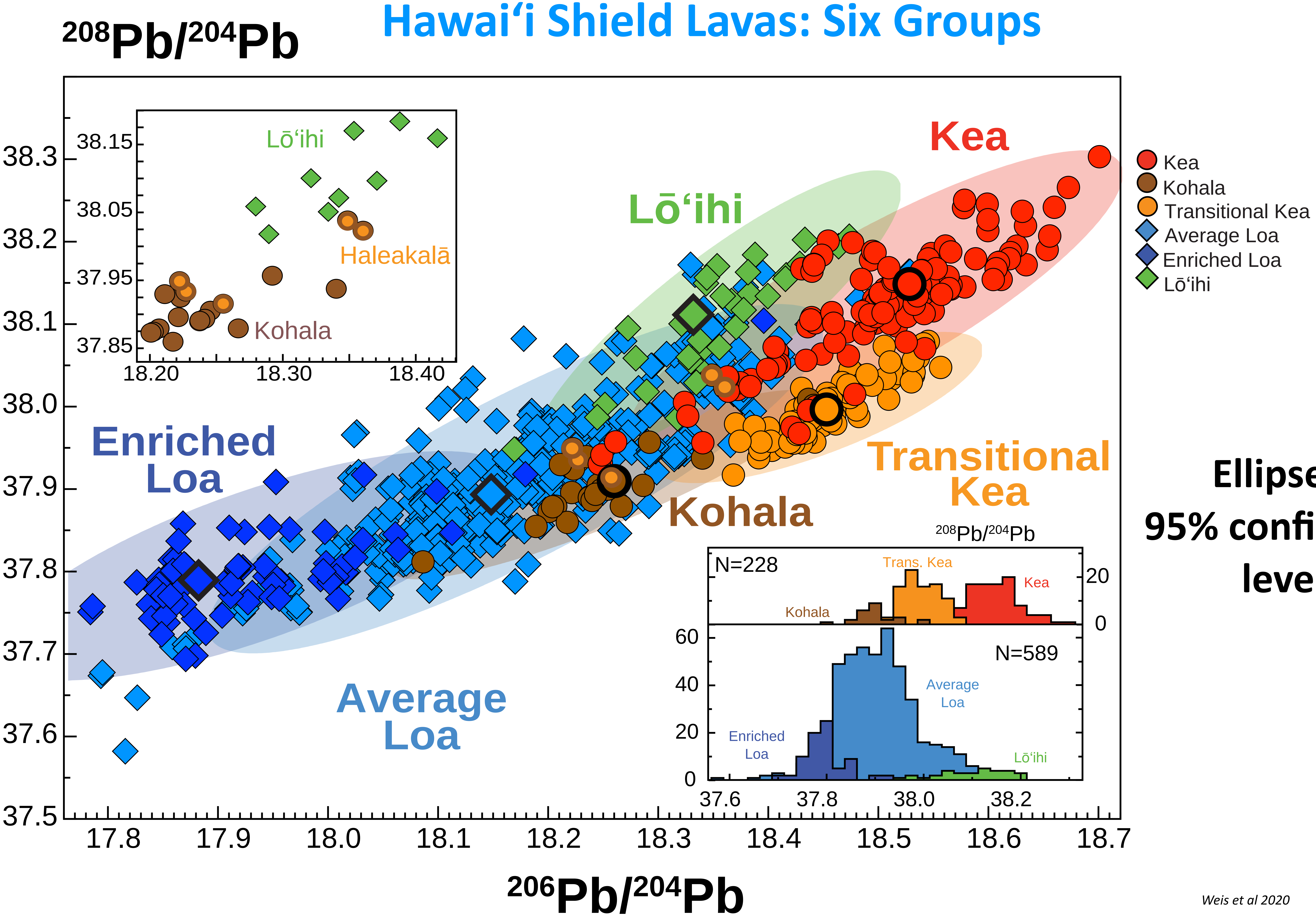


Ellipses:

95% confidence level

Weis et al 2020

Hawaiʻi Shield Lavas: Six Groups



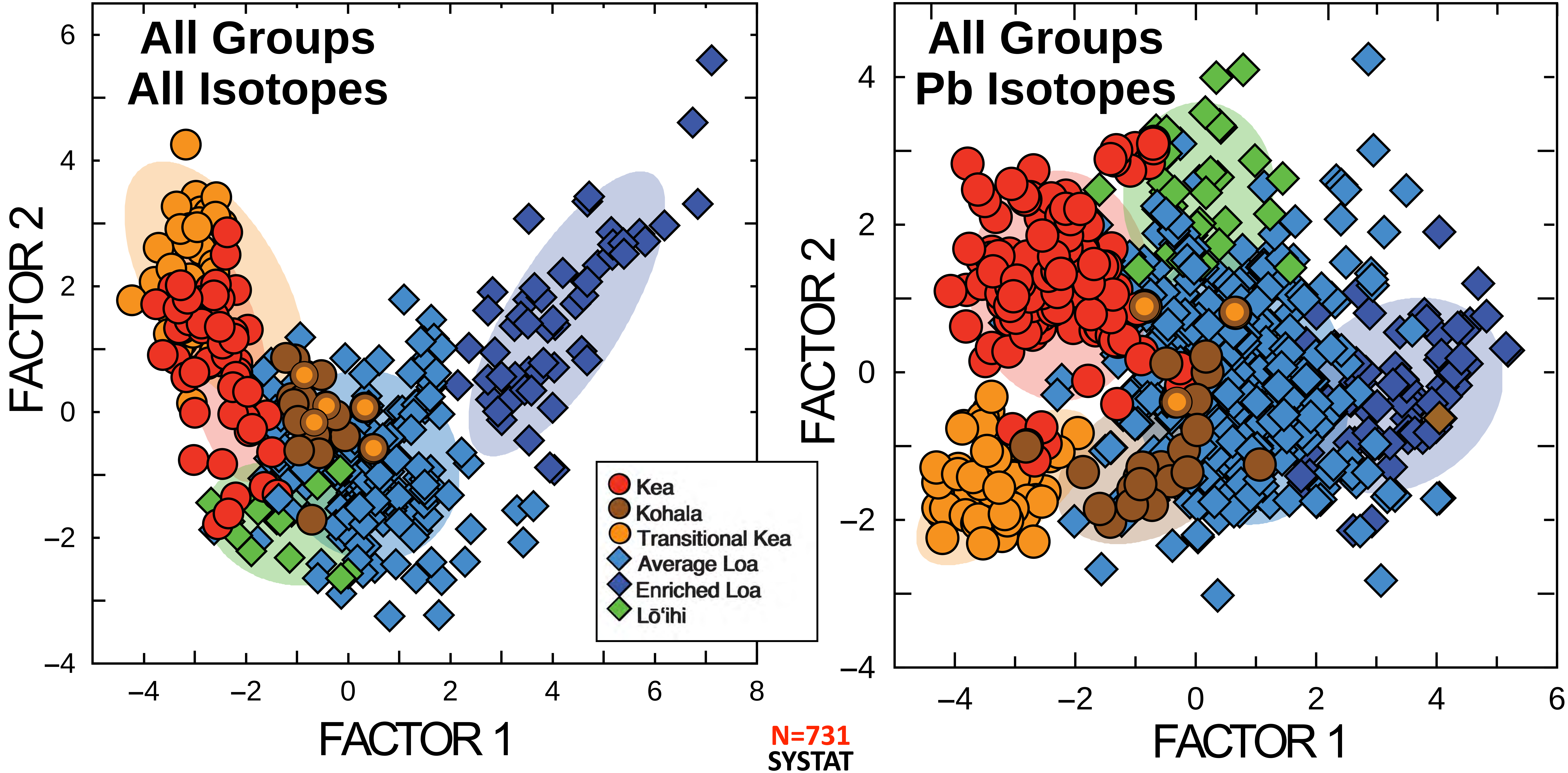
Ellipses:

95% confidence level

Weis et al 2020

Parametric Statistical Analysis: all 6 Hawaiian Subgroups: LDA Canonical Scores

More multivariate space exists between each sub group when all isotopic systems are applied as predictors compared to when only Pb isotope ratios are used



