A Finer Structure of the Hawaiian Mantle Plume: Relation to the Earth's deep mantle

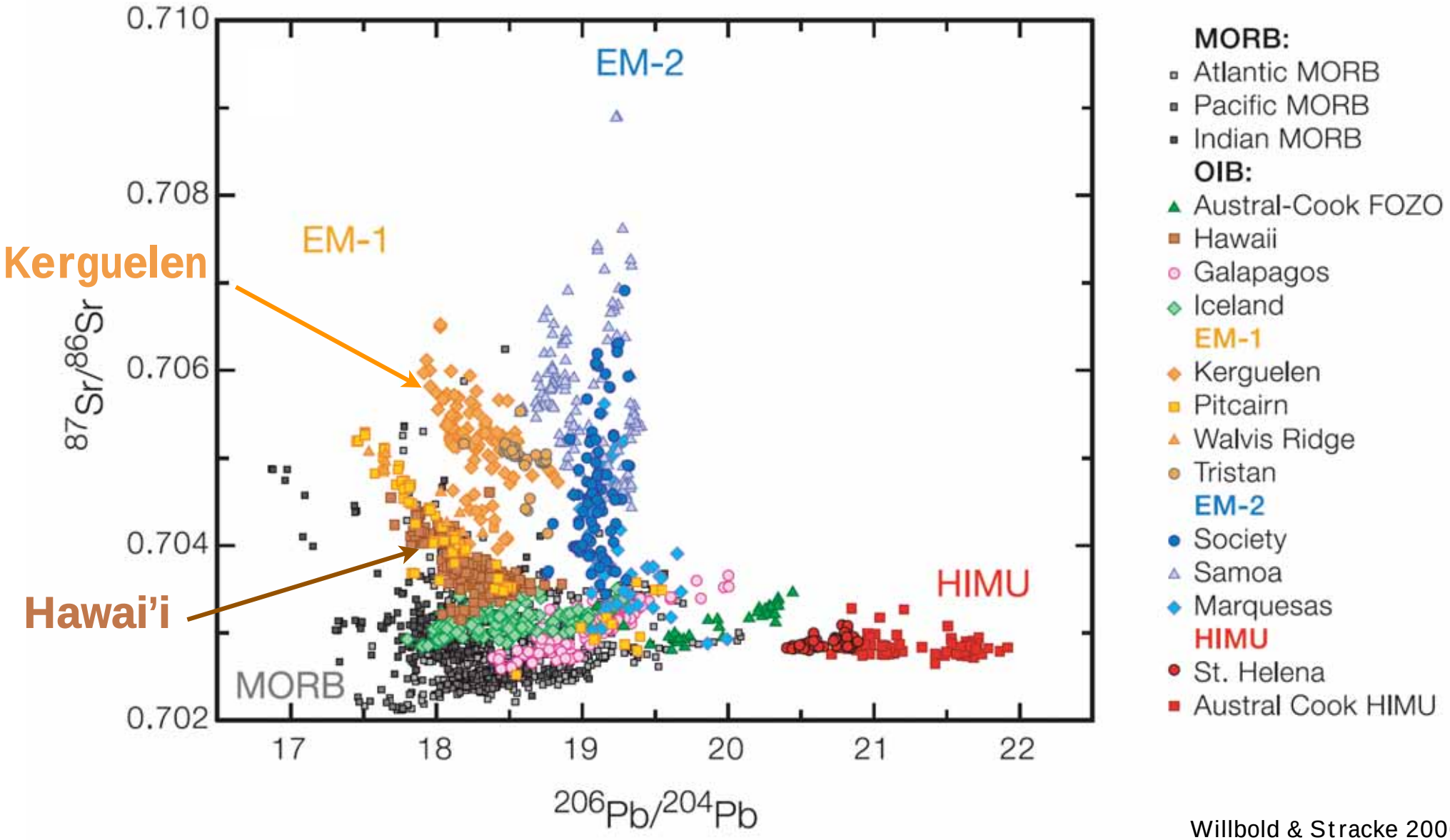
Dominique Weis

Collège de France - Dec 2016
Flow in the Deep Mantle

STANFORD UNIVERSITY

pcigr

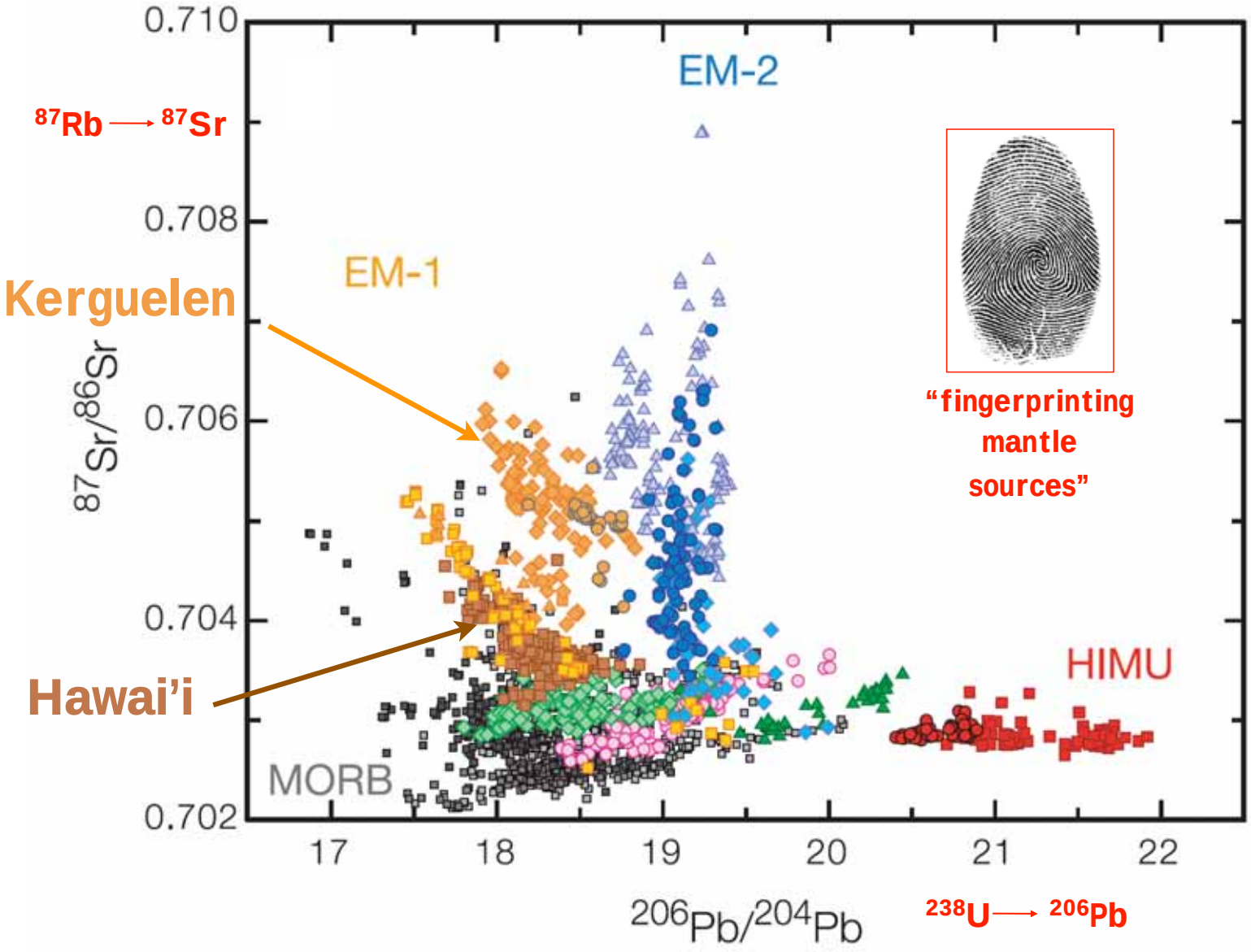
Oceanic Islands, Mantle Plumes and Mantle End-Members



Willbold & Stracke 2006

Oceanic Islands, Mantle Plumes and Mantle End-Members

Isotopic ratios are time-integrated signatures



"fingerprinting mantle sources"

MORB:
- Atlantic MORB
- Pacific MORB
- Indian MORB

OIB:

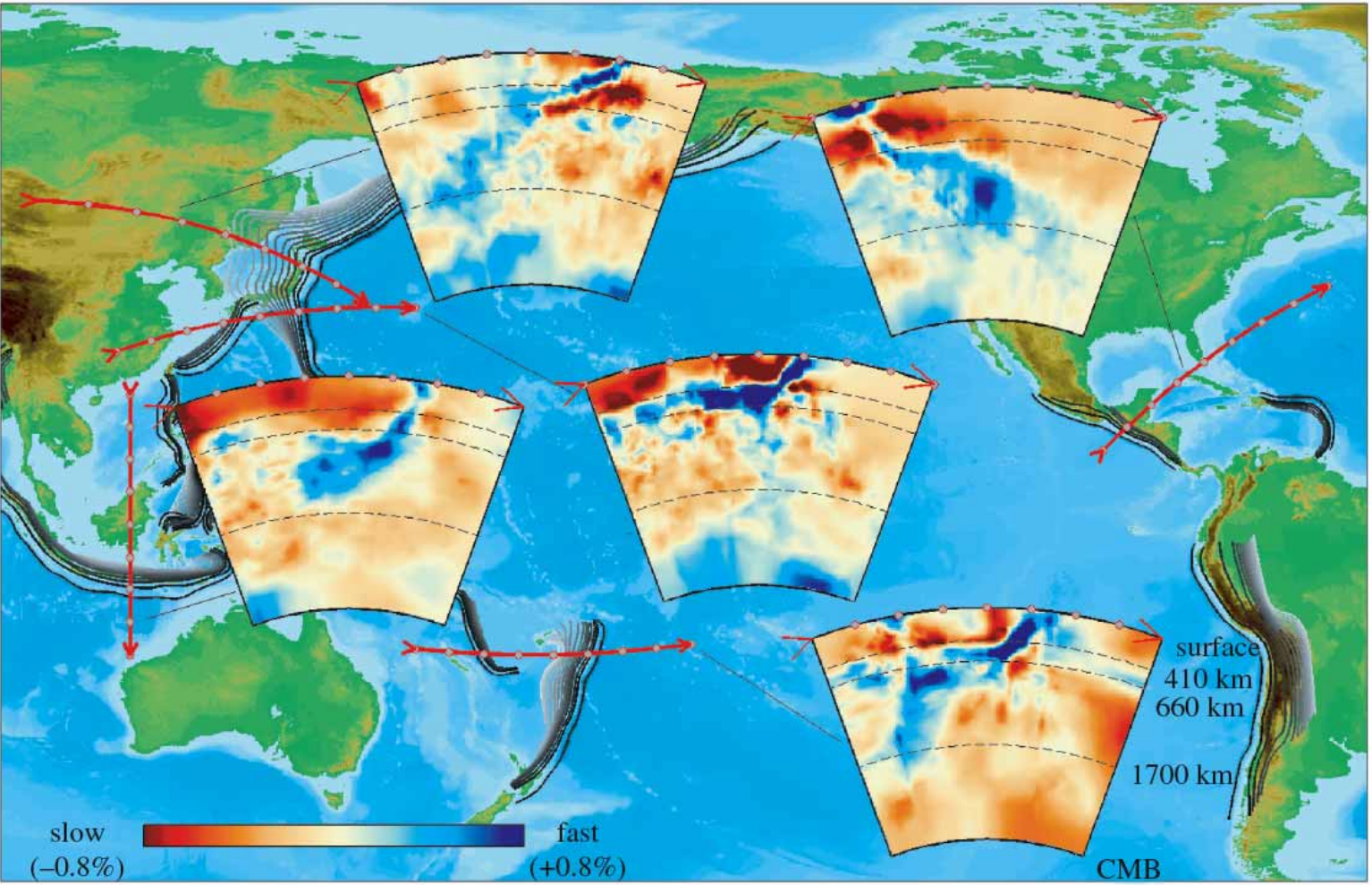
Austral-Cook FOZO
Hawaii
Galapagos
Iceland

EM-1
- Kerguelen
- Pitcairn
- Walvis Ridge
- Tristan

EM-2
- Society
- Samoa
- Marquesas

HIMU
- St. Helena
- Austral Cook HIMU

Willbold & Stracke 2006



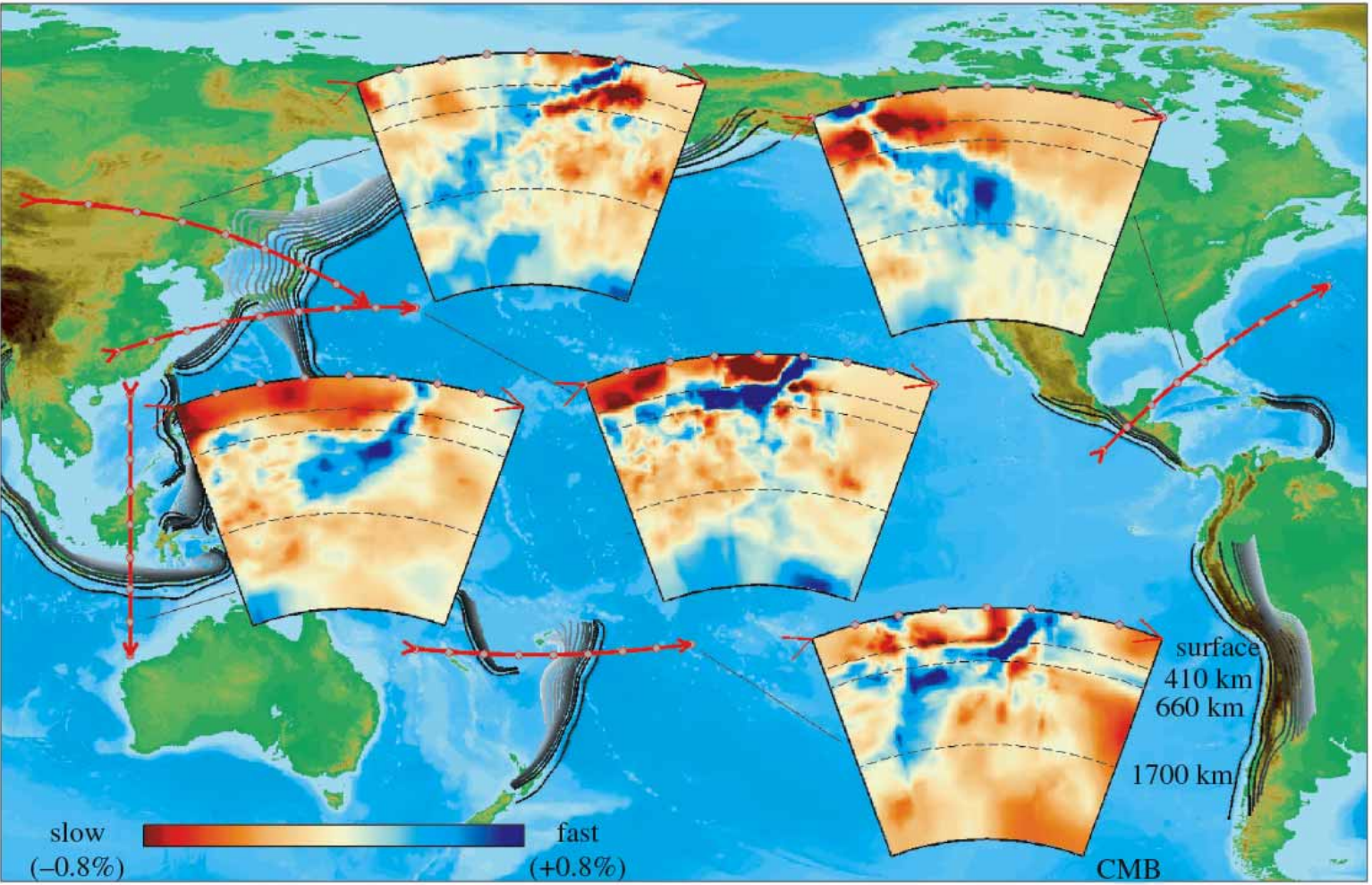
Albarède & Van der Hilst 2002

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.

Subducting Slabs & Recycling



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Recycled Material Mass Balance

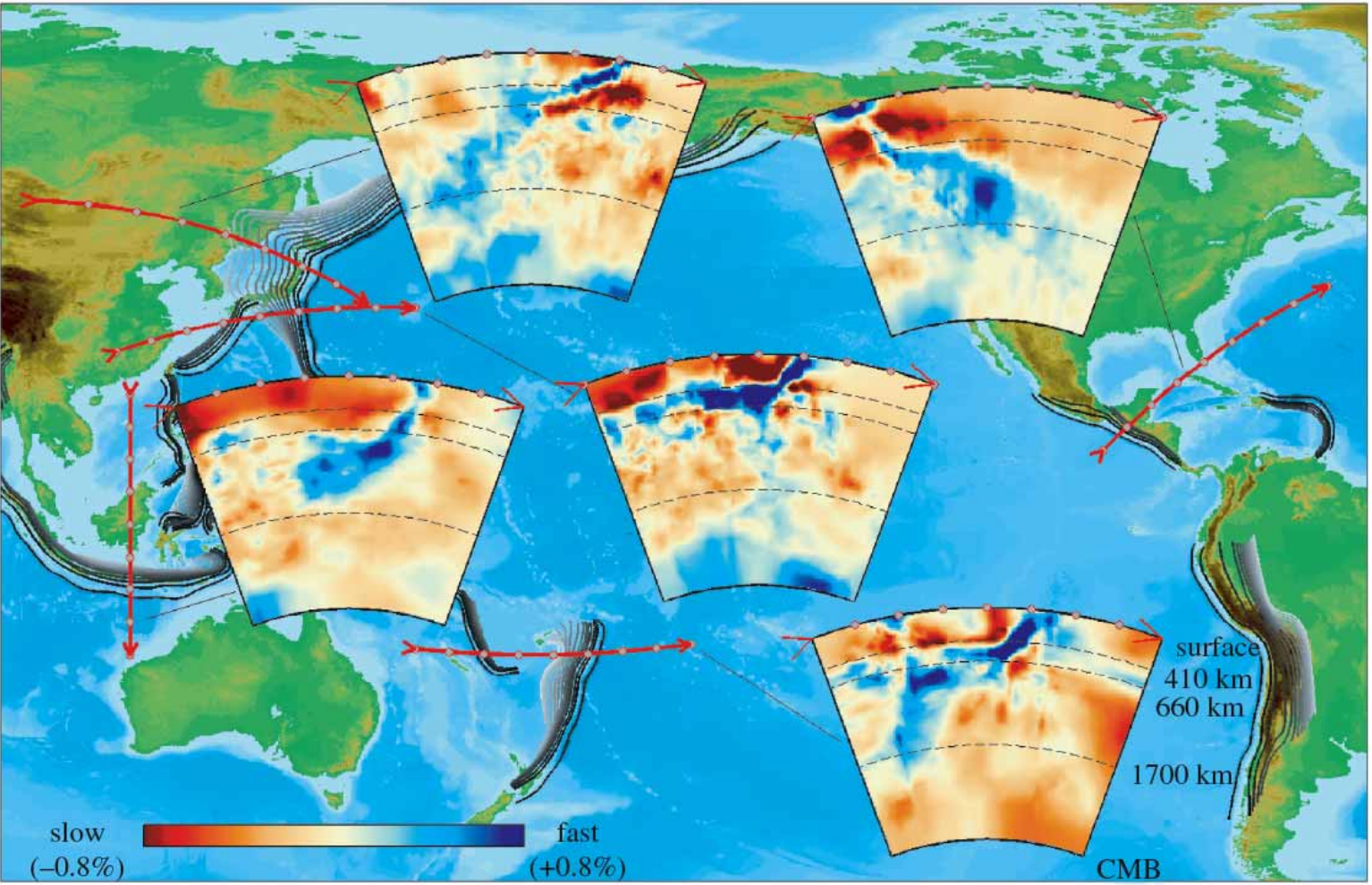
Sediment – 0.3-0.7 km^3/year subducts

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

Oceanic Crust – 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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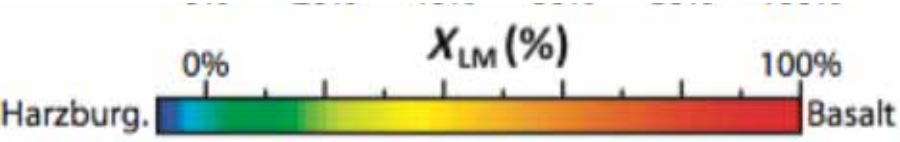
How could the mantle not be heterogeneous?

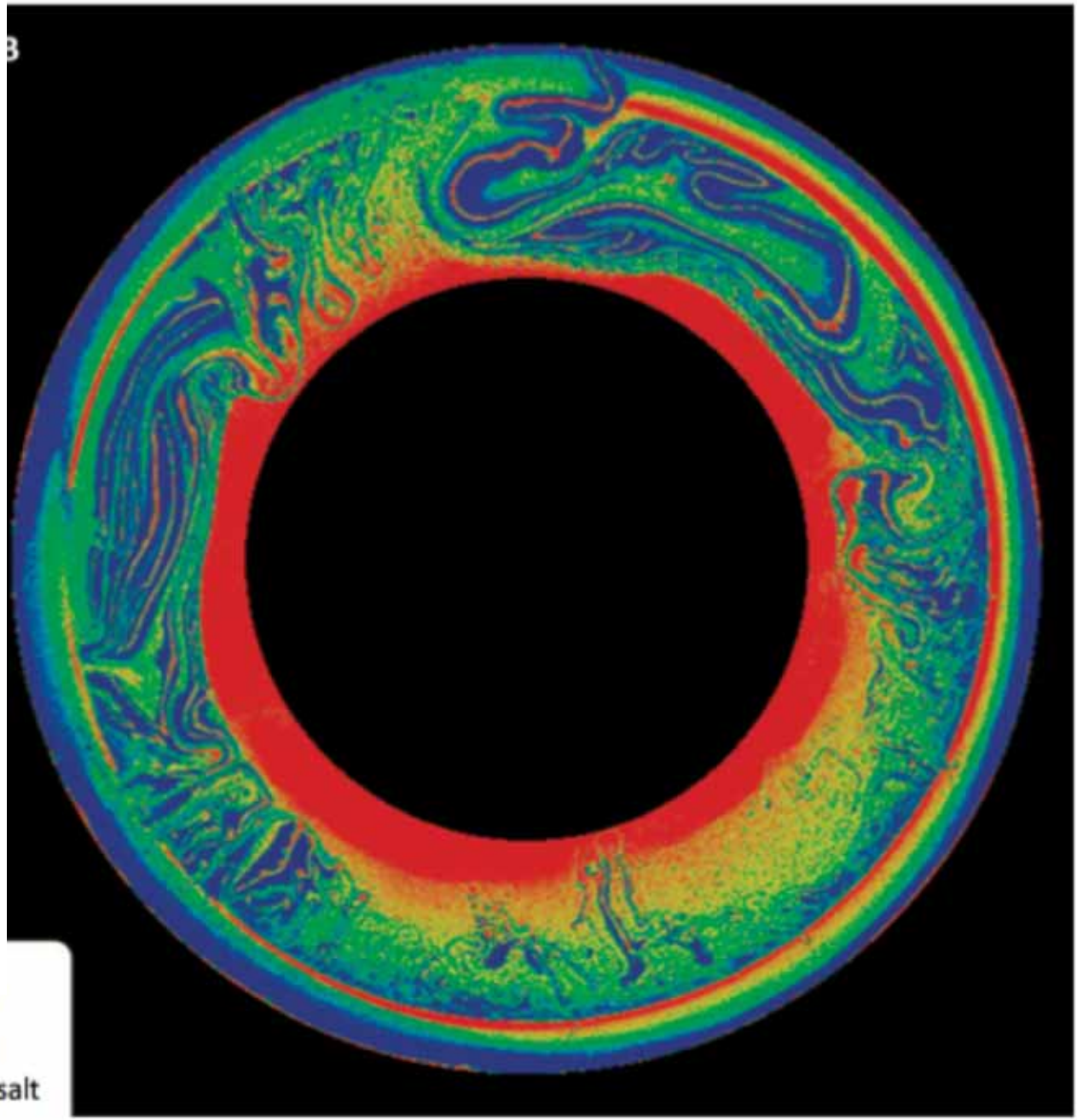
Dynamic Models and Mantle Heterogeneity

Dynamic model of the compositional heterogeneity of the mantle after 4.65 Ga of mixing