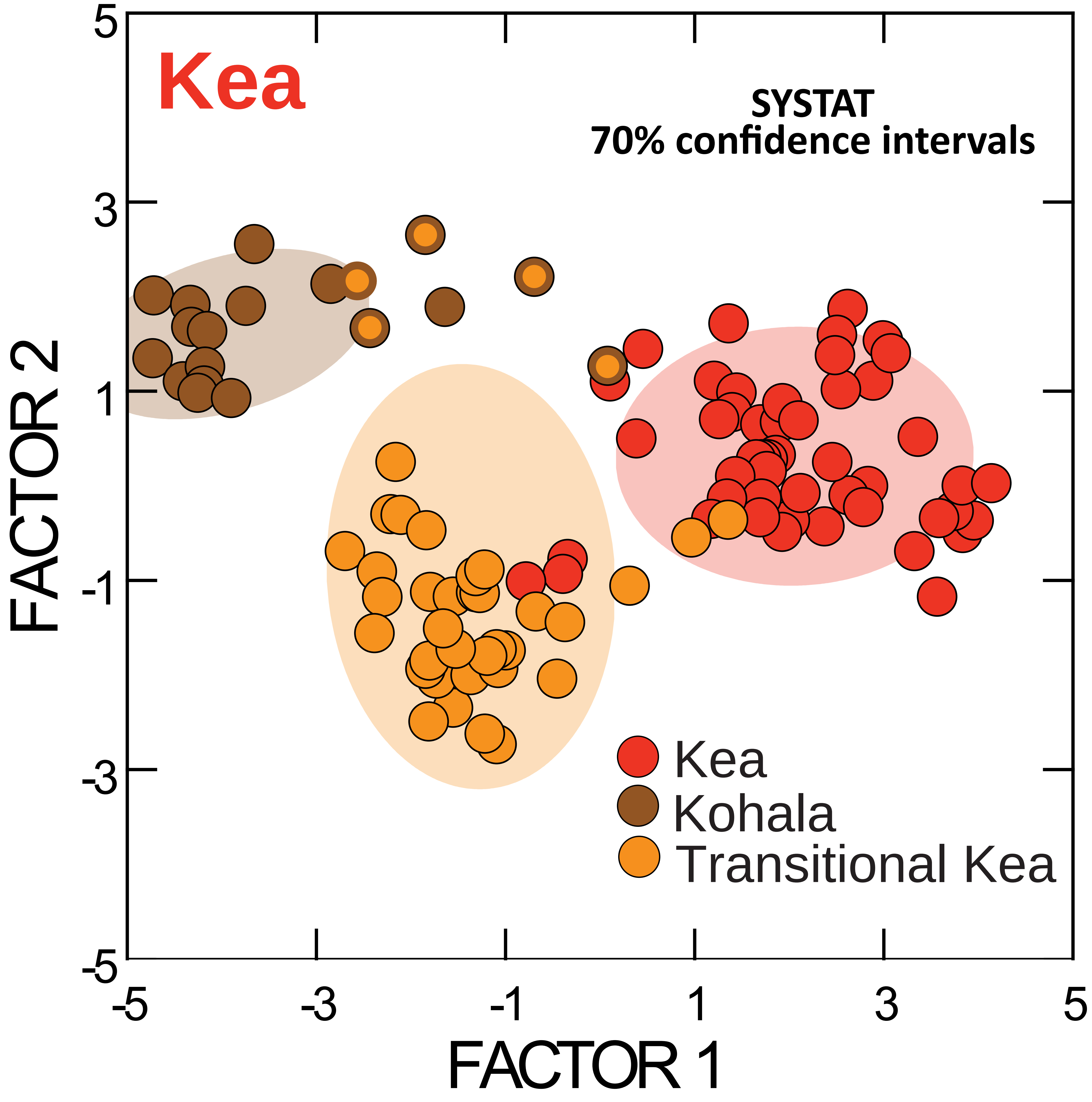
N=731
SYSTAT
70% confidence intervals

Weis et al 2020

Kea and Loa: LDA Canonical Scores, all Radiogenic Isotope Systems

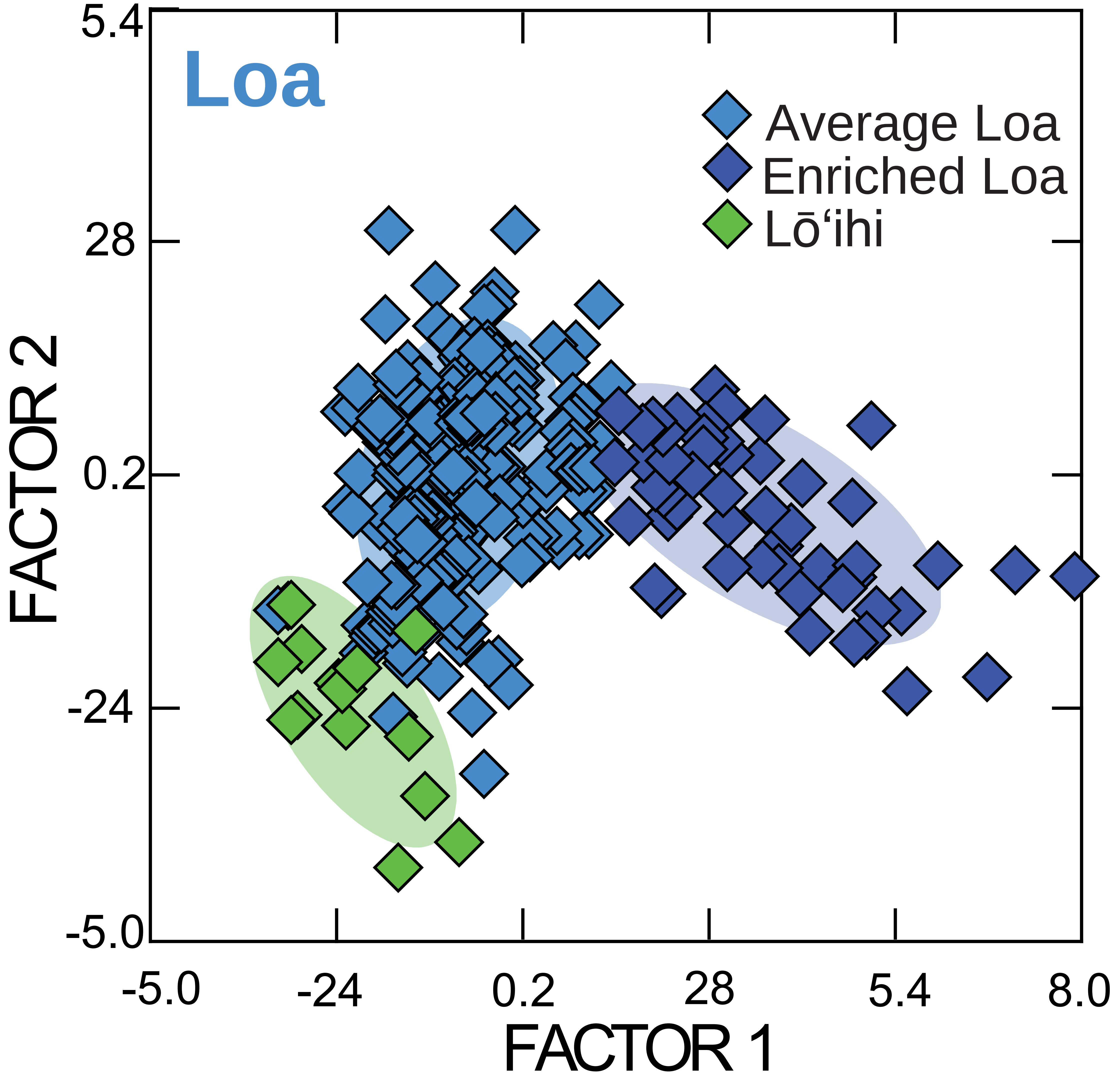
Group Frequencies

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



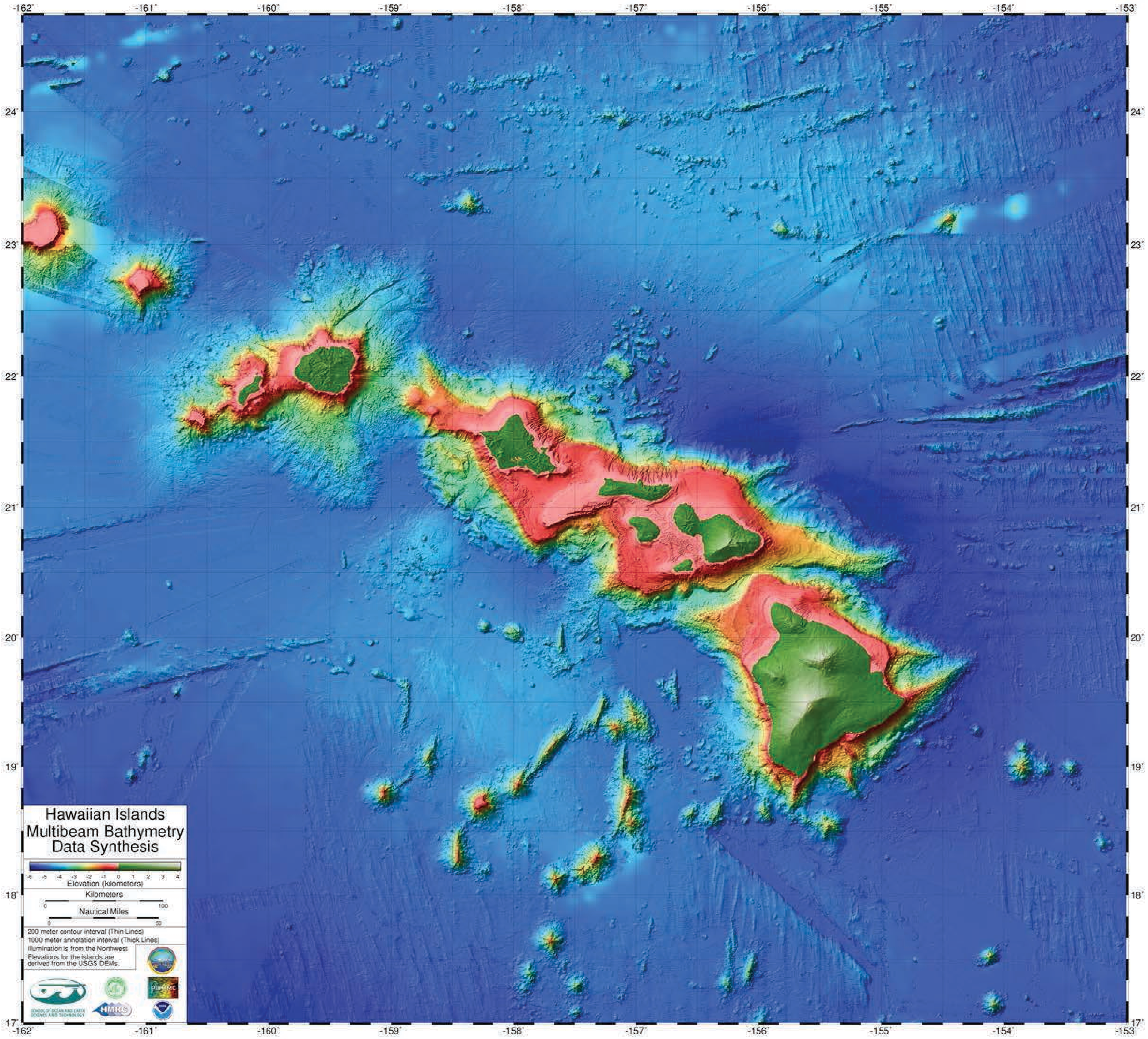
Group Frequencies

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

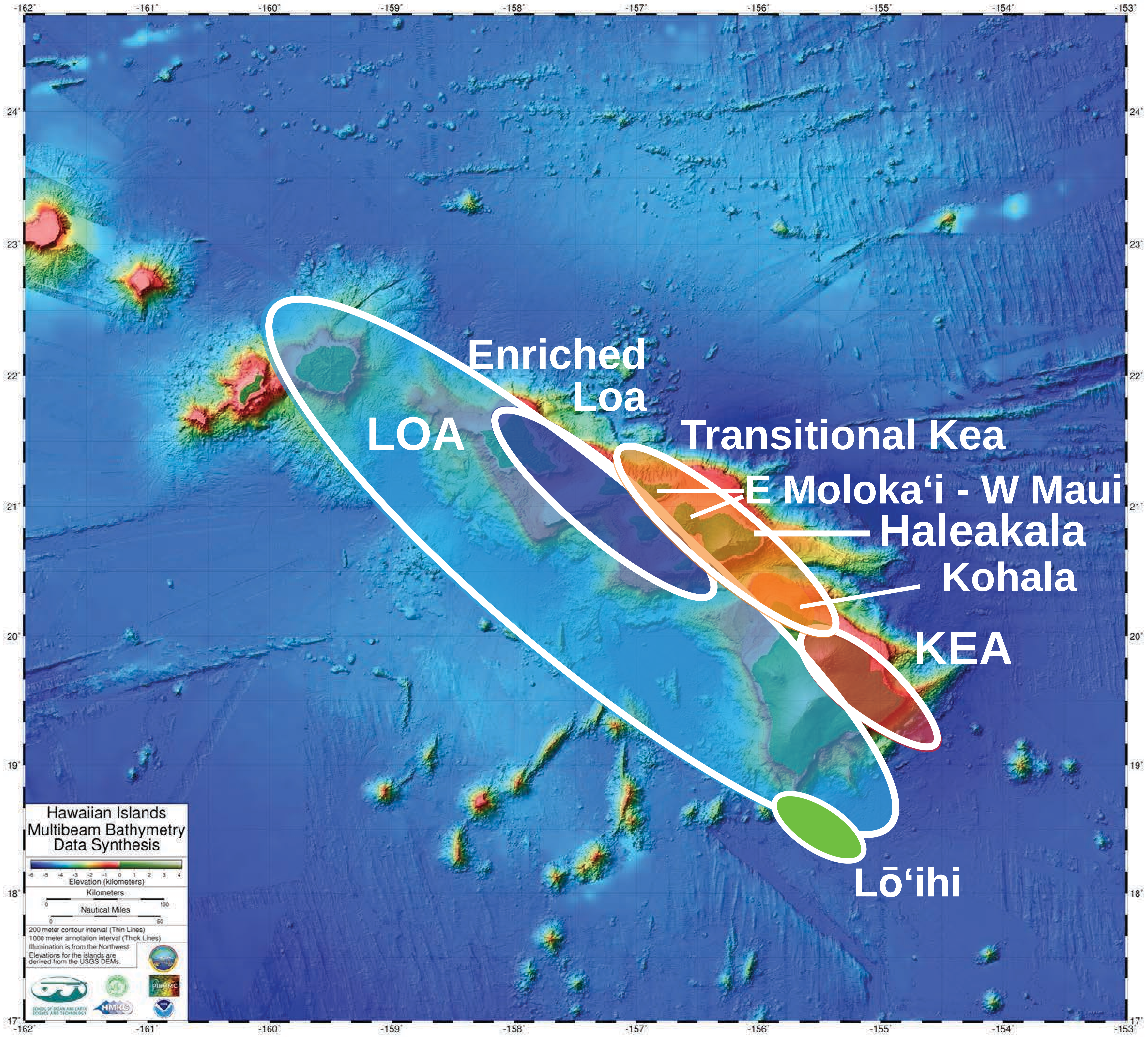


Weis et al 2020

Geographical Distribution of Hawai‘i Geochemical Components



Geographical Distribution of Hawai‘i Geochemical Components



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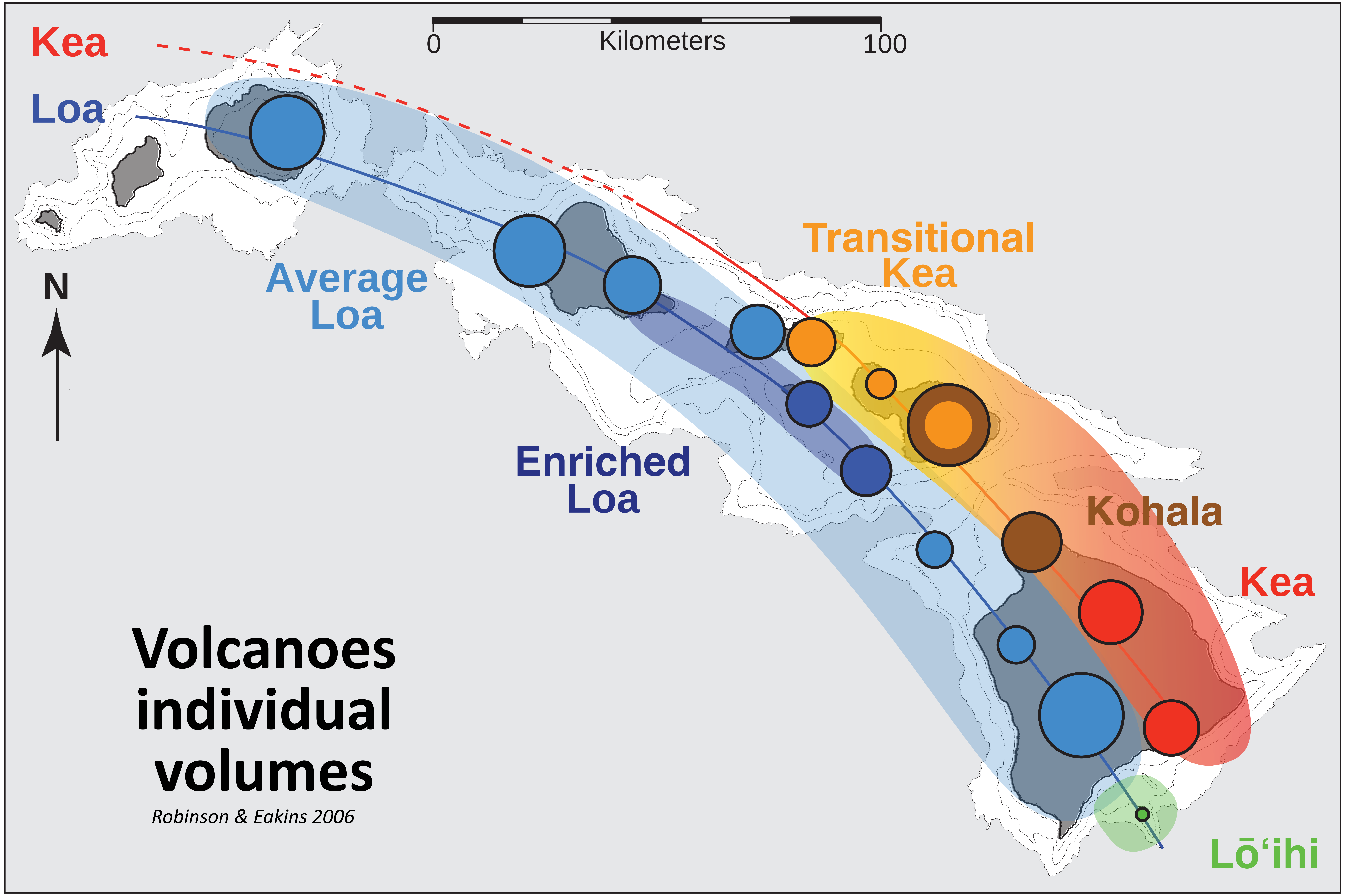
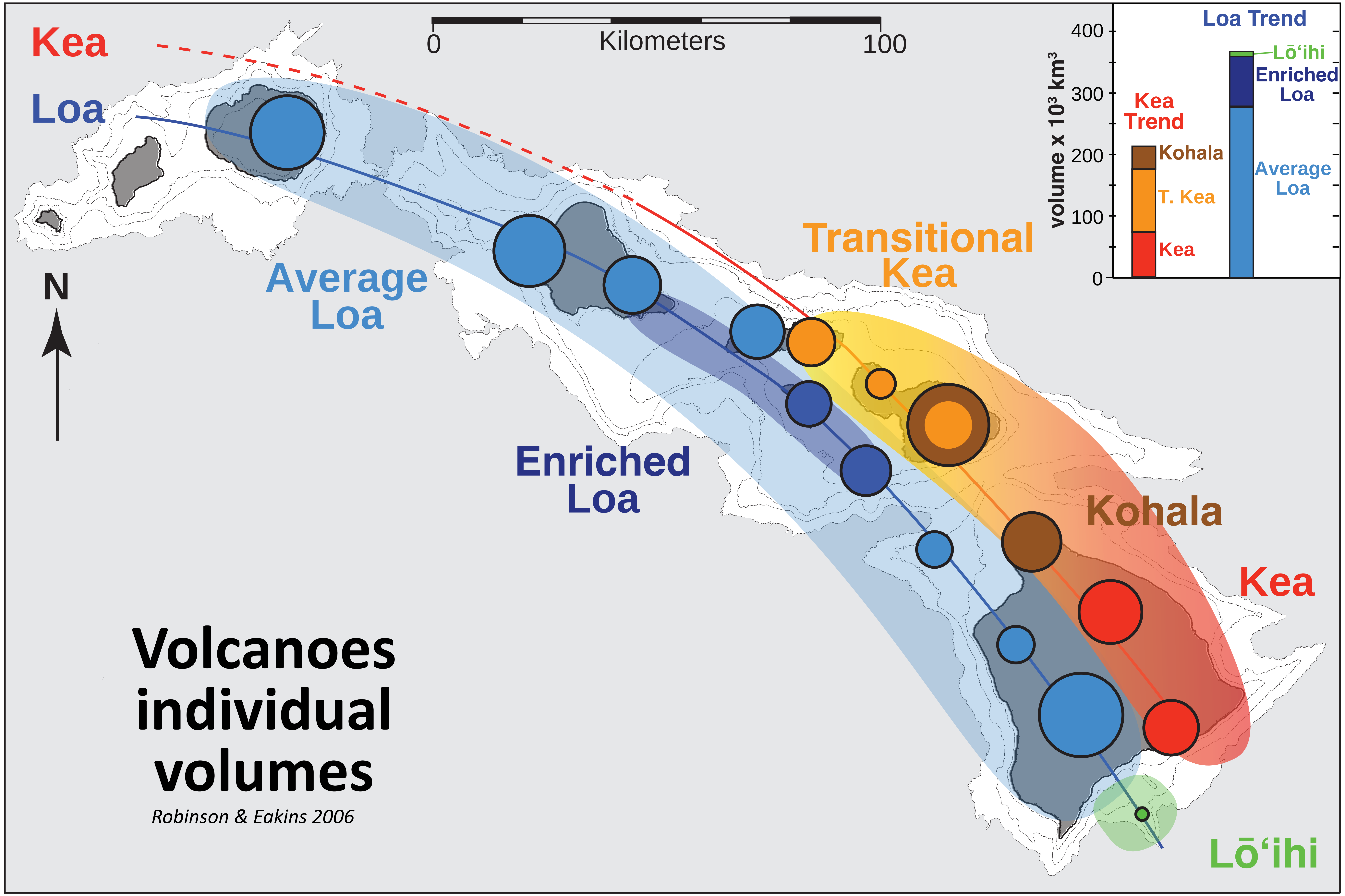


Volcanoes individual volumes

Robinson & Eakins 2006

Weis et al 2020

Geographical Distribution of Hawaiʻi Geochemical Components

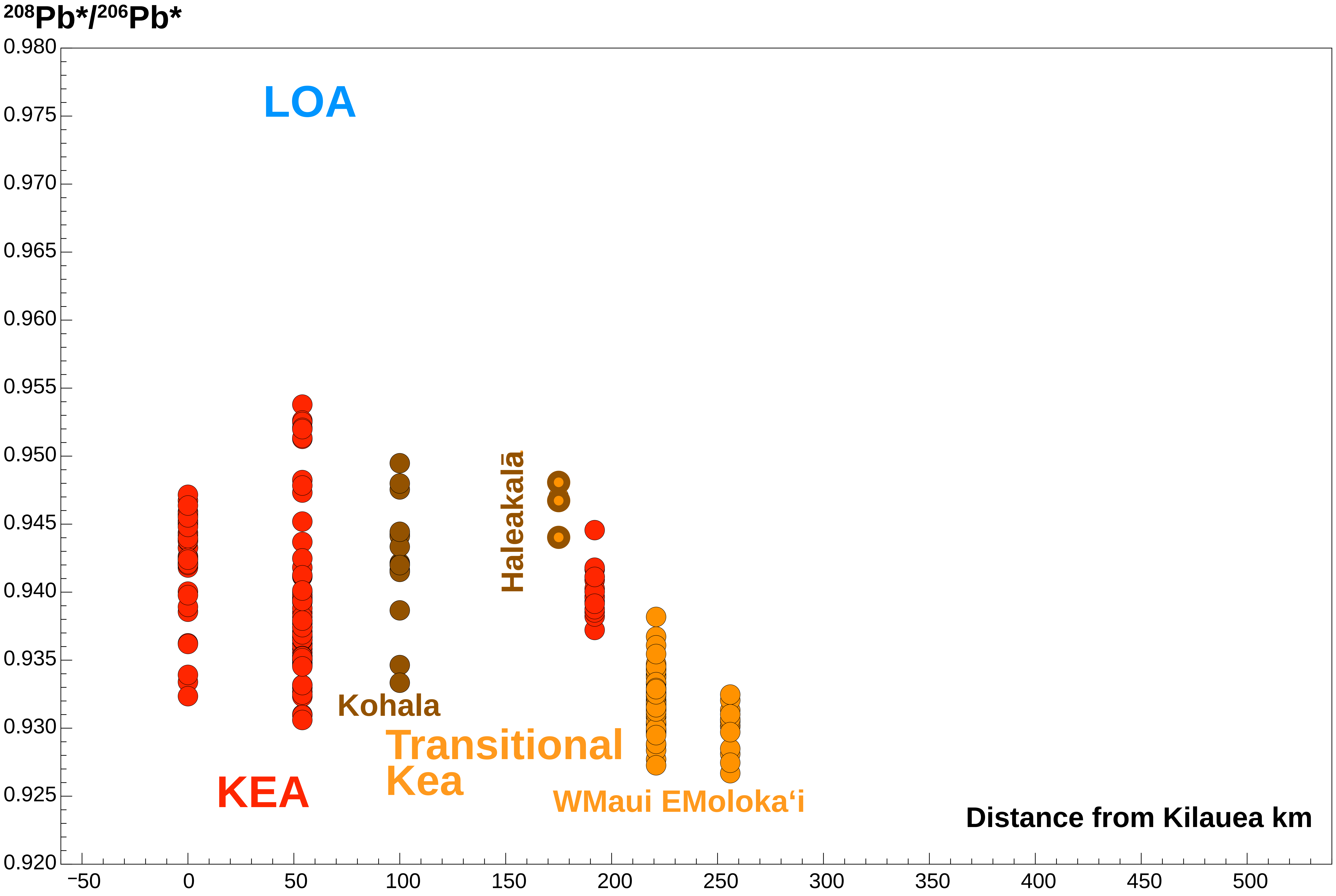


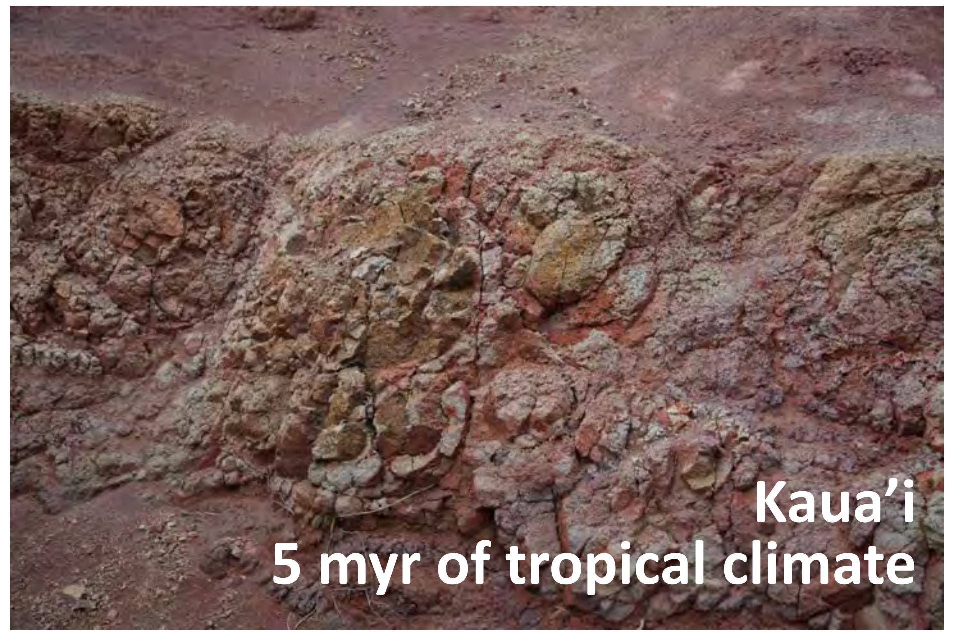
Volcanoes individual volumes

Robinson & Eakins 2006

Weis et al 2020

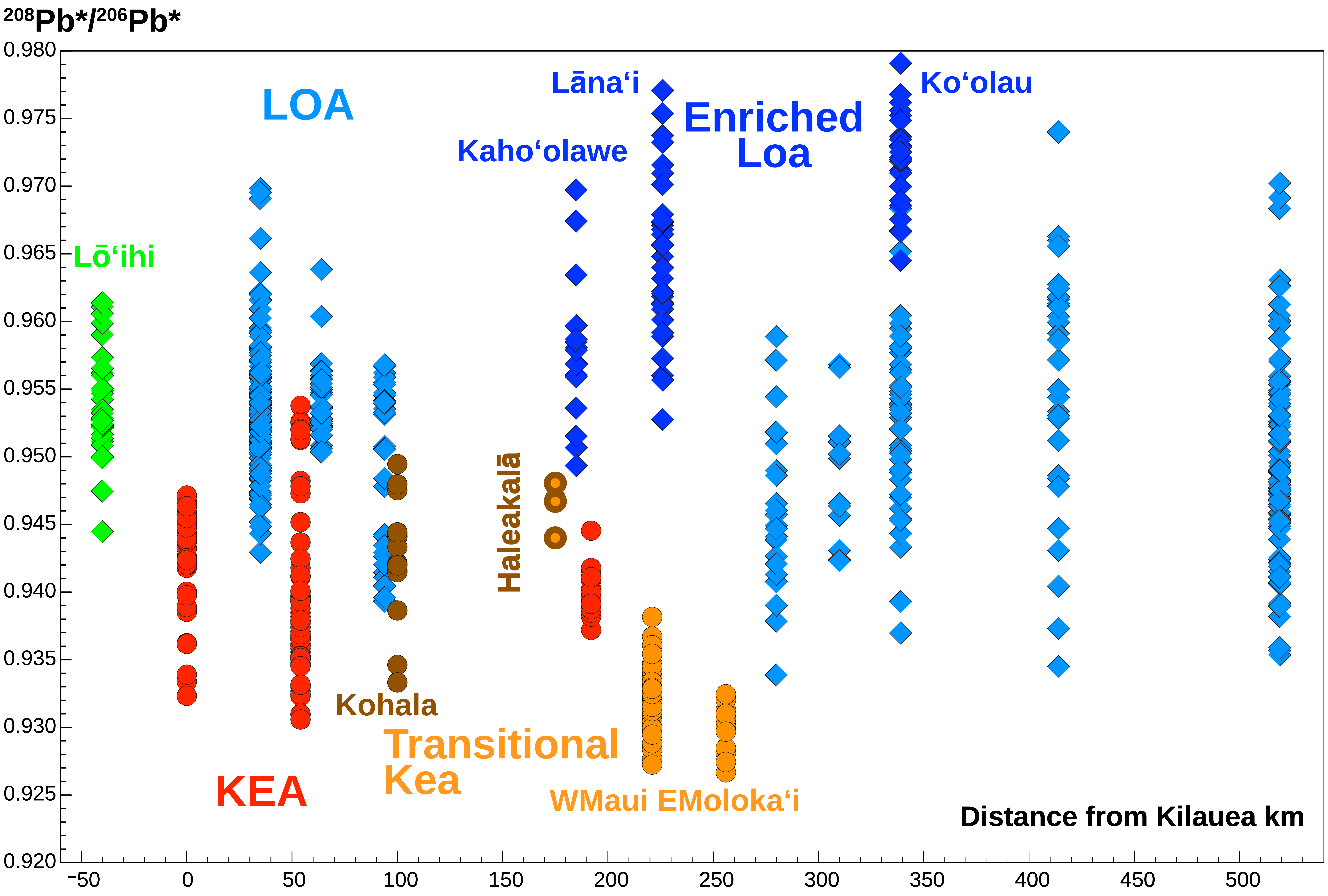
Over 5 Myr, Lōʻihi to Kauaʻi

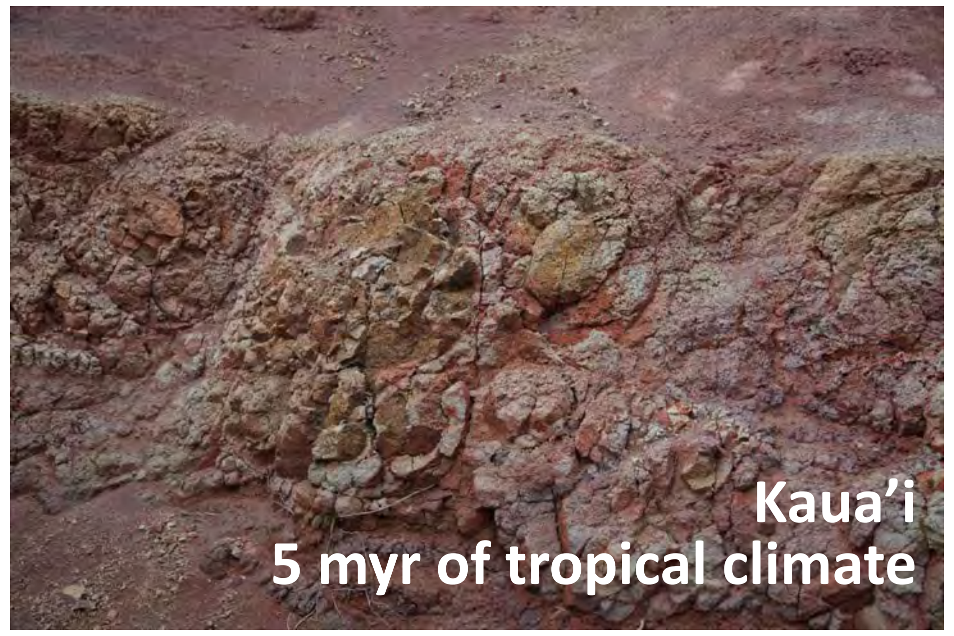




Weis et al 2020

Over 5 Myr, Lōʻihi to Kauaʻi

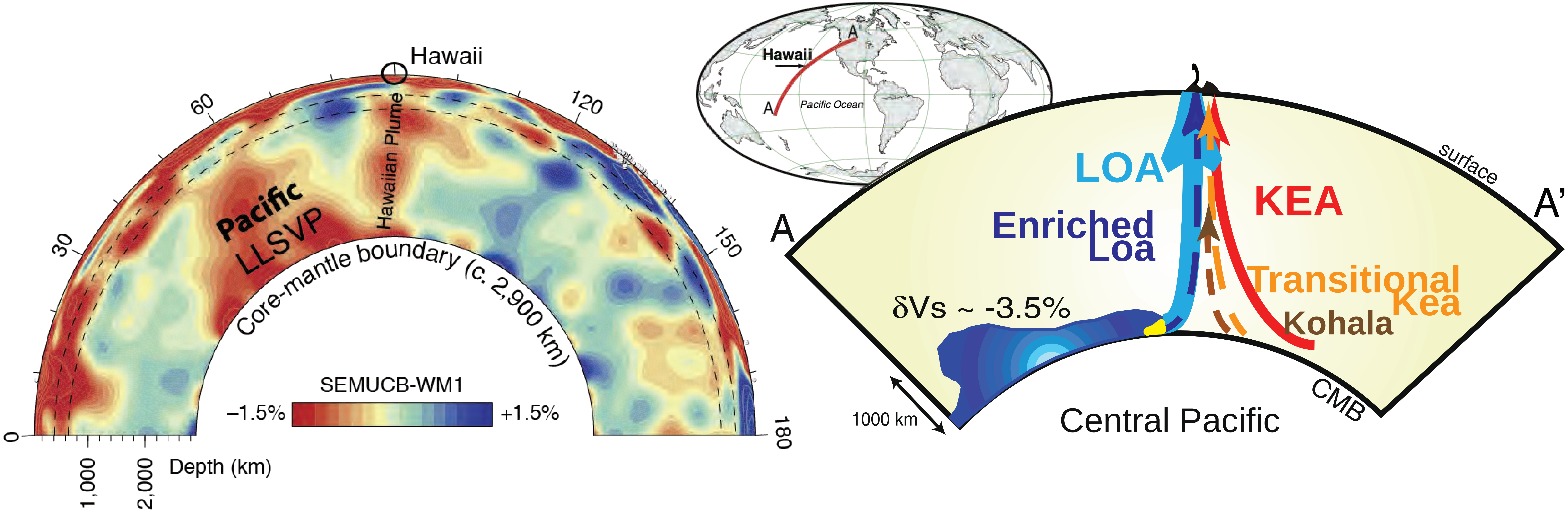




Weis et al 2020

Seismically-Imaged Mantle Heterogeneity and Potential Source of Hawaiian Geochemical Variation

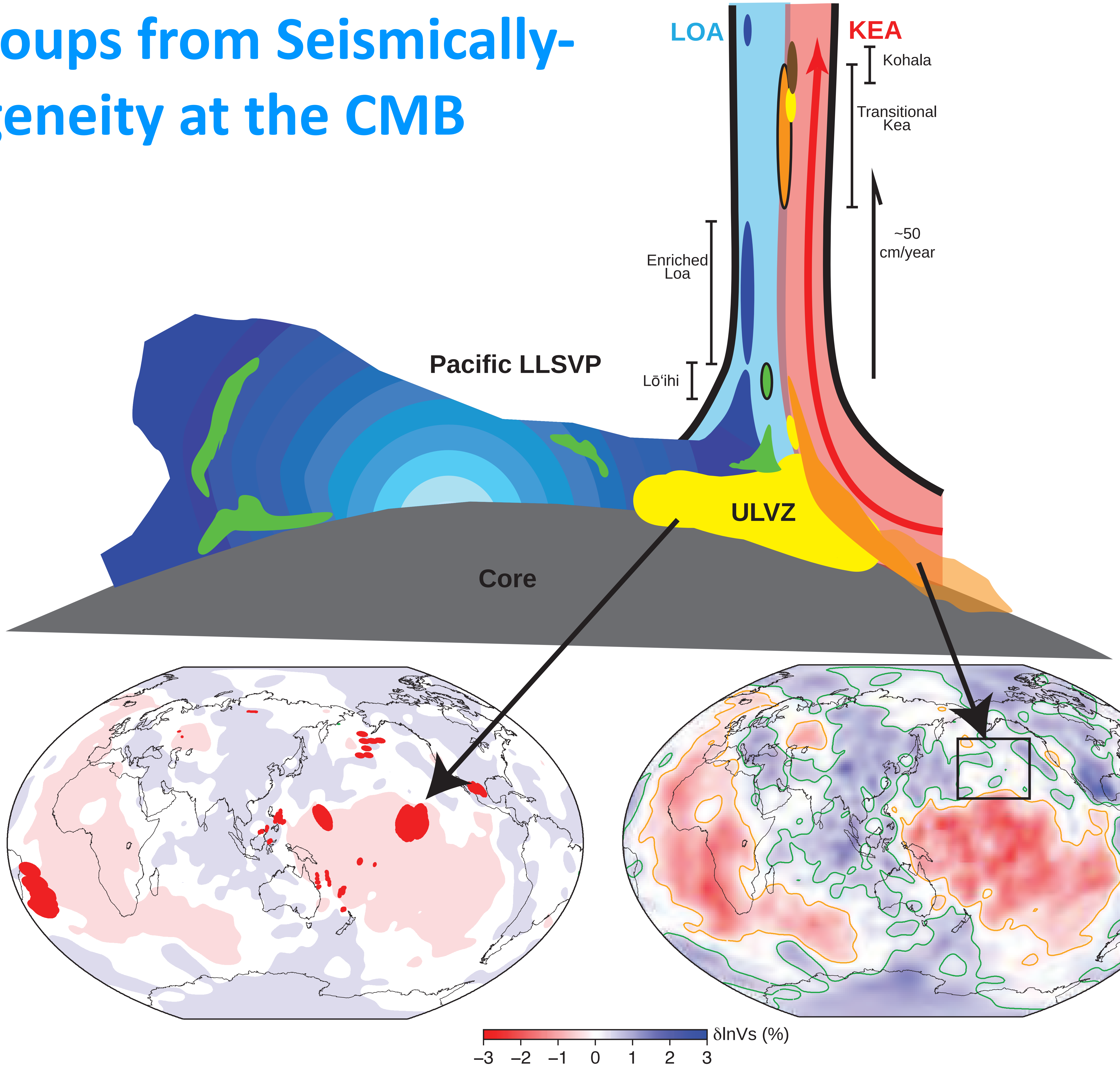
Cross-section of possible lower mantle origin of Hawaiian geochemical groups



French & Romanowicz 2015
Torsvik et al 2017

Modified from Weis et al 2011

Potential Origin of Hawaiian Geochemical Groups from Seismically-Imaged Heterogeneity at the CMB