– Variable mixing of recycled and primordial materials

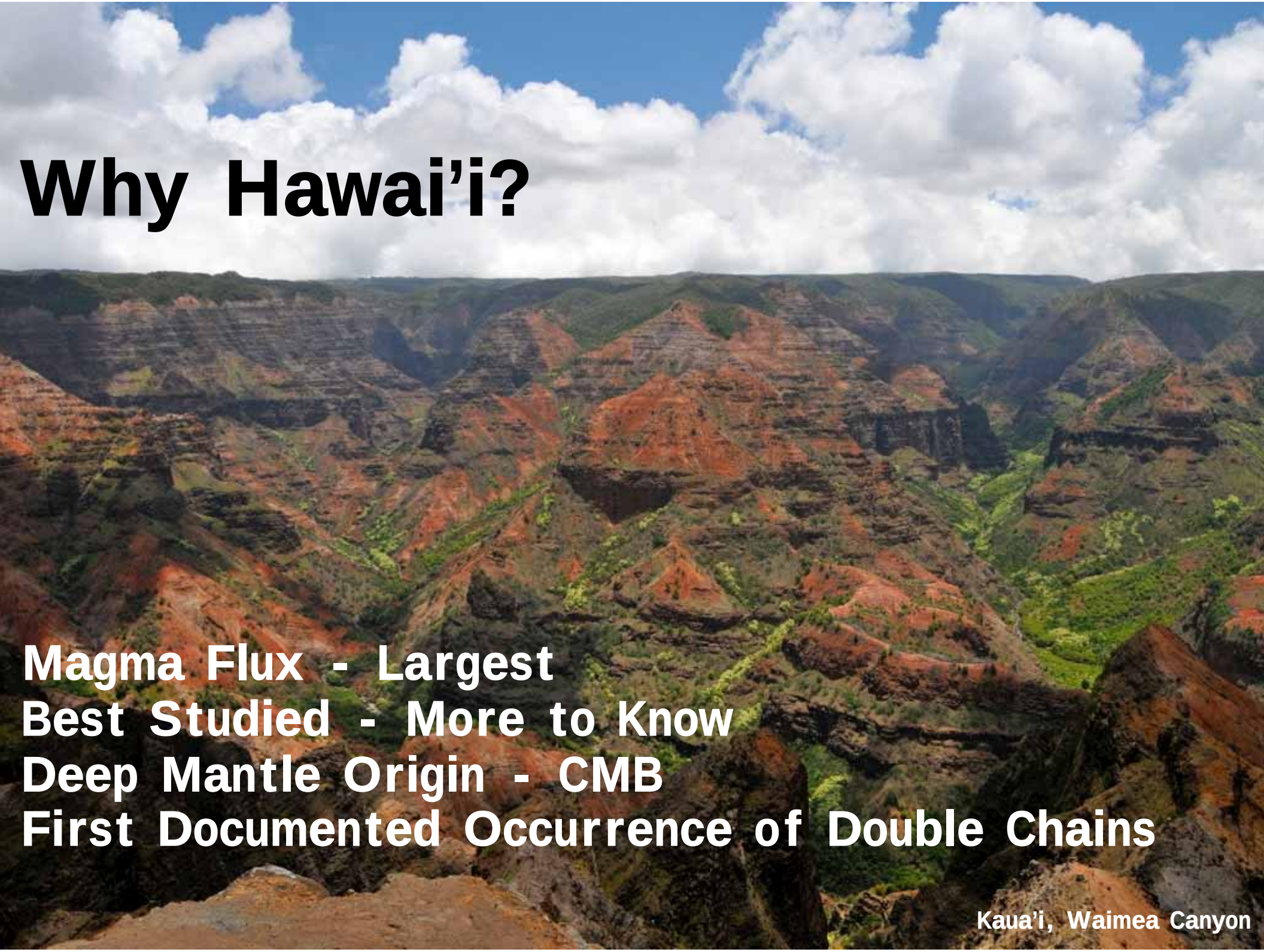
– Most of the mantle is depleted in composition, i.e. has been partially melted





Ballmer et al, 2015

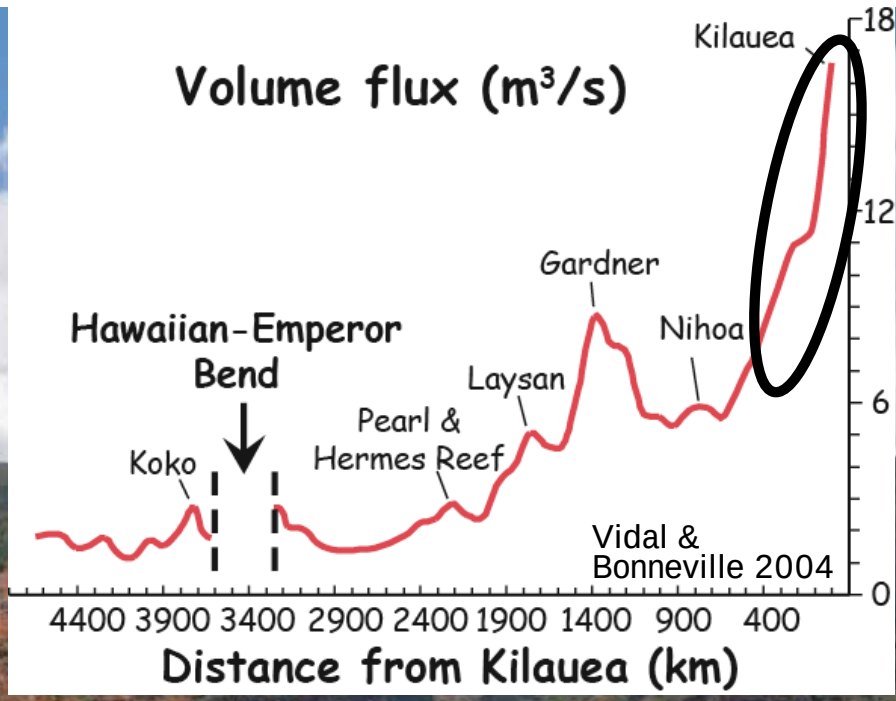
Why Hawai'i?



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

Kaua'i, Waimea Canyon

Why Hawai'i?



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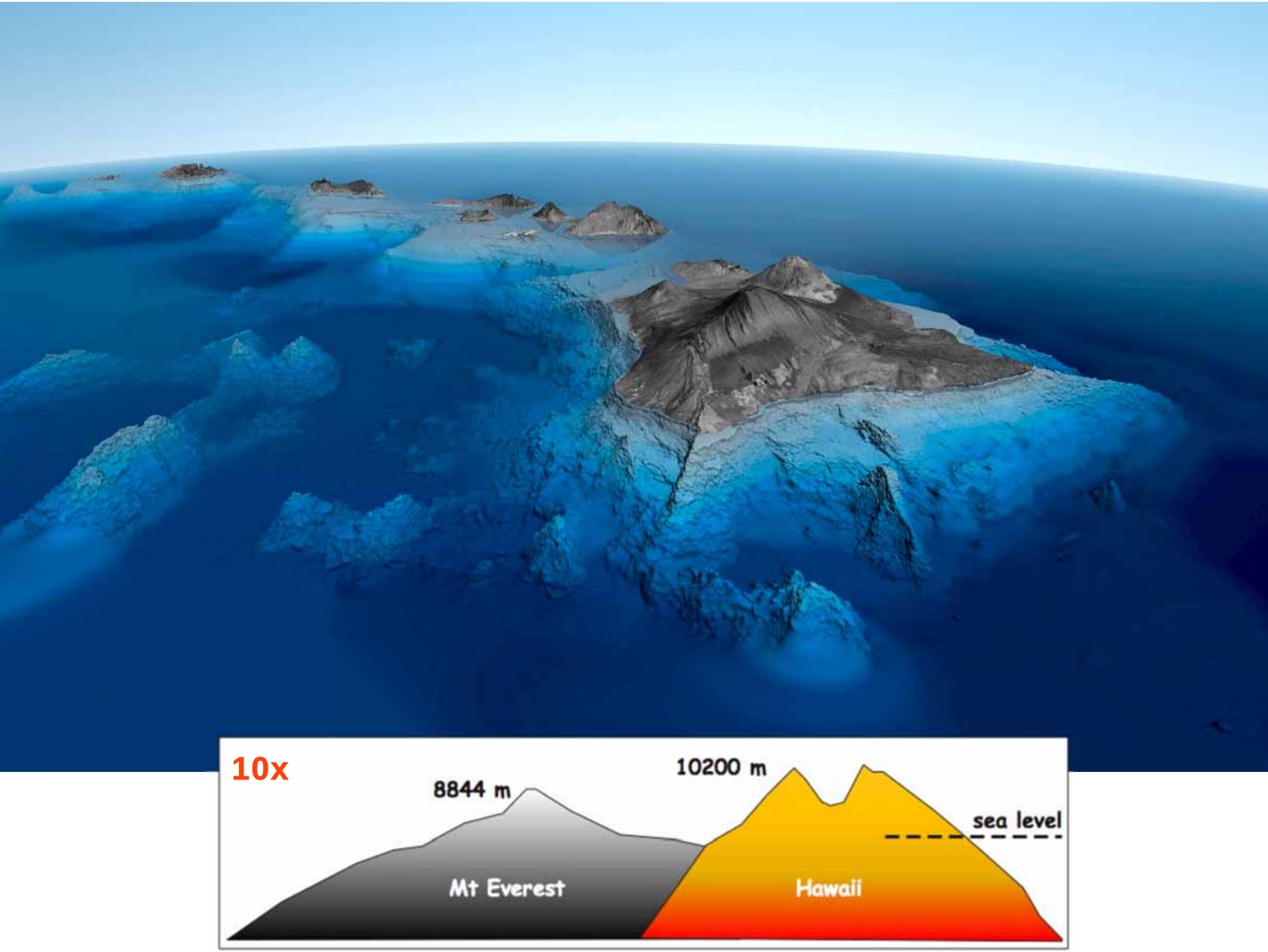
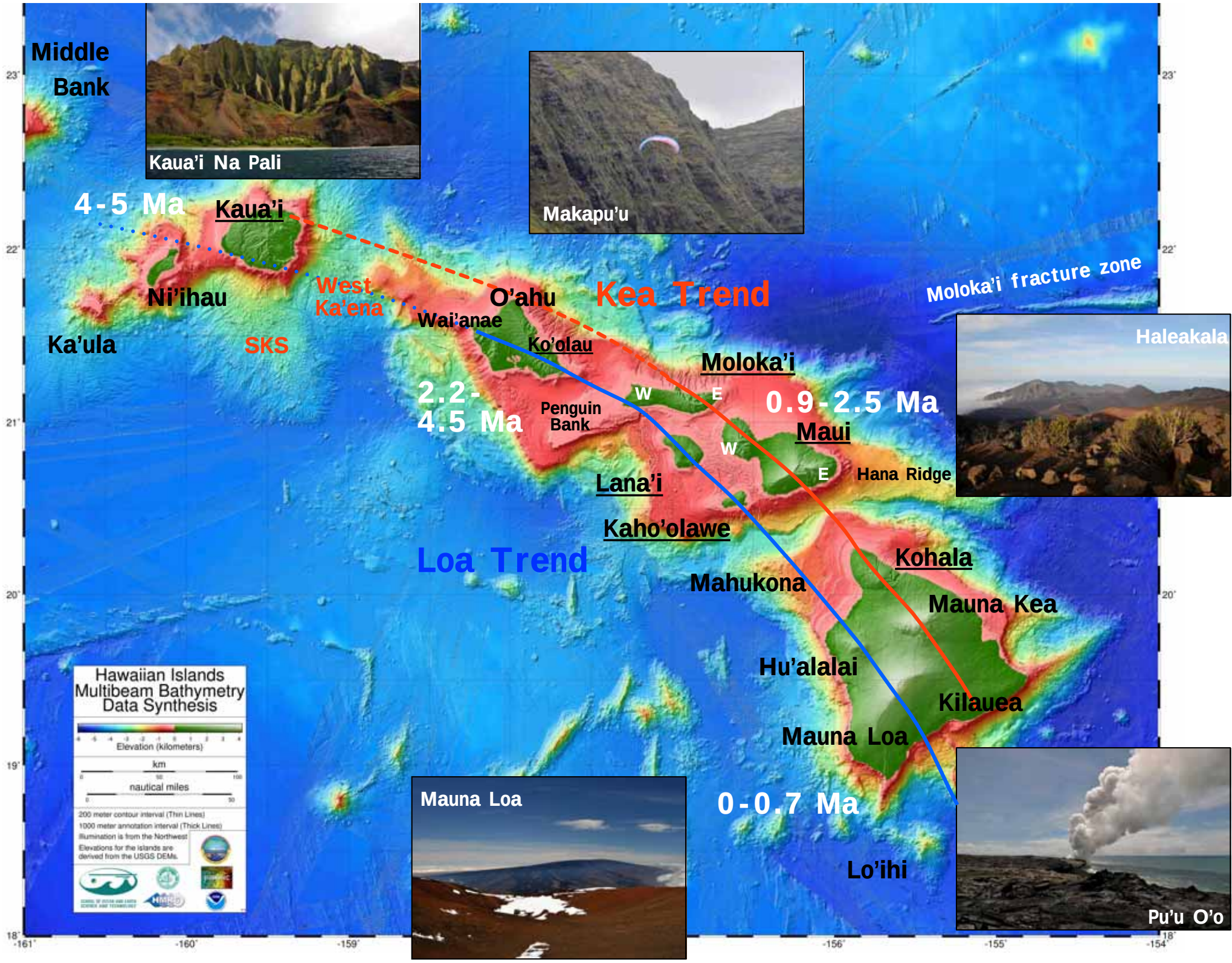
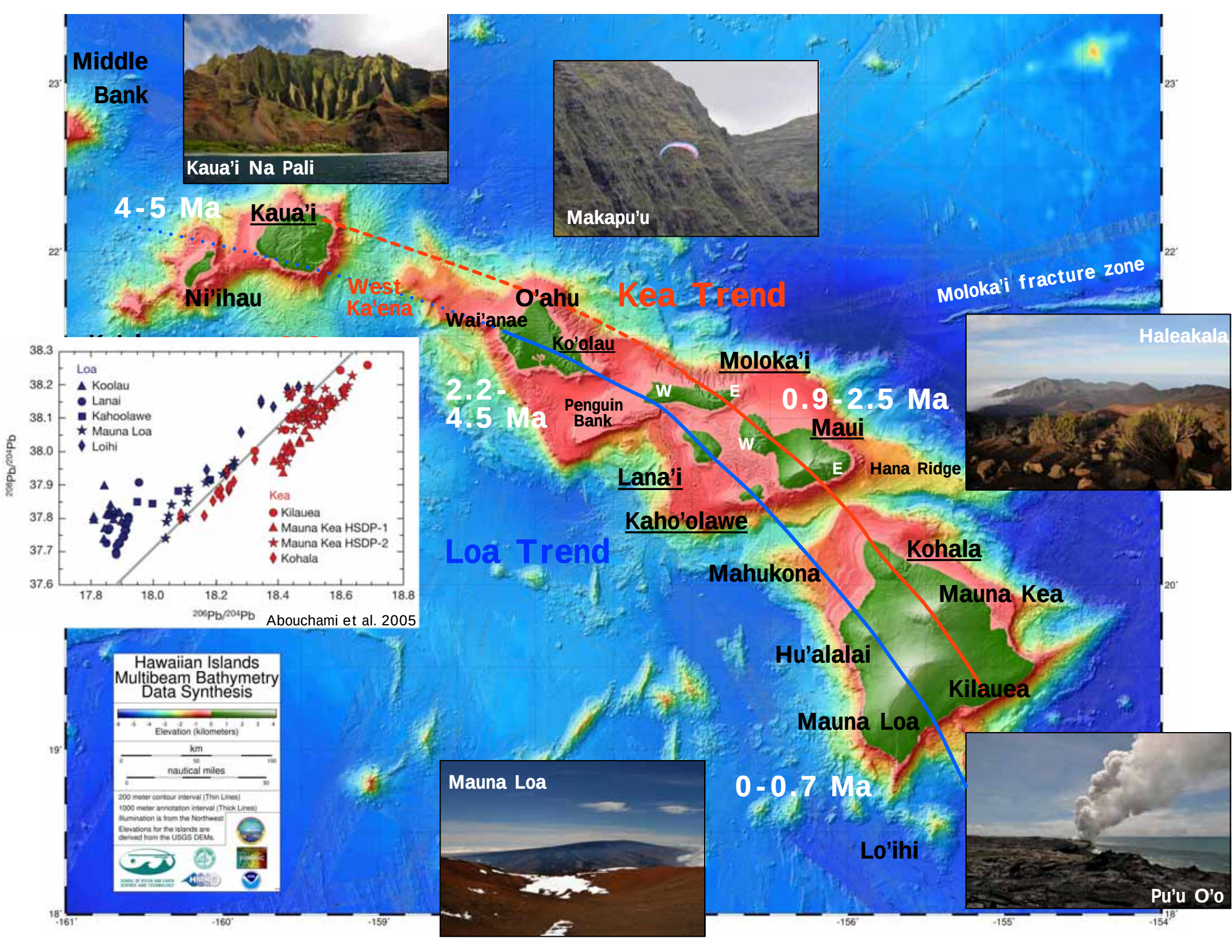

10x
8844 m
10200 m
sea level
Mt Everest
Hawaii


Middle Bank
Kaua'i Na Pali
Makapu'u
4-5 Ma
Kaua'i
West Ka'ena
Ni'ihau
O'ahu
Kea Trend
Moloka'i fracture zone
Ka'ula
SKS
Wai'anae
Ko'olau
Moloka'i
2.2-4.5 Ma
Penguin Bank
W
E
0.9-2.5 Ma
Haleakala
Maui
W
E
Hana Ridge
Lana'i
Kaho'olawe
Loa Trend
Kohala
Mahukona
Mauna Kea
Hu'alalai
Kilauea
Mauna Loa
0-0.7 Ma
Lo'ihi
Pu'u O'o
Mauna Loa
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°
21°
20°
19°
18°
-161°
-160°
-159°
-156°
-155°
-154°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206Pb/204Pb
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Abouchami et al. 2005
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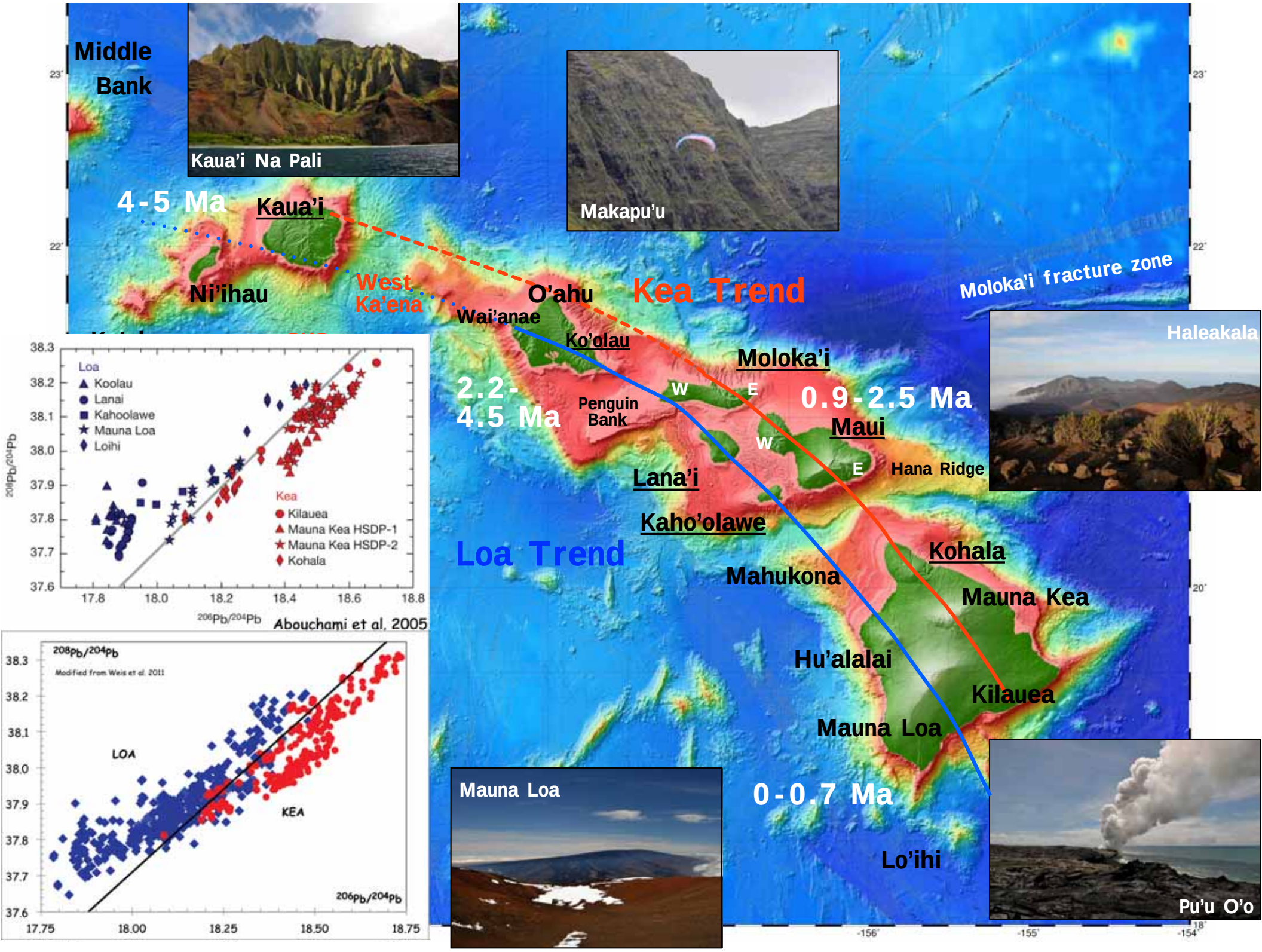
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208Pb/204Pb
Modified from Weis et al. 2011
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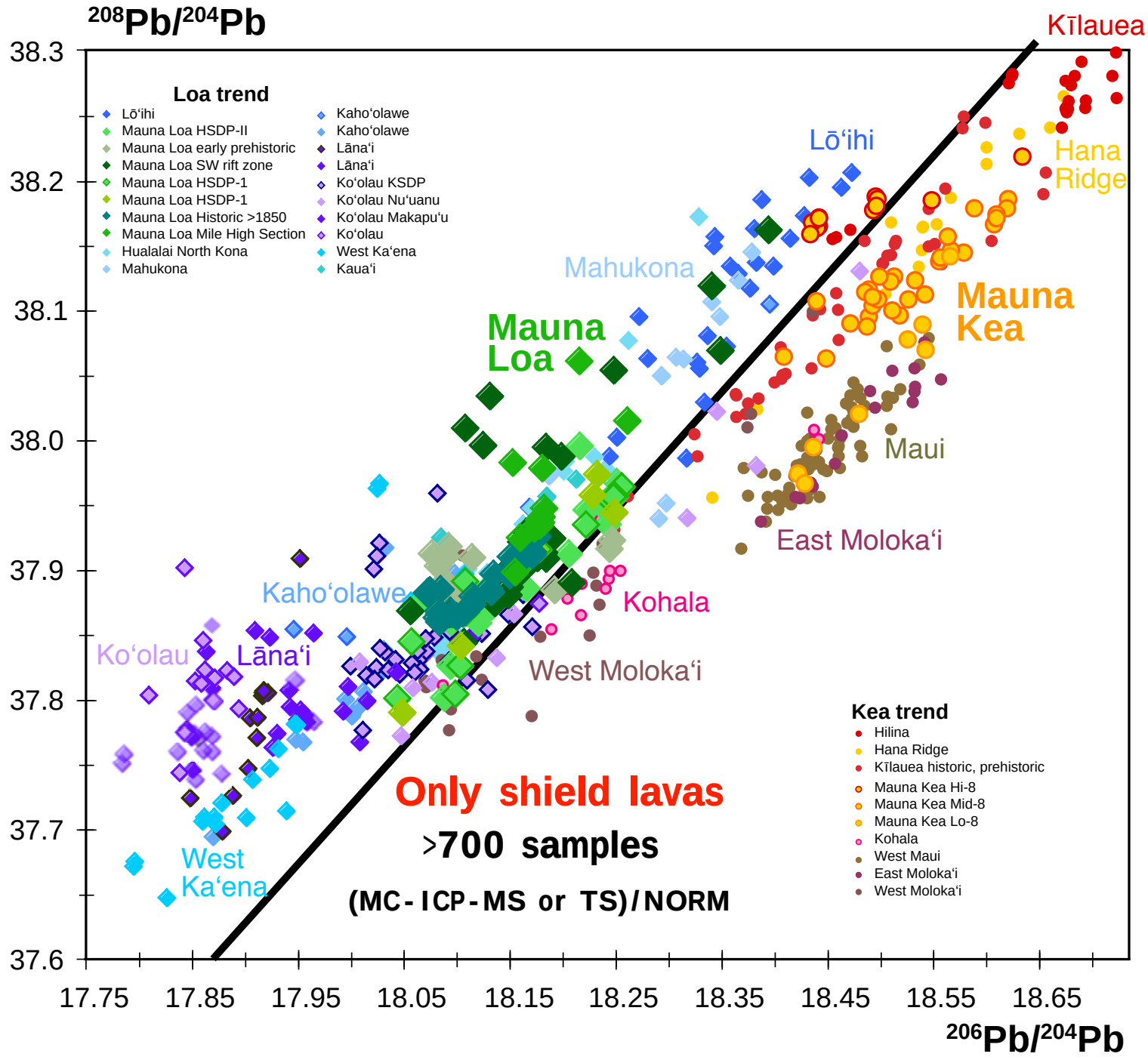
High-Precision Pb Data: Hawai'i



Weis et al. 2011

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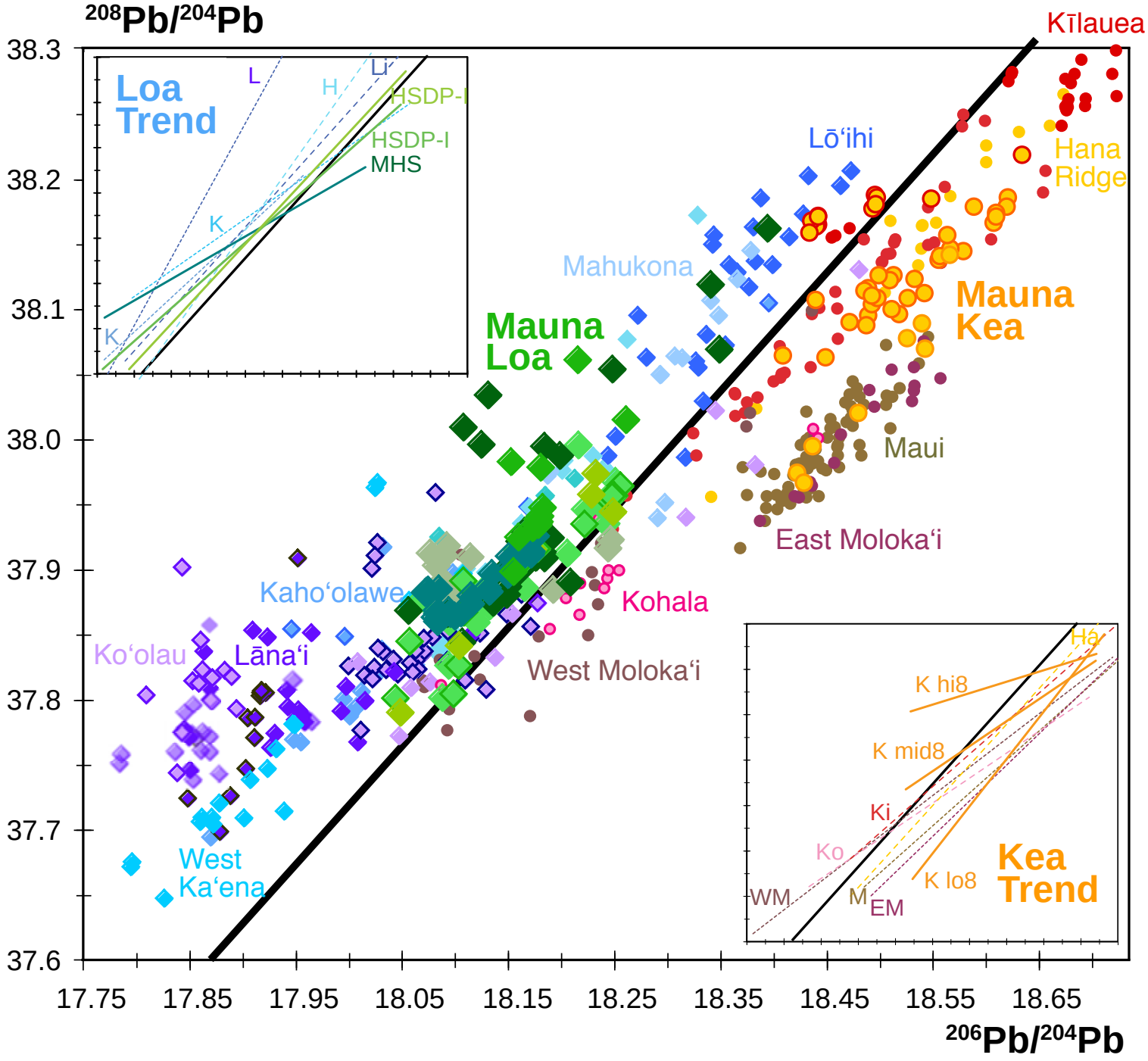