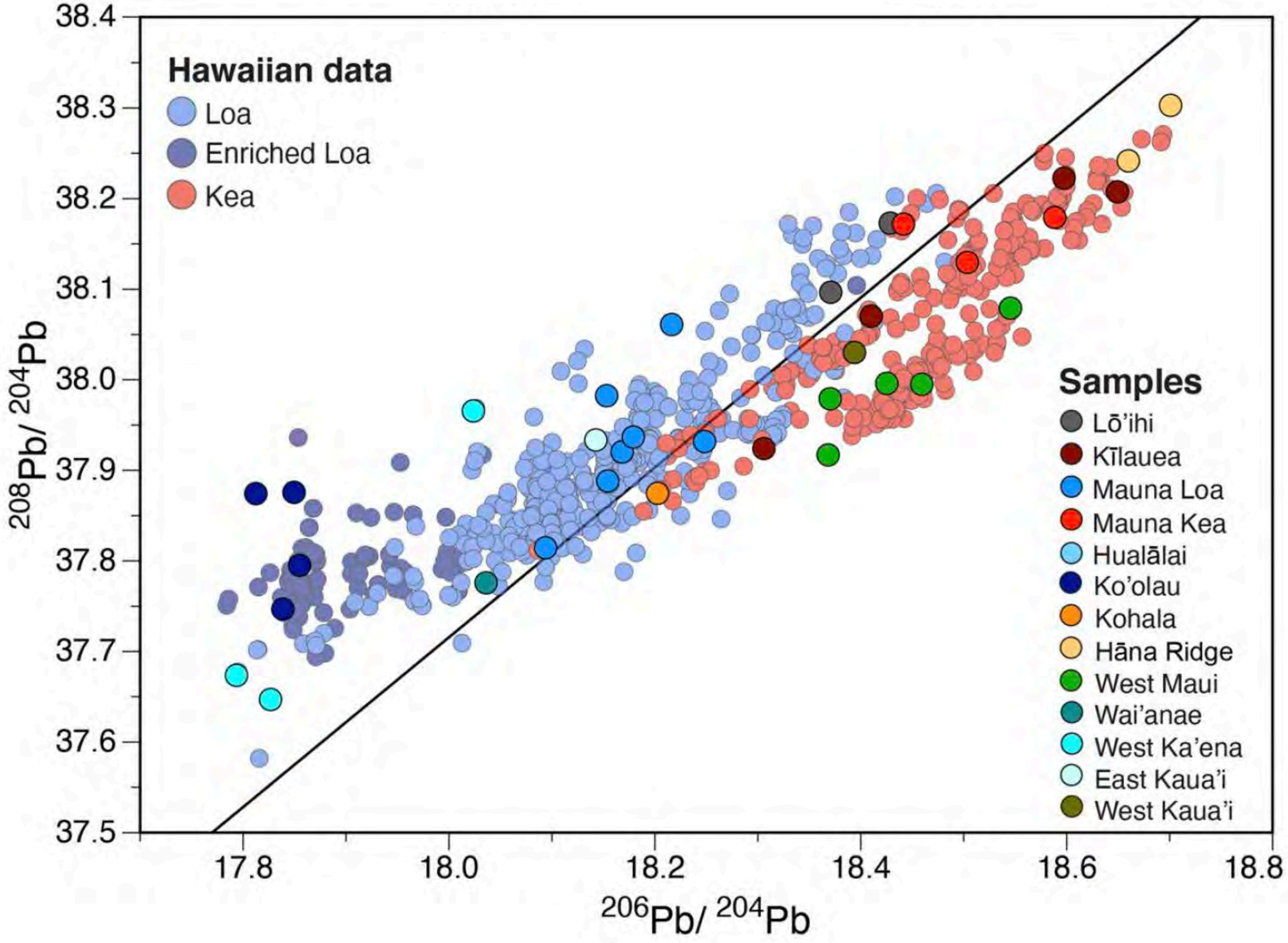
Weis et al 2020

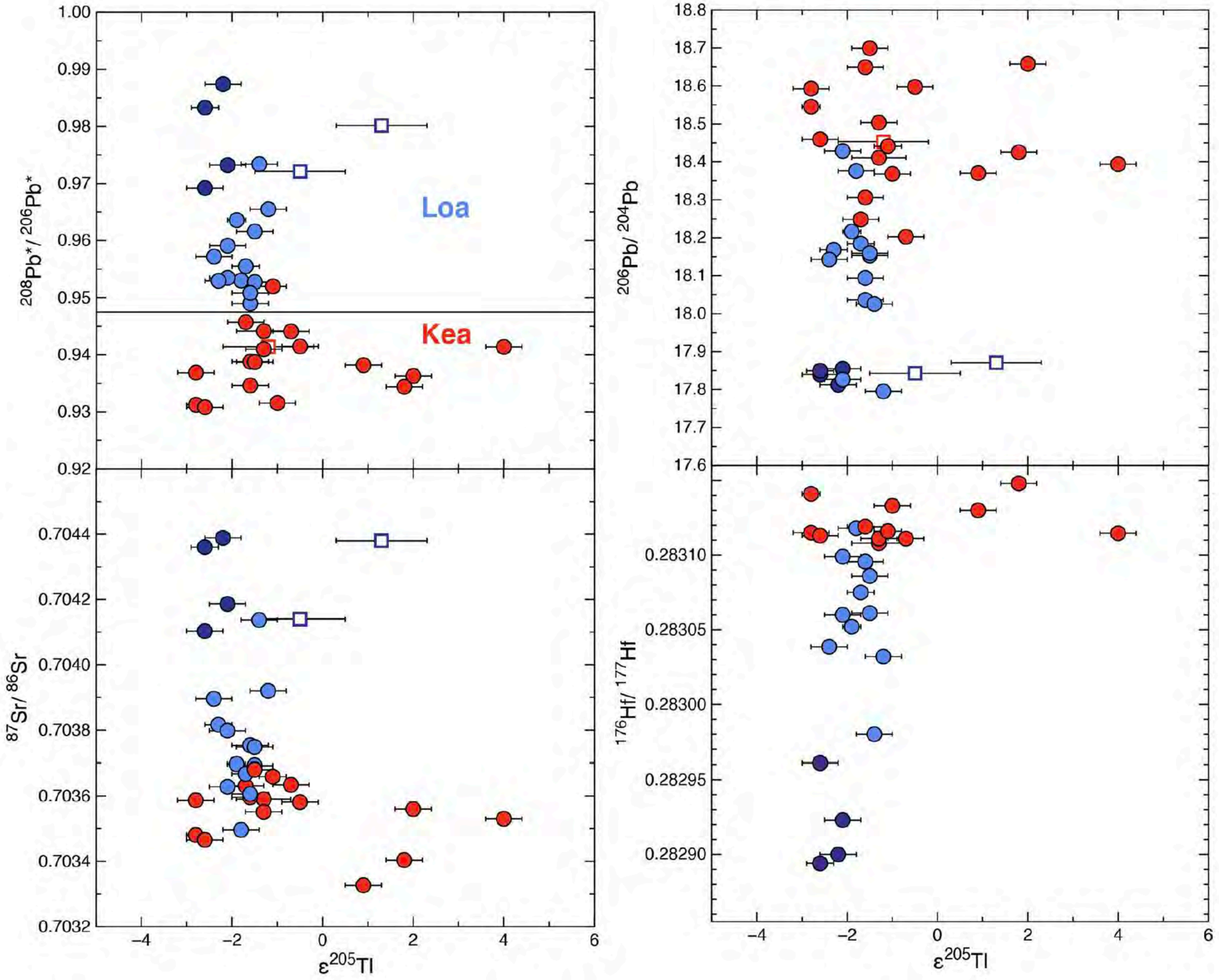
LOA: **Heterogeneity inside LLSVP (ULVZ)**

KEA: **Heterogeneity outside the LLSVP (Ambient Pacific Mantle)**

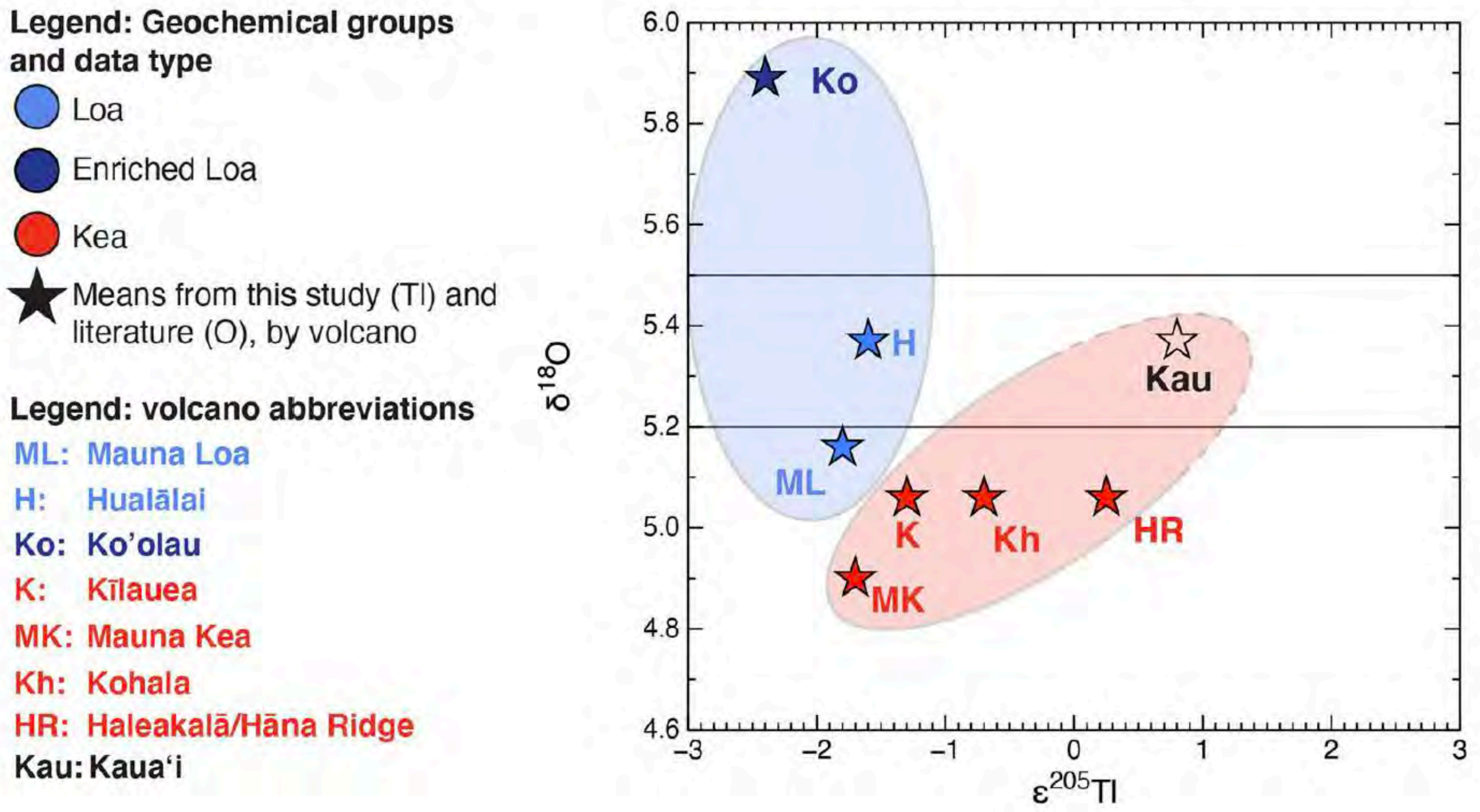
Yu & Garnero 2018

Thallium Isotopic Compositions: Evidence for Recycled Materials on the Kea Side of the Hawaiian Mantle Plume

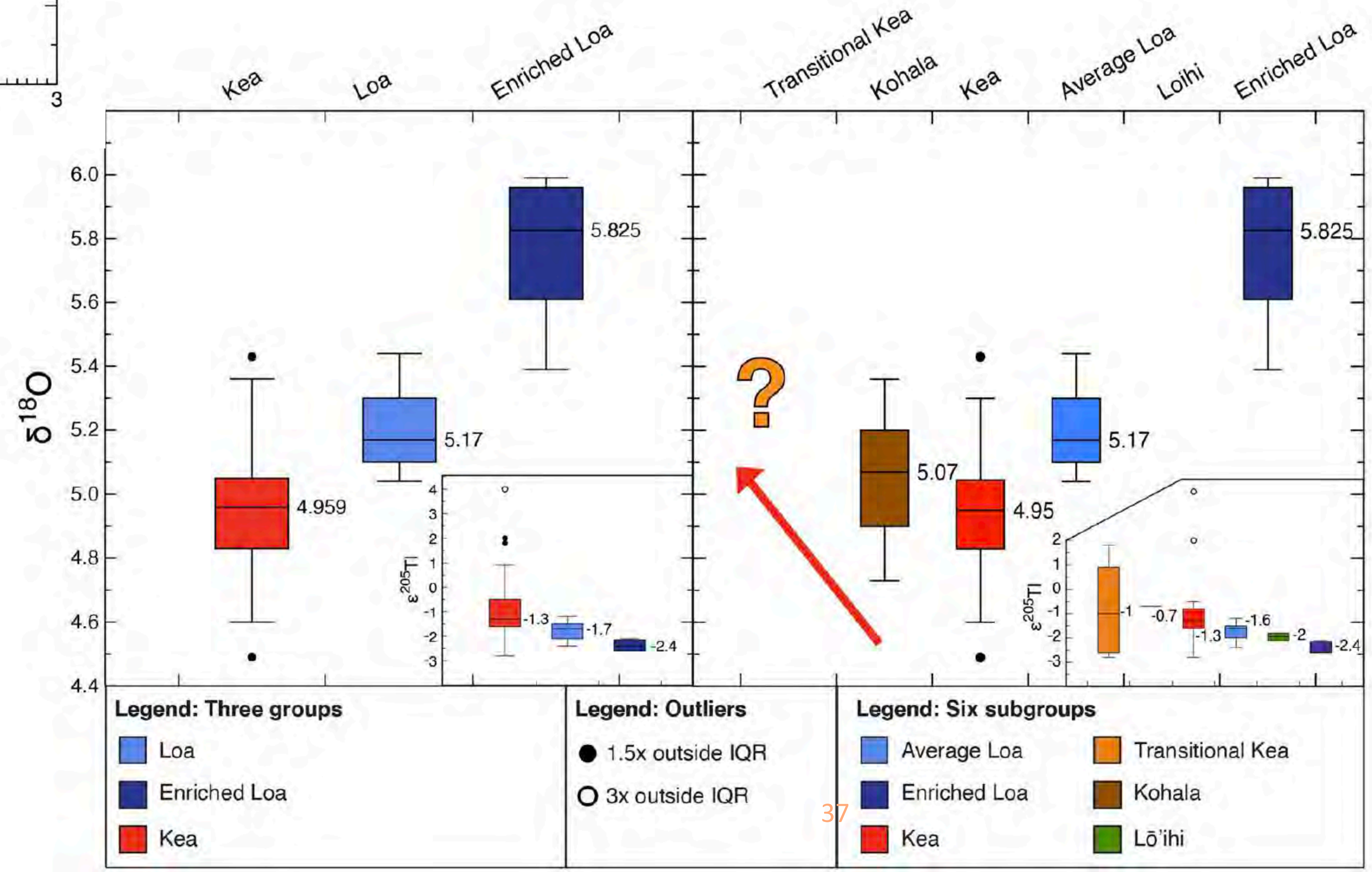




Williamson et al 2021



Williamson et al 2021



Hawaiian Islands Geochemistry

- There is a clear difference between Loa and Kea trend volcanoes:
  - Kea Volcanoes ≈ Ambient Pacific Mantle (+ ancient, recycled pelagic sediment)
    The Kea trend samples the Pacific deep mantle.
  - Loa enriched compositions come from LLSVP and ULVZ (Enriched Loa).

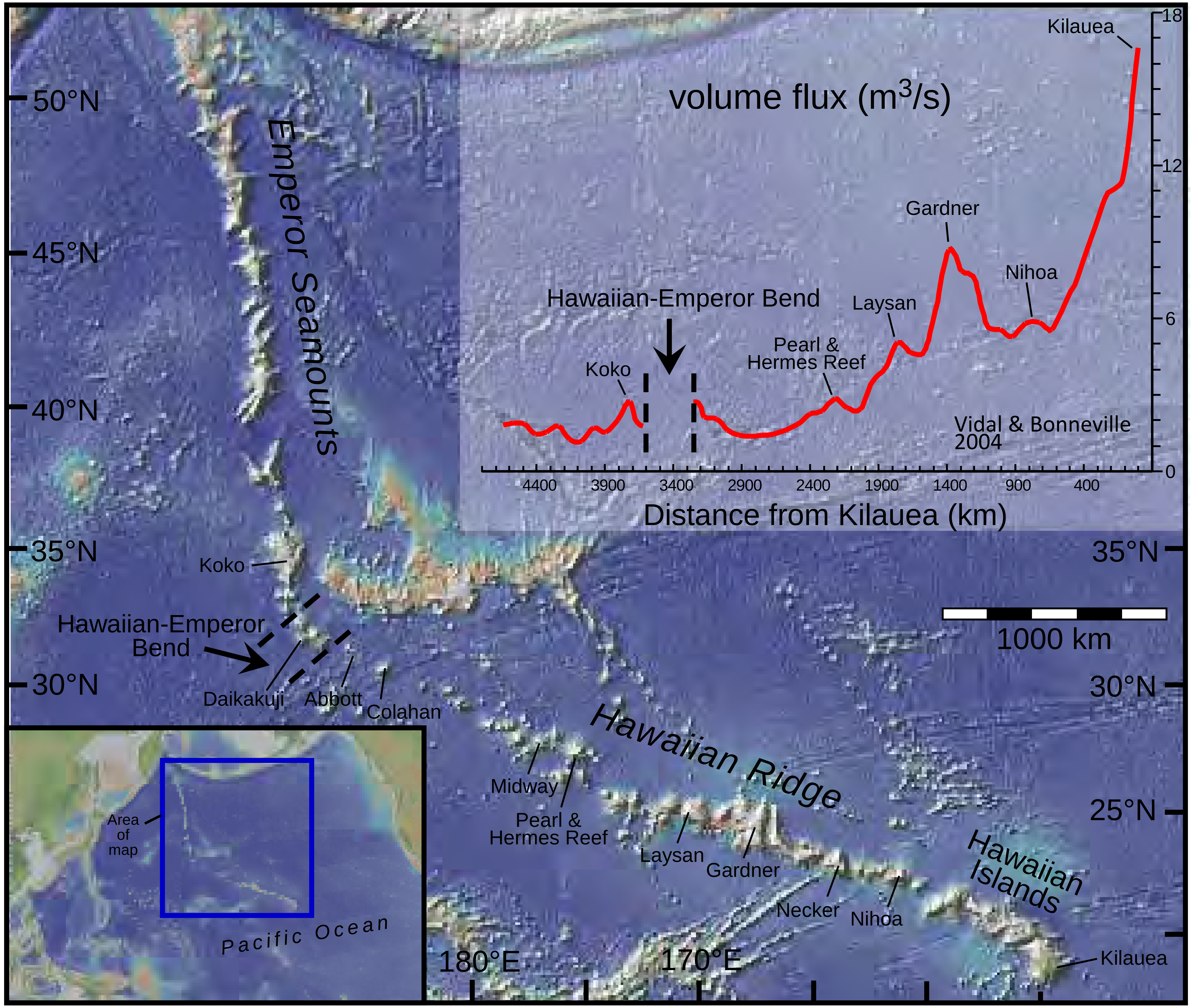
- Statistically, **six groups** can be identified on Hawaii:
  - two major ones: **Kea and Loa**, plus,
  - four minor ones, **finite** in time/space: (WMaui-EMolokaʻi, Kohala), (Enriched Loa, Lō’ihi).

- Both Loa and Kea trends are *heterogeneous* and composed of multiple compositional components. Loa is much more heterogeneous (by a factor of 1.5-2)

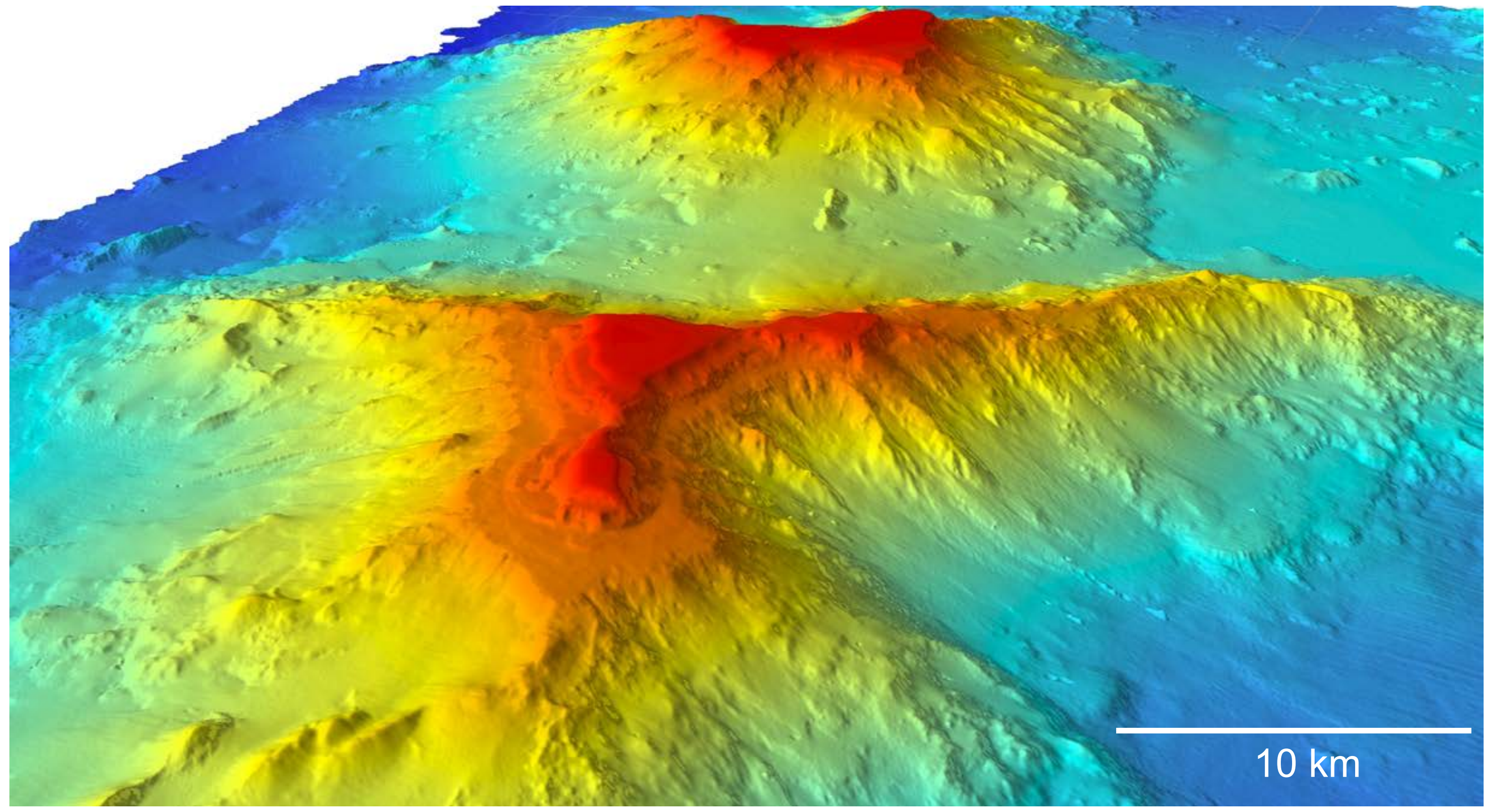
- Hawaiʻi is also unique because there are enough samples and high precision data for robust statistical analysis.

Mauna Kea post-shield cones

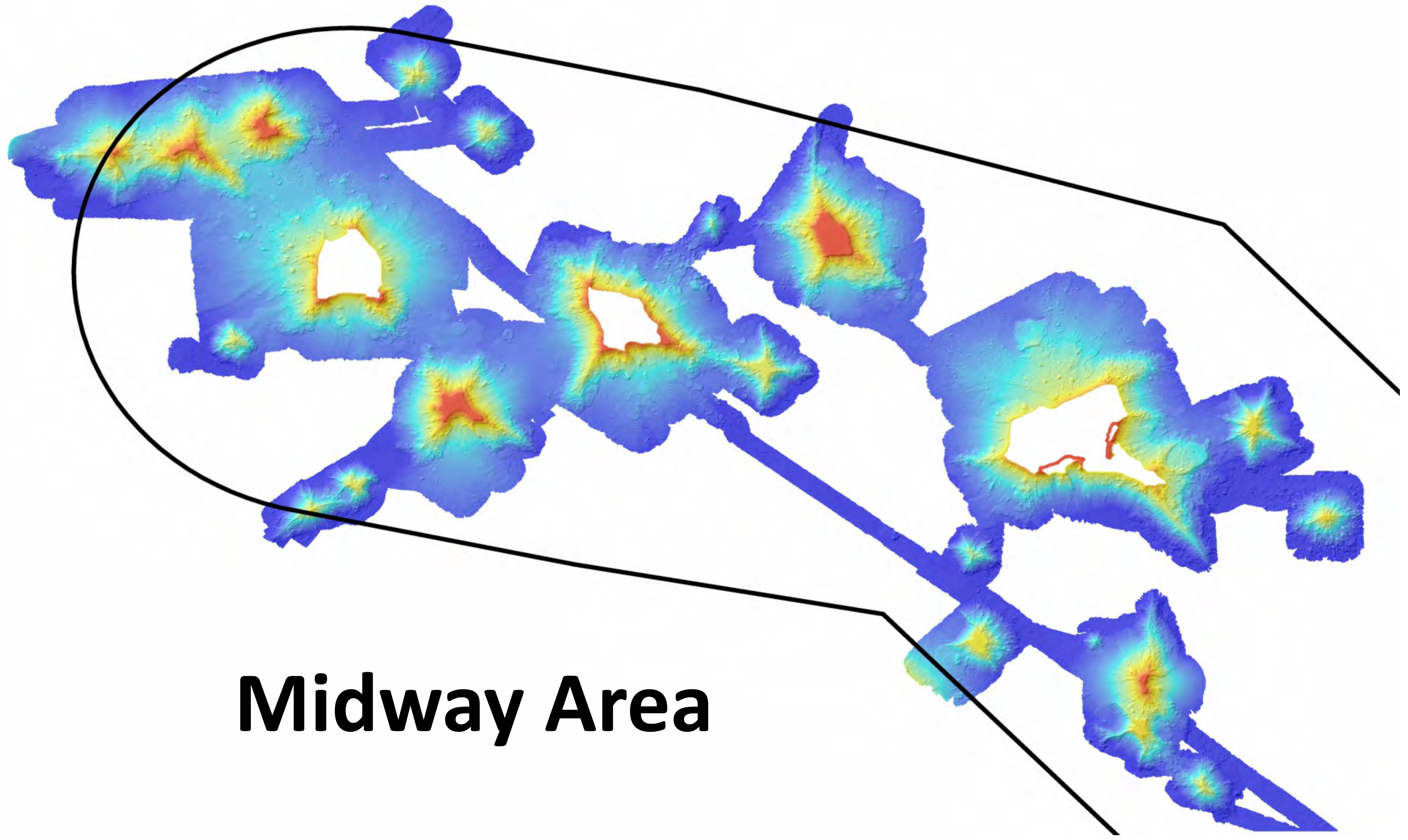
Hawaiian Ridge - Emperor Seamounts: 85 myr