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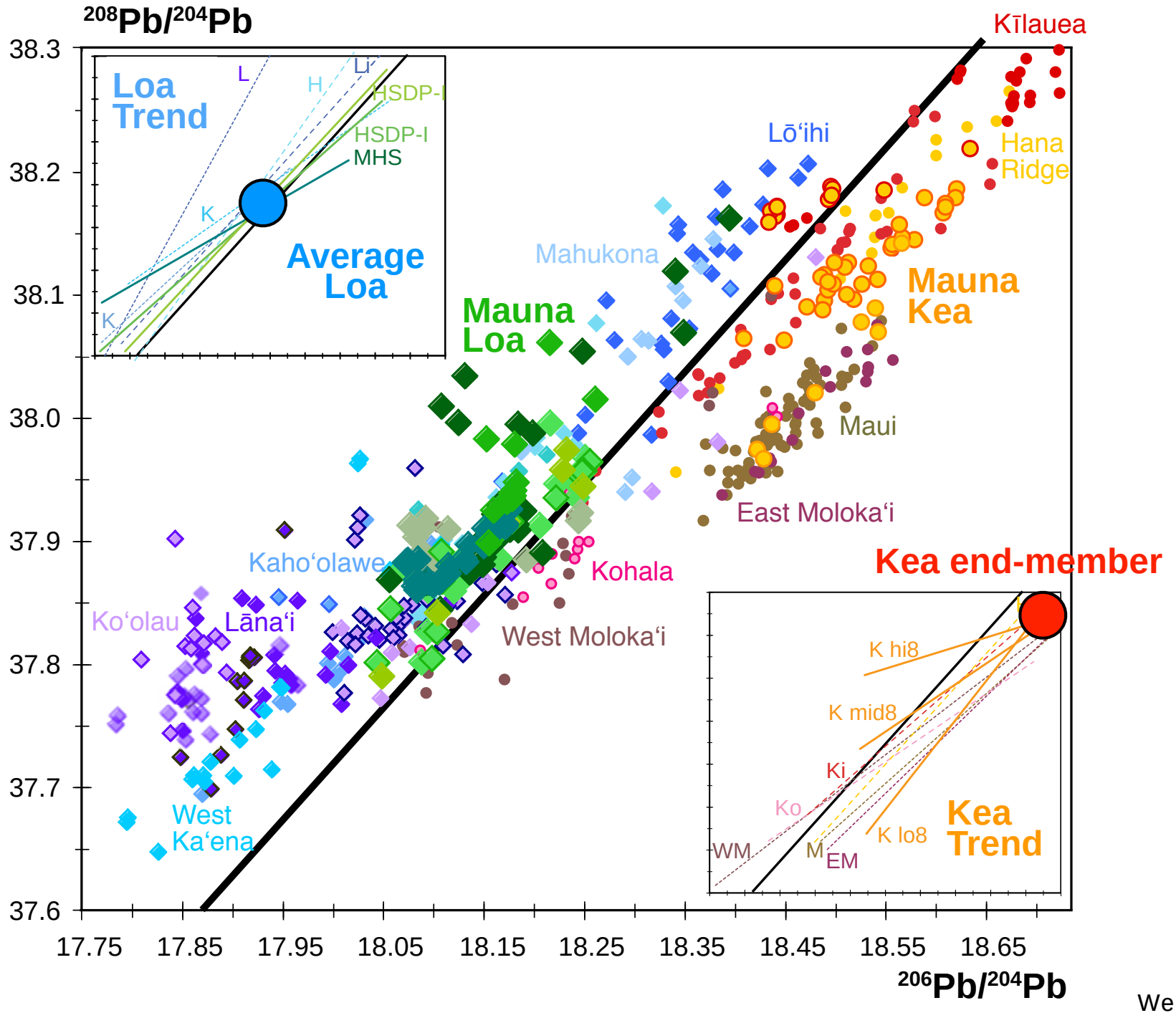
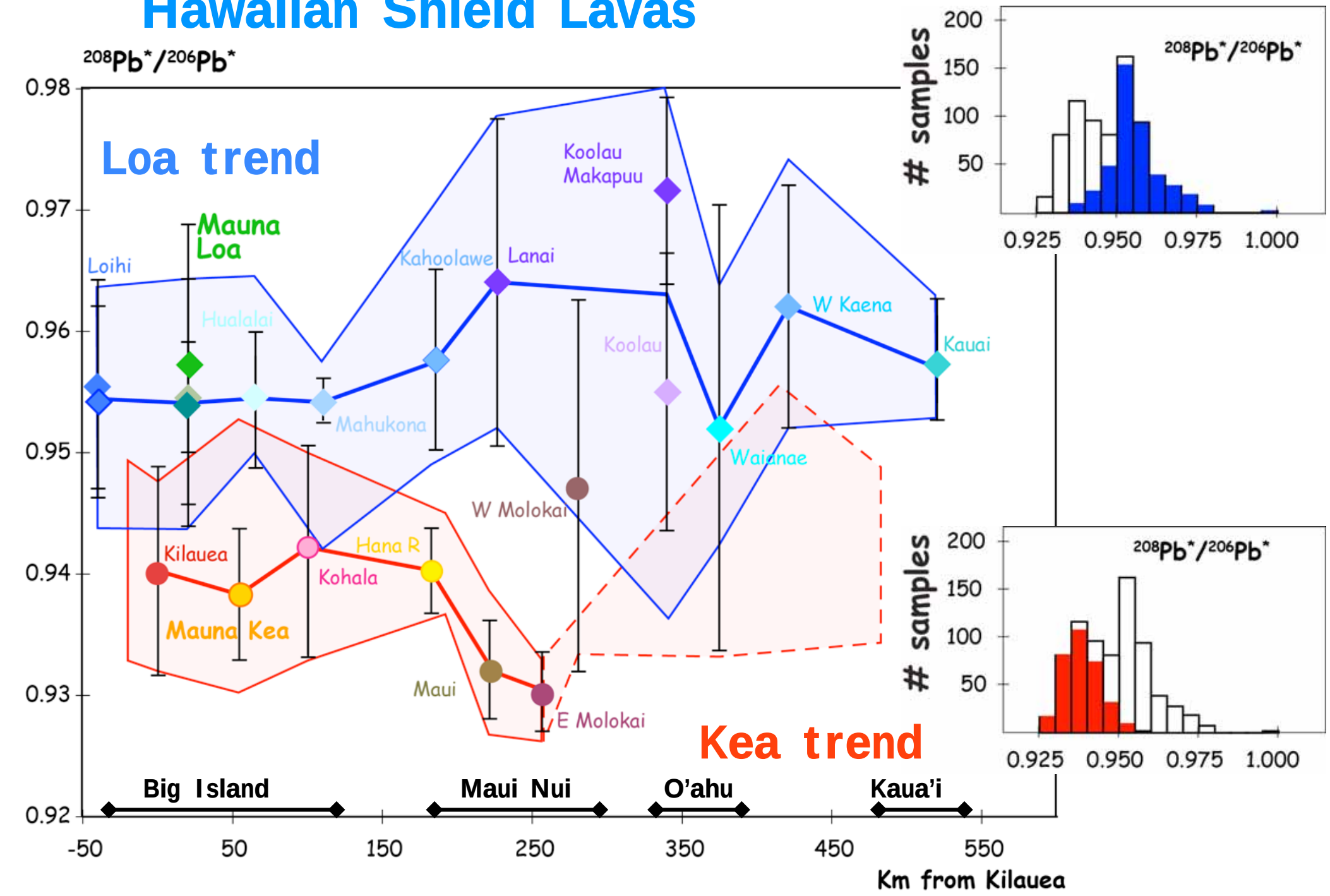


Weis et al. 2011

Hawaiian Shield Lavas



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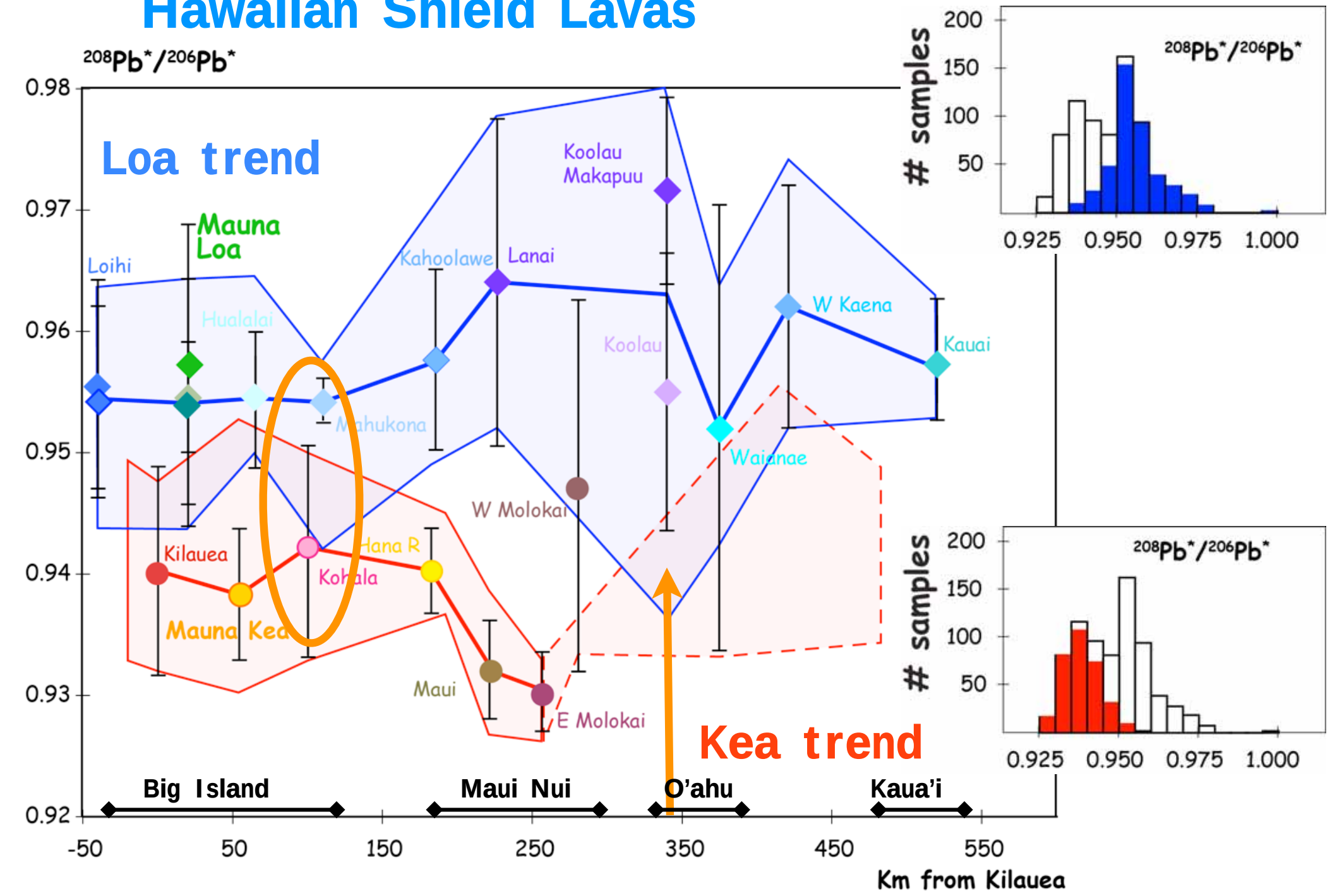
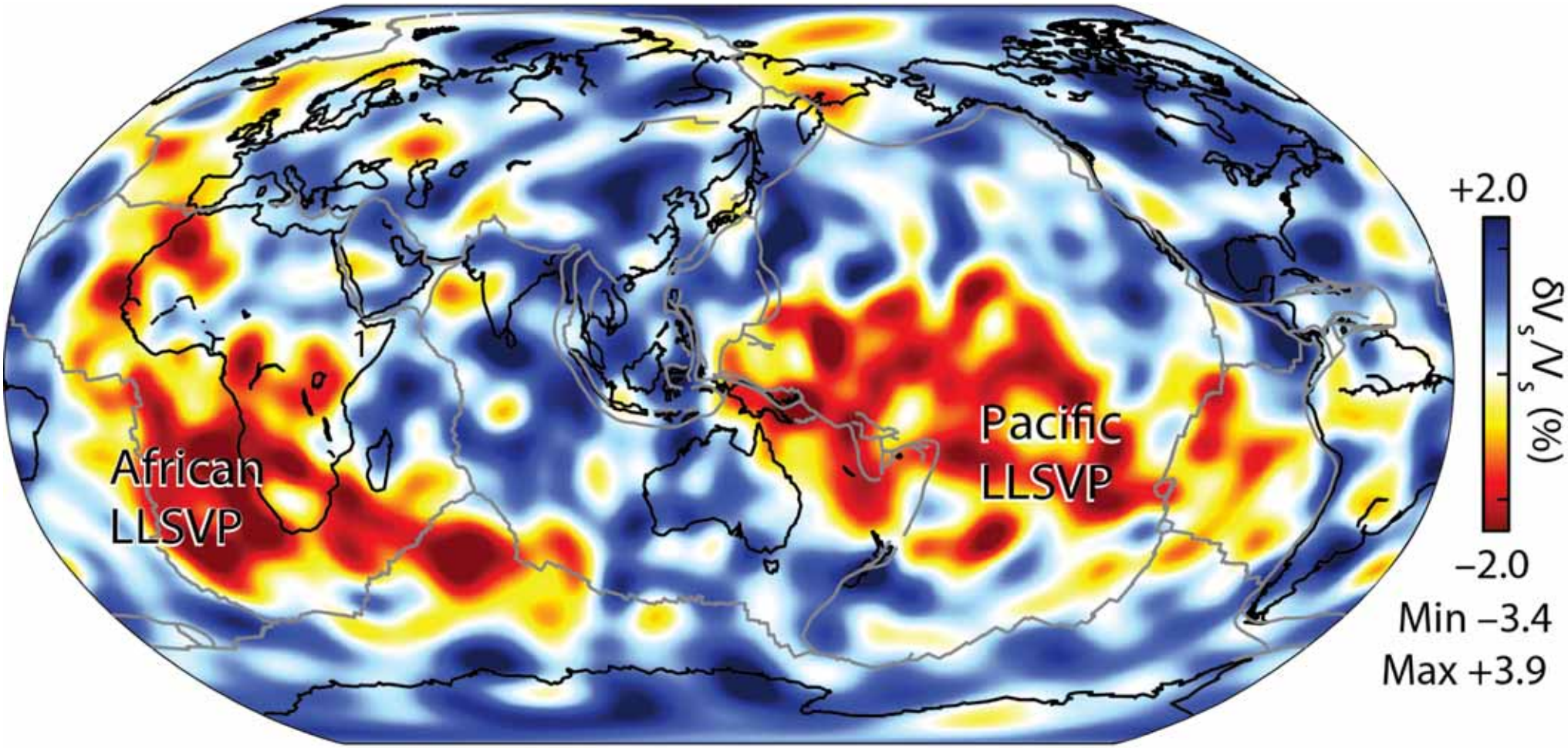


Significant cross-over at Kohala-Mahukona & Ko'olau

Weis et al. 2011

Seismic tomography shows deep mantle heterogeneity



- Shear wave seismic tomographic model of the mantle at 2800 km depth
- 2 large, low shear wave velocity provinces (named the LLSVPs), underneath the Pacific Ocean and the African plate
- Anomalies caused by elevated density, i.e. compositional changes

French & Romanowicz 2015

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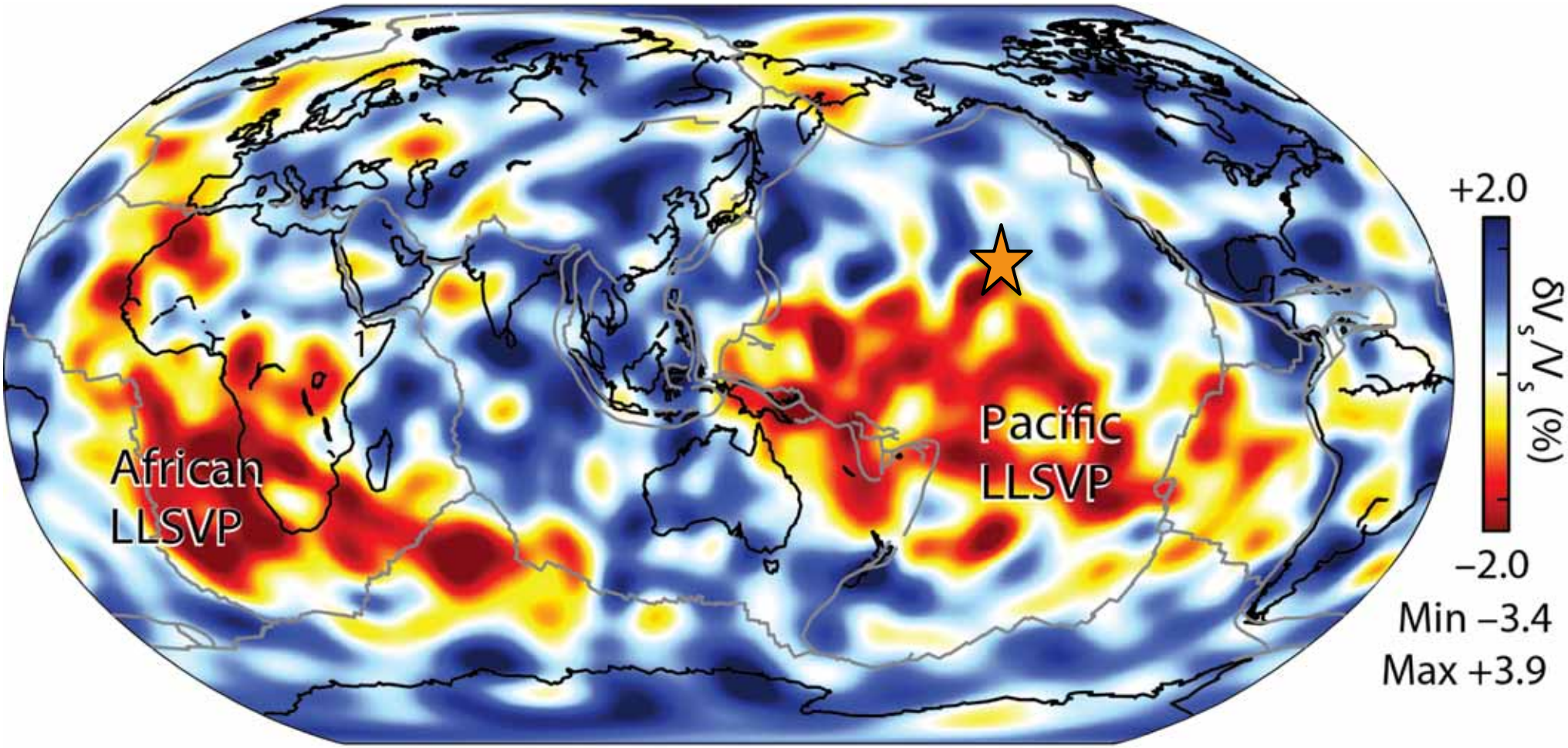

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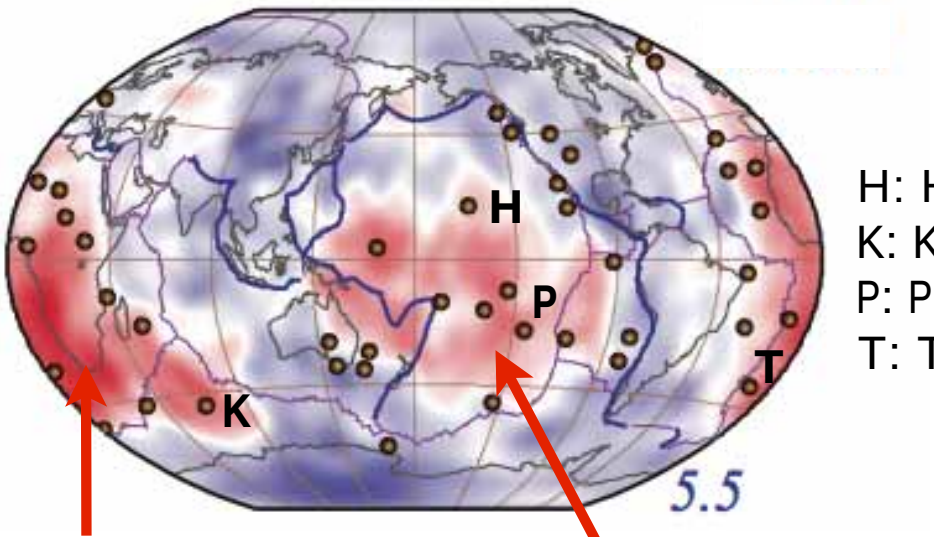
Lowermost-mantle V_s perturbations

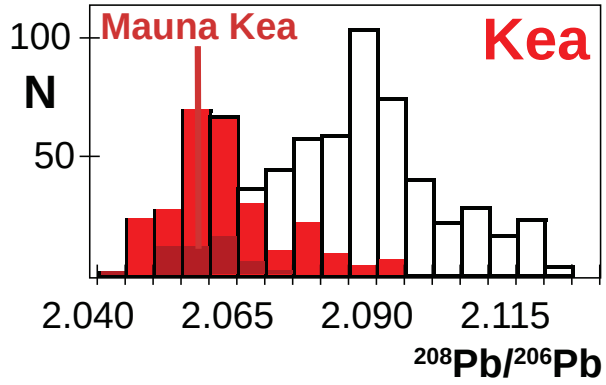


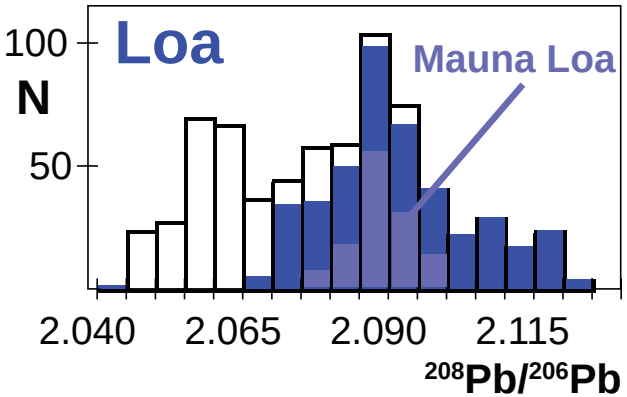
African LLSVP

Pacific LLSVP

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

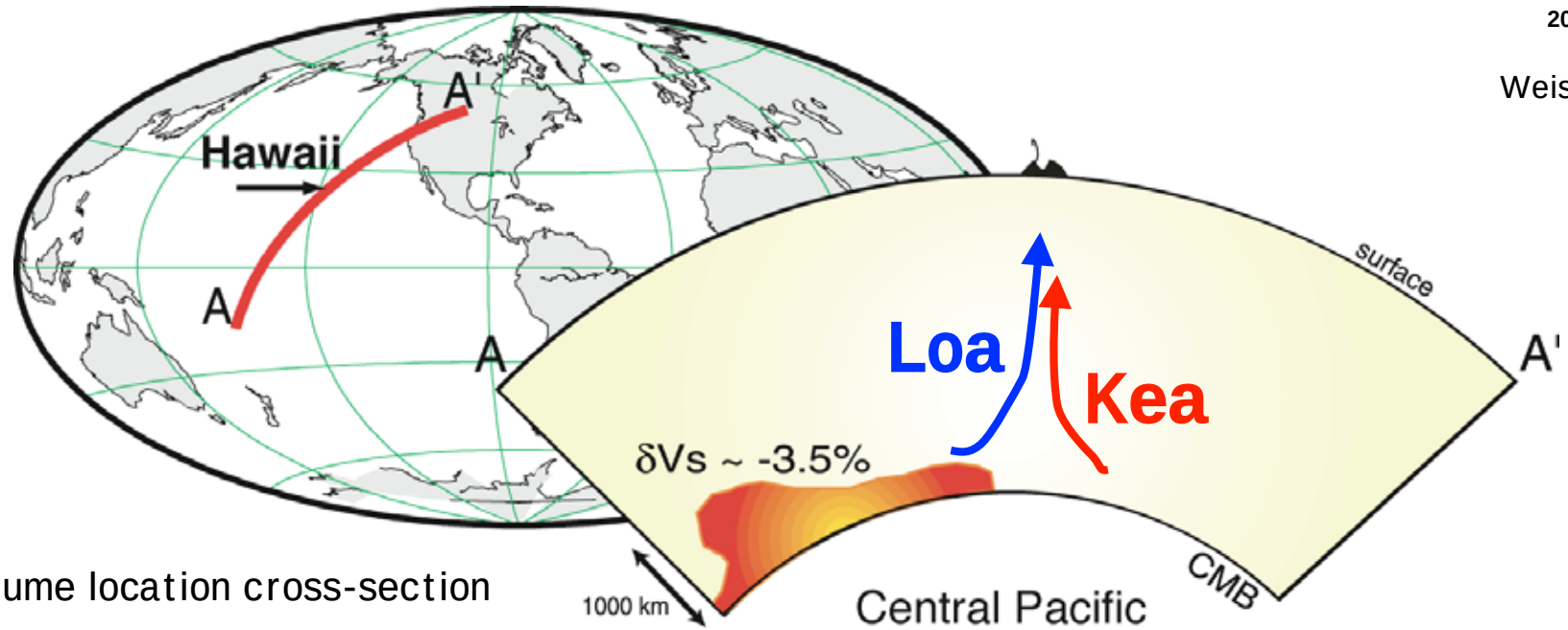
Modified from Thorne et al. 2004





Weis et al. 2011

LLSVP: Large Low Shear Velocity Province



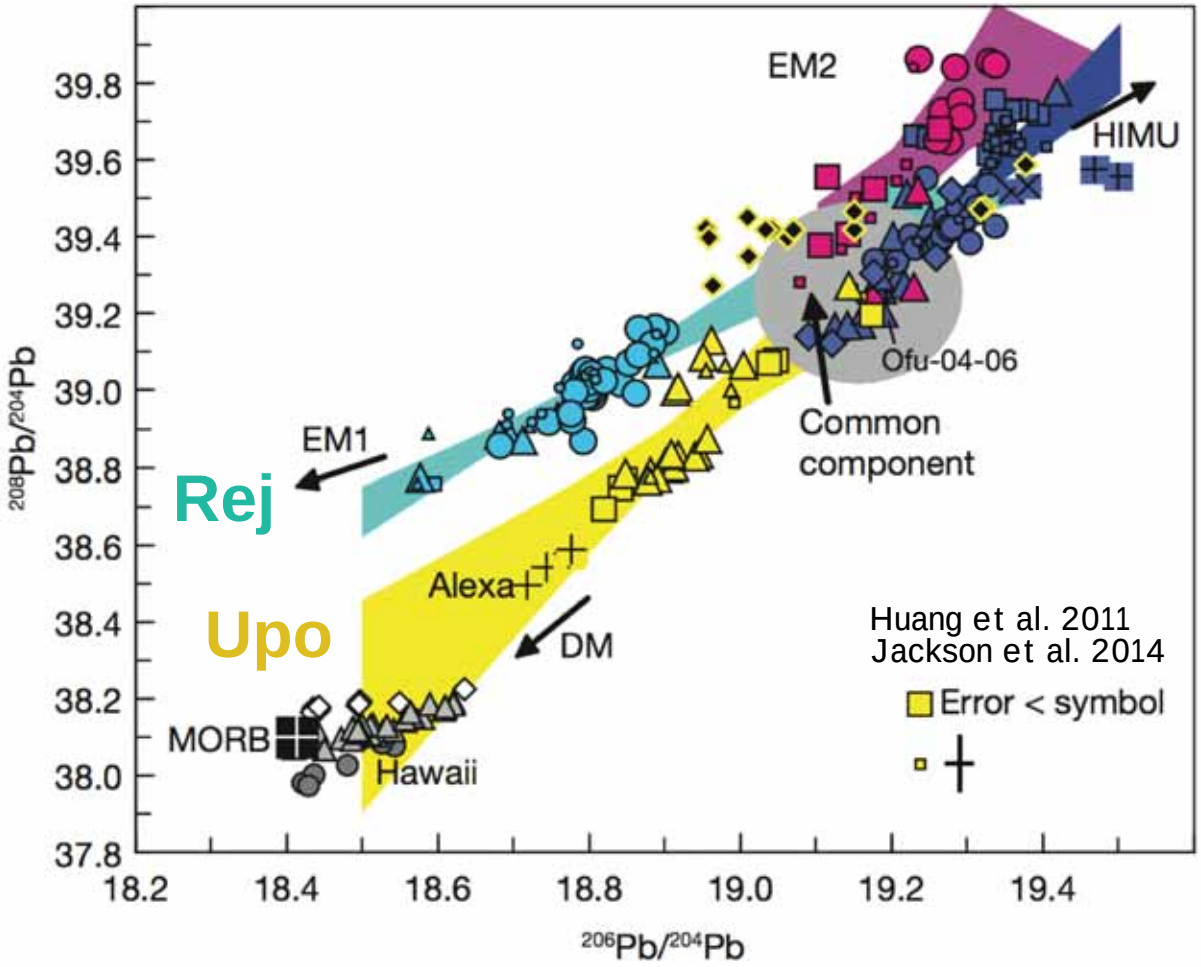
Possible plume location cross-section

after Breger & Romanowicz 1998

Evidence in Other Mantle Plumes in the Pacific

Samoa

Malu Vai



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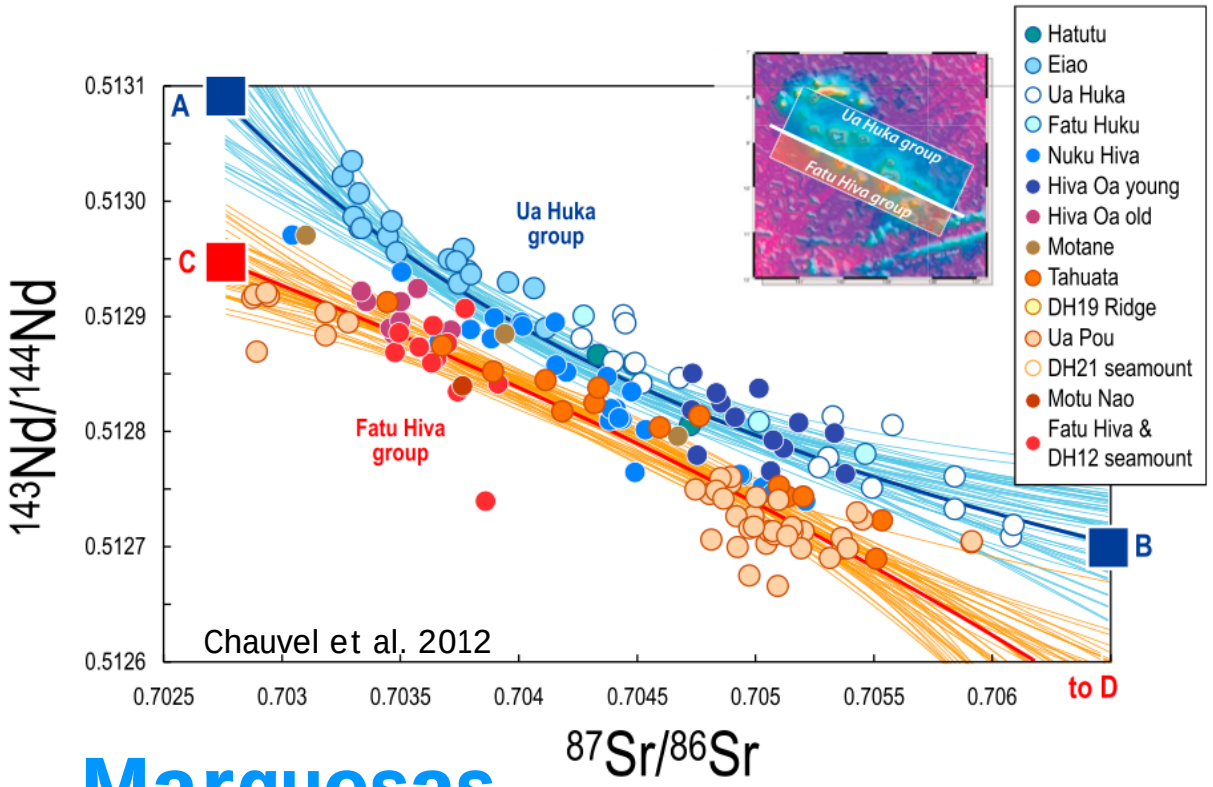


Marquesas
Polynesia

Society Islands

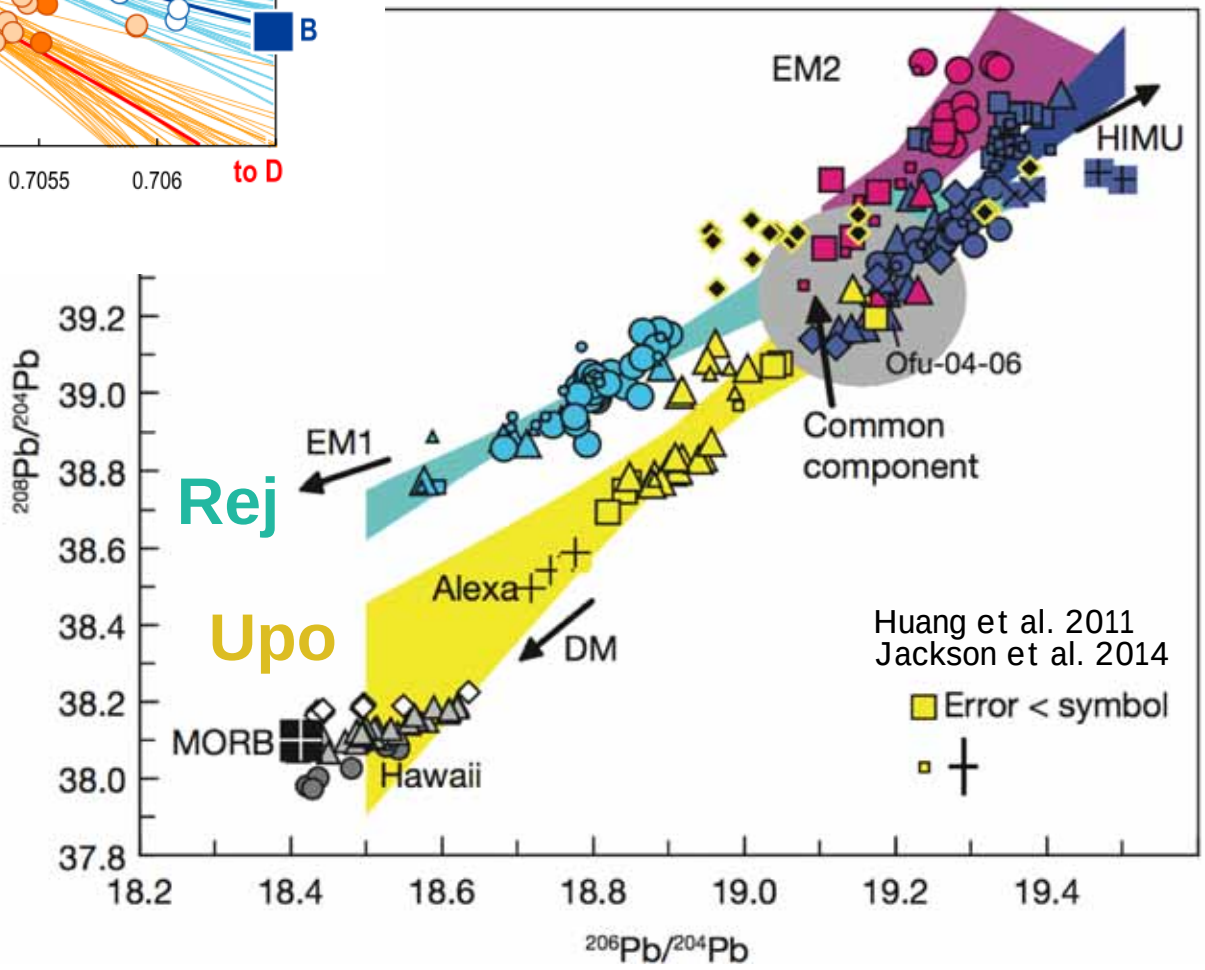
Payne et al. 2013

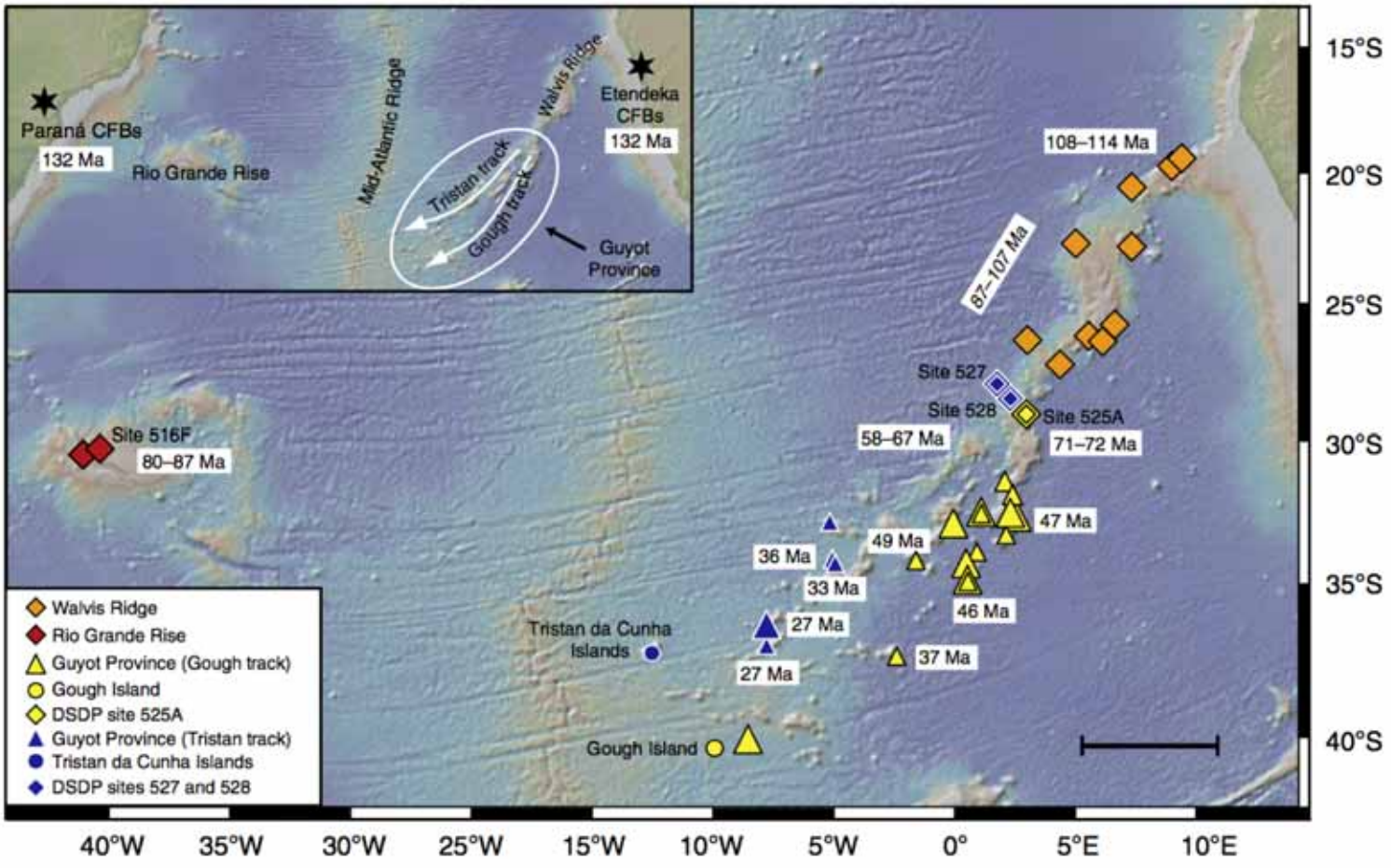
Galapagos

Harpp et al. 2015

Samoa

Malu Vai





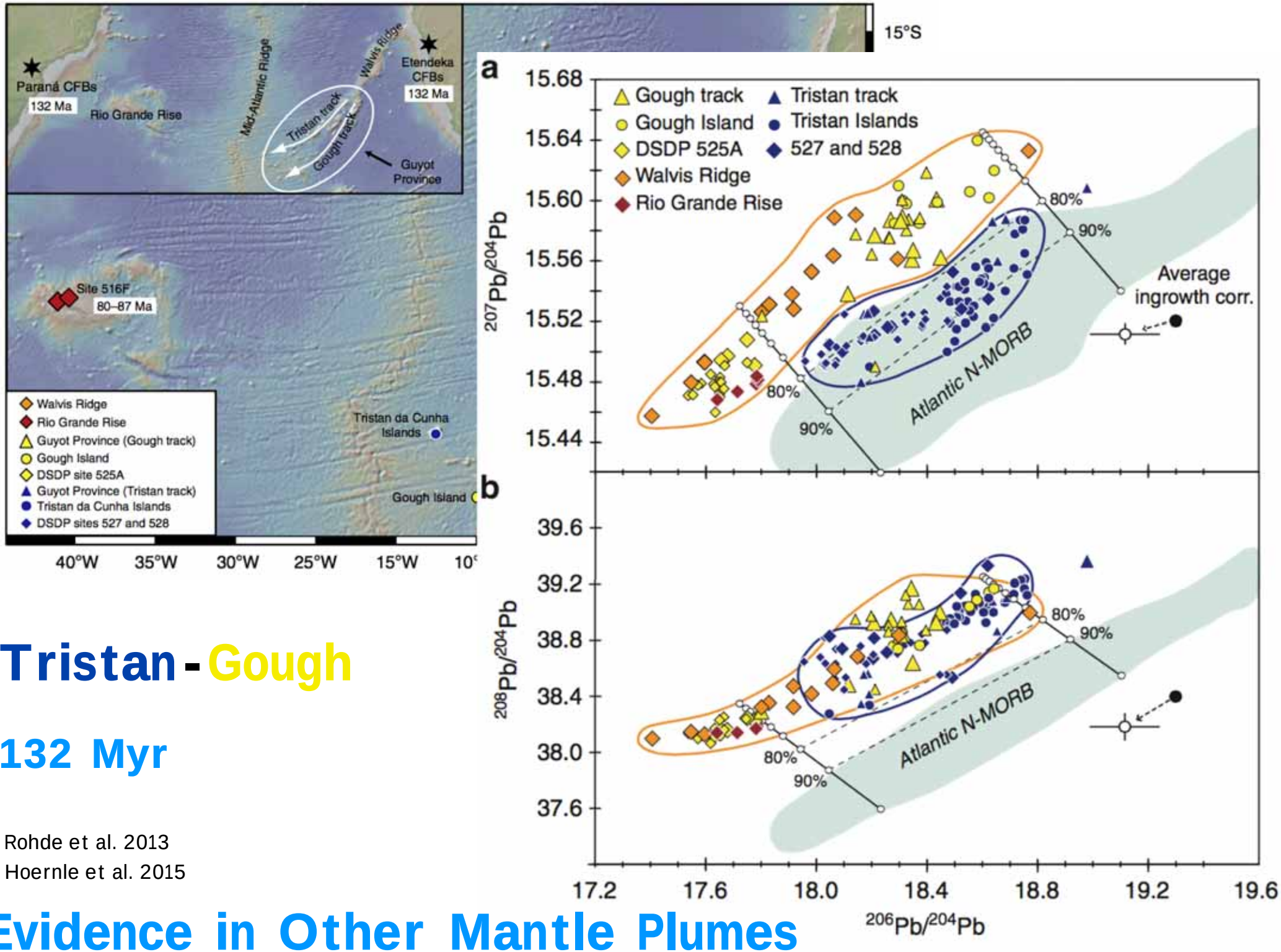
Tristan-Gough

Atlantic Ocean

132 Myr

Rohde et al. 2013
Hoernle et al. 2015

Evidence in Other Mantle Plumes



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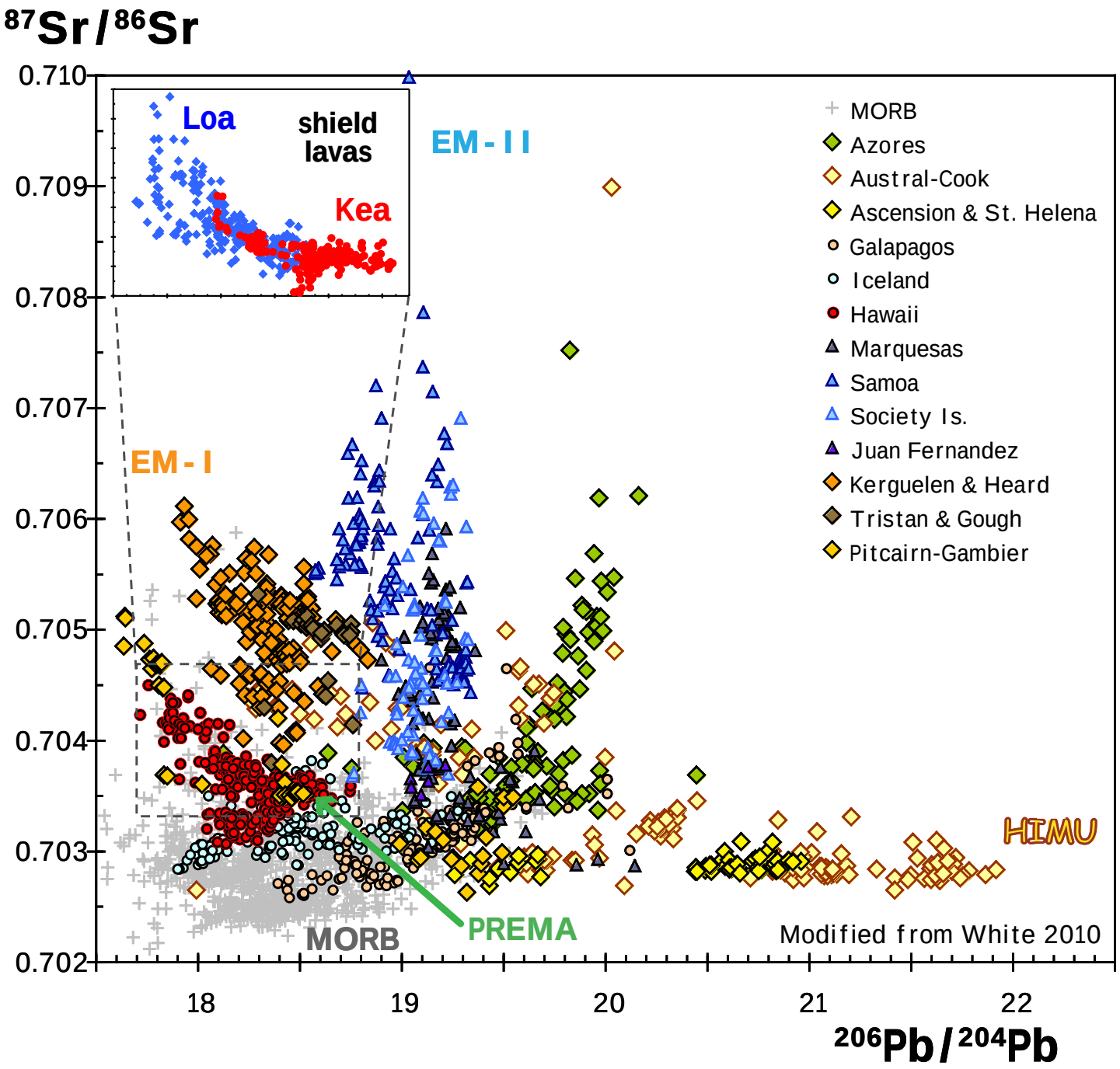
Evidence in Other Mantle Plumes

OIB Source Components



Weis et al. 2011

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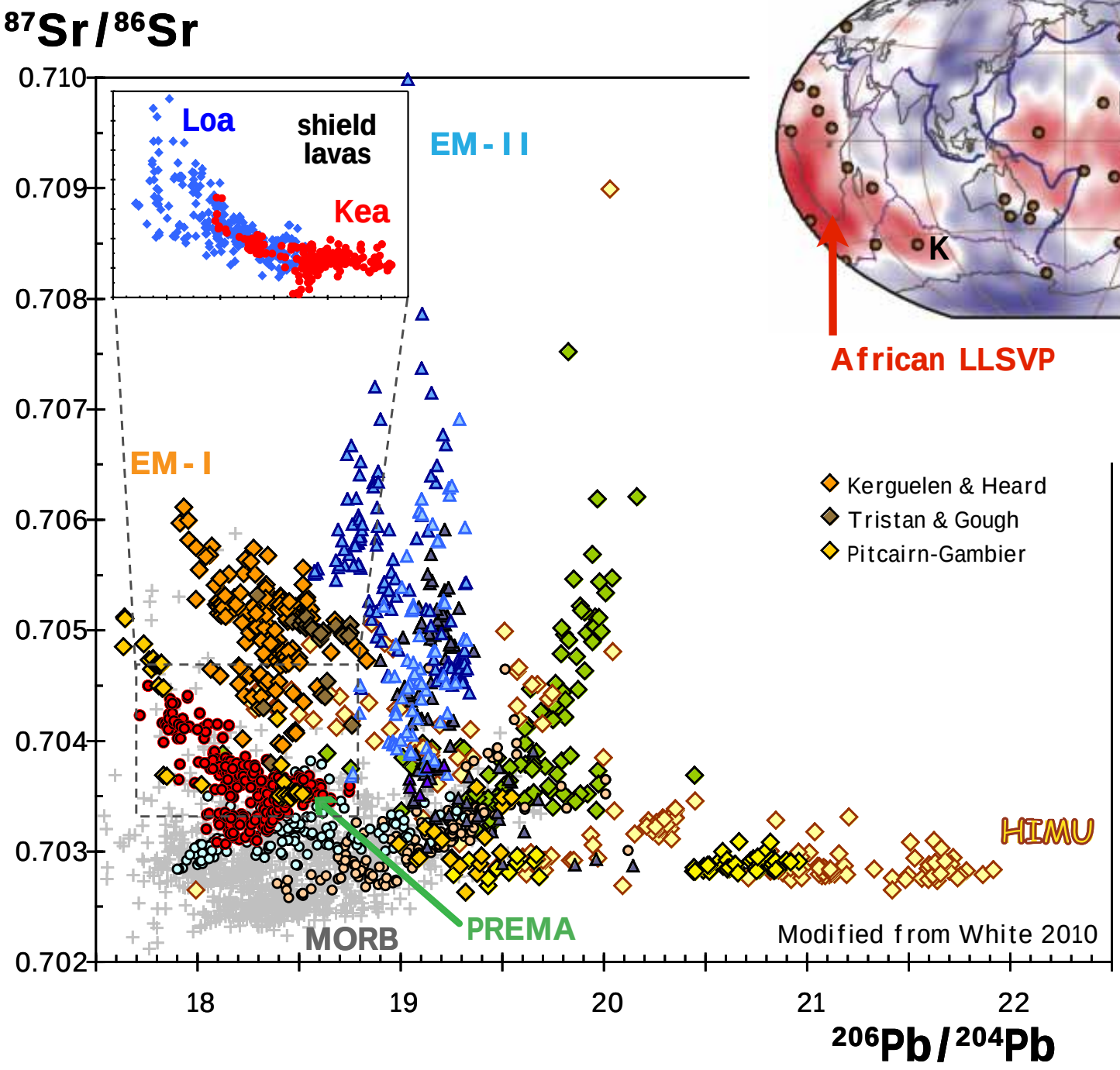

Lowermost-mantle V_s perturbations

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

Modified from Thorne et al. 2004

LLSVP: Large Low Shear Velocity Province

EM-I MANTLE PLUMES: Hawai'i and Pitcairn from the Pacific LLSVP and Kerguelen and Tristan from the African LLSVP

Different compositions!