**R/V Falkor Mapping,
Schmidt Ocean Institute 2013**

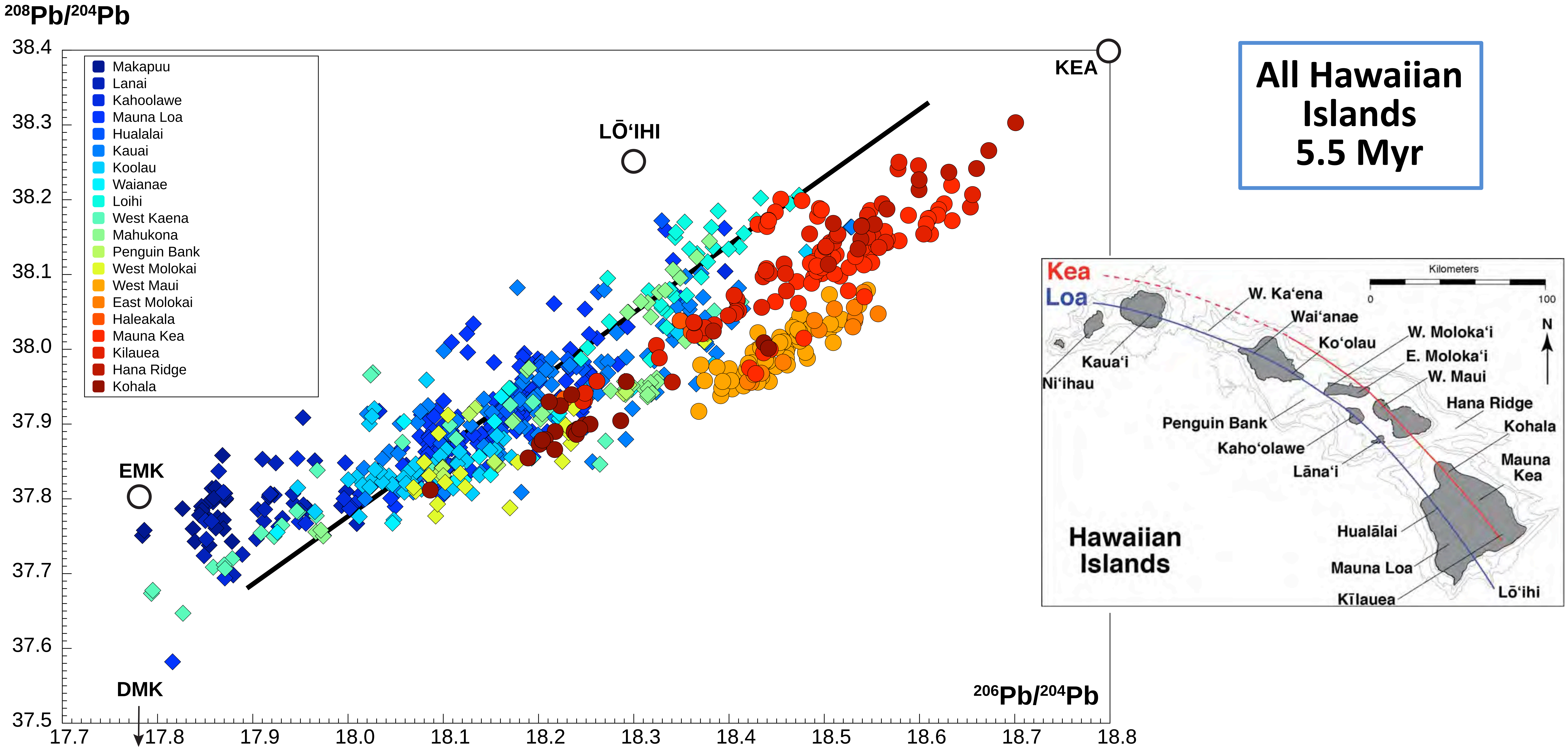


Turnif & Academician Berg Seamounts



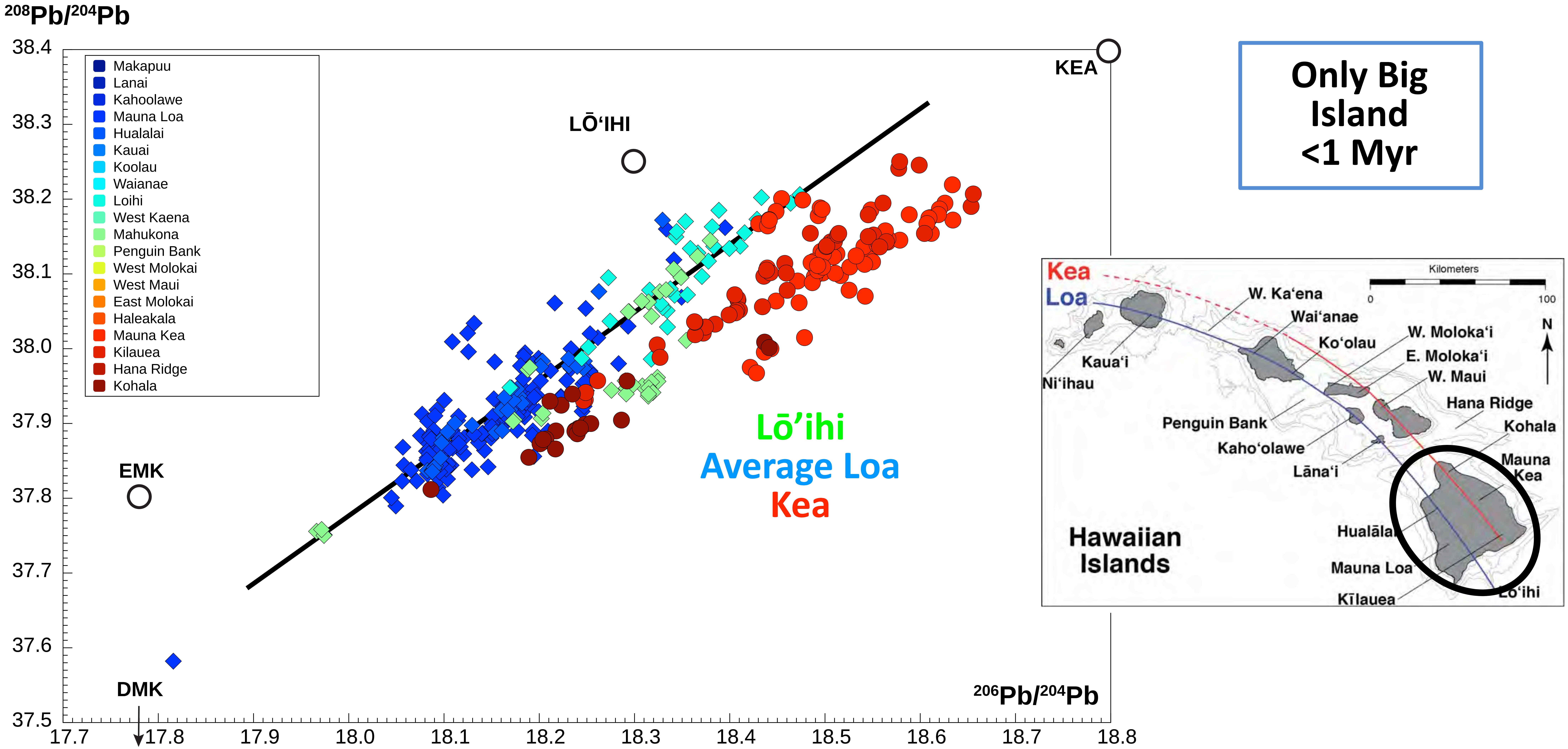
Midway Area

Loa Trend Heterogeneities: The Lōʻihi Example



All Hawaiian Islands
5.5 Myr

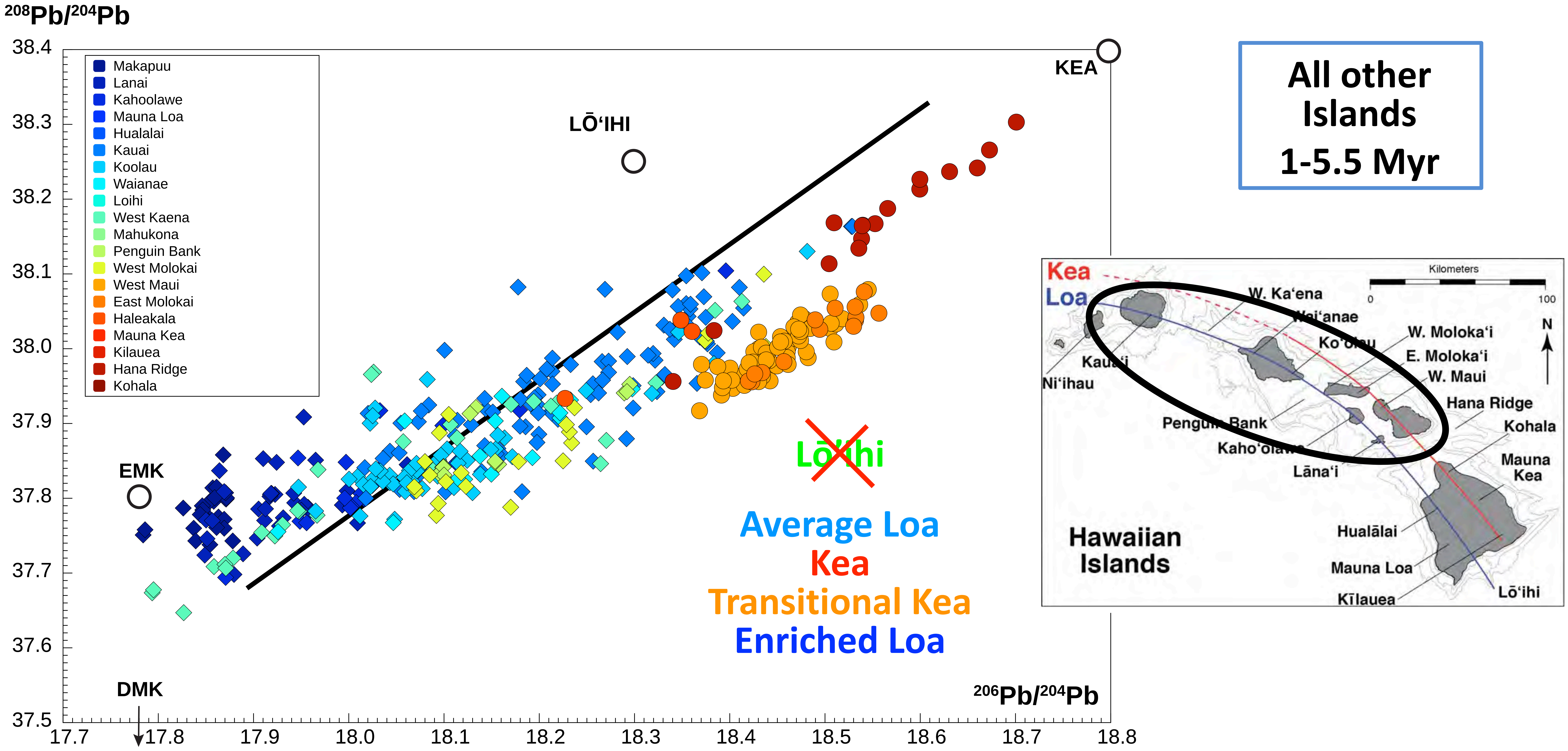
Loa Trend Heterogeneities: The Lō‘ihi Example



Lō’ihi
Average Loa
Kea

Only Big Island
<1 Myr

Loa Trend Heterogeneities: The Lōʻihi Example

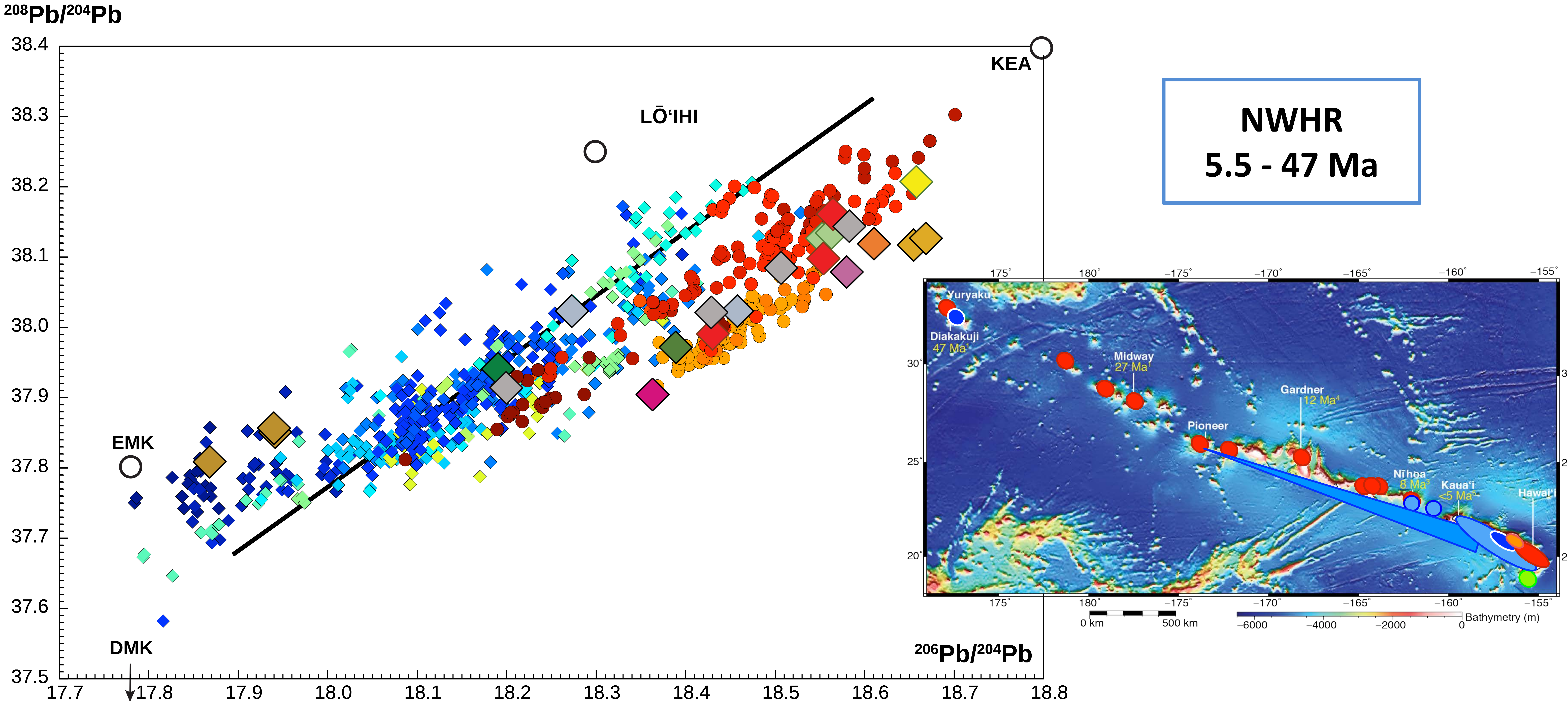


All other Islands
1-5.5 Myr

~~Lōʻihi~~

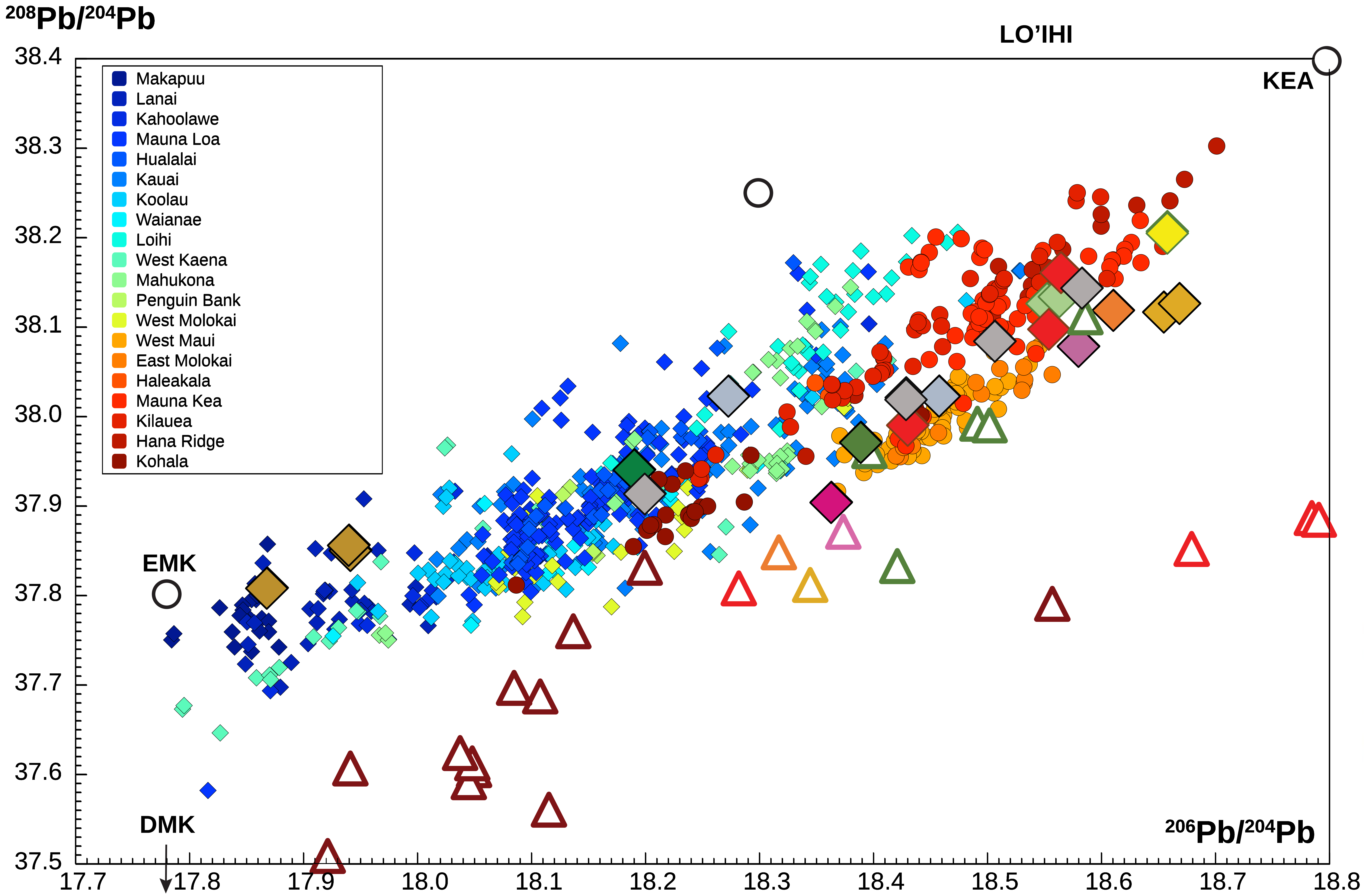
Average Loa
Kea
Transitional Kea
Enriched Loa

NWHR

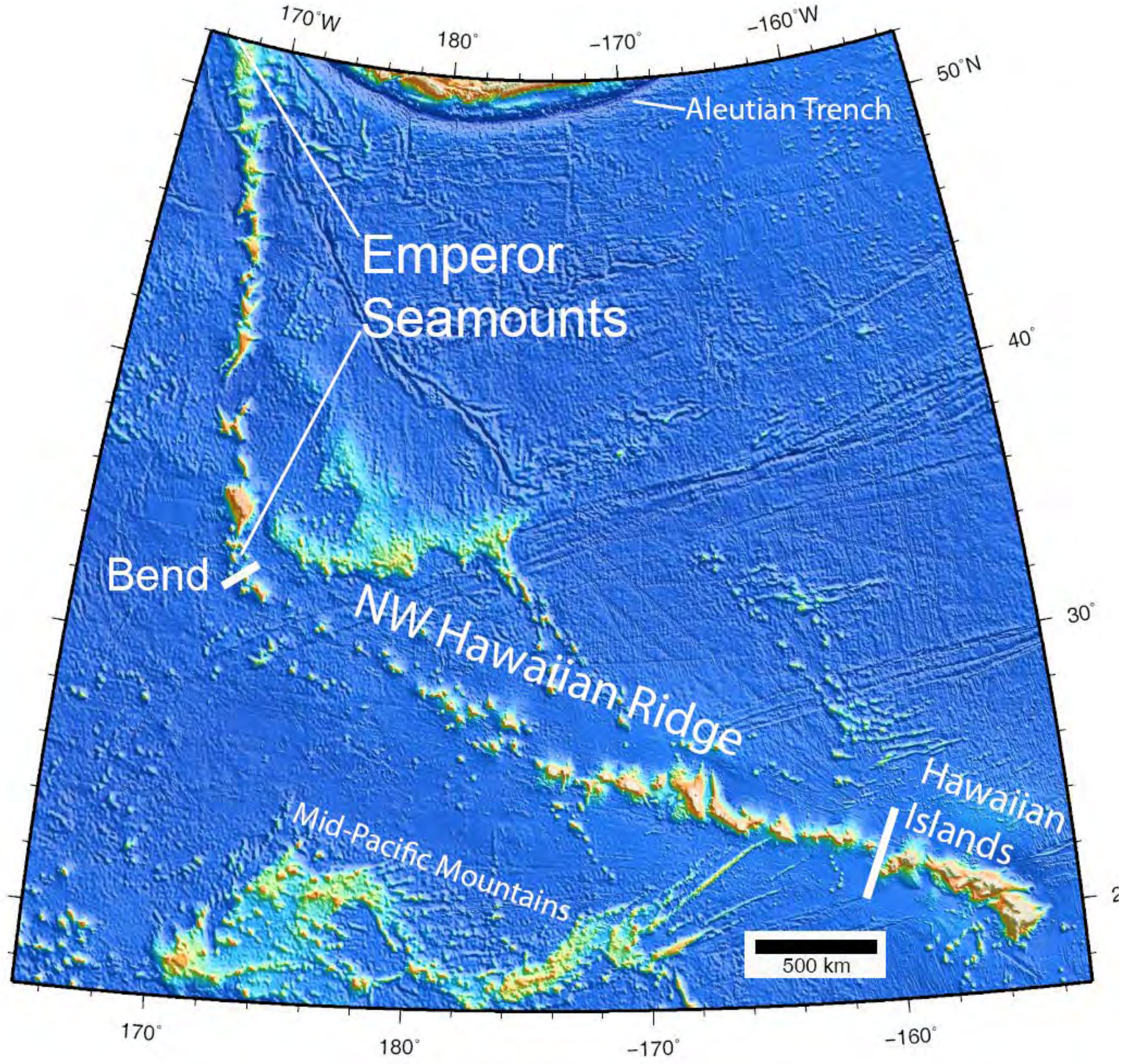


NWHR
5.5 - 47 Ma

Emperor Seamounts clearly have a Depleted Component not present anywhere else in Hawai‘i