Weis et al. 2011

How to Move Forward?
Need to Break some Boundaries …

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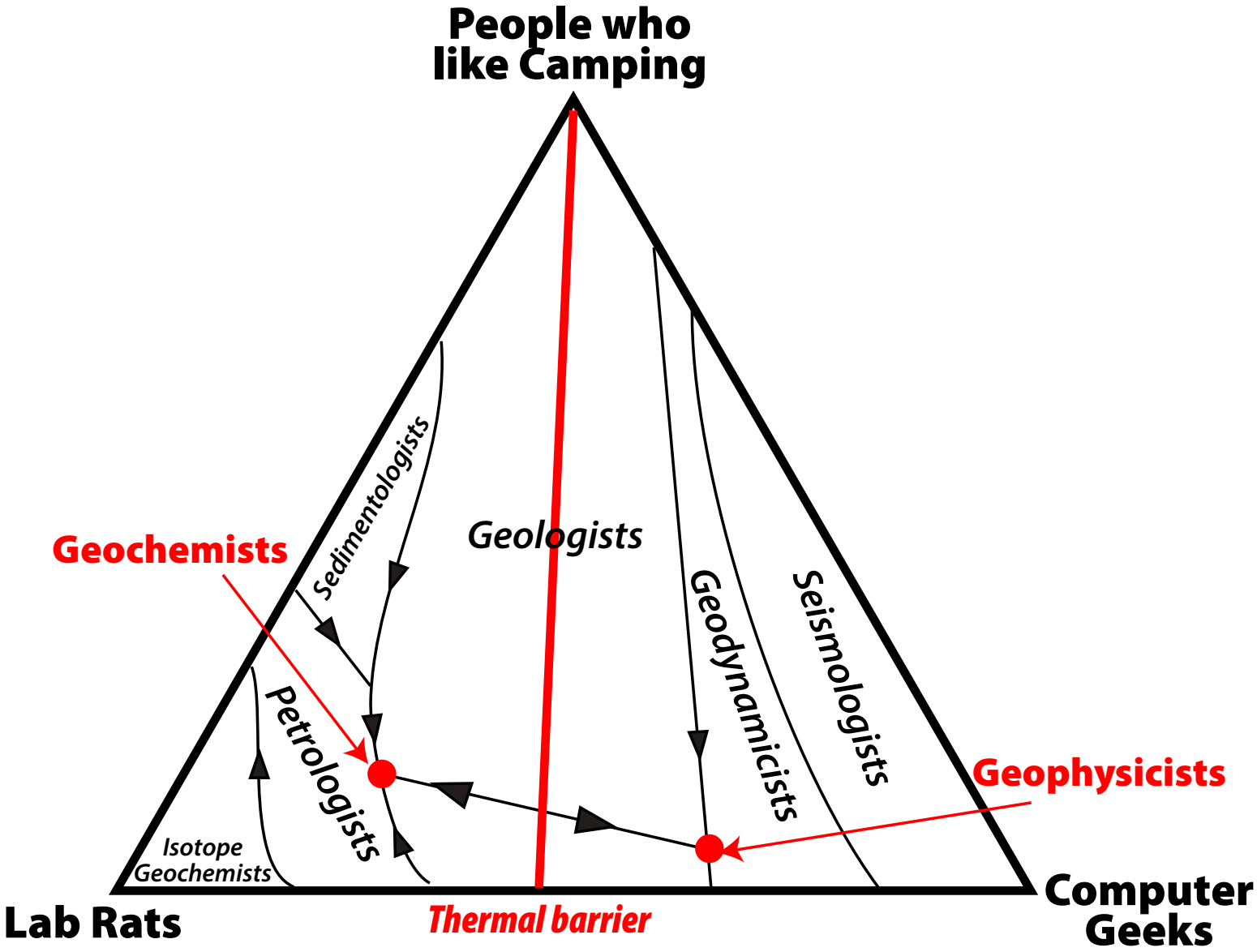
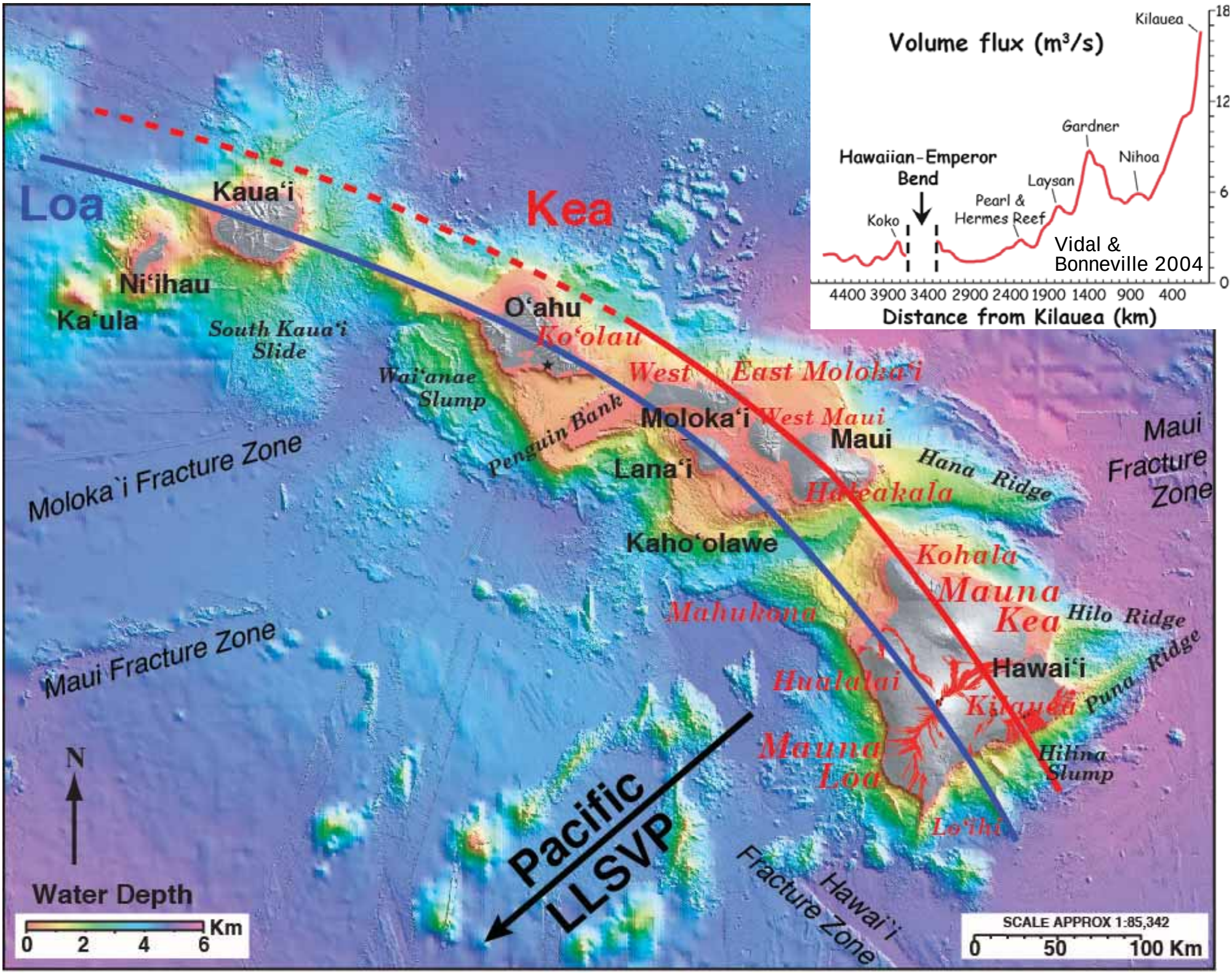
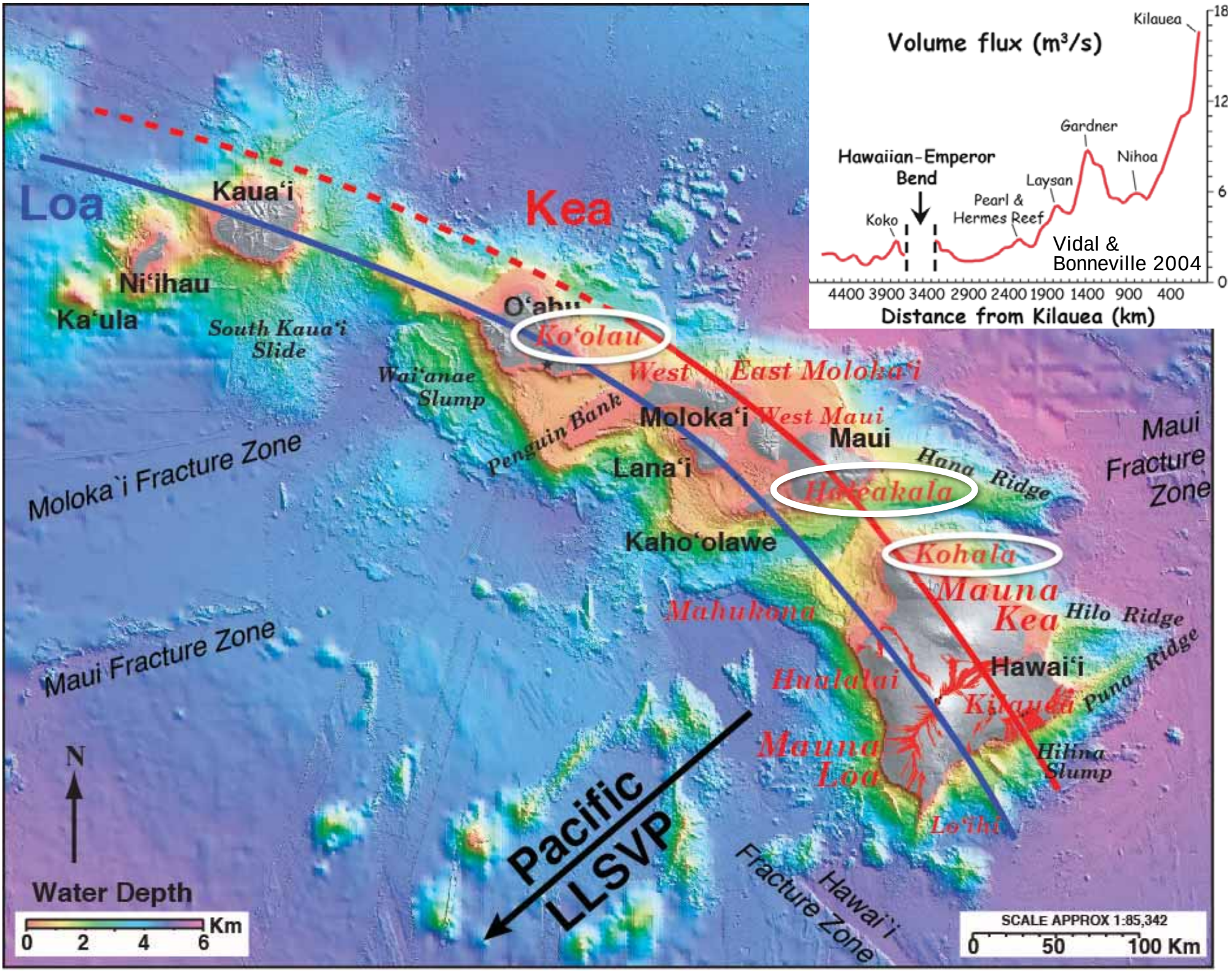
Need to Break some Boundaries …



Experiments at 1 atm, 298 K


Hawai’i
Back to Hawai’i
Shield Lavas
Kilauea Crater, April 2008


Loa
Kea
Kaua'i
Ni'ihau
Ka'ula
South Kaua'i Slide
O'ahu
Ko'olau
West
East Moloka'i
Wai'anae Slump
Penguin Bank
Moloka'i
West Maui
Maui
Lana'i
Hana Ridge
Haleakala
Moloka`i Fracture Zone
Maui Fracture Zone
Kaho'olawe
Kohala
Mauna Kea
Hilo Ridge
Mahukona
Hawai'i
Hualalai
Kilauea
Puna Ridge
Mauna Loa
Hilina Slump
Lo'ihi
Pacific LLSVP
Hawai`i Fracture Zone
N
Water Depth
0 2 4 6 Km
SCALE APPROX 1:85,342
0 50 100 Km
Volume flux (m³/s)
Kilauea
Gardner
Nihoa
Hawaiian-Emperor Bend
Laysan
Pearl & Hermes Reef
Koko
Vidal & Bonneville 2004
18
12
6
0
4400 3900 3400 2900 2400 1900 1400 900 400
Distance from Kilauea (km)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Water Depth
Km
0 2 4 6
SCALE APPROX 1:85,342
0 50 100 Km
Volume flux (m³/s)
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Hawaiian-Emperor Bend
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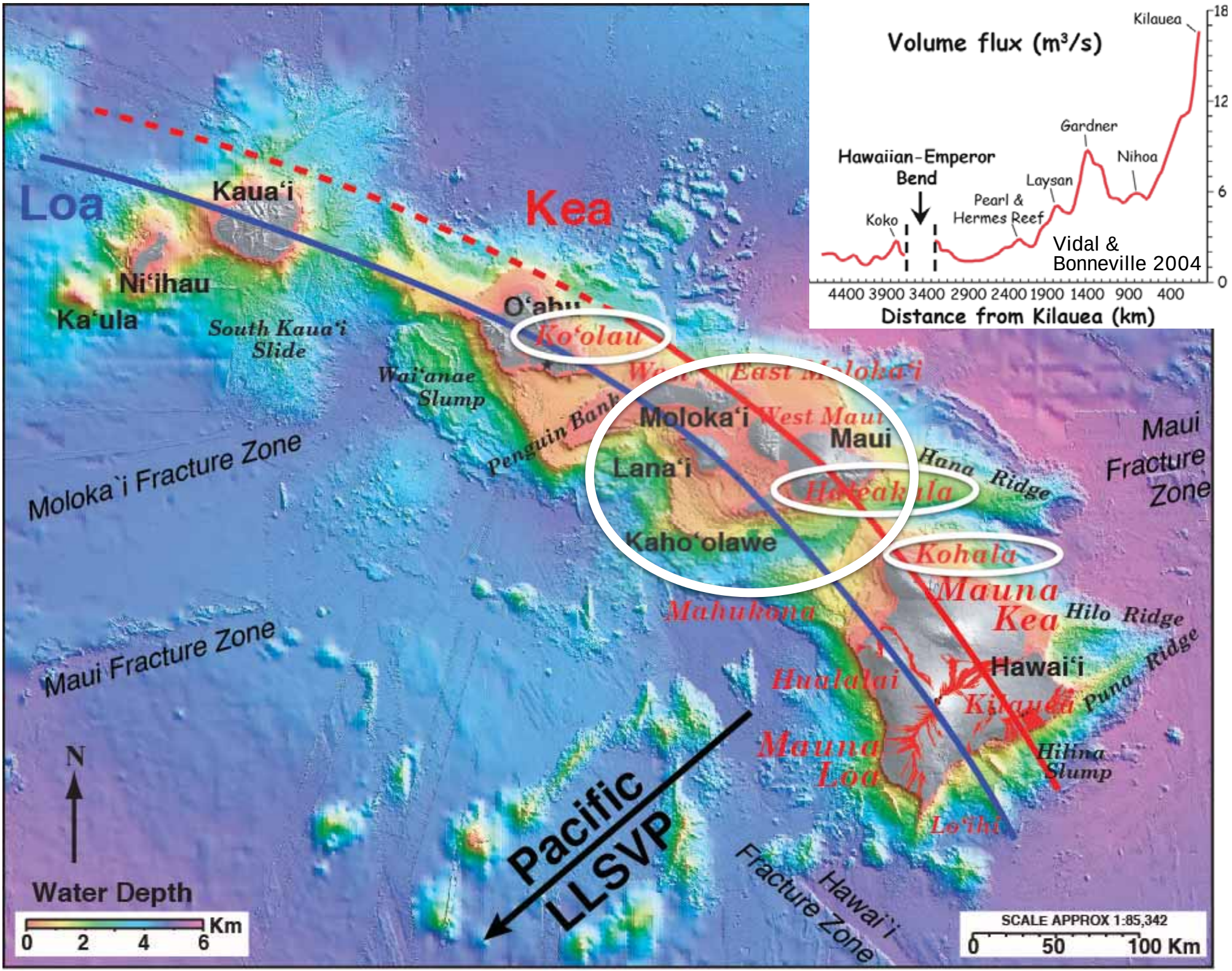
Distance from Kilauea (km)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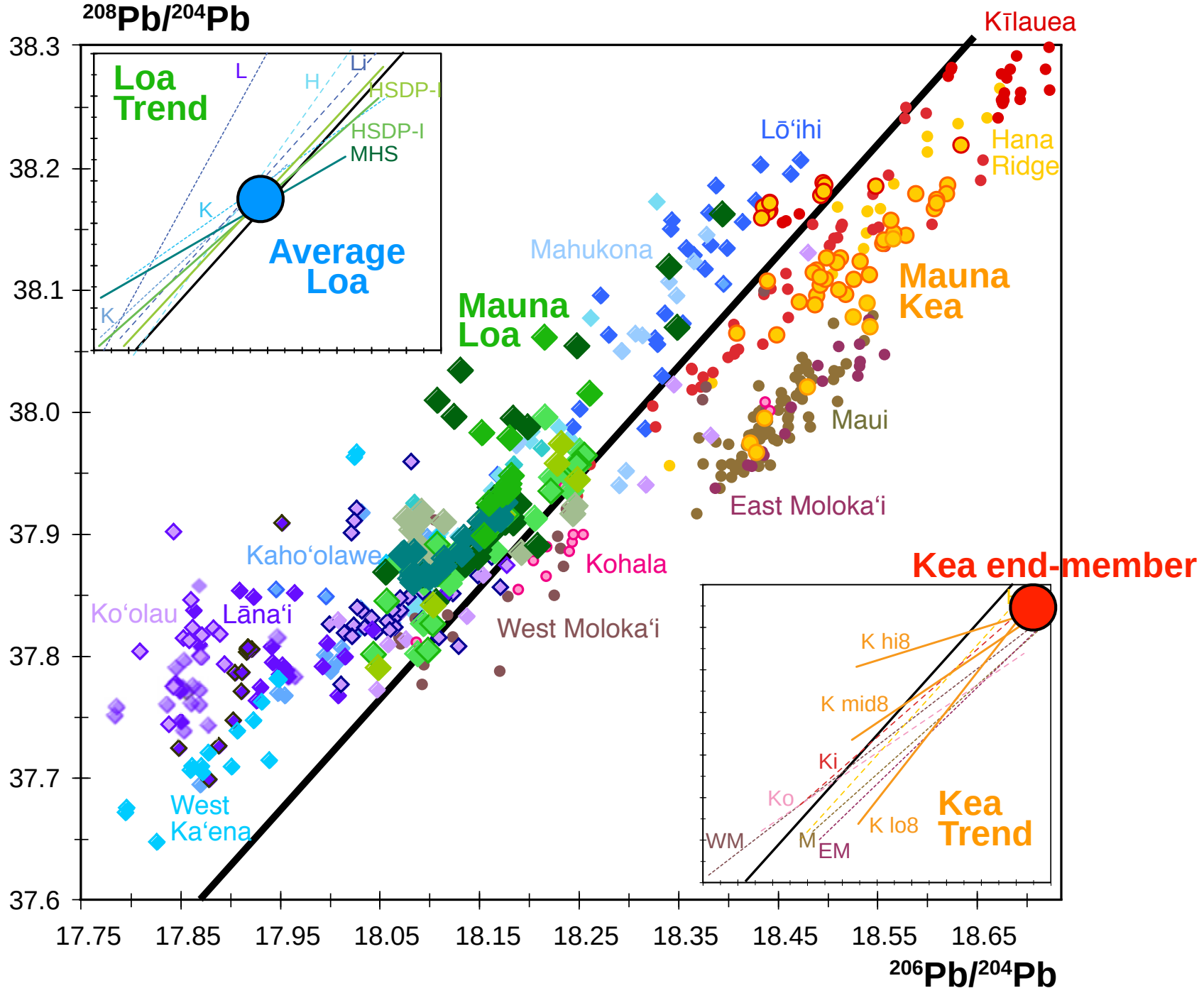
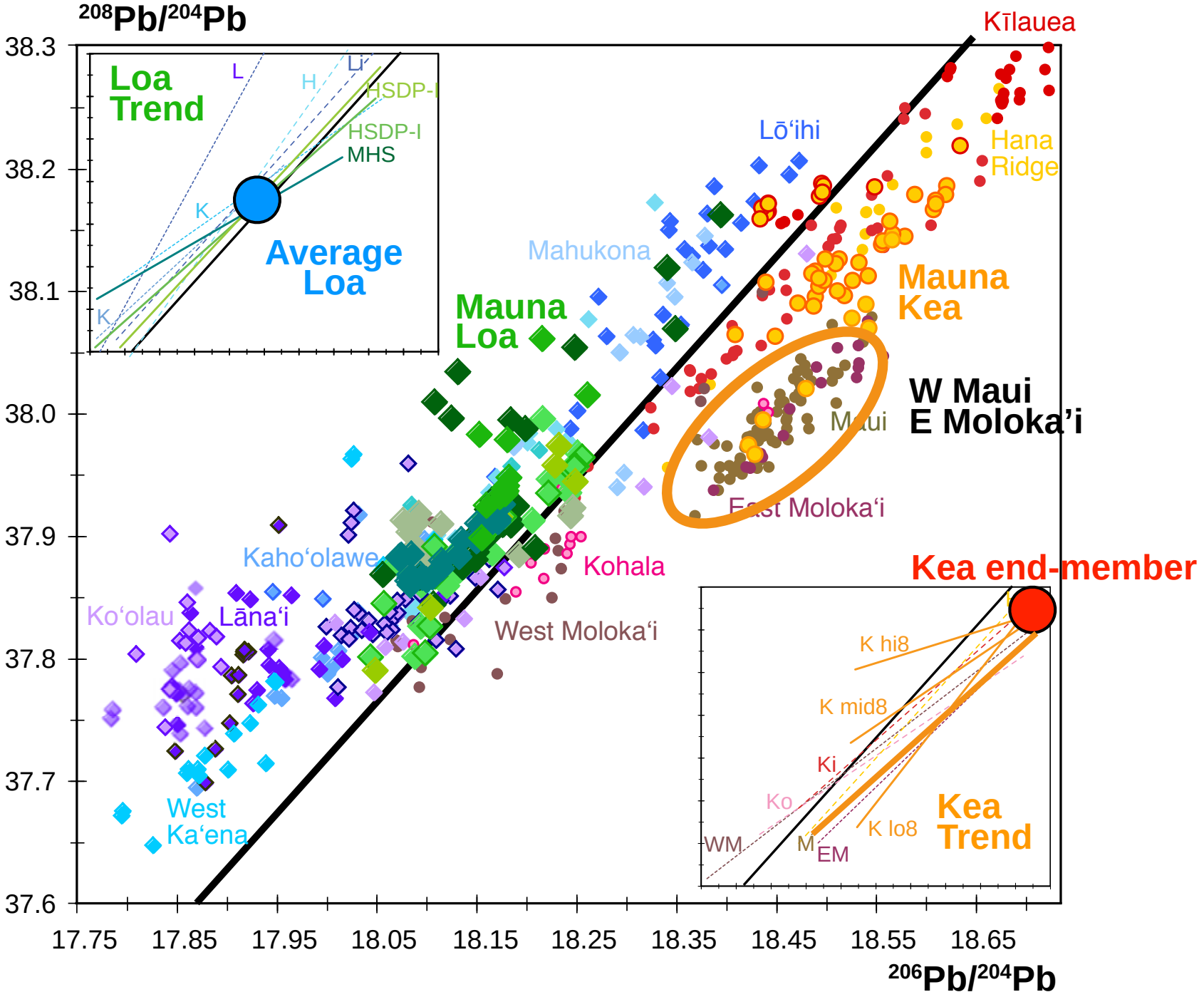
Mahukona
Hawai'i
Hualalai
Kilauea
Puna Ridge
Mauna Loa
Hilina Slump
Lo'ihi
Moloka`i Fracture Zone
Maui Fracture Zone
Maui Fracture Zone
Hawai`i Fracture Zone
Pacific
LLSVP
N
Water Depth
0 2 4 6 Km
SCALE APPROX 1:85,342
0 50 100 Km
Volume flux (m³/s)
Kilauea
Gardner
Nihoa
Laysan
Pearl & Hermes Reef
Koko
Hawaiian-Emperor Bend
Vidal & Bonneville 2004
18
12
6
0
4400 3900 3400 2900 2400 1900 1400 900 400
Distance from Kilauea (km)

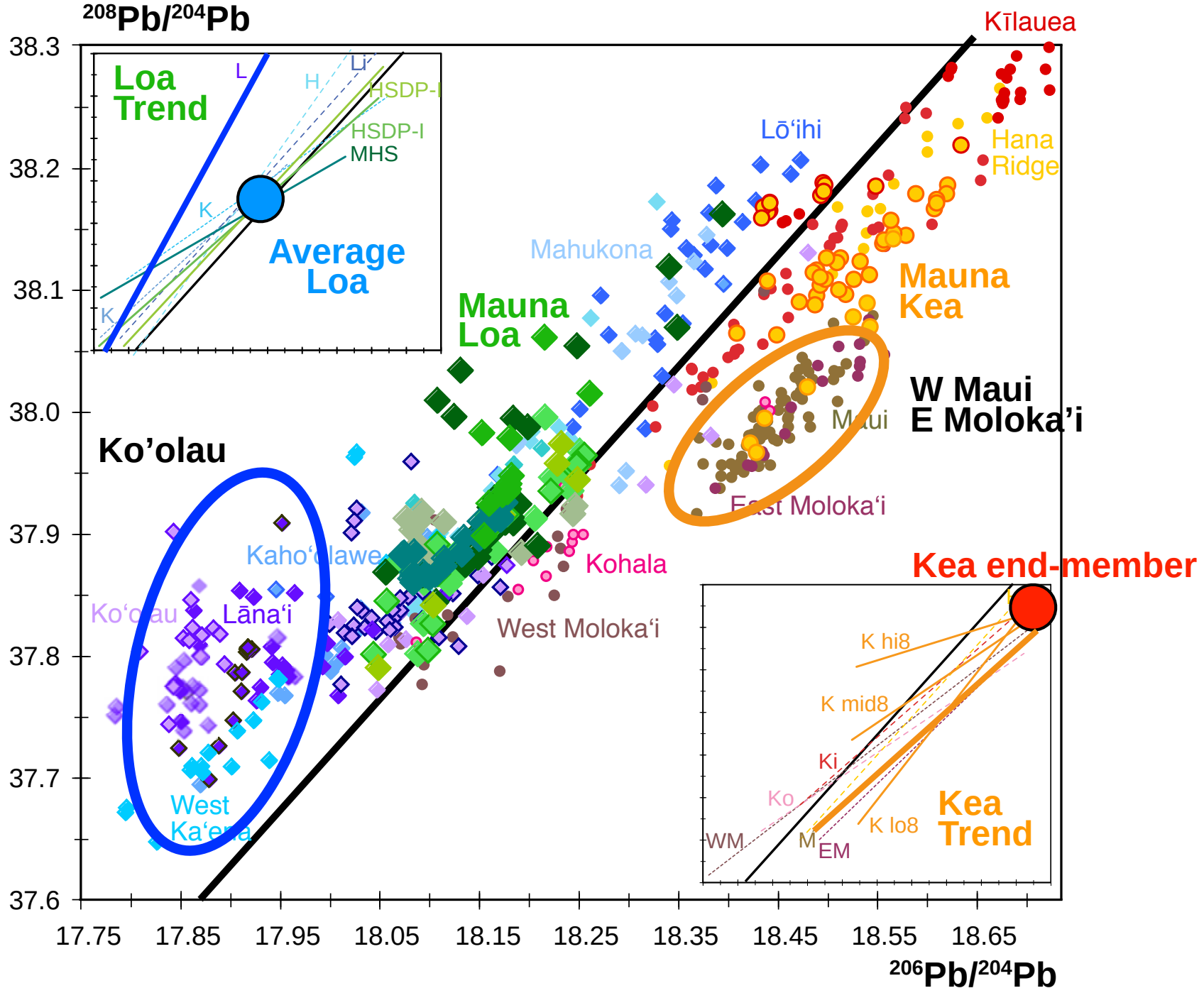
High-Precision Pb Data: Hawai'i



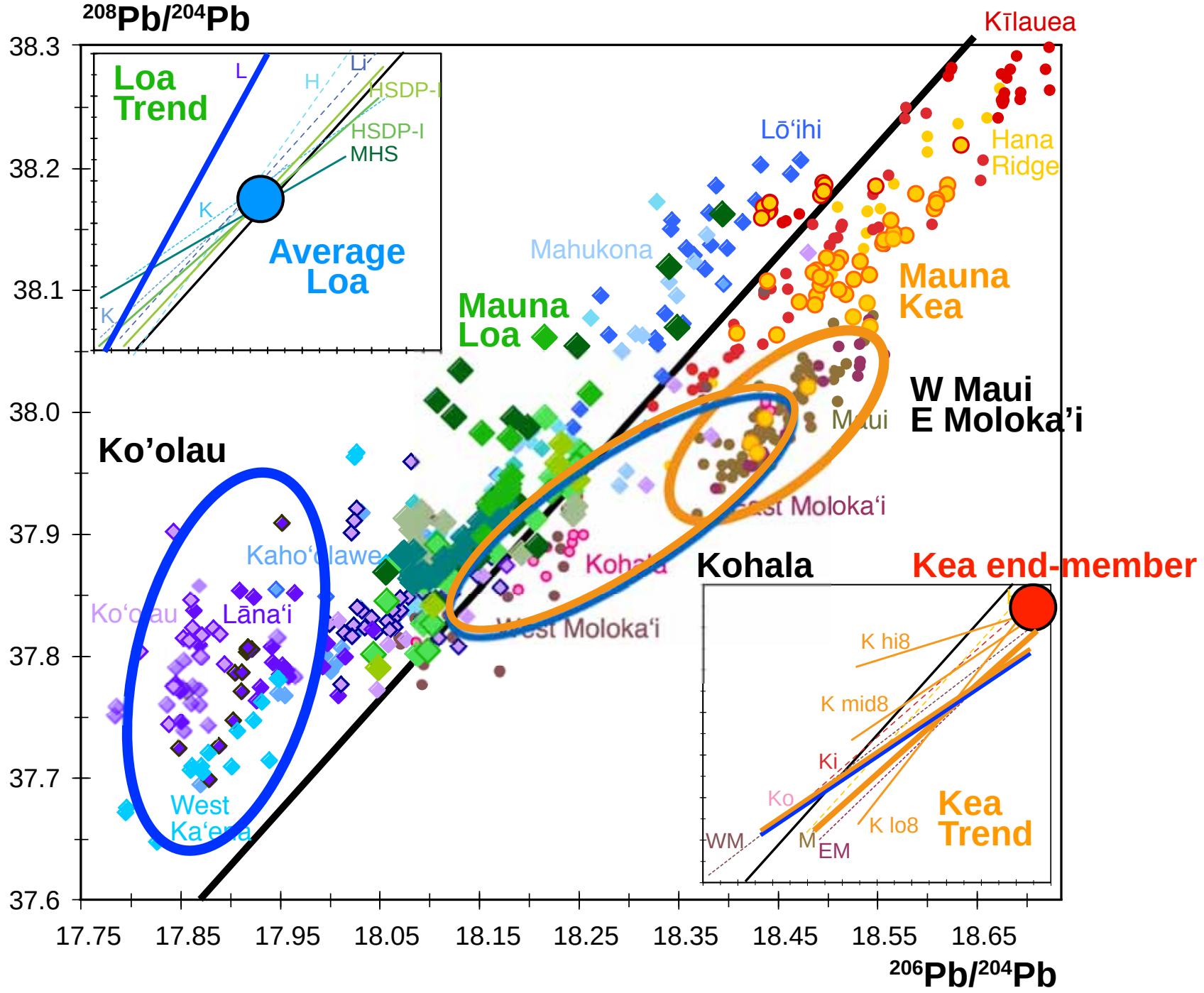
High-Precision Pb Data: Hawai'i



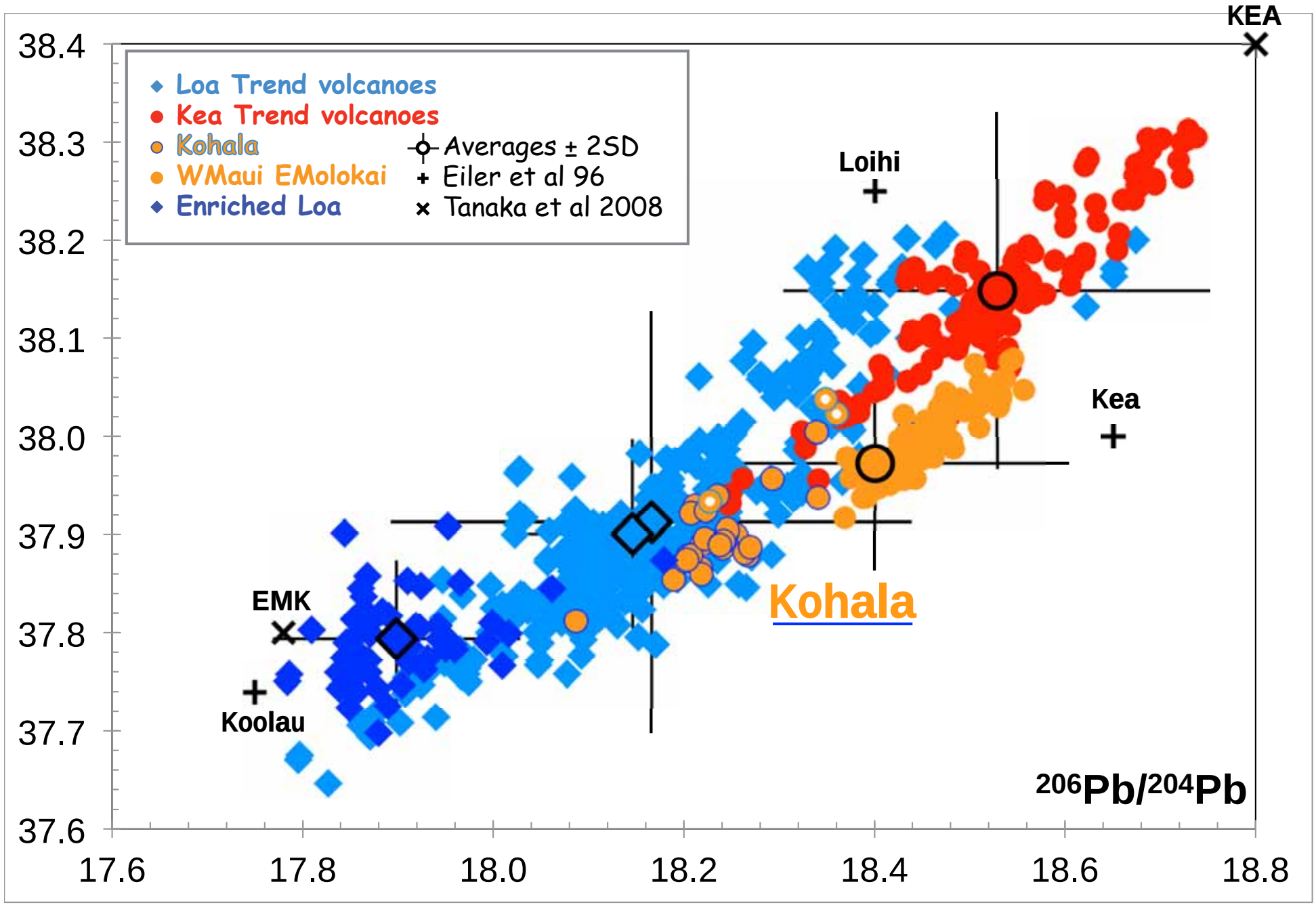
High-Precision Pb Data: Hawai'i



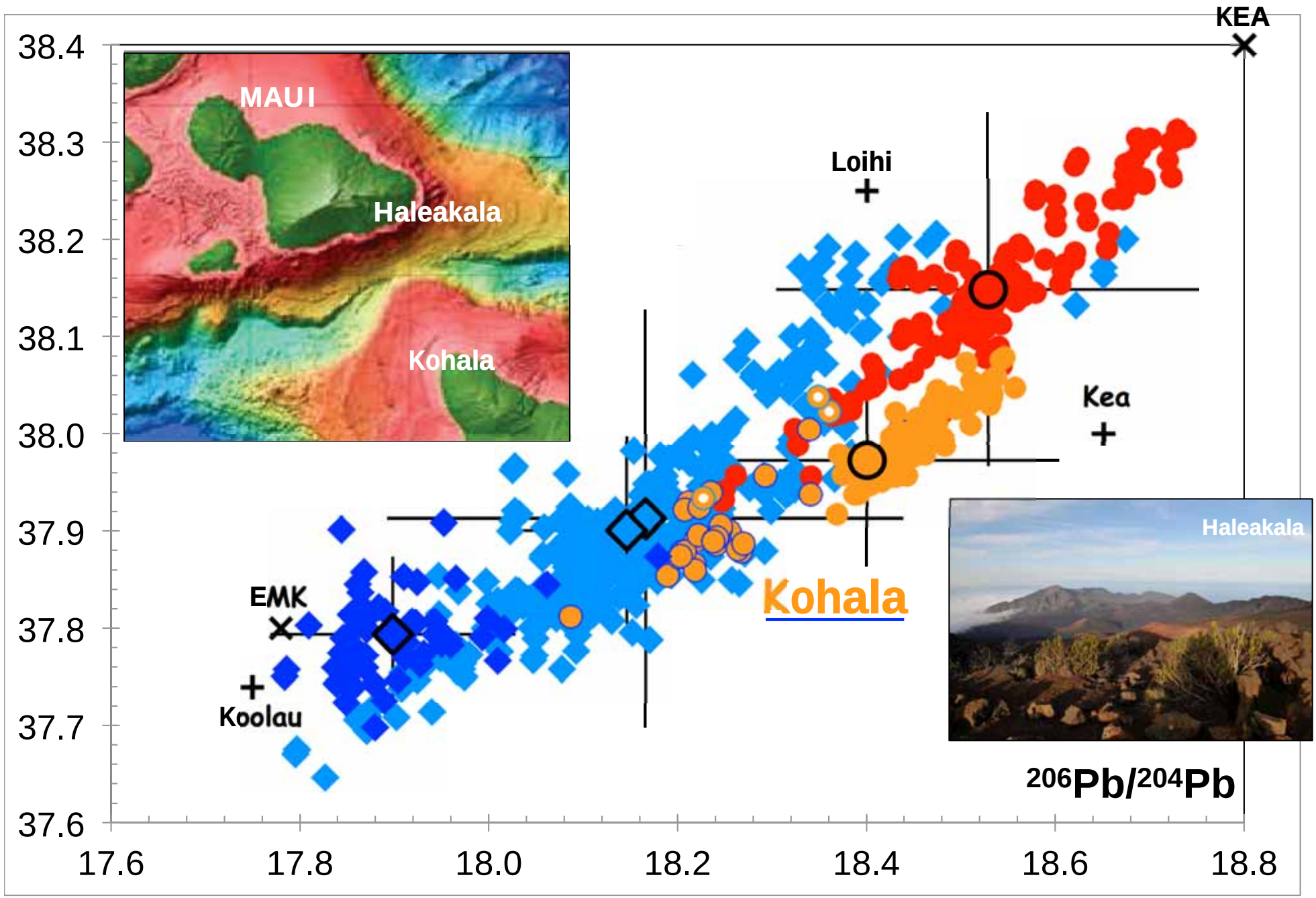
High-Precision Pb Data: Hawai'i



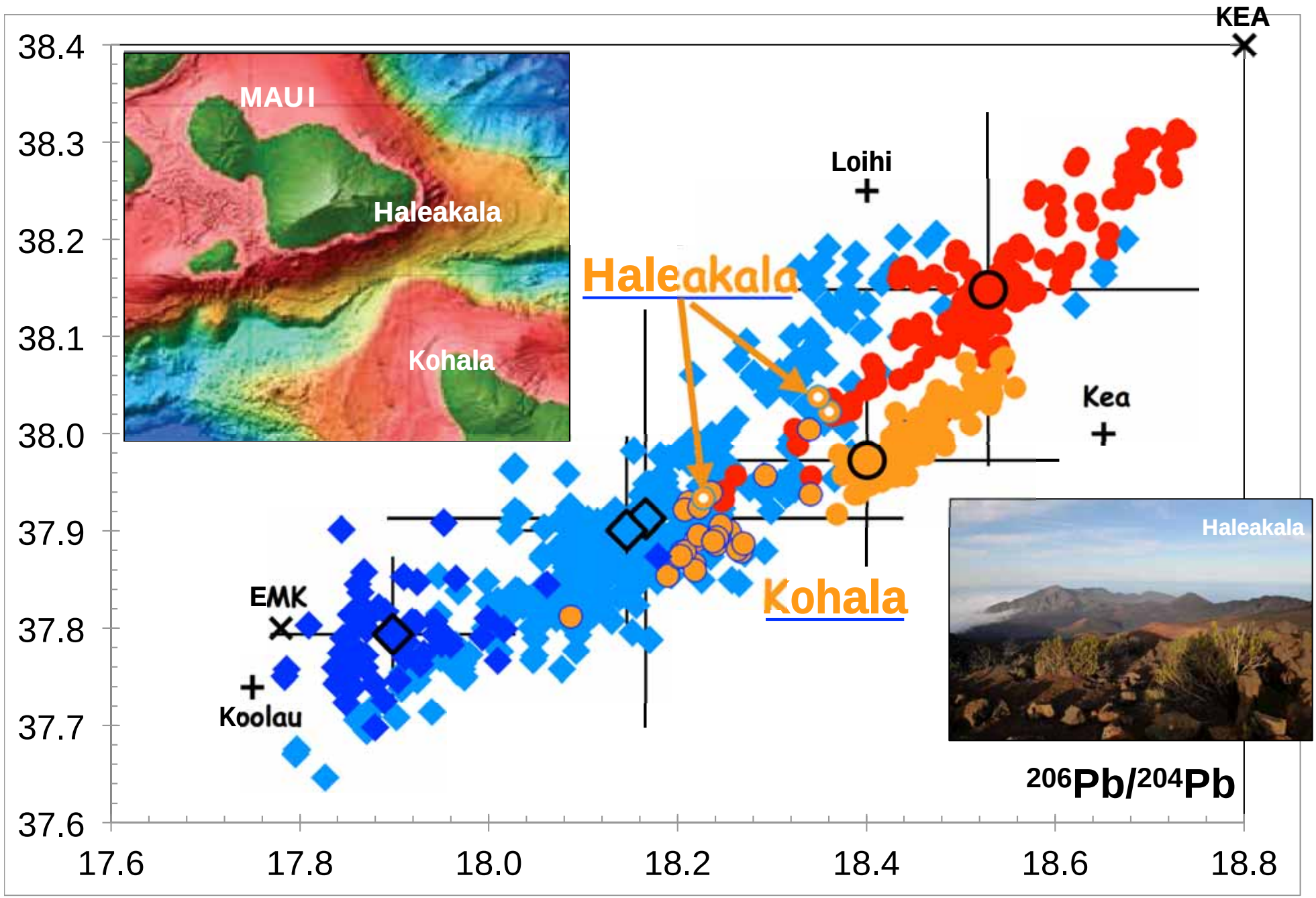
High-Precision Pb Data: a Different Look



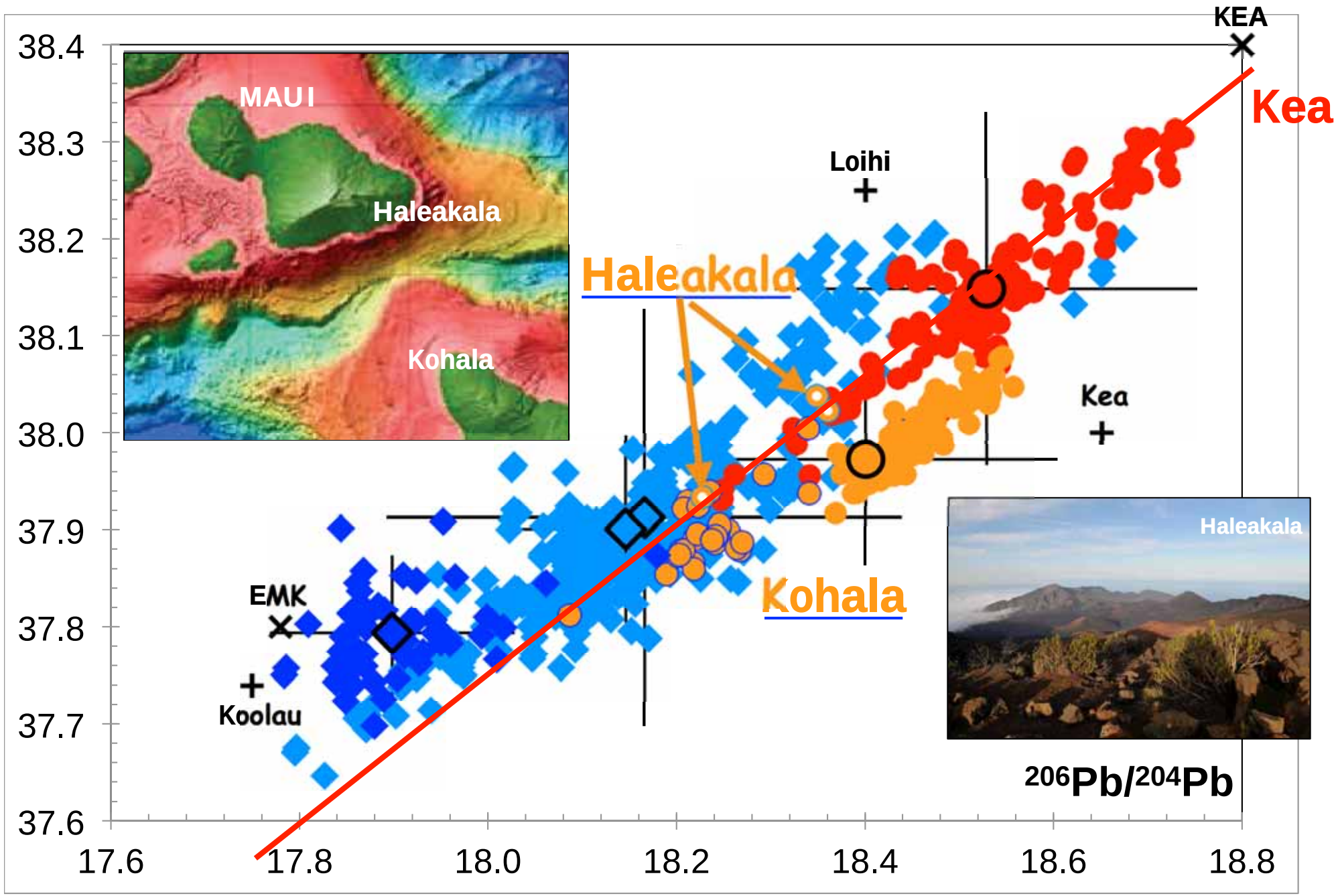
High-Precision Pb Data: a Different Look



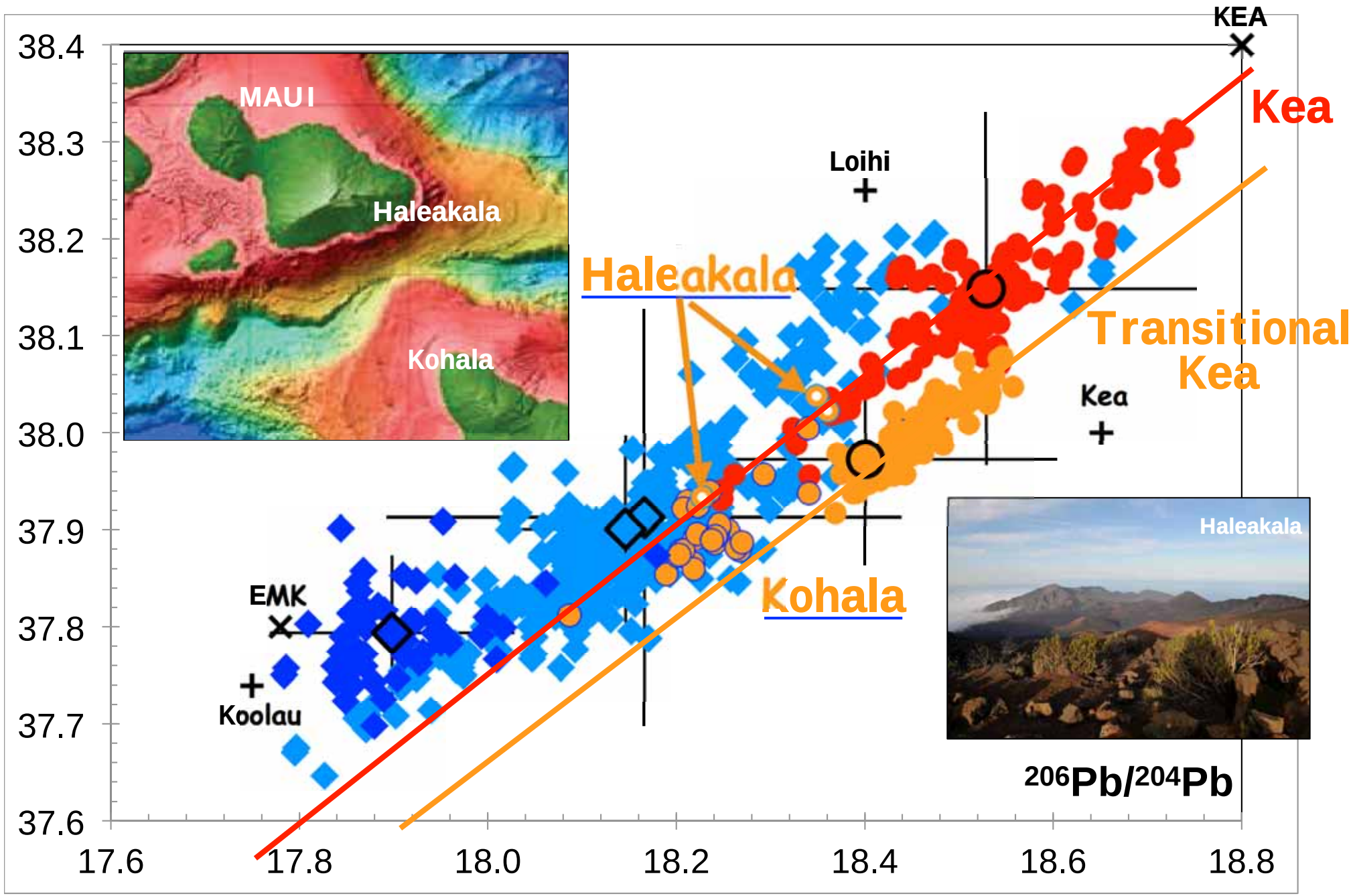
High-Precision Pb Data: a Different Look