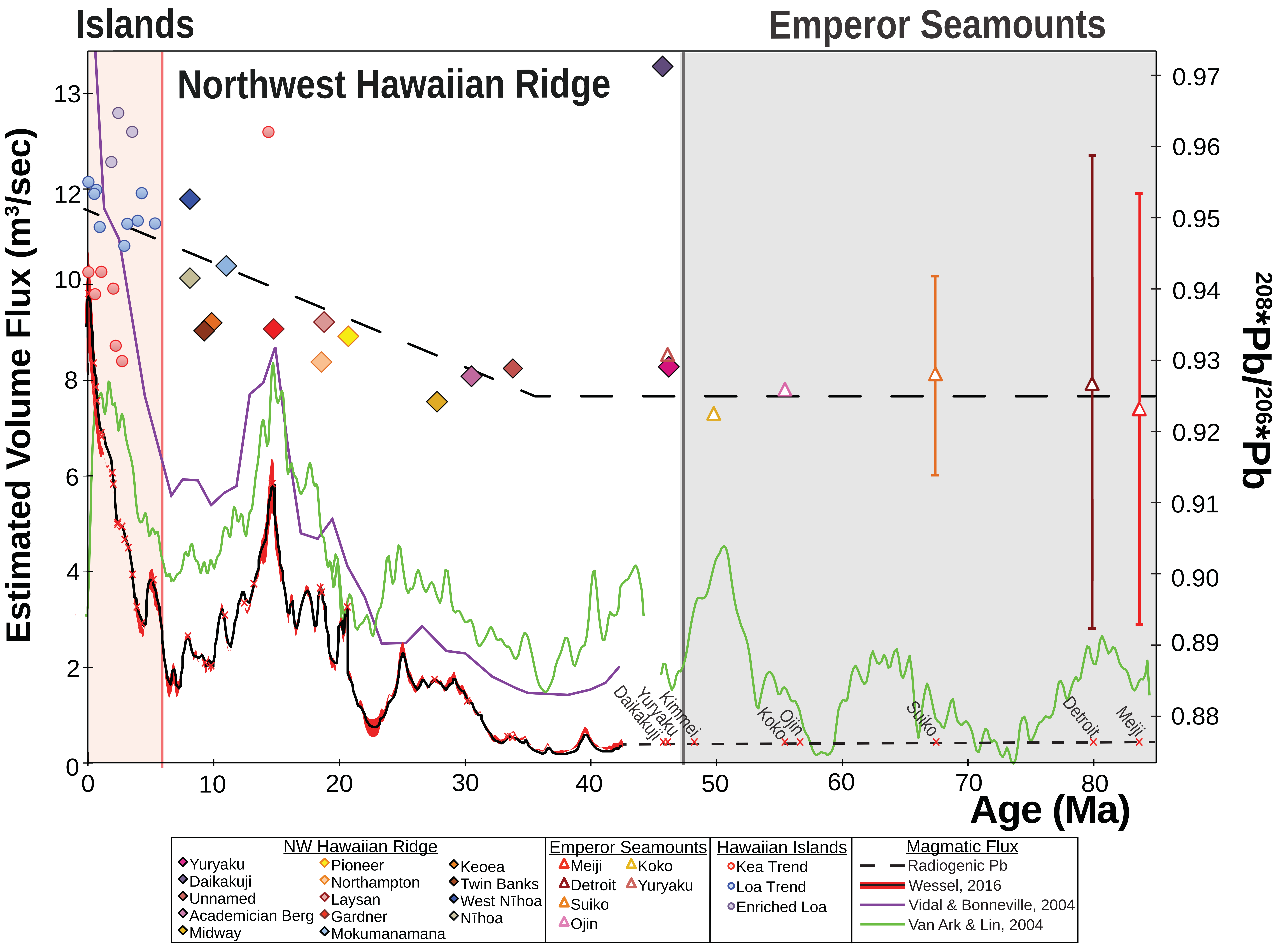


Emperor Seamounts >50-81 Ma



Garcia et al 2015

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



Harrison et al 2017

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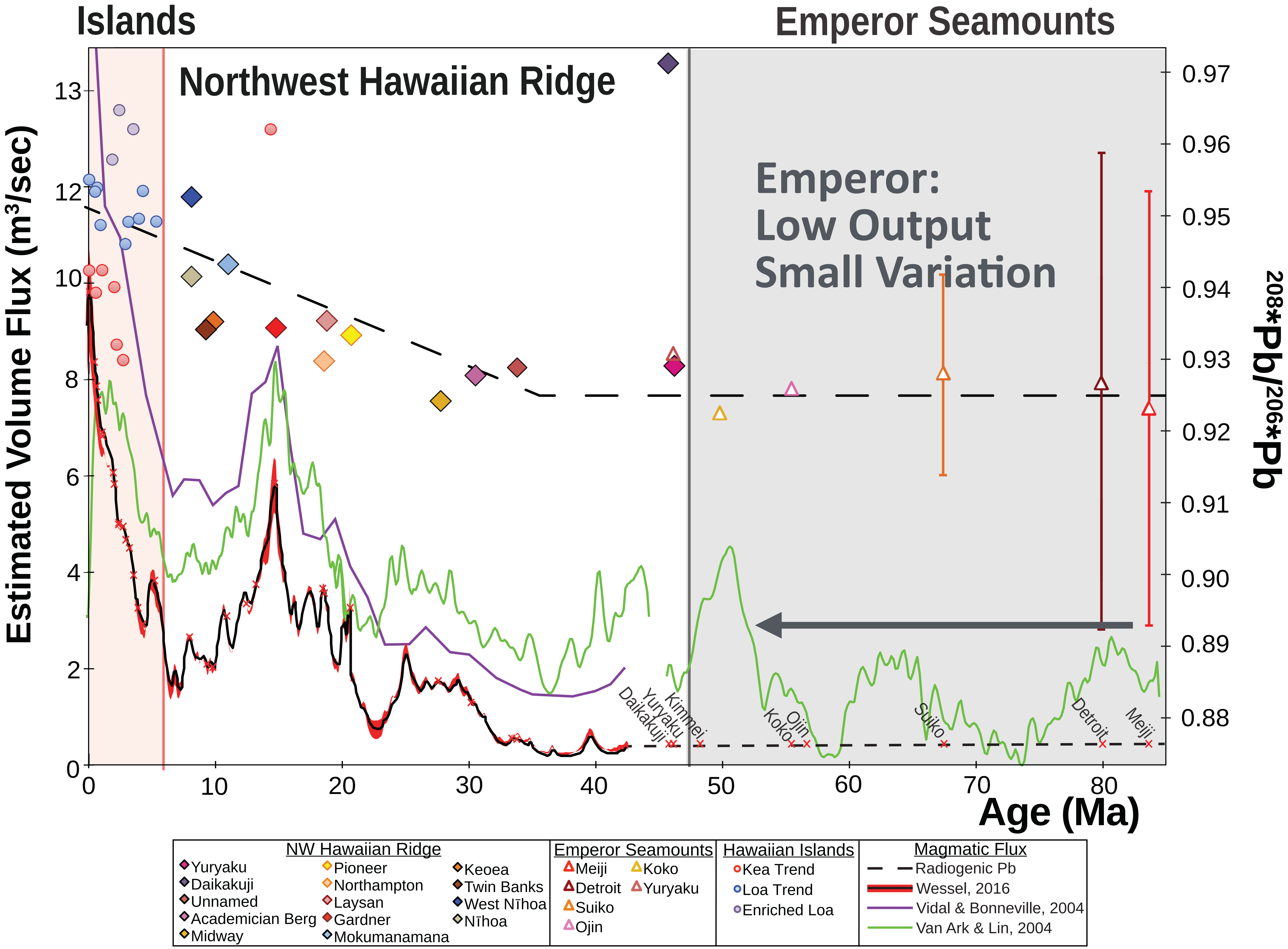

Harrison et al 2017

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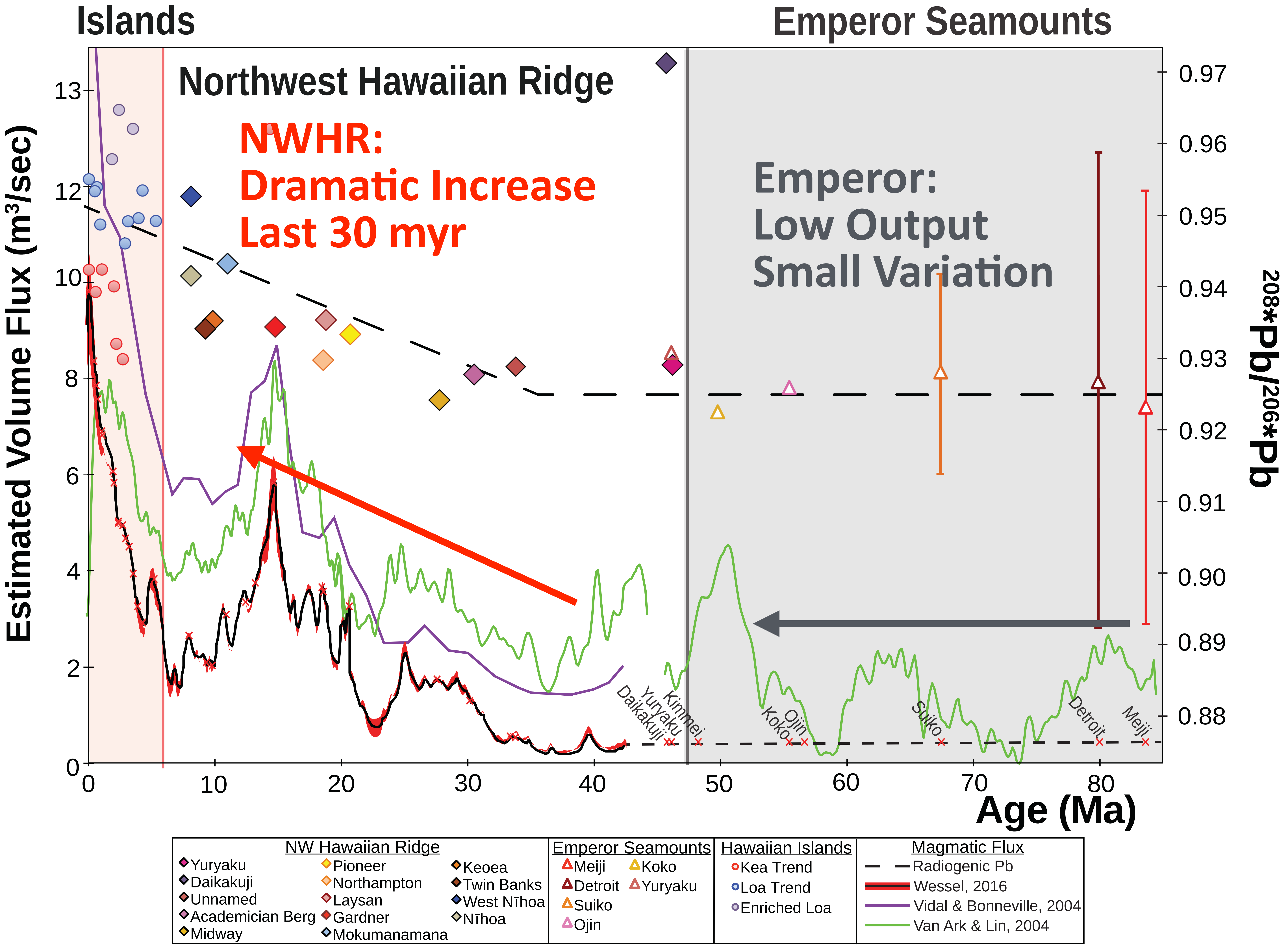
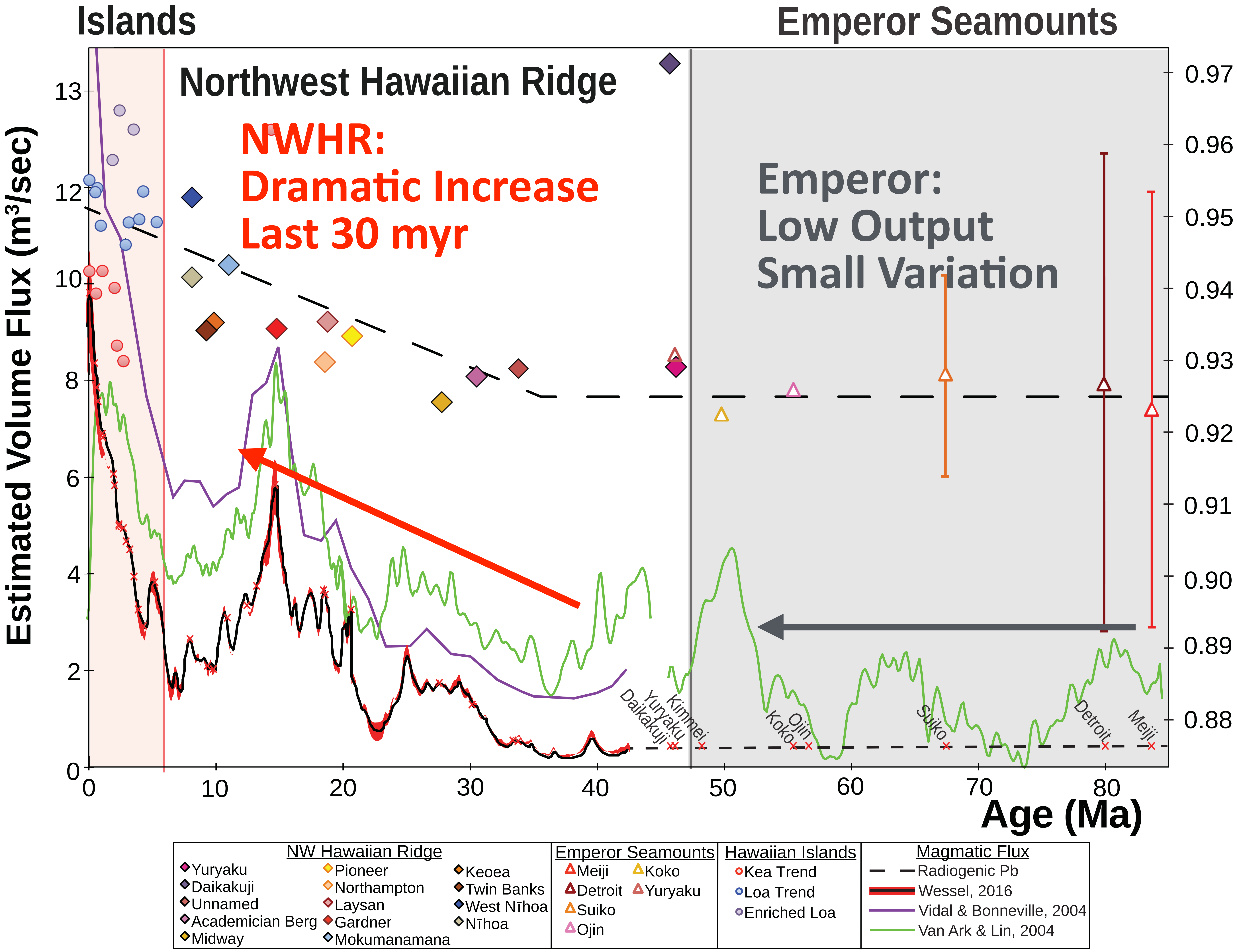


NWHR:
Dramatic Increase
Last 30 myr

Emperor:
Low Output
Small Variation

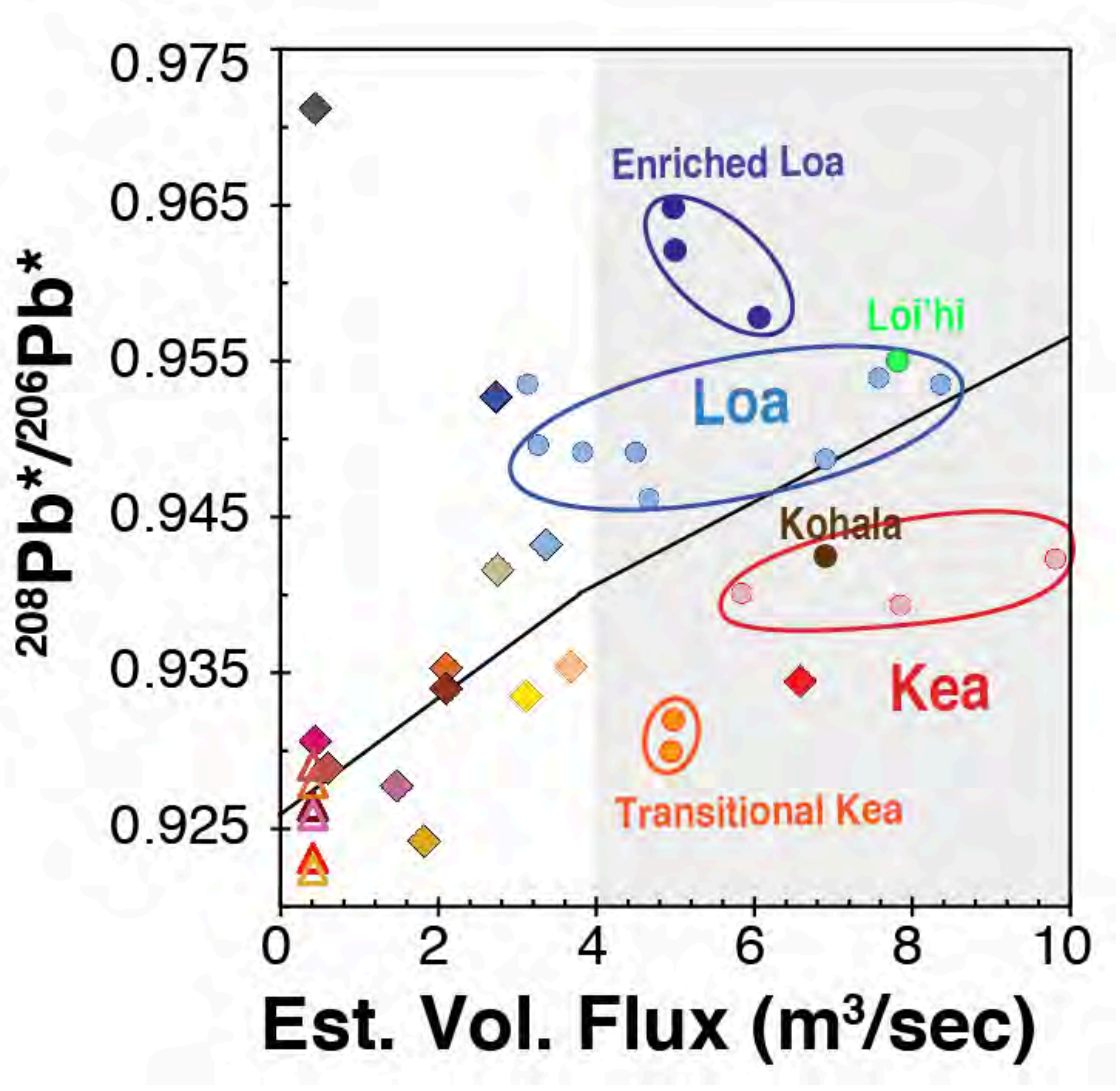
Harrison et al 2017

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



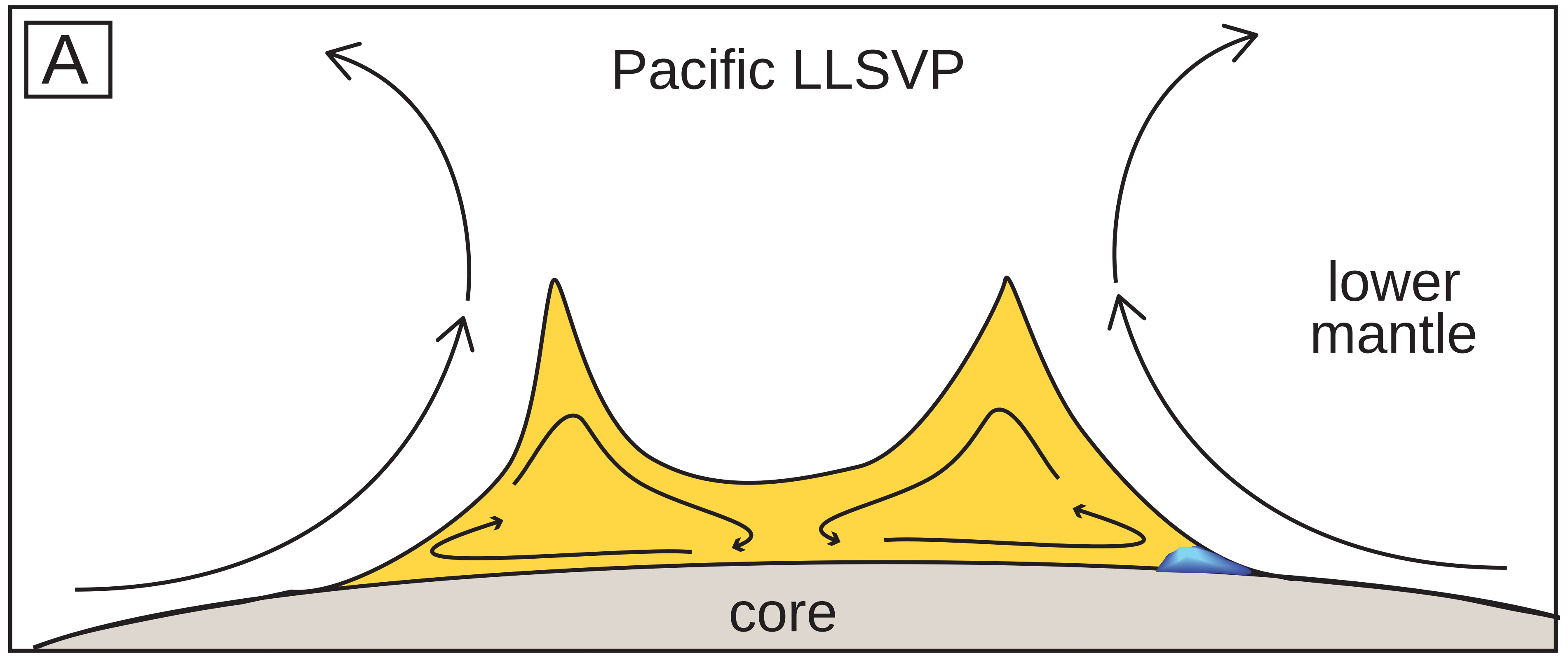
NWHR: Dramatic Increase Last 30 myr

Emperor: Low Output Small Variation



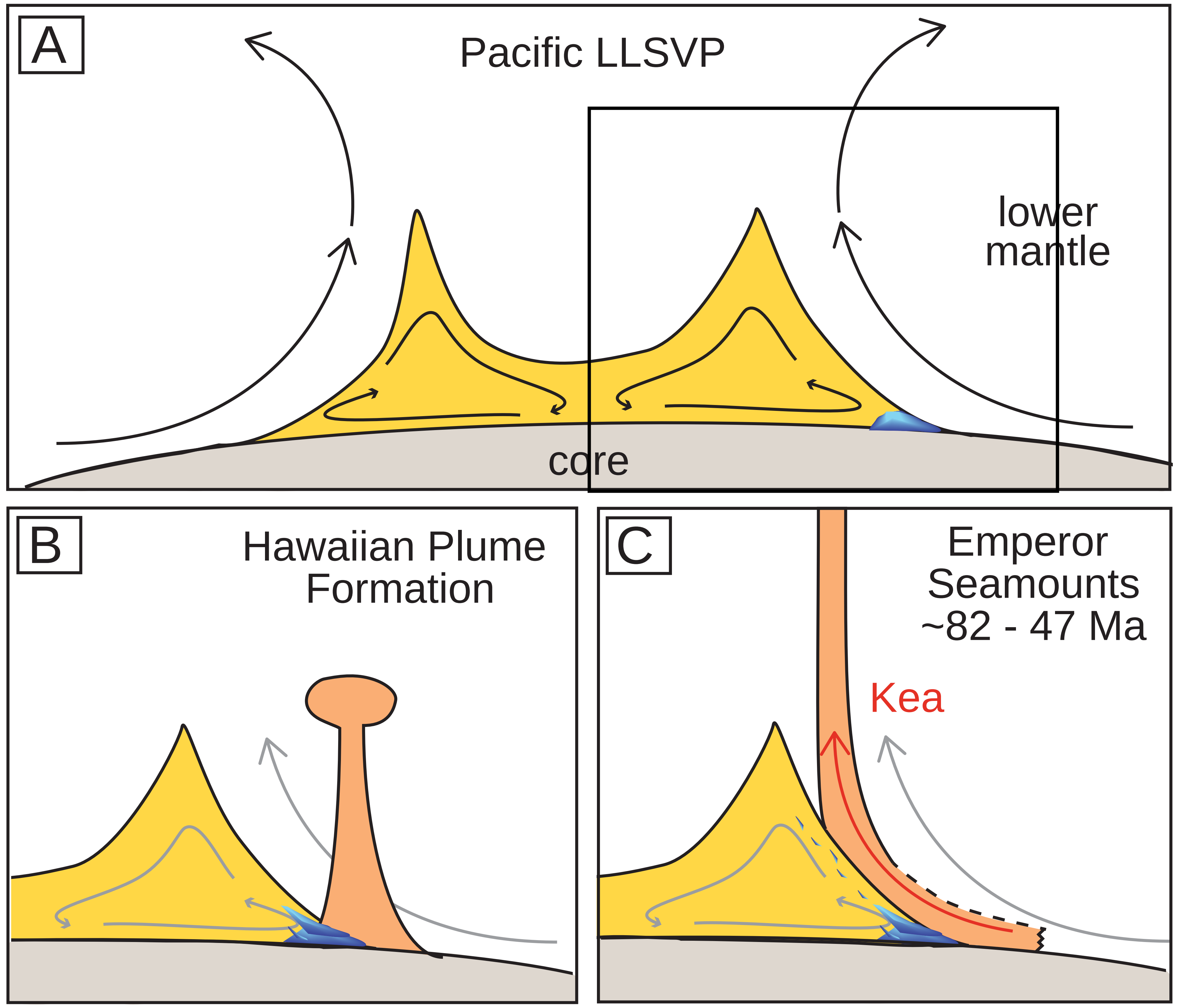
Harrison et al 2017

Evolution of the Hawaiian Plume Source at the CMB since inception



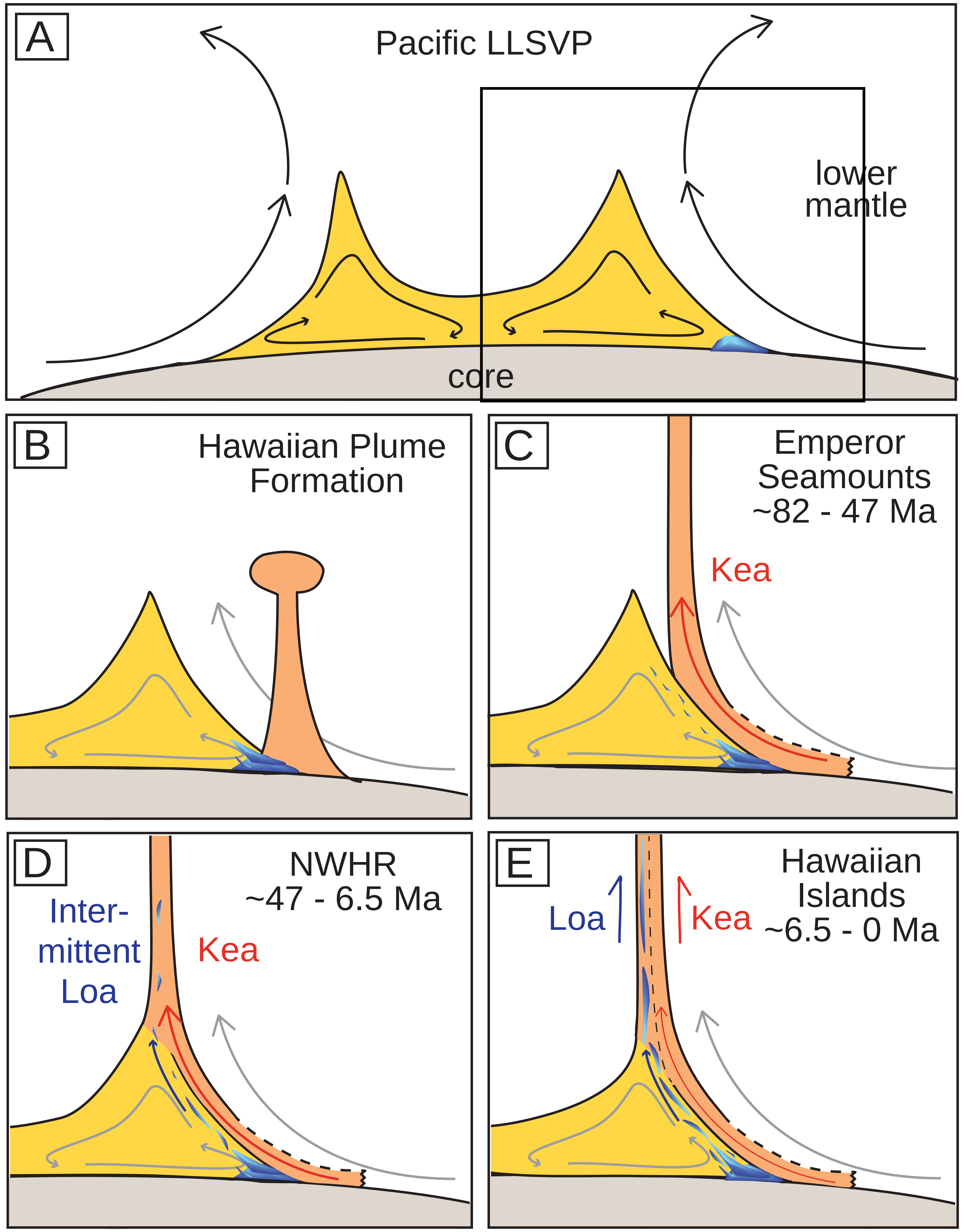
Harrison et al 2017

Evolution of the Hawaiian Plume Source at the CMB since inception



Harrison et al 2017

Evolution of the Hawaiian Plume Source at the CMB since inception



Harrison et al 2017

Implications for the Deep Mantle and LLSVPs

Kaua'i, NaPali coast

- Mantle plume tails are dynamic and can change compositionally with time.