High-Precision Pb Data: a Different Look

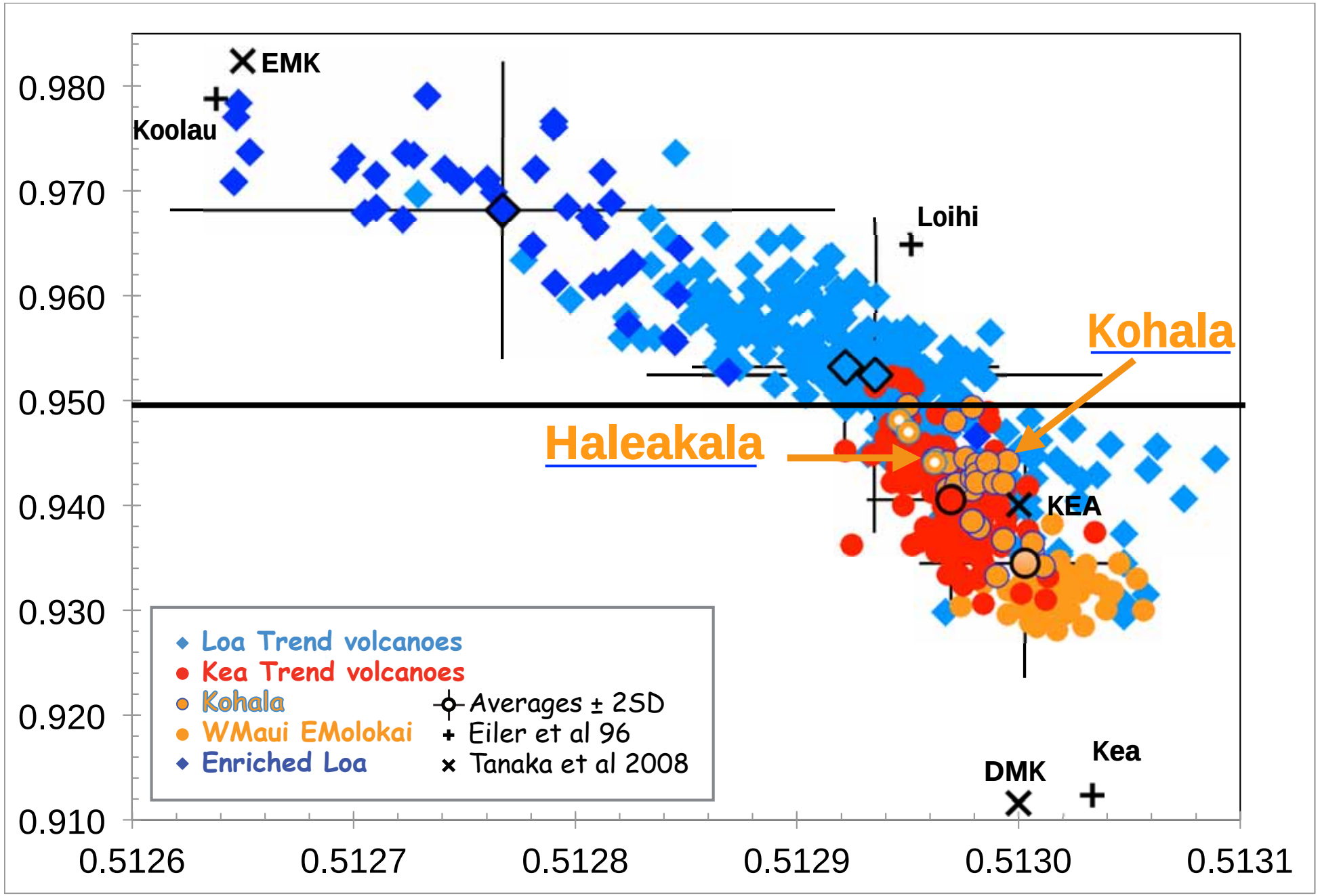


High-Precision Pb Data: a Different Look

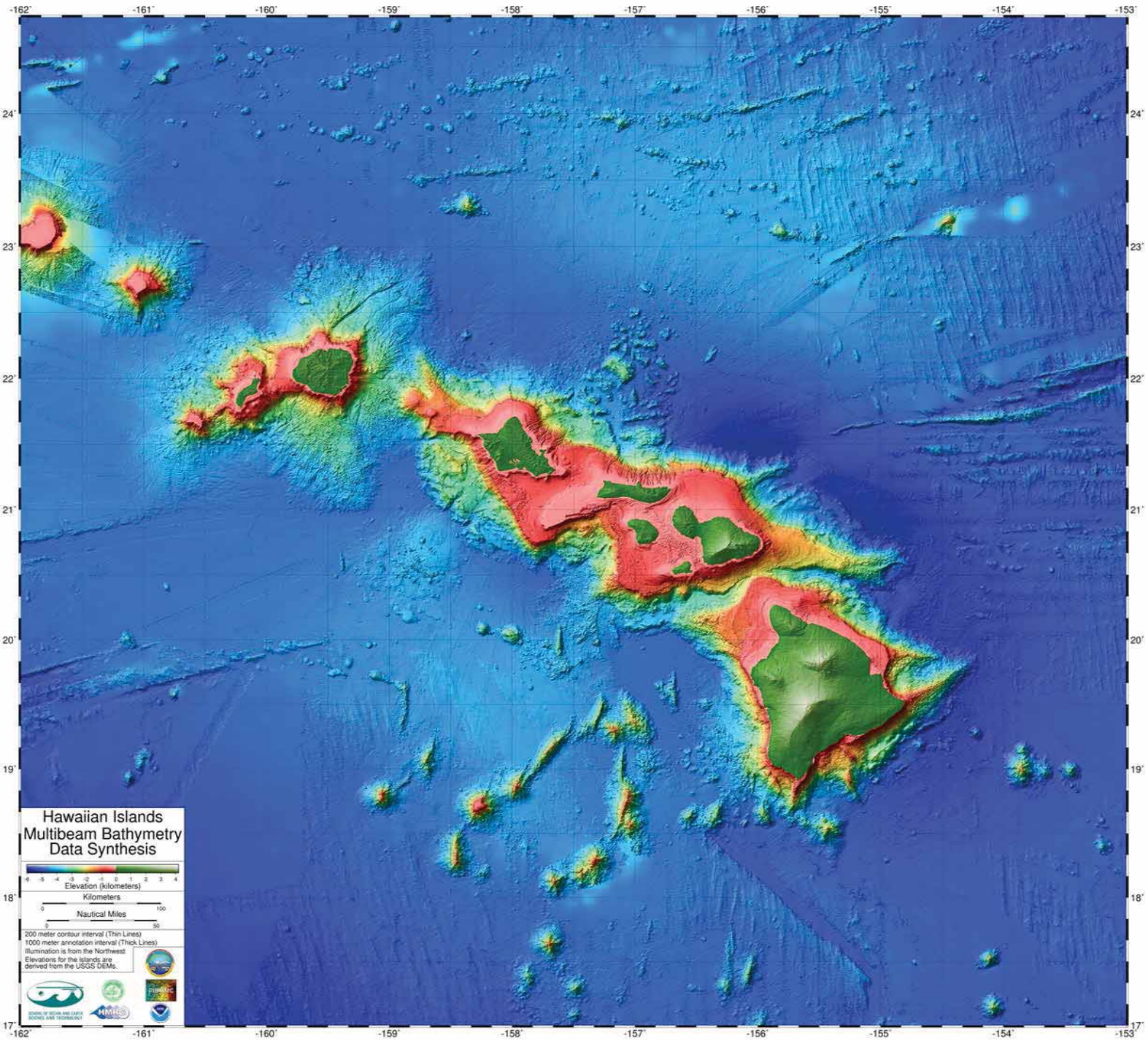


a Different Look

Only shield lavas
~600 samples



Geographical Distribution of Hawai'i Geochemical Components



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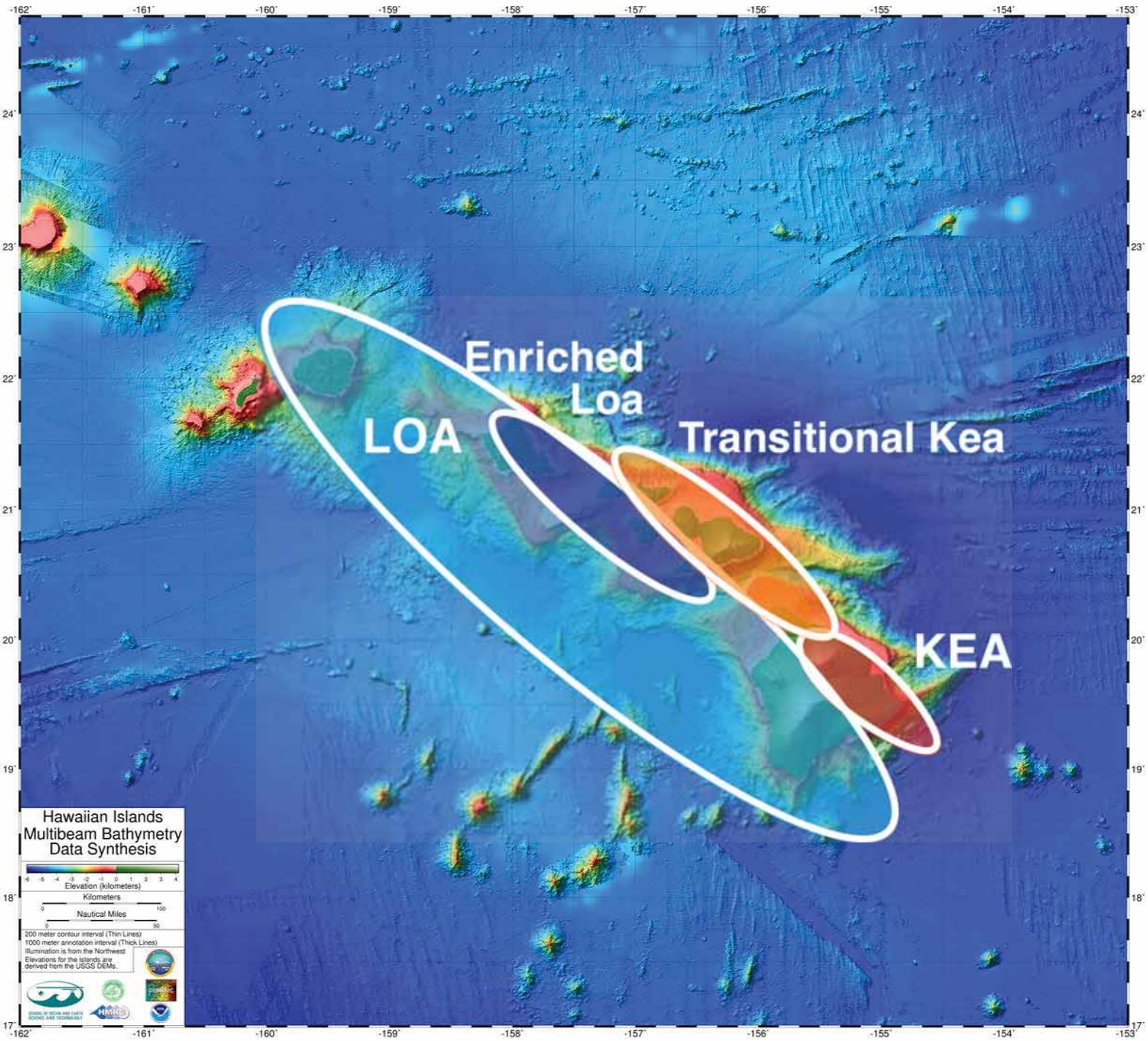


Geographical Distribution of Hawai'i Geochemical Components

Enriched Loa

LOA

Transitional Kea

E Molokai - W Maui

Haleakala

Kohala

KEA

Hawaiian Islands Multibeam Bathymetry Data Synthesis

Elevation (kilometers)

Kilometers

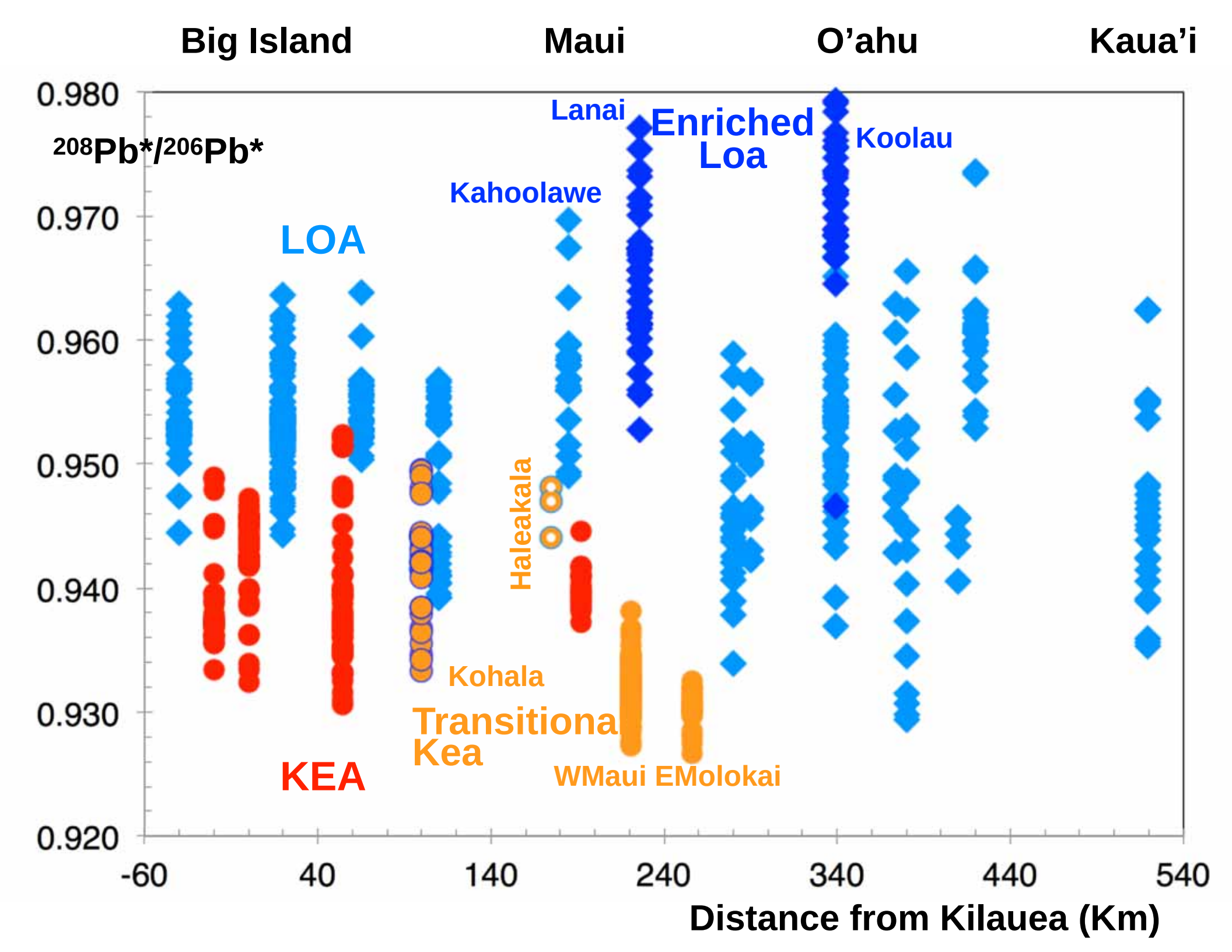
Nautical Miles

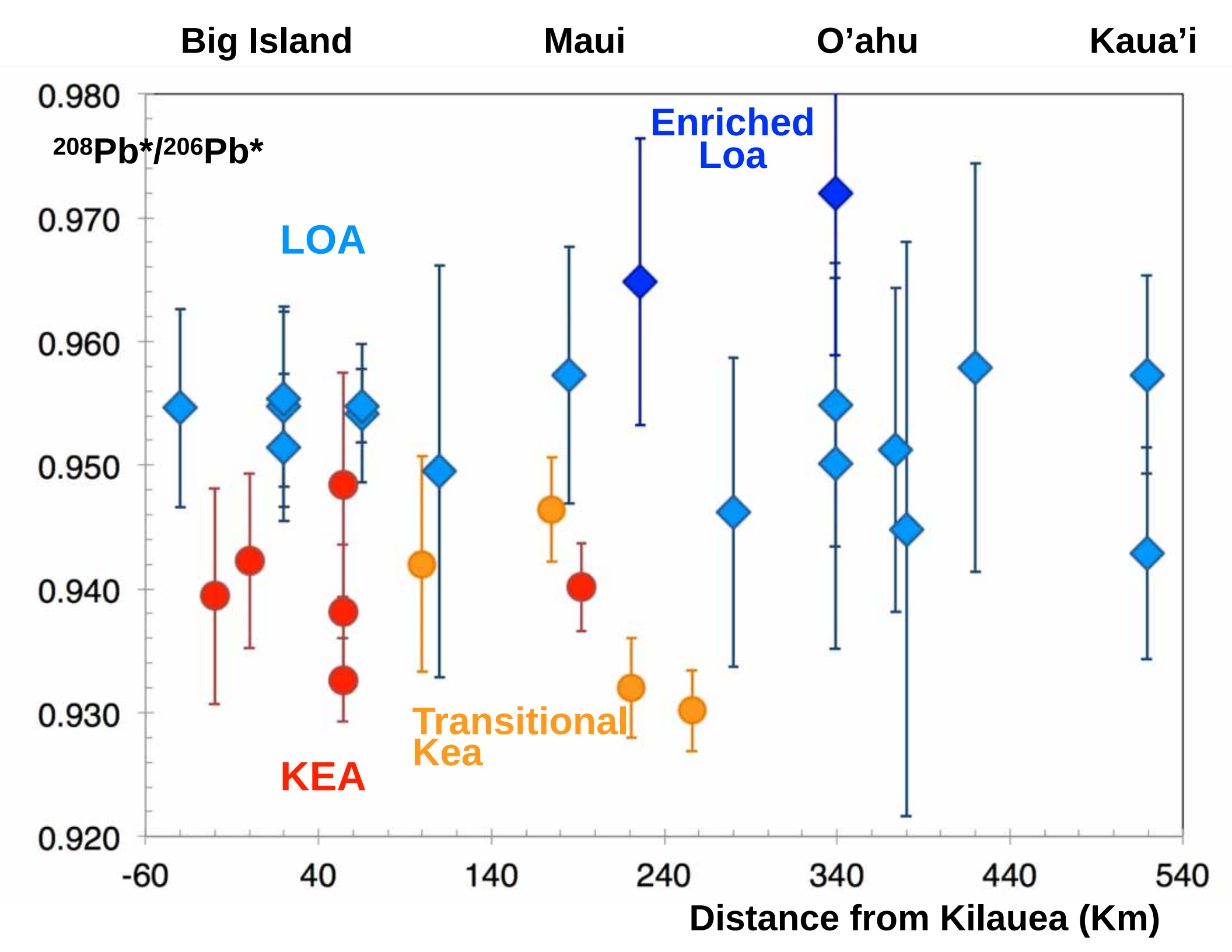
200 meter contour interval (Thin Lines)

1000 meter annotation interval (Thick Lines)

Illumination is from the Northwest

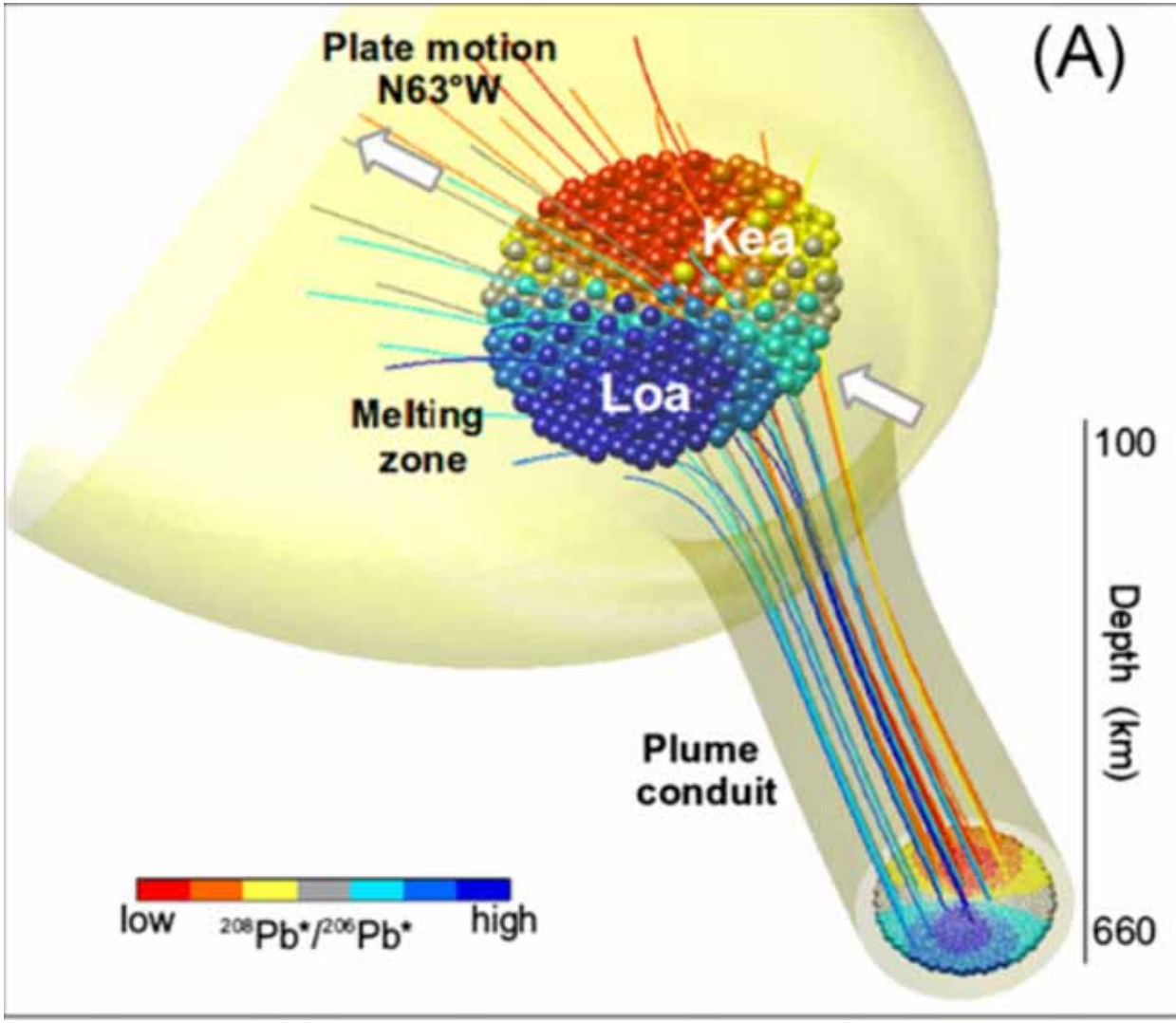
Elevations for the islands are derived from the USGS DEMs.