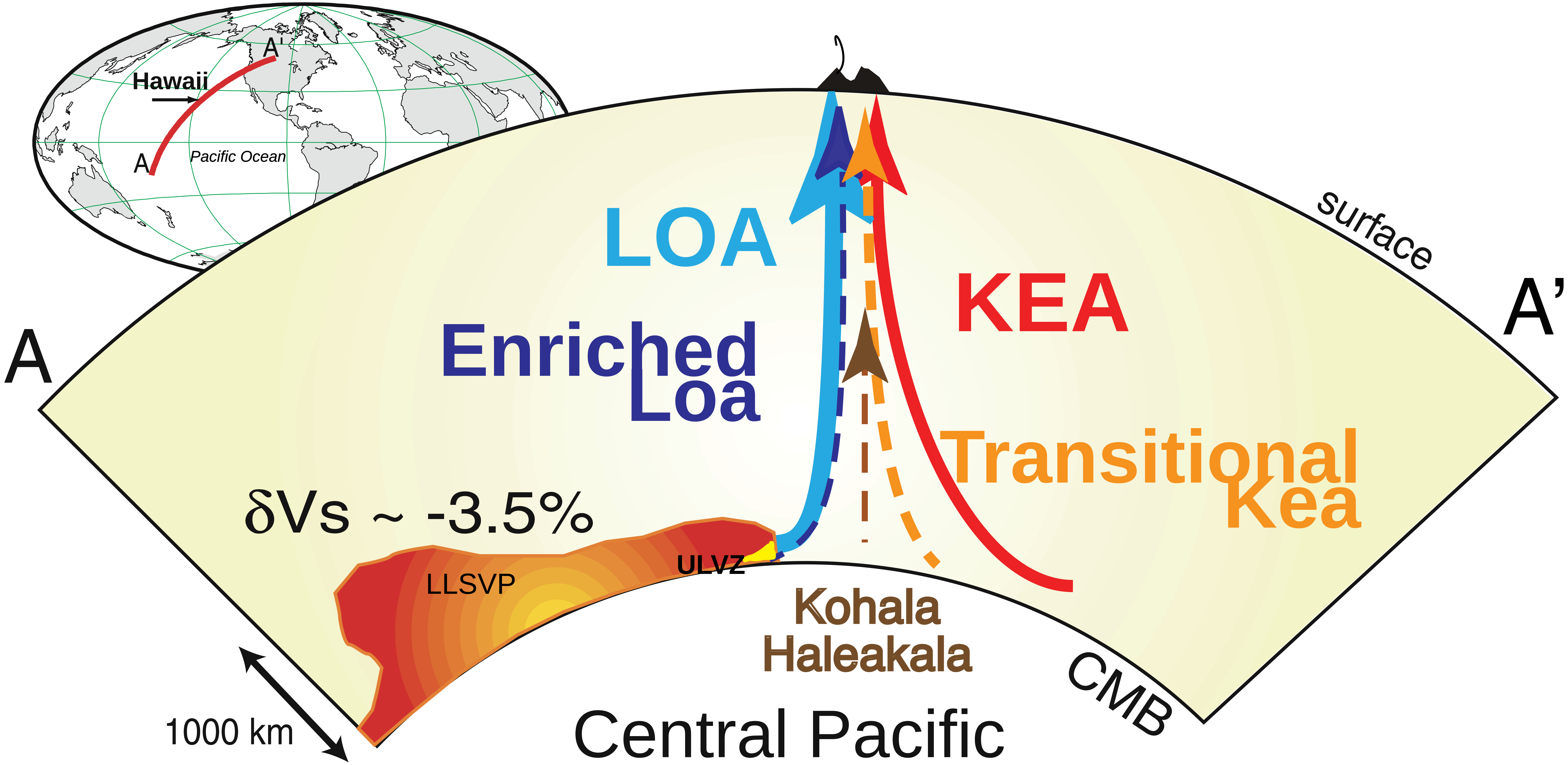
- Hawaiian plume drift samples multiple mantle domains which has impact on:
  - Geochemistry, spatial organization and timing
  - Magmatic Flux
  - Volcanic Propagation Rate

- 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.

Model: a Fine Structure of the Hawaiian Mantle Plume

with a compositional gradient away from the Pacific ULVZ that provides the enriched components in the Loa Trend volcanoes



Model: a Fine Structure of the Hawaiian Mantle Plume

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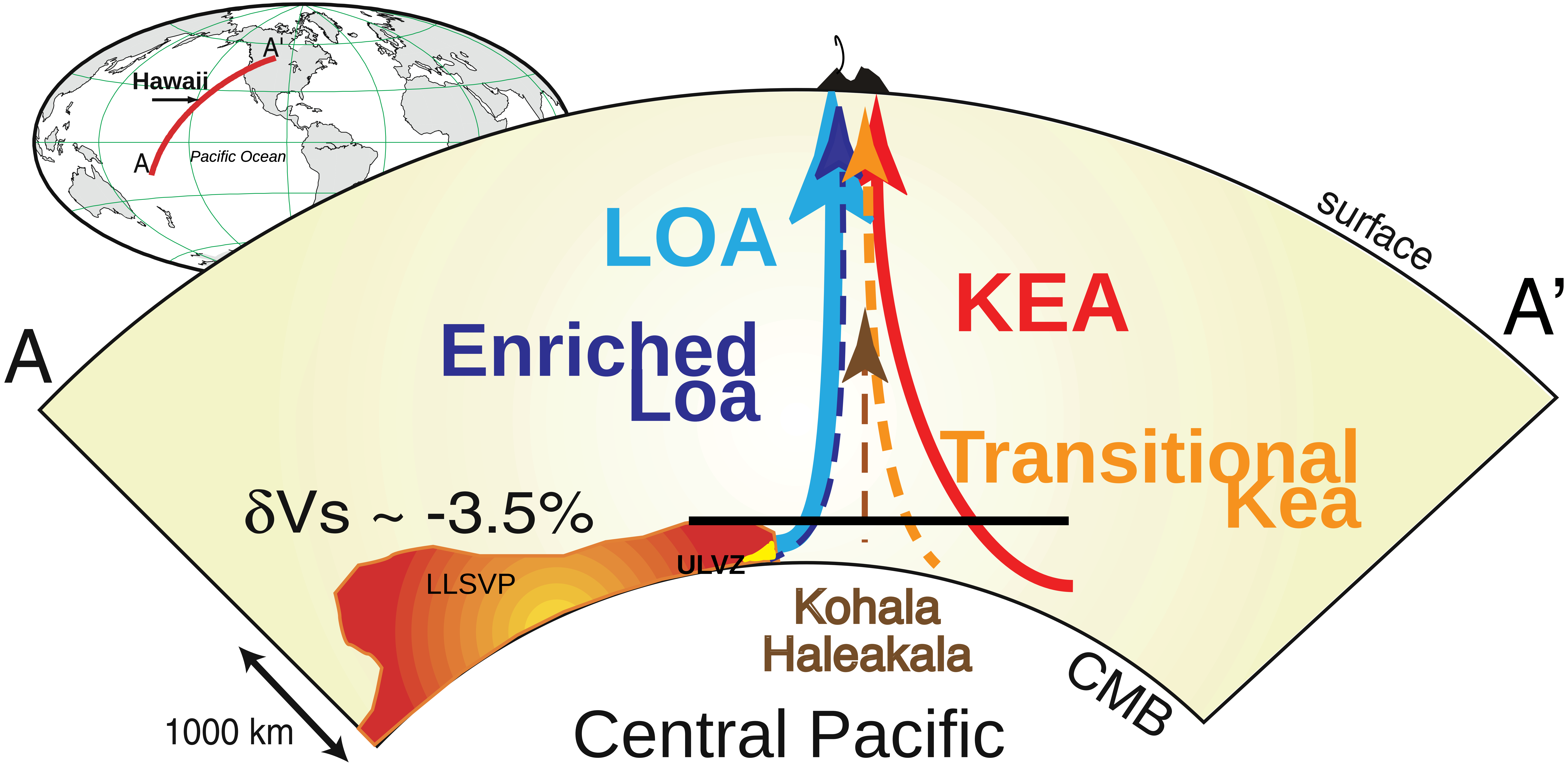
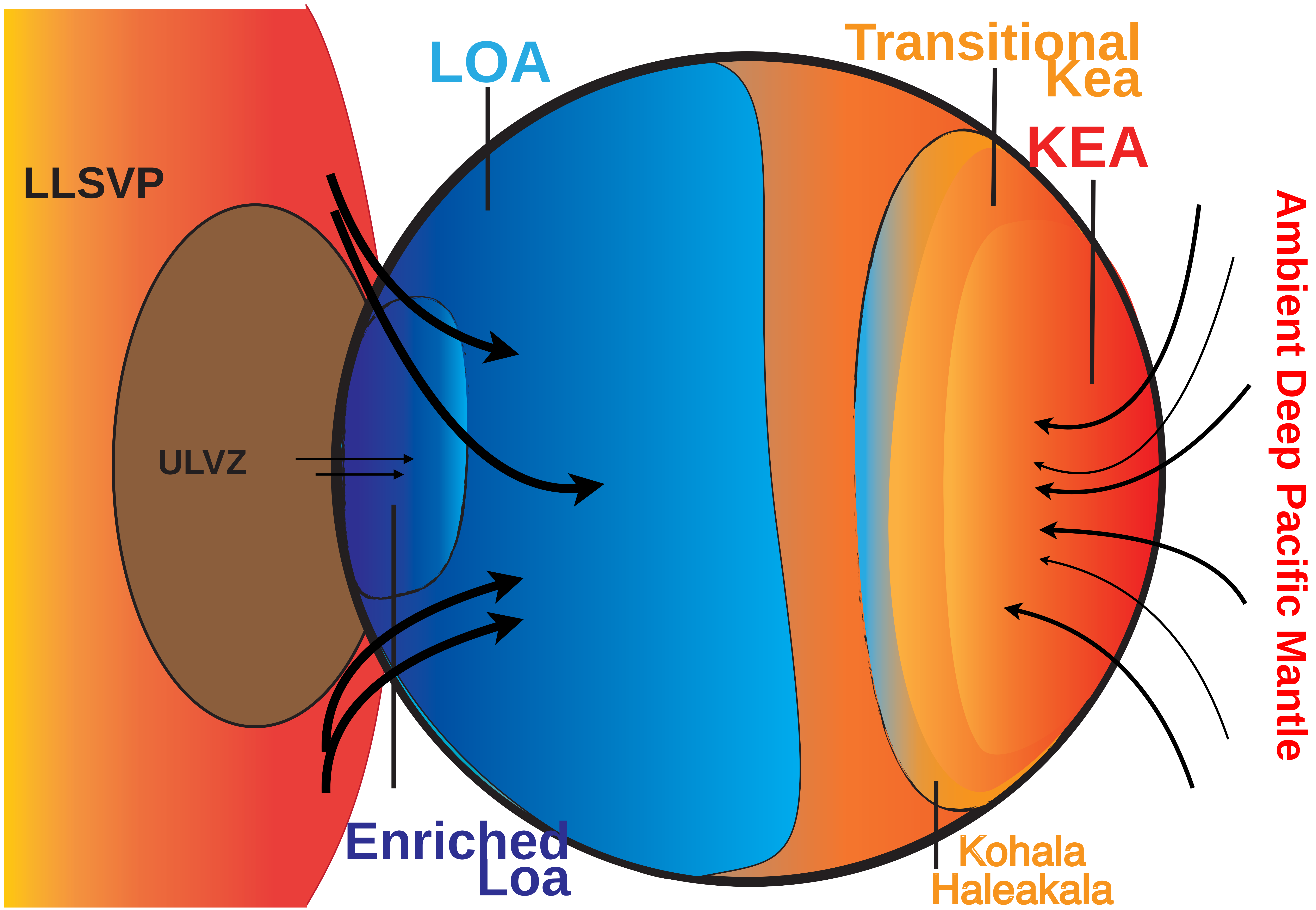


Conceptual Cross Section:

Mapping the Hawaiian Geochemical Components at the Base of the Mantle



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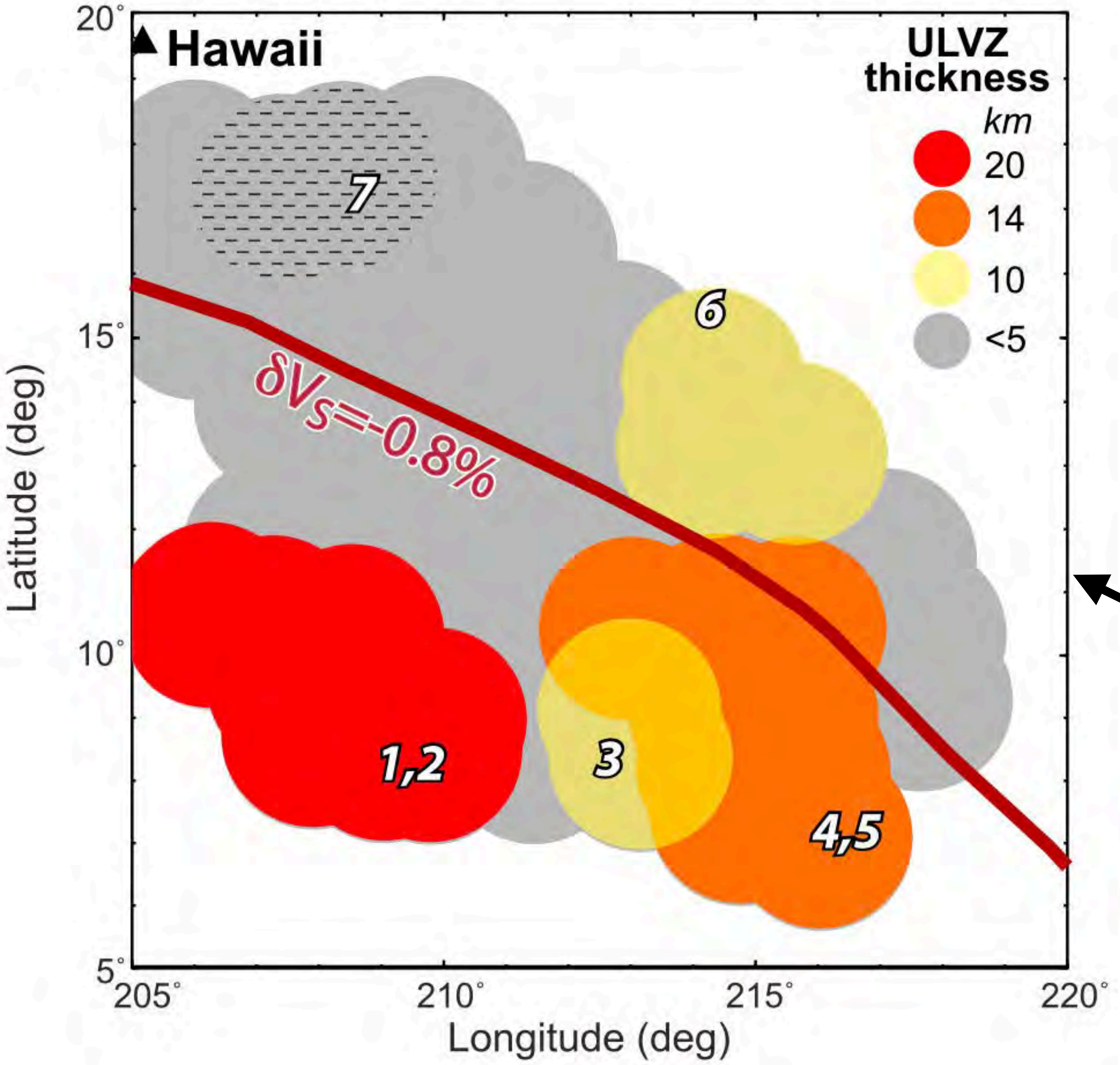
Diane Hanano
Catherine Armstrong
Andrew Greene -Inês Nobre Silva
Maia Kuga - Lisa Swinnard

Kathy Gordon - Marg Amini
Dave Daquioag -Claude Maerschalk - Bruno Kieffer
Liyan Xing - Jane Barling

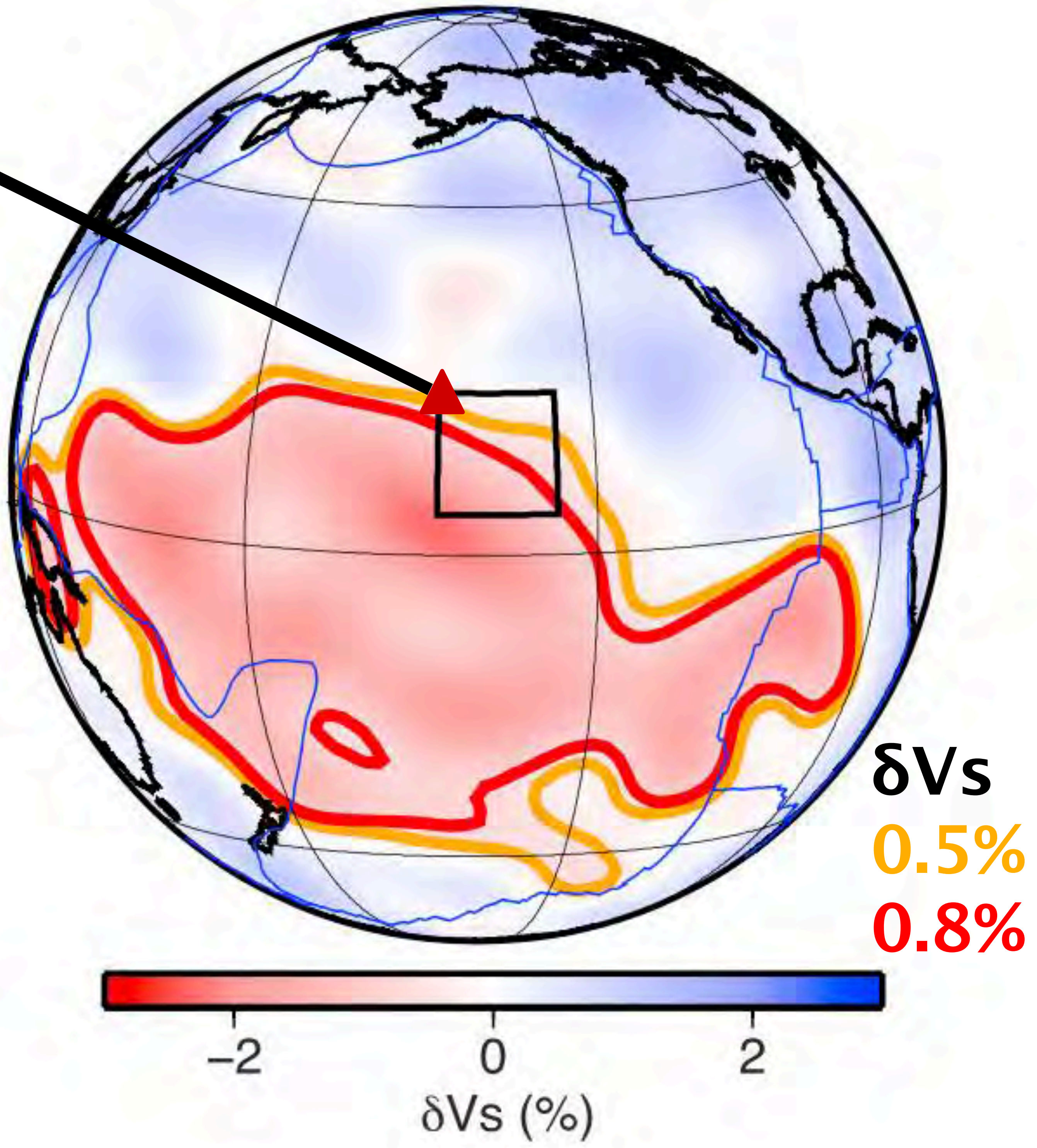
Thank You !

Kaua'i, Sunset

ULVZ Thickness Distribution Map

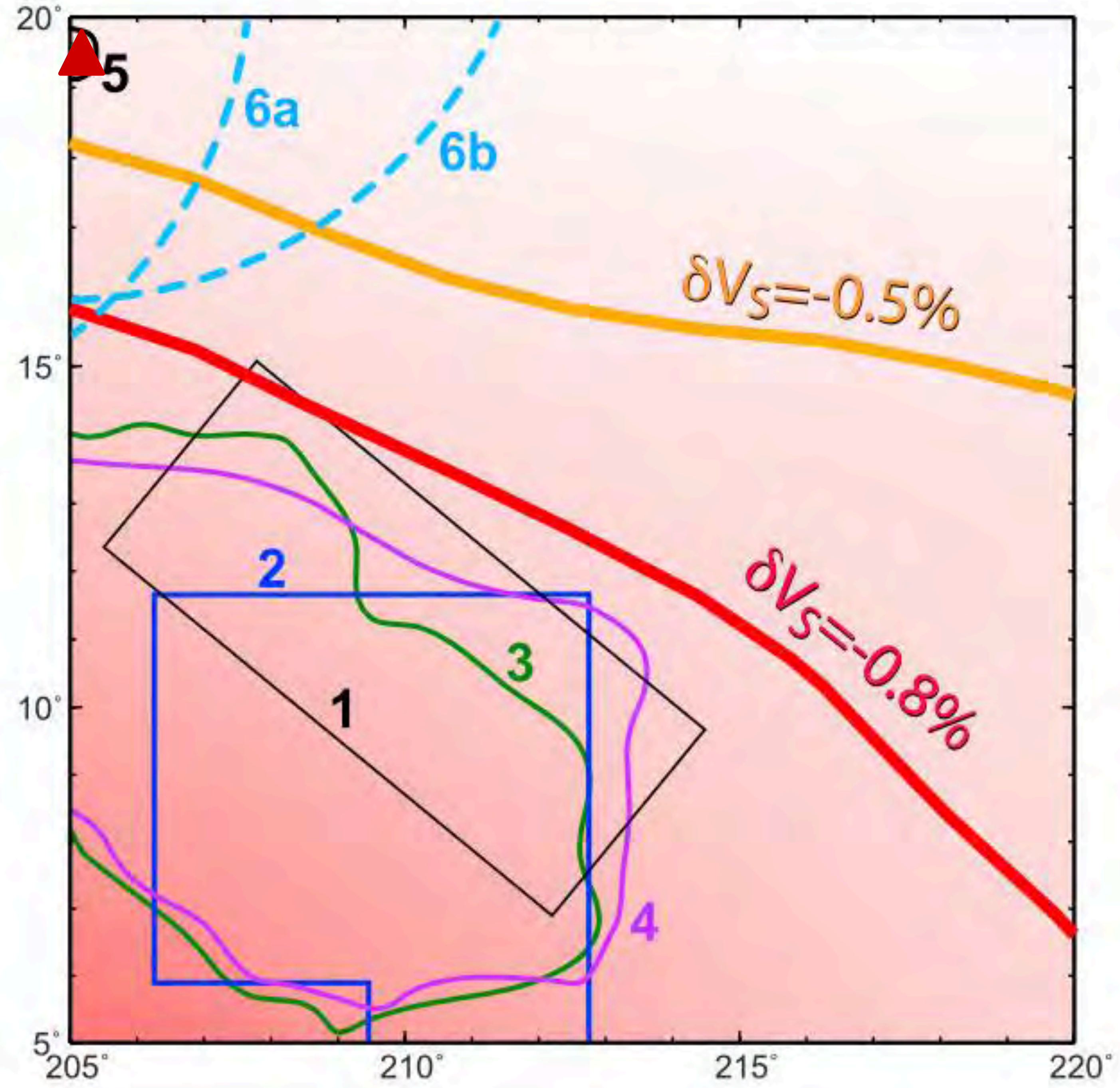


Lower Mantle Shear Velocity Heterogeneity



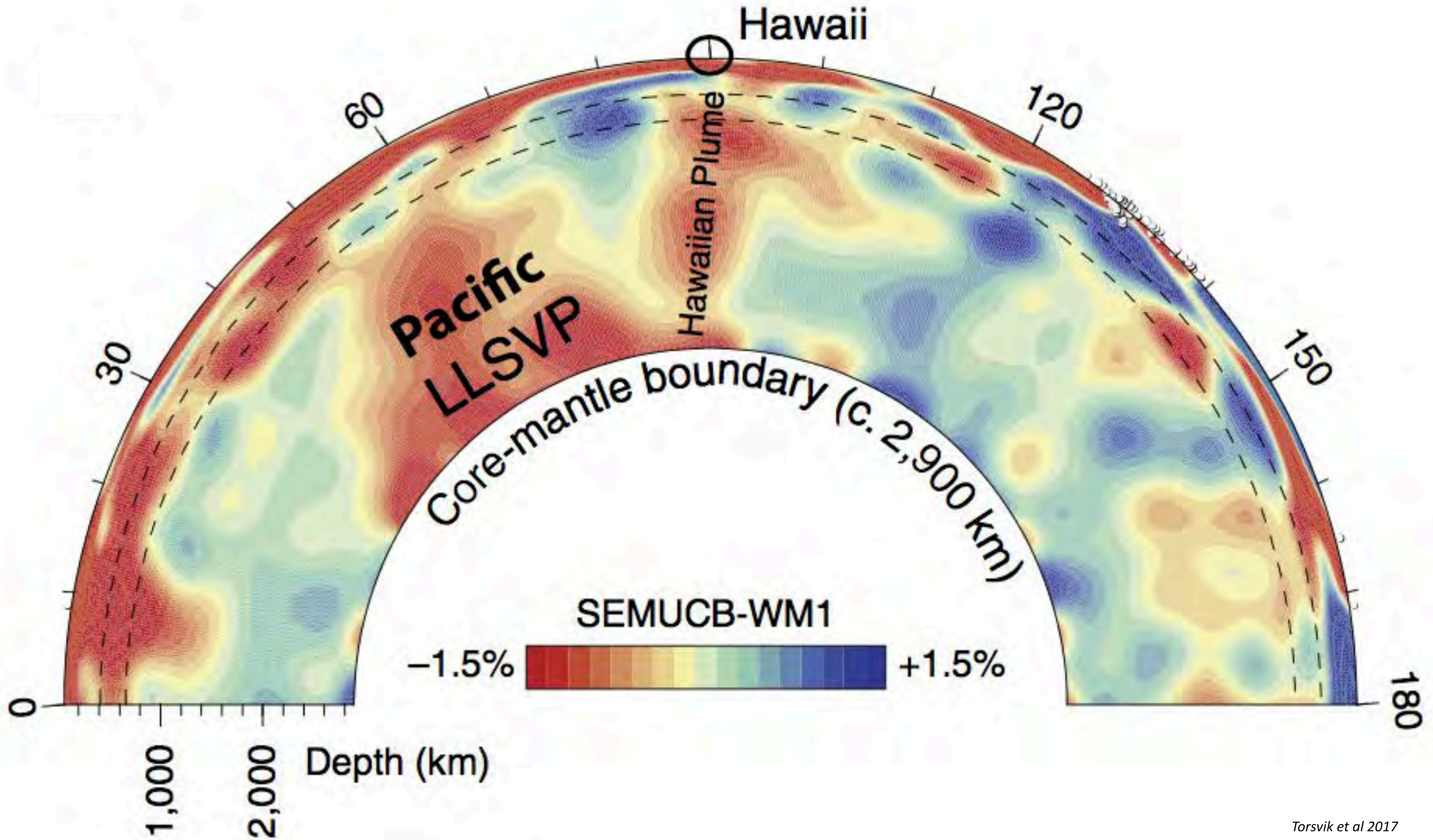
S20RTS

Zhao et al 2015



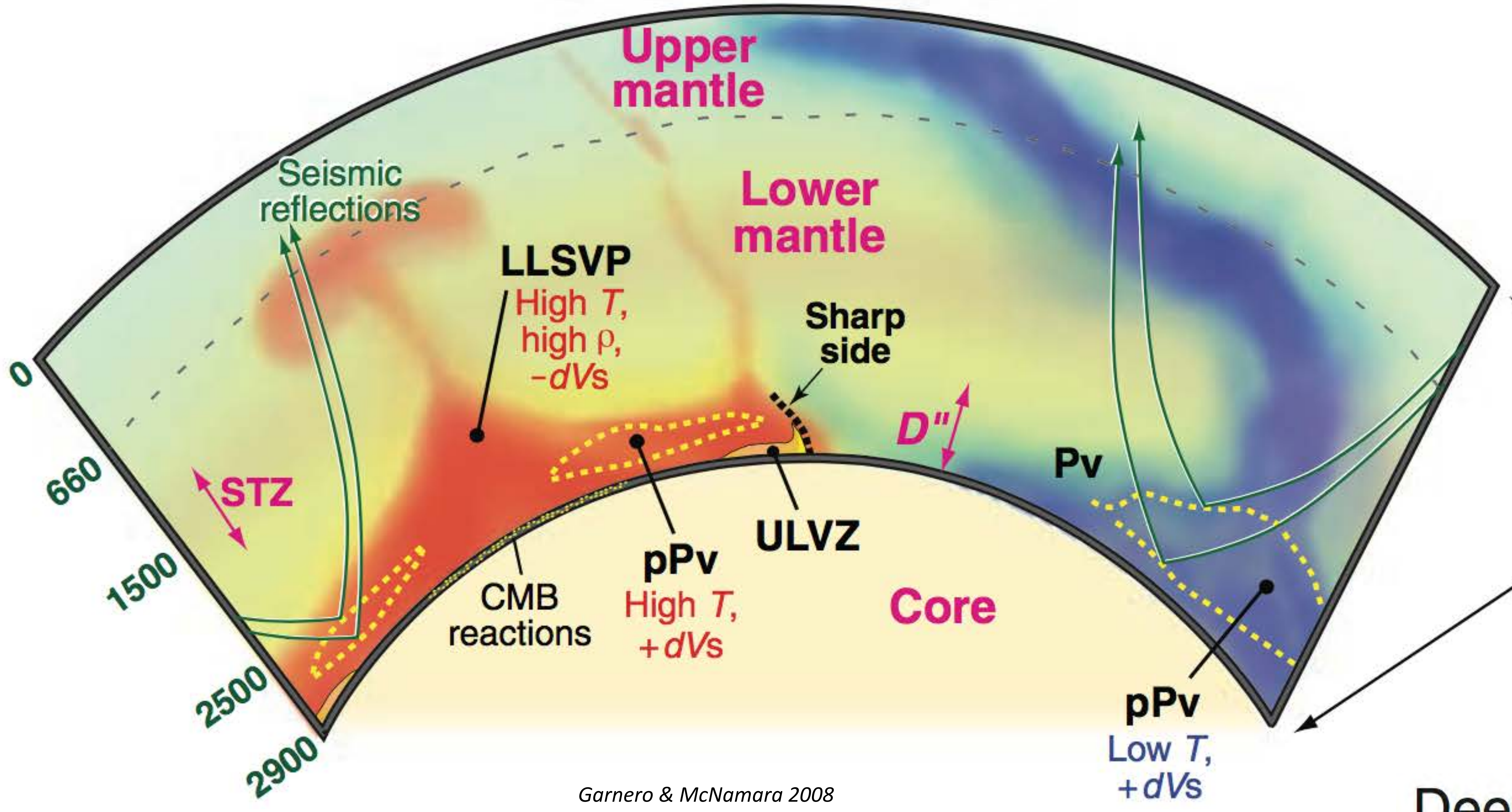
δVs contours

N-S Vertical Slice of the SEMUCB-WM143 Mantle Tomography Model through the Pacific LLSVP



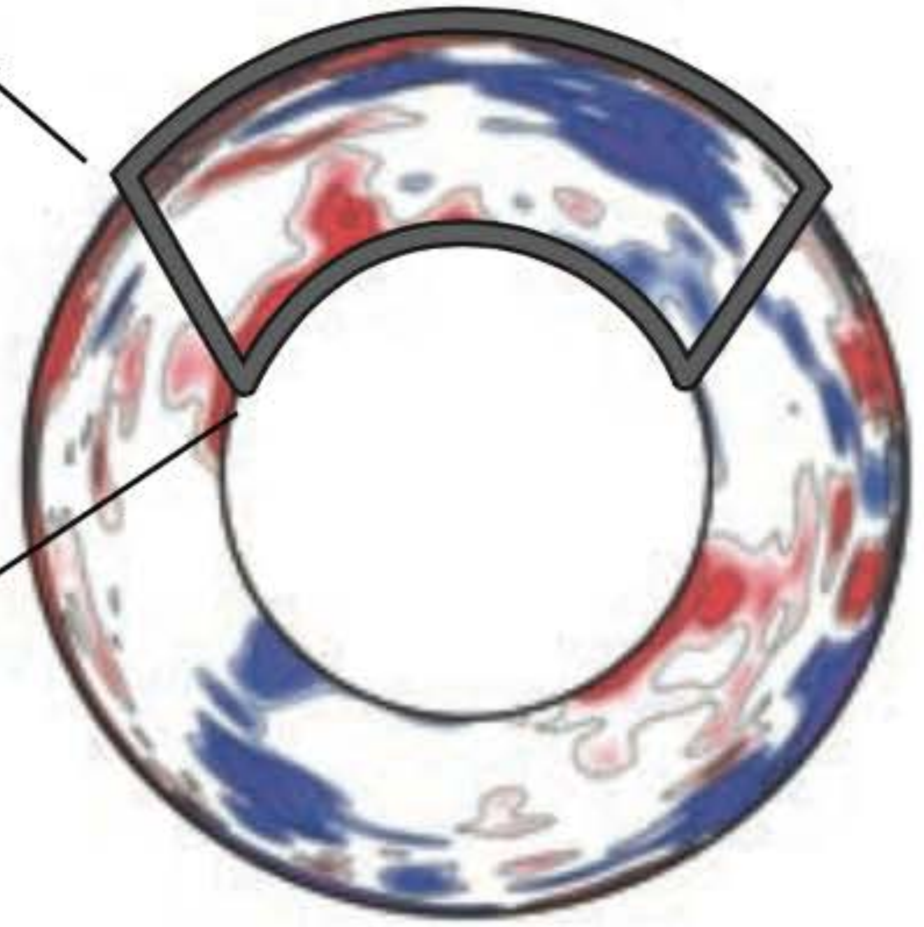
Torsvik et al 2017

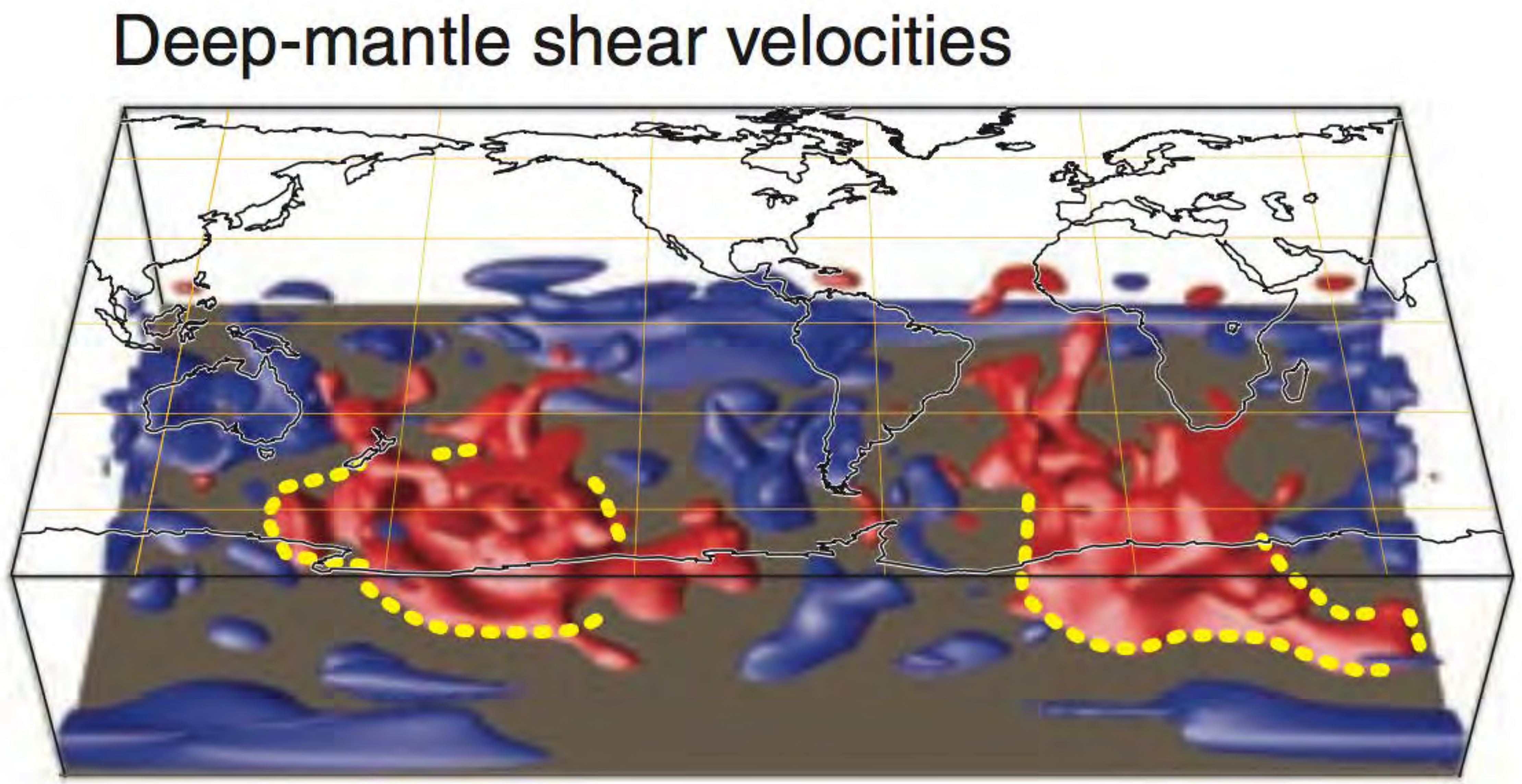
High (blue) and Low (red) Seismic Shear Velocity Variations in Earth’s Mantle



Garnero & McNamara 2008

Equatorial cross section
View from the south





Deep-mantle shear velocities

Shear velocity perturbations between 660 km depth and the CMB, isocontoured at ±0.6% (blue/ red) for model S20RTS. Sharp LLSVP edges = yellow dashed lines.

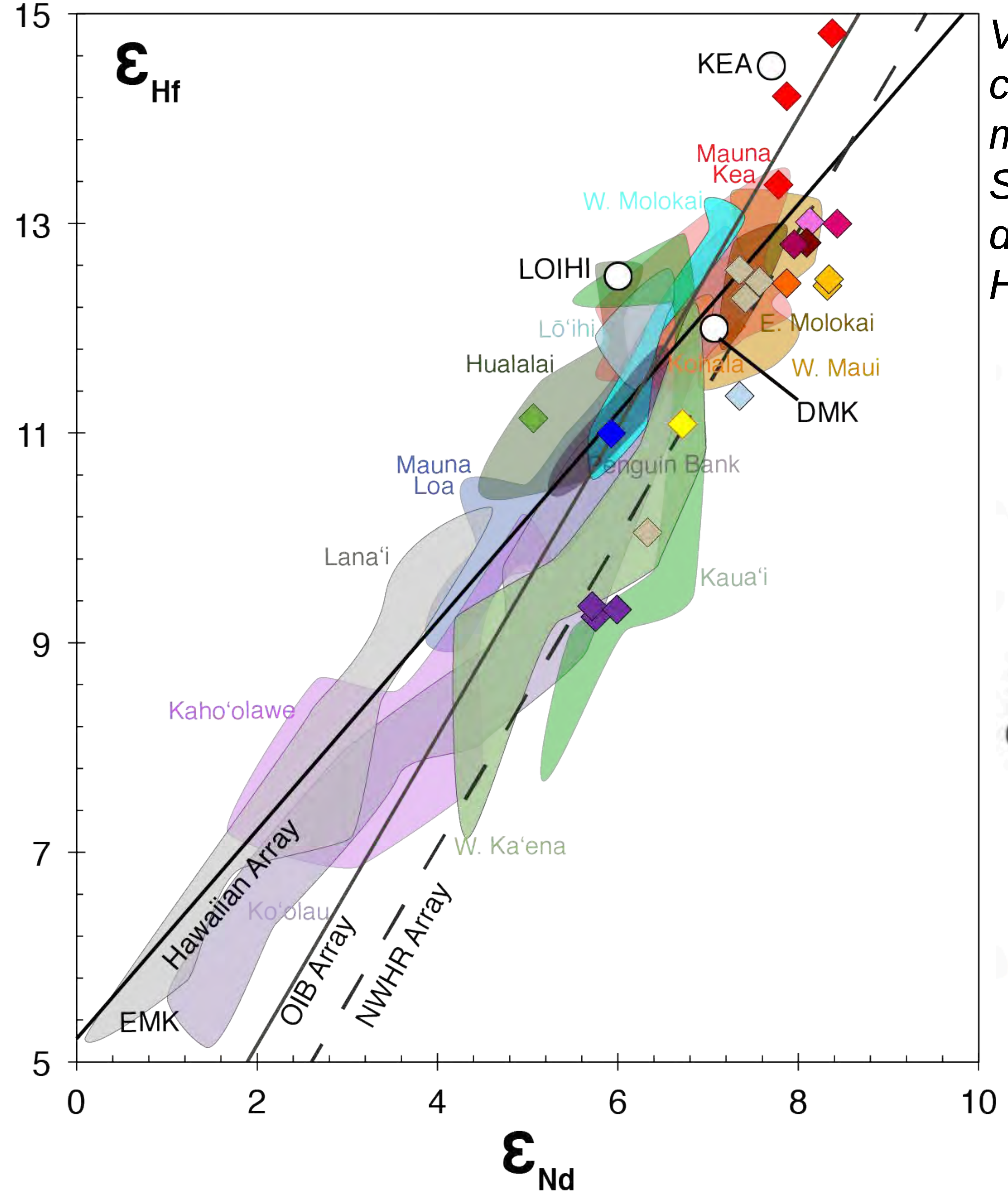
Why Hawai‘i?

Link Deep Mantle and Geochemistry
Magma Flux and Source Components
Origin of Enriched Components (EM-I)

Kaua‘i, NaPali coast

New Nd-Hf Array for Hawaii

V. Radiogenic Hf isotopes (EpiHf up to 43 in continental xenoliths) originate from ancient MORB melting that creates small fractionations of Lu-Hf, Sm-Nd in the restite lithosphere that grow to large differences in isotopic signature; High Hf also in Hawaiian xenoliths!



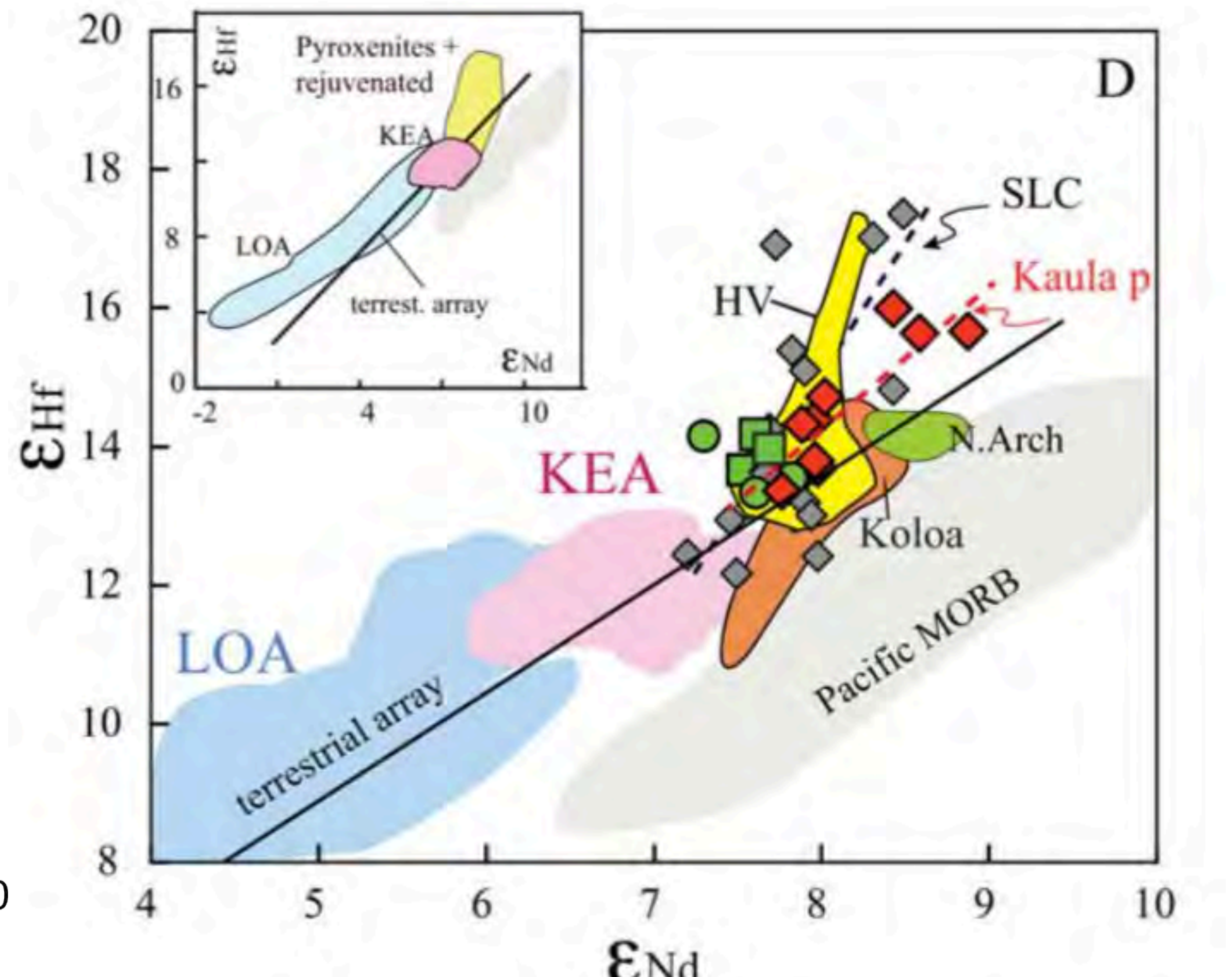
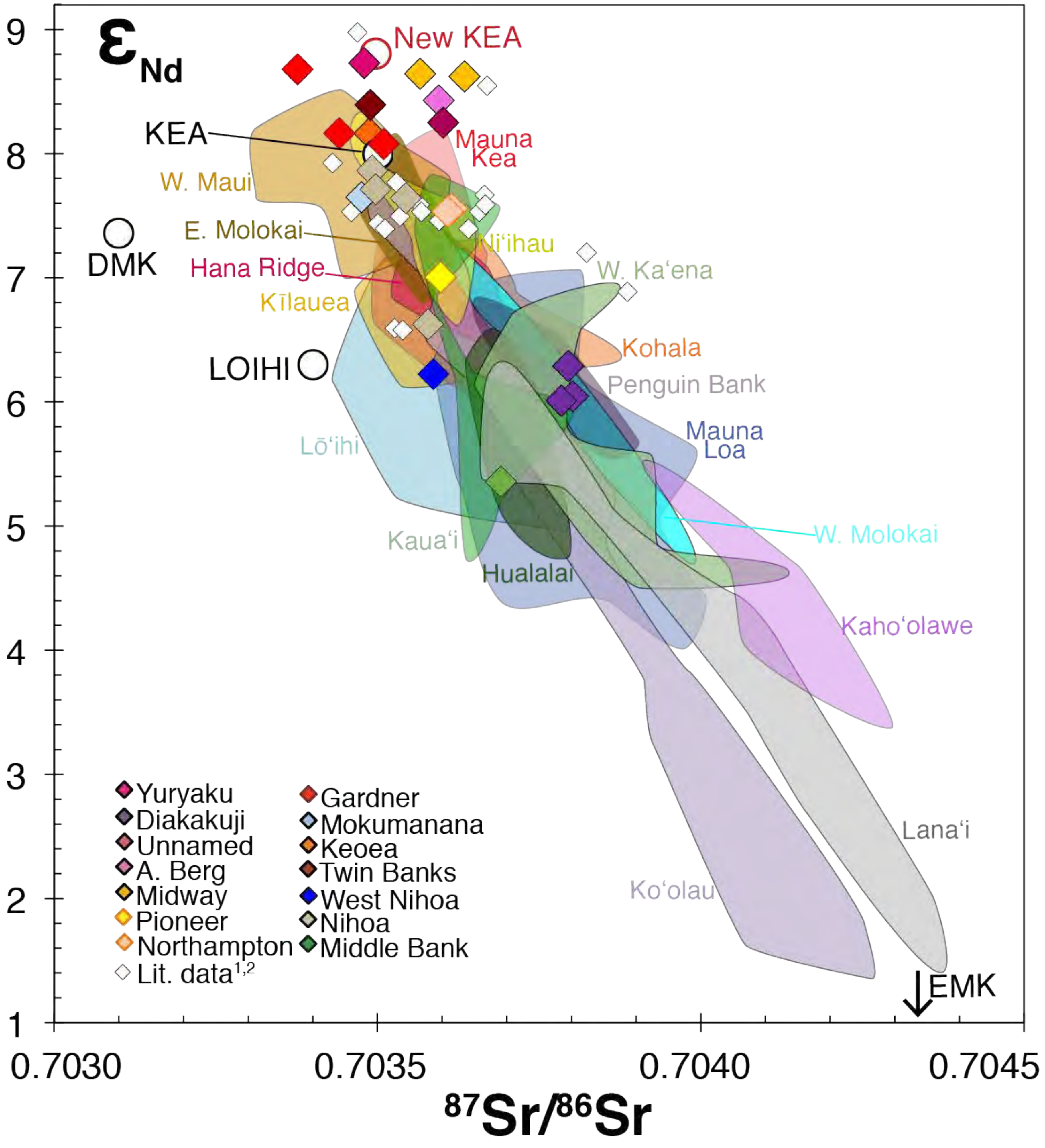
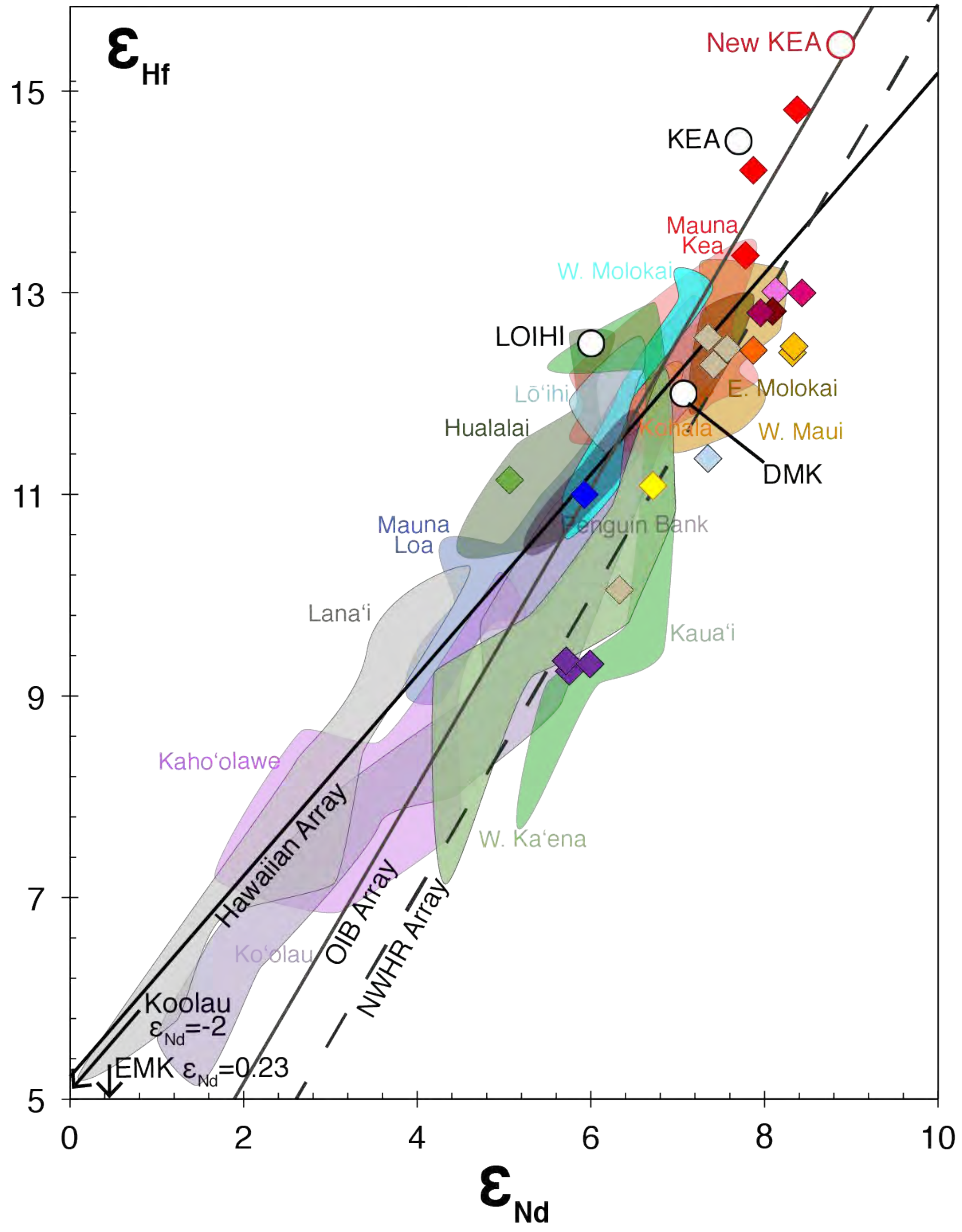


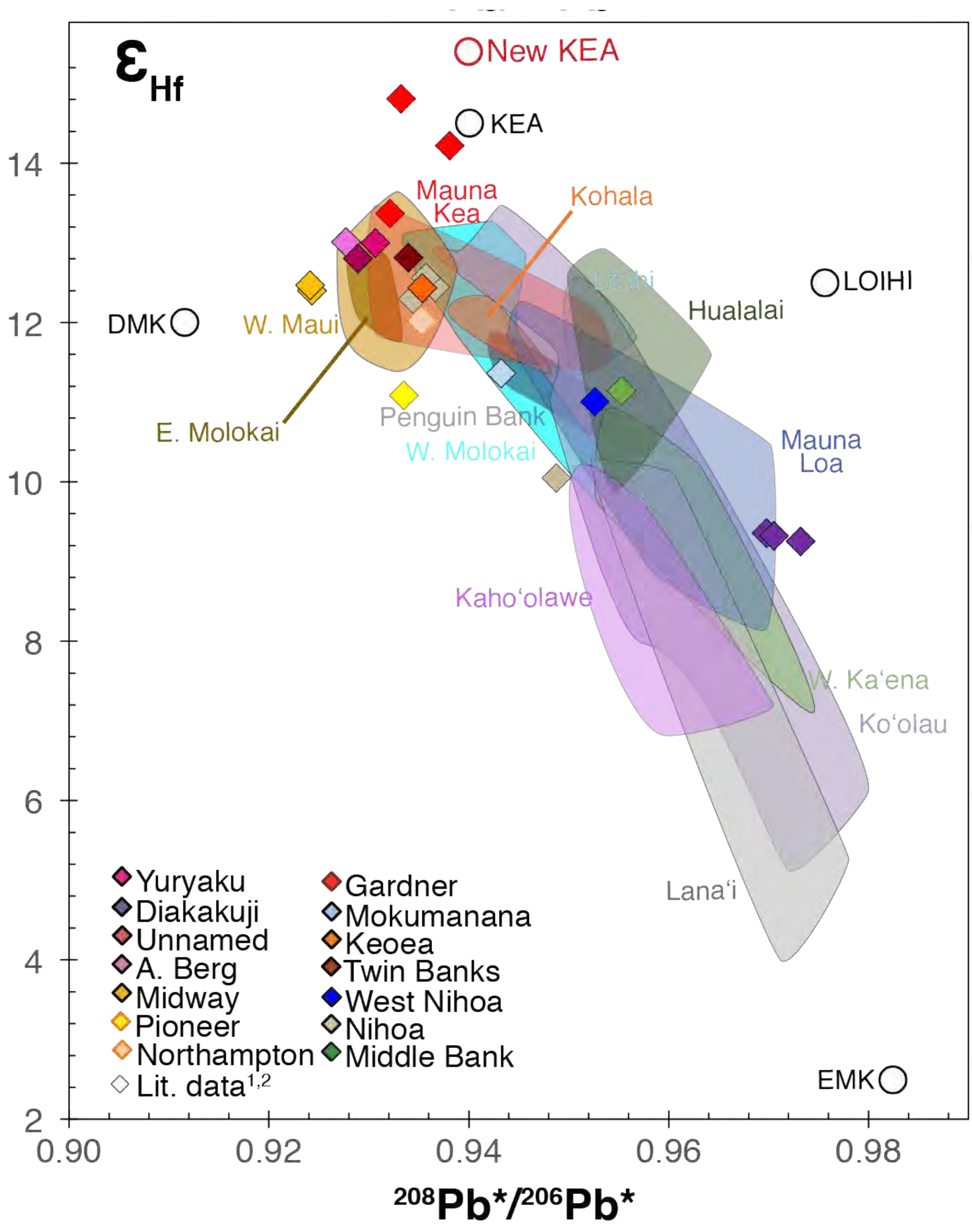
Figure from Bizimis et al., 2013

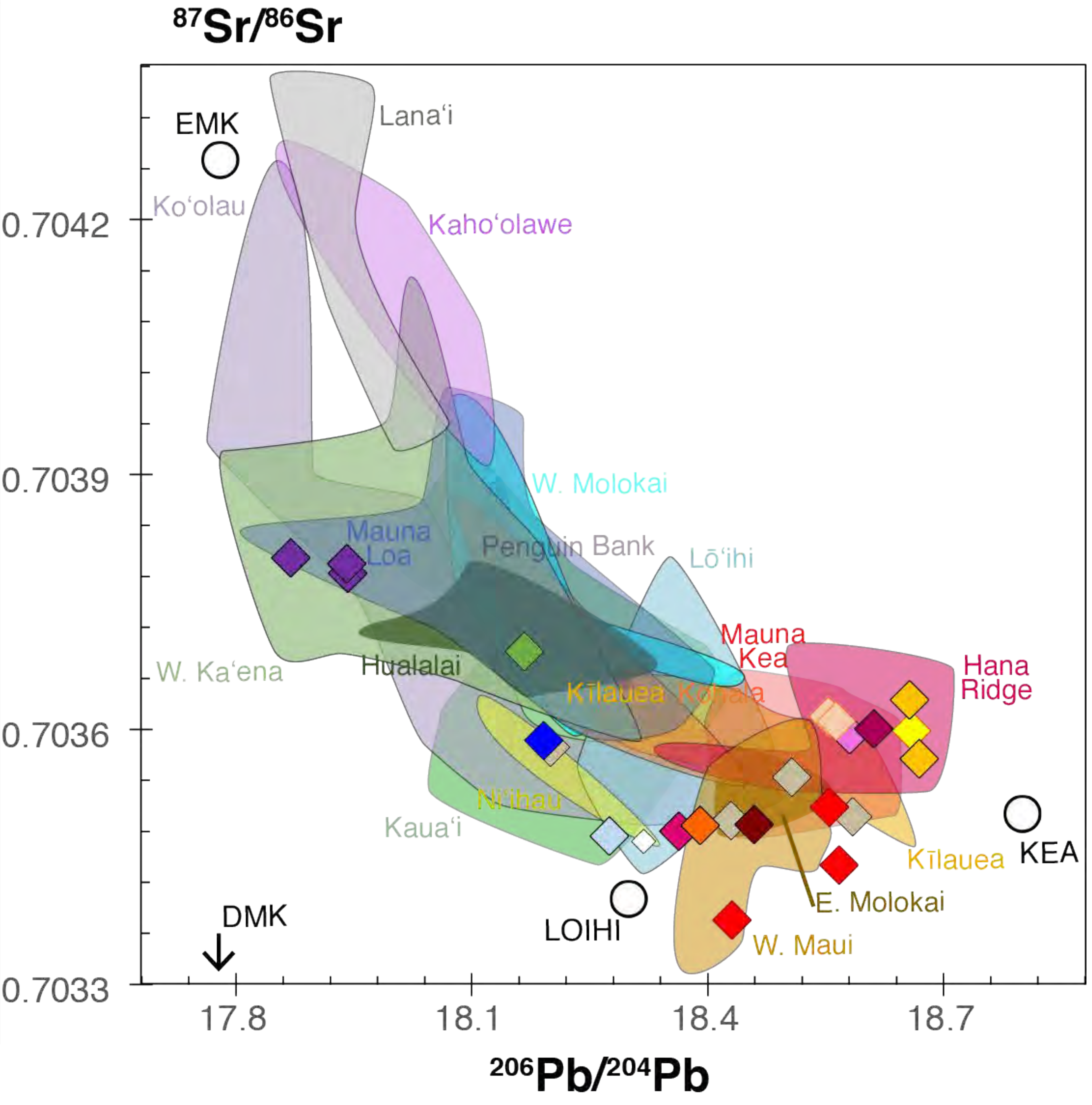
NWHR Shield Isotopes





NWHR Shield Isotopes





Very limited isotopic data were available for the entire Hawaiian Ridge up to now

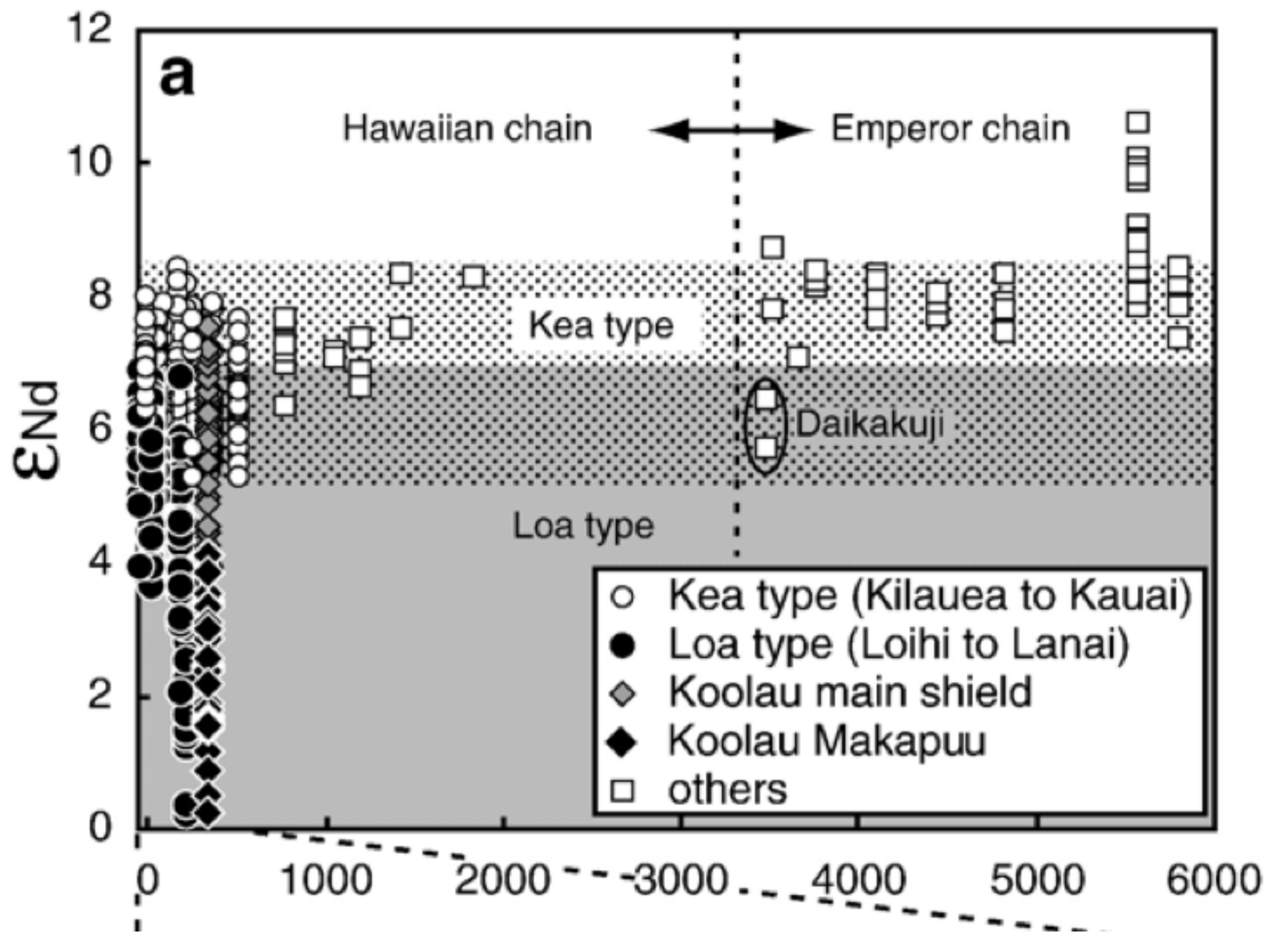
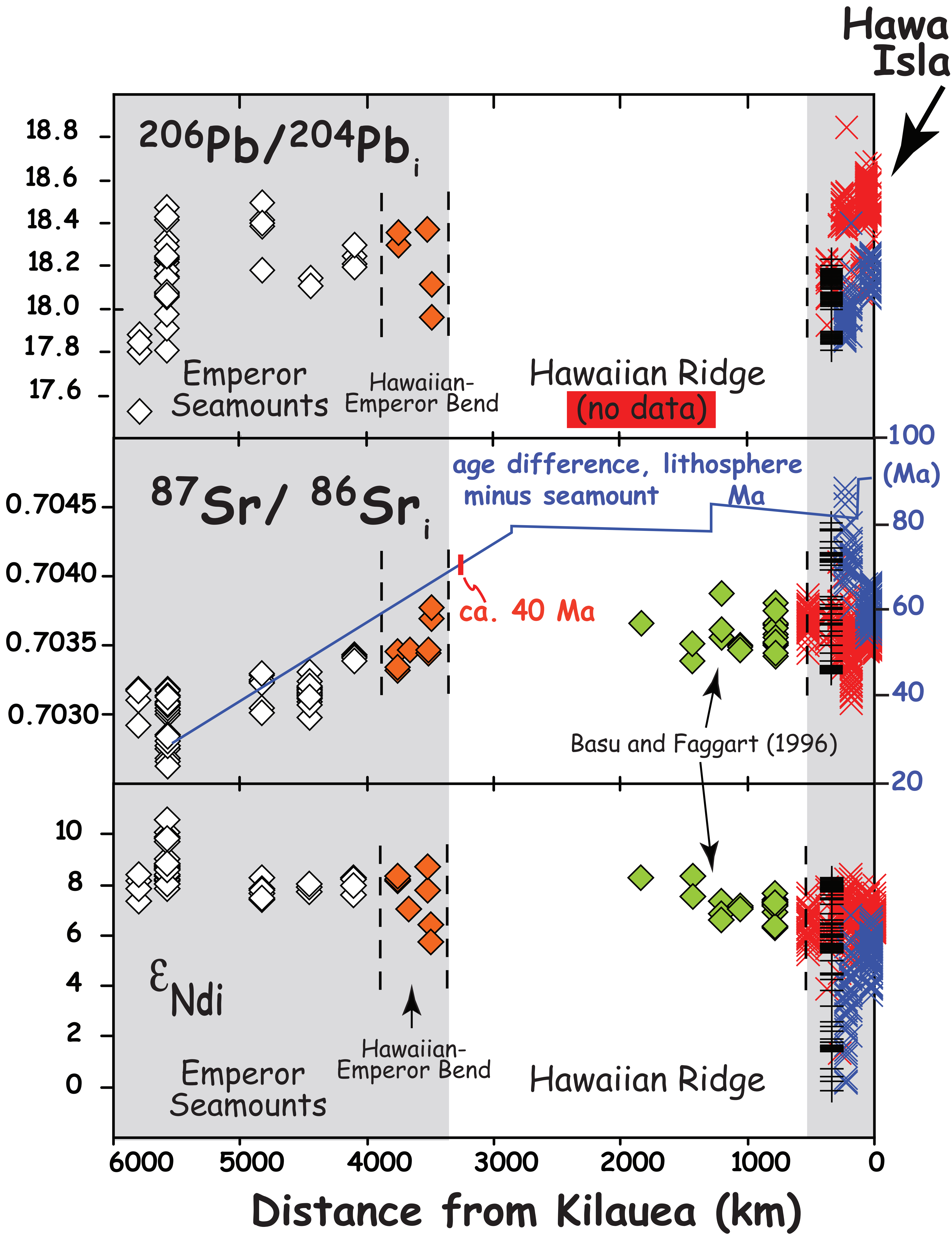


Figure from Tanaka et al. (2008) DSDP & ODP samples



Hawaiian Islands: Two Geochemical Signatures

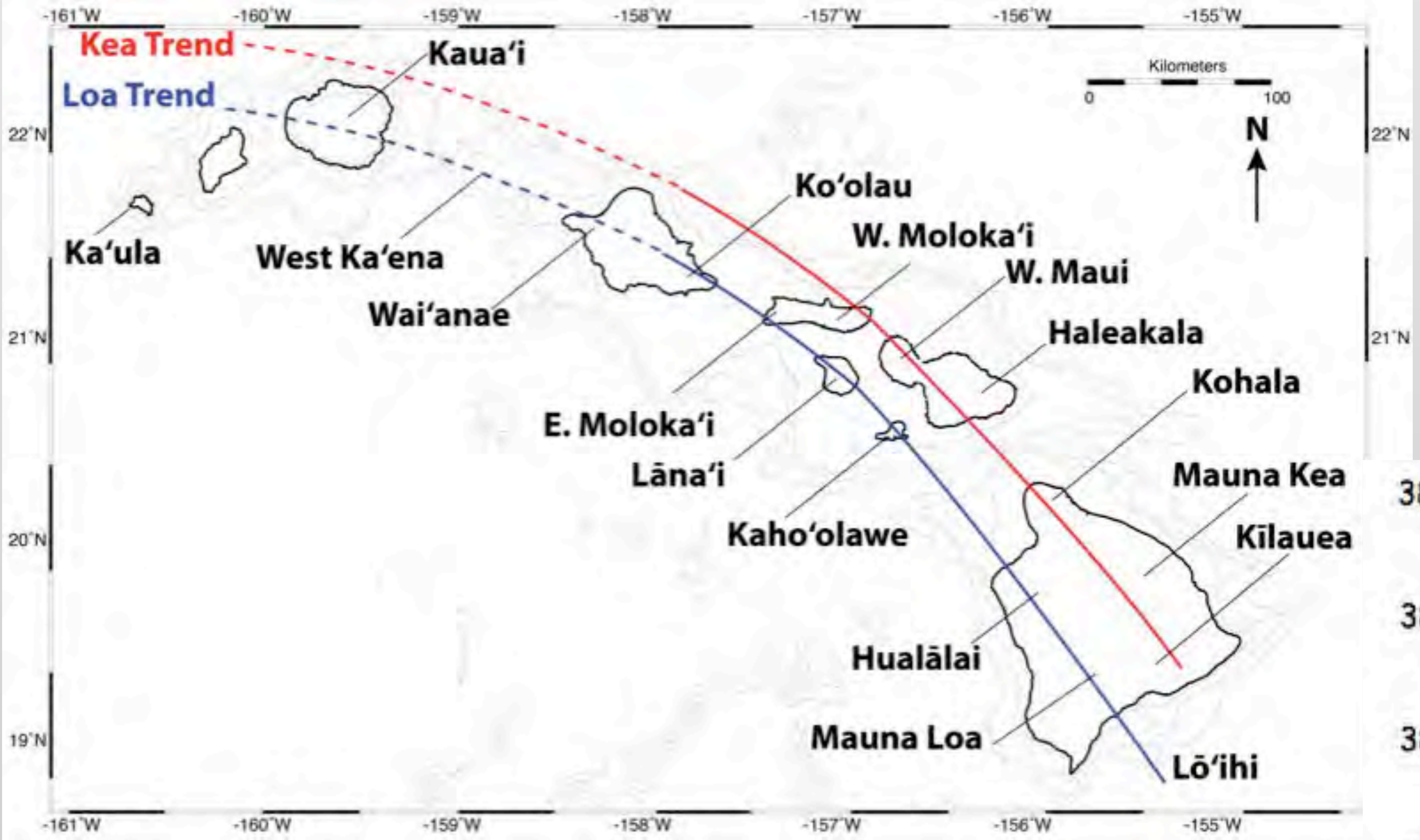


Figure modified from Harrison et al., 2015

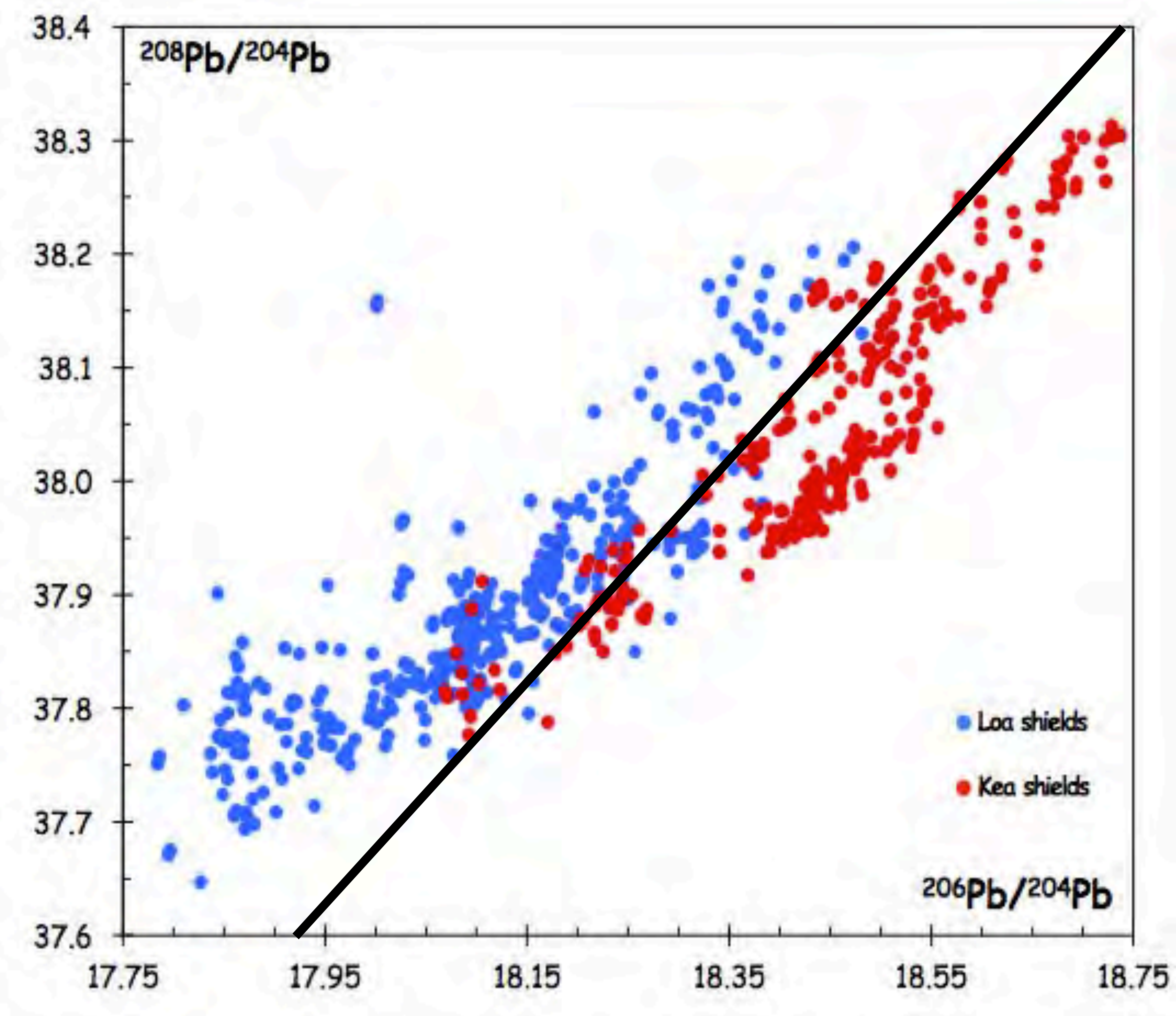


Figure modified and updated from Weis et al., 2011