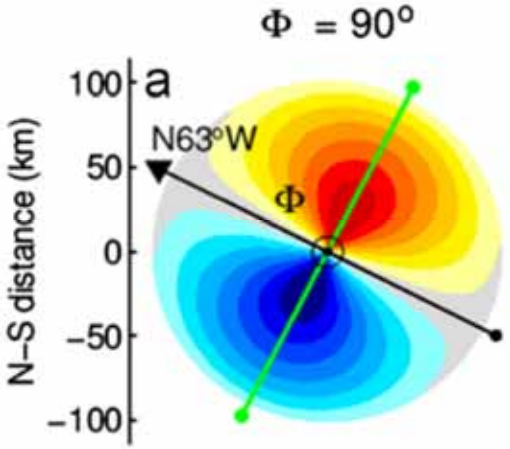

Big Island
Maui
O'ahu
Kaua'i
0.980
0.970
0.960
0.950
0.940
0.930
0.920
208Pb*/206Pb*
LOA
KEA
Lanai
Enriched Loa
Koolau
Kahoolawe
Haleakala
Kohala
Transitiona Kea
WMaui EMolokai
-60
40
140
240
340
440
540
Distance from Kilauea (Km)


Big Island
Maui
O'ahu
Kaua'i
0.980
$^{208}Pb^*/^{206}Pb^*$
0.970
0.960
0.950
0.940
0.930
0.920
Enriched Loa
LOA
Transitional Kea
KEA
-60
40
140
240
340
440
540
Distance from Kilauea (Km)

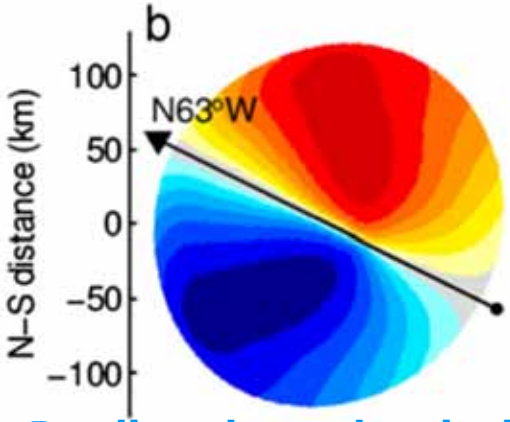
Numerical Simulation of the Hawaiian Plume

Radiogenic Pb zonation across the conduit and melting zones, flow trajectories

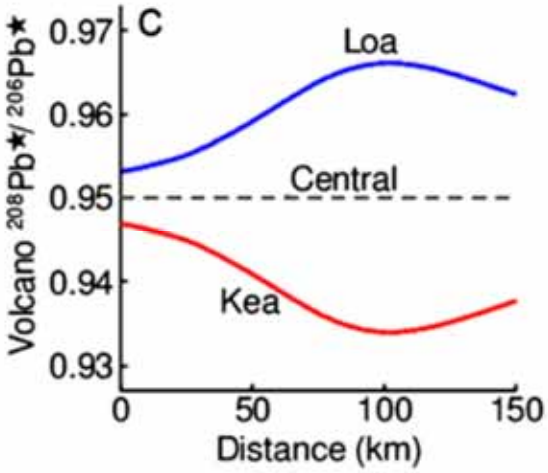




Plume conduit structure



Predicted geochemical zonation across the Hawaiian melting zone



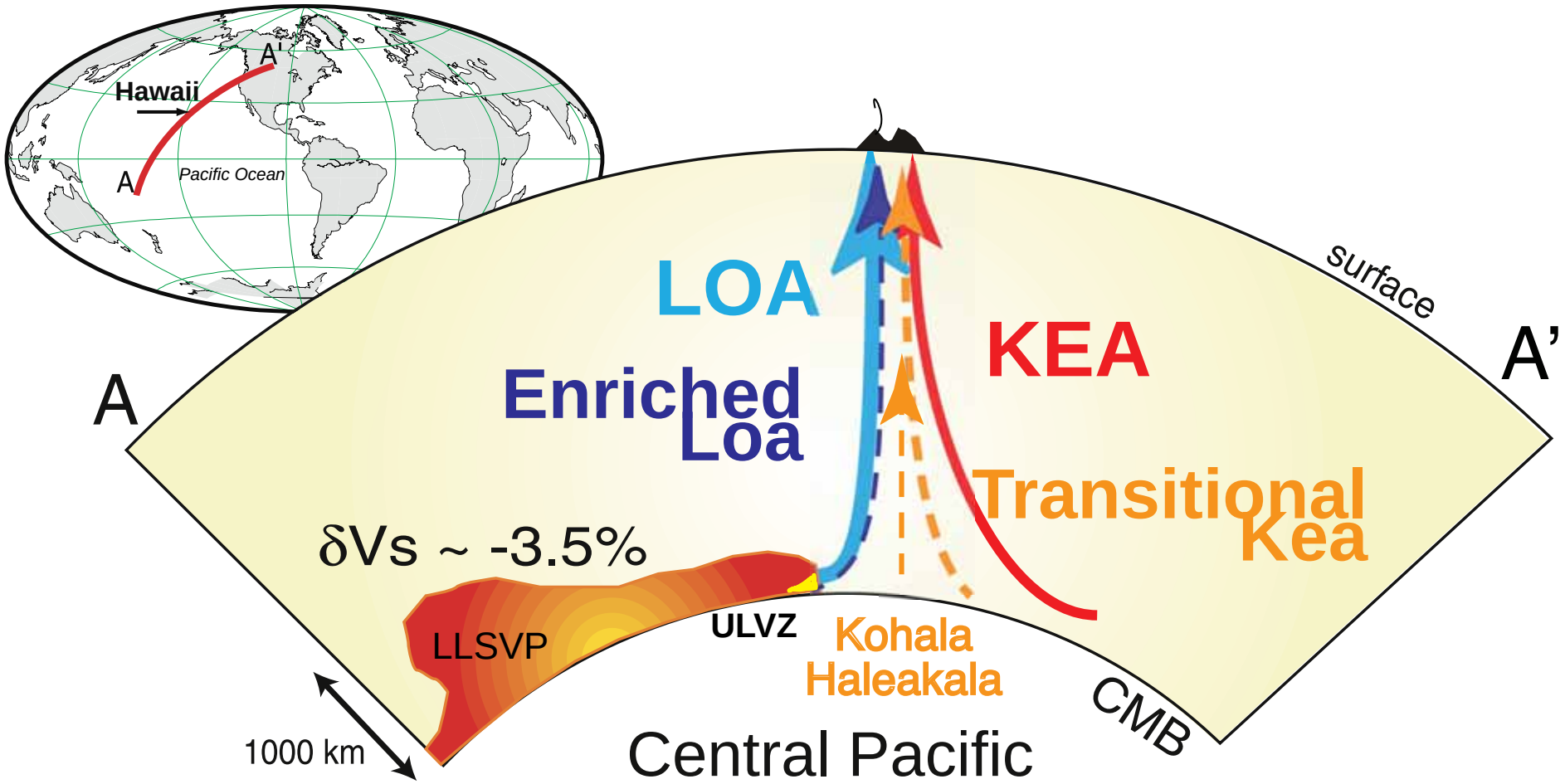
Predicted geochemical zonation for a central volcano

Farnetani et al 2012

Updated 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



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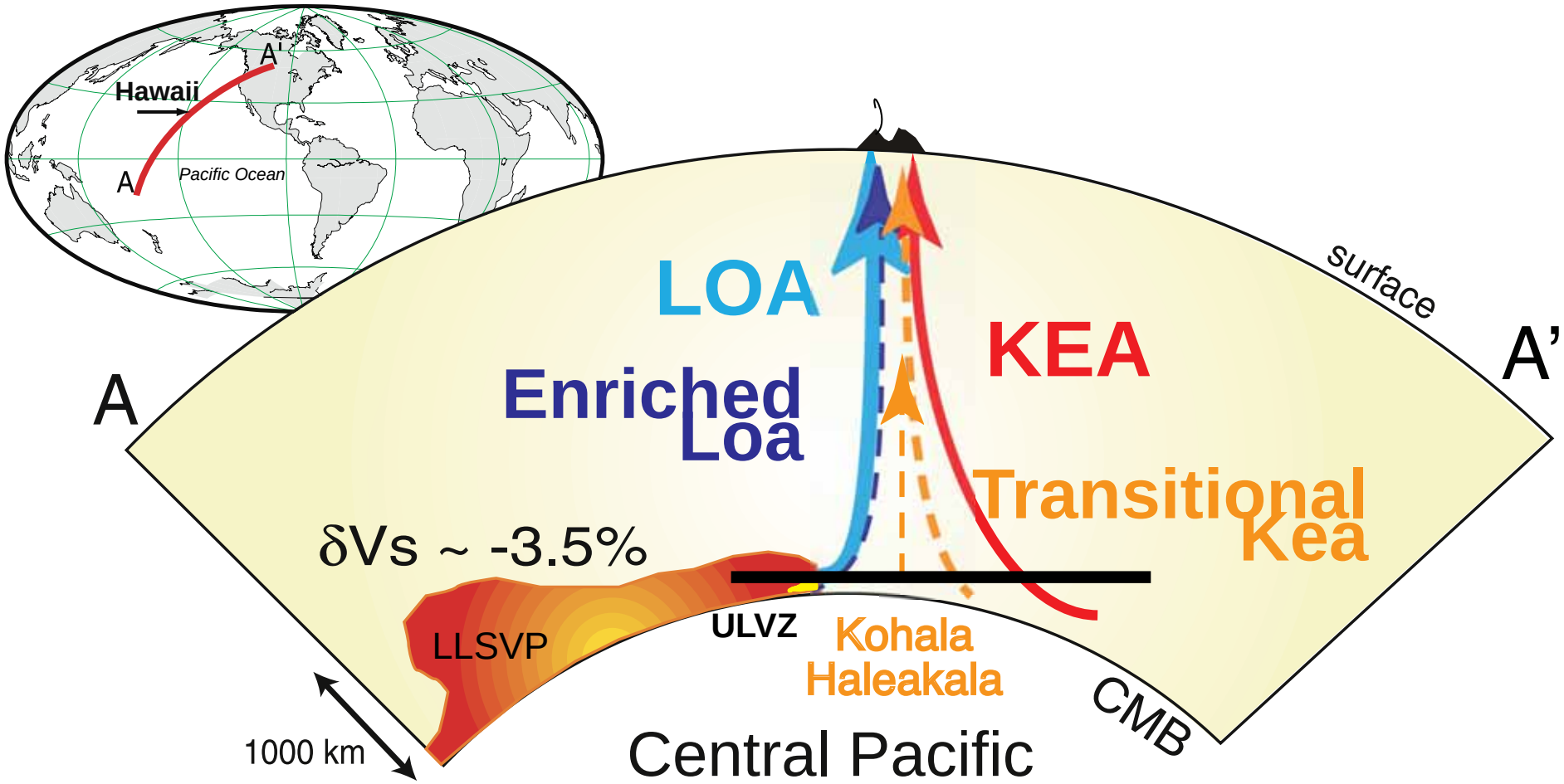
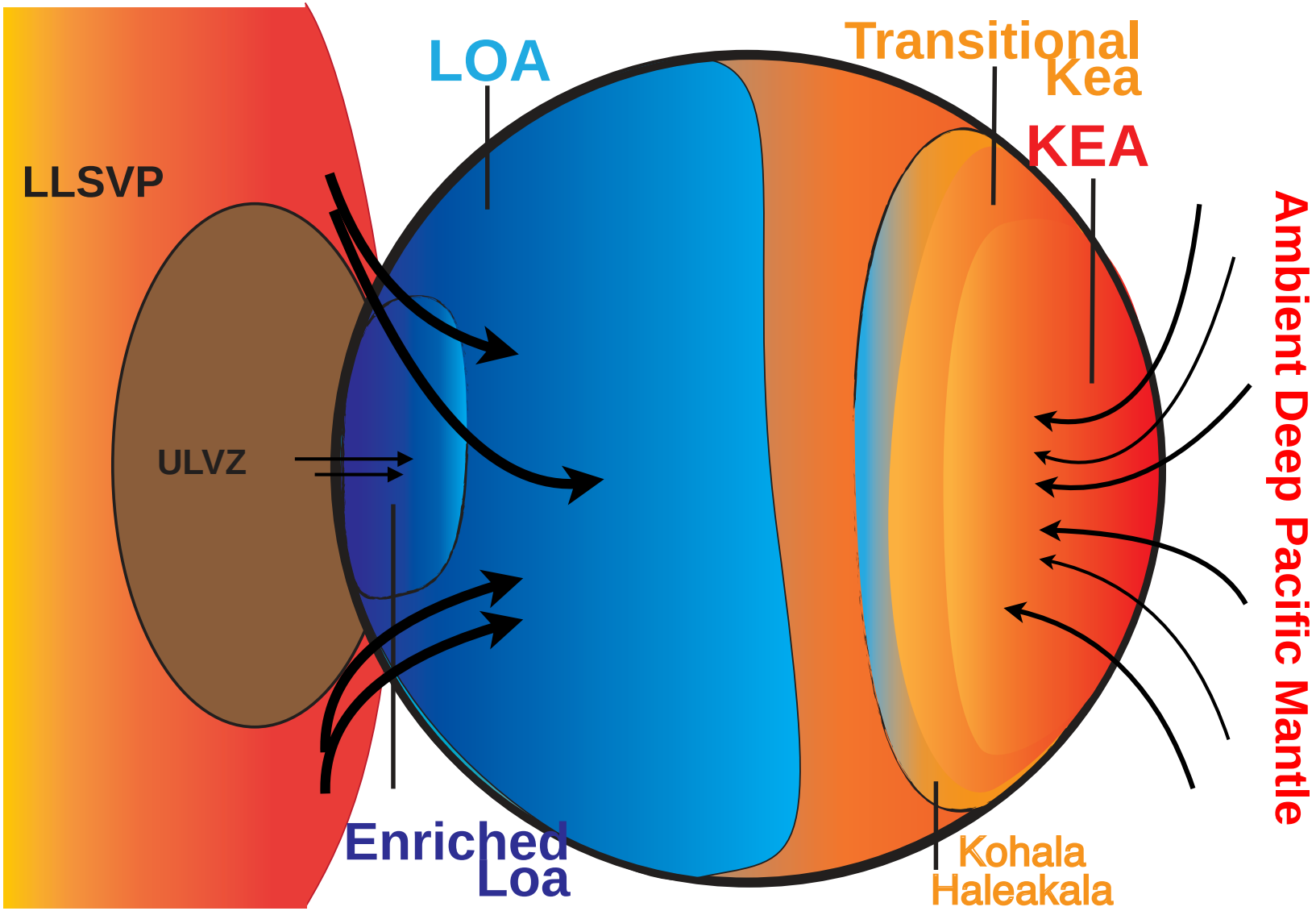


Conceptual Cross Section:

Mapping the Hawaiian Geochemical Components at the Base of the Mantle

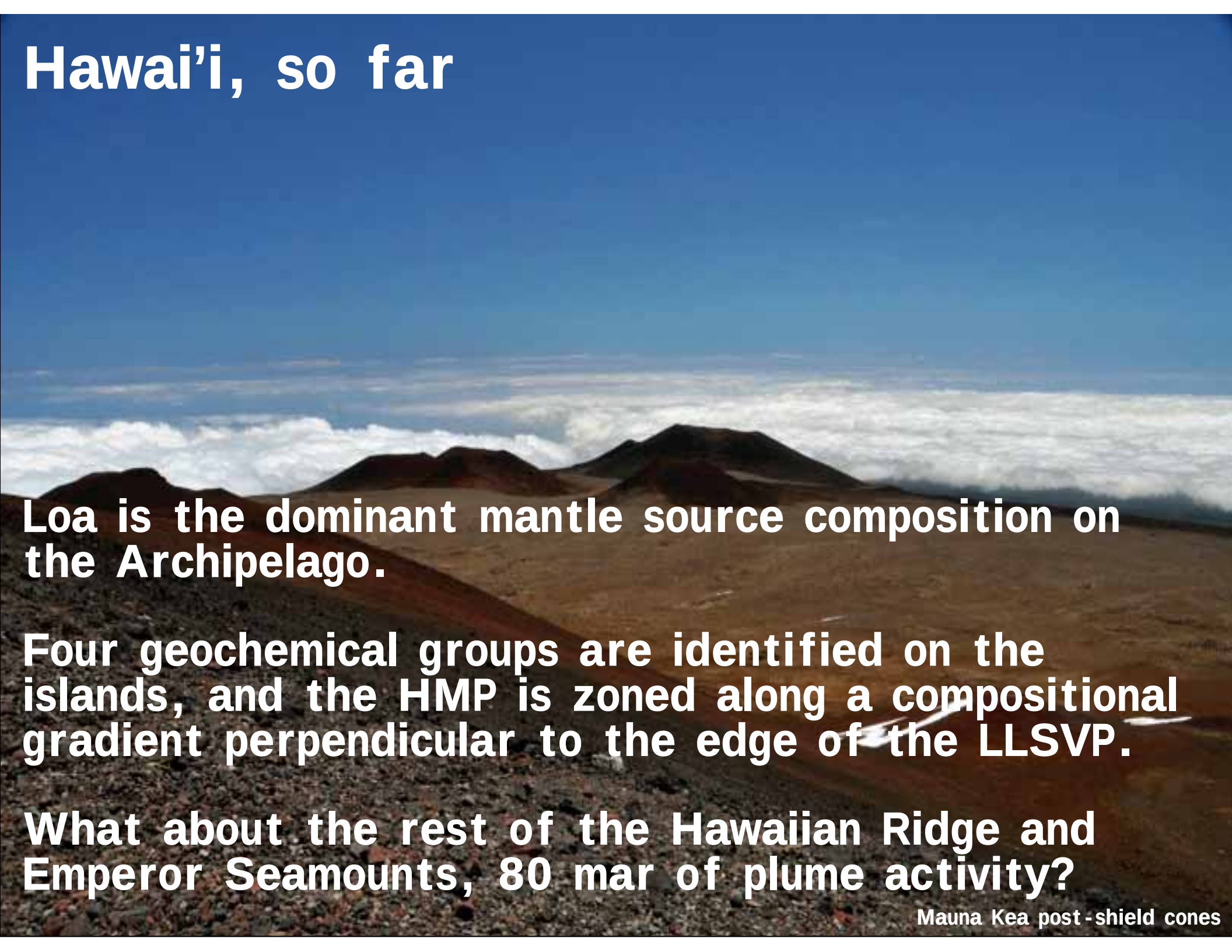


Hawai'i, so far

Loa is the dominant mantle source composition on the Archipelago.

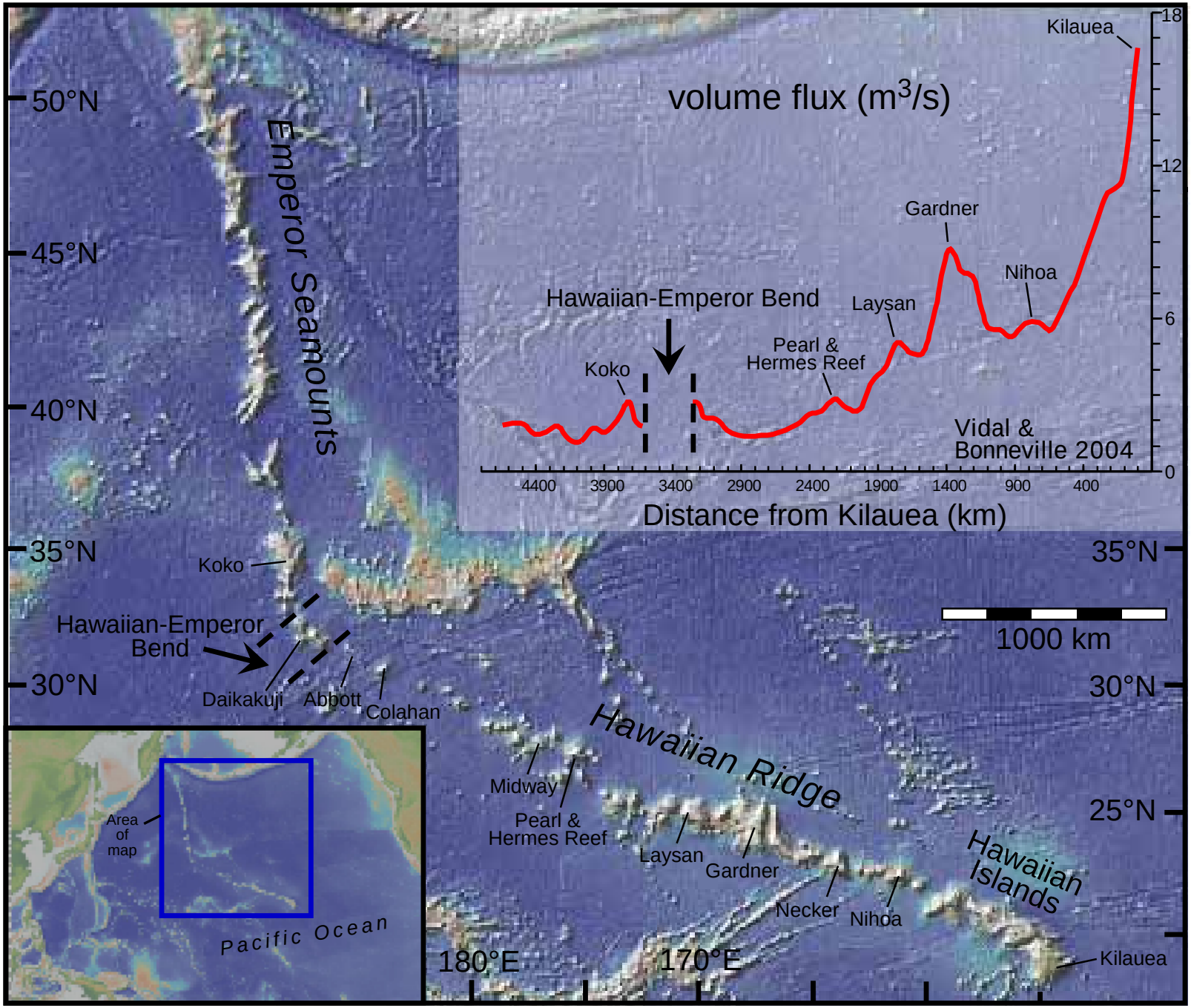
Four geochemical groups are identified on the islands, and the HMP is zoned along a compositional gradient perpendicular to the edge of the LLSVP.

What about the rest of the Hawaiian Ridge and Emperor Seamounts, 80 mar of plume activity?

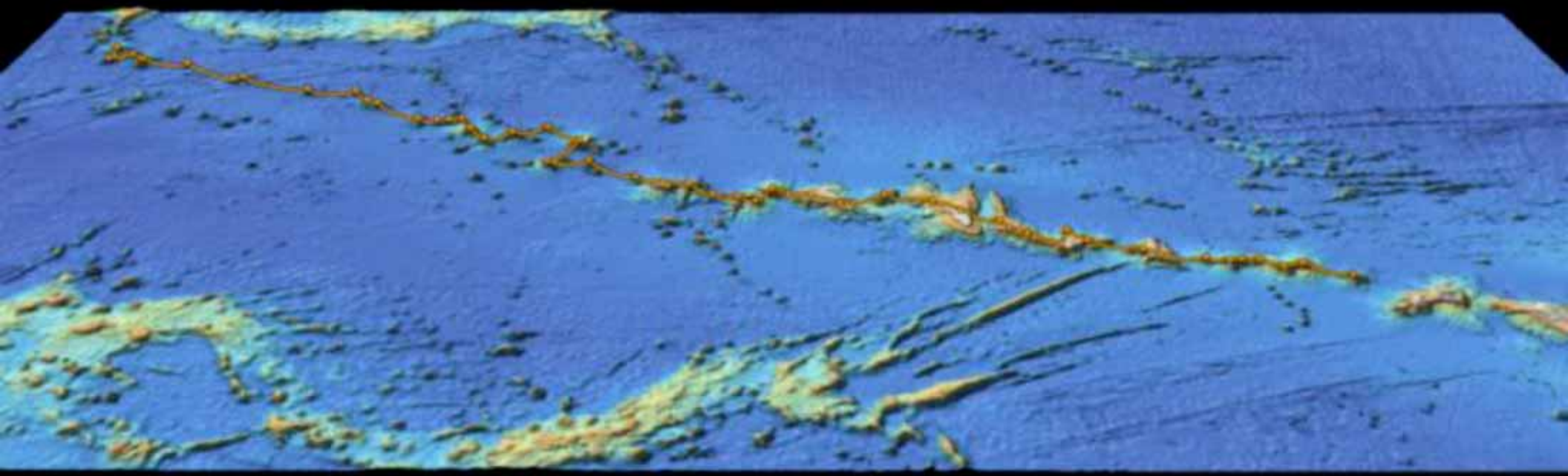


Mauna Kea post-shield cones

Hawaiian Ridge - Emperor Seamounts: 85 myr

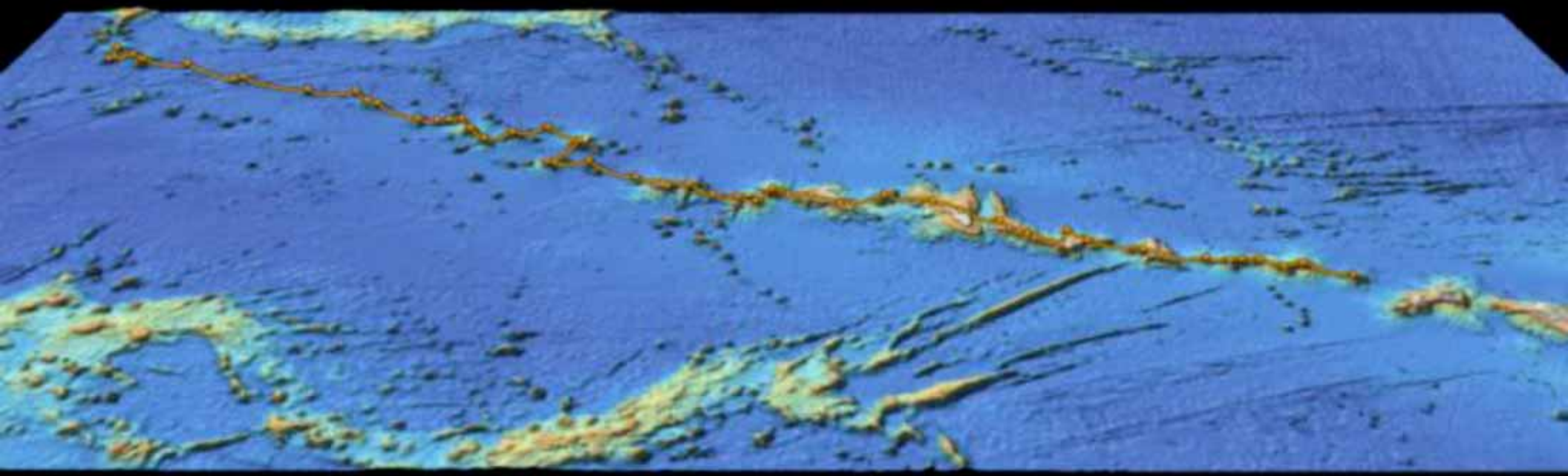


Northwestern Hawaiian Ridge Movie



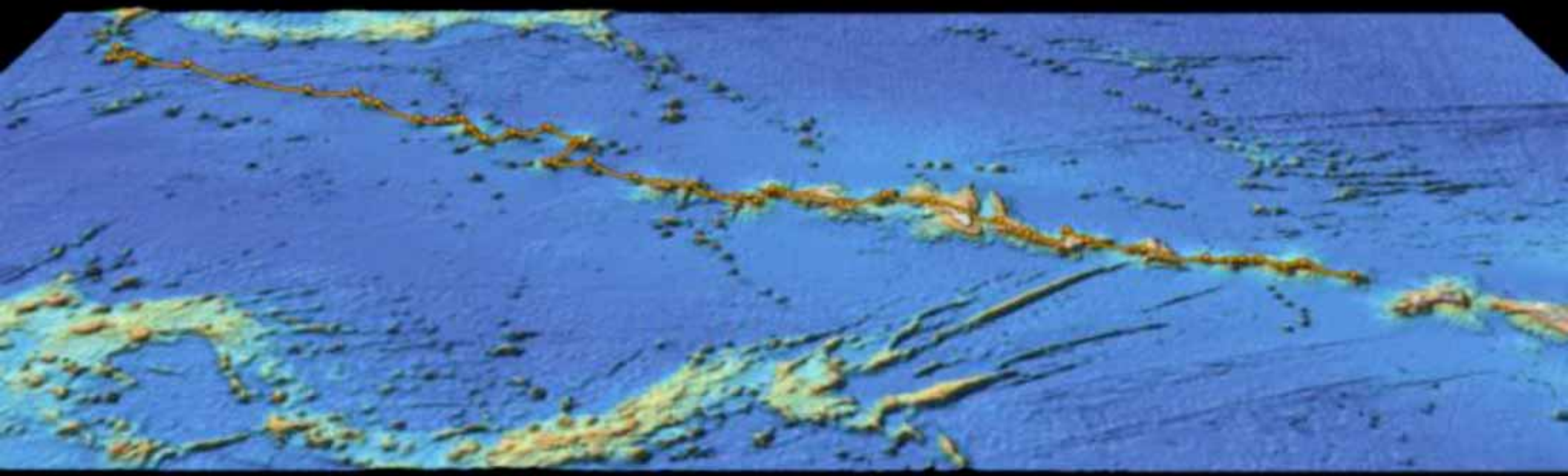
John Smith, SOEST

Northwestern Hawaiian Ridge Movie



John Smith, SOEST

Northwestern Hawaiian Ridge Movie



John Smith, SOEST

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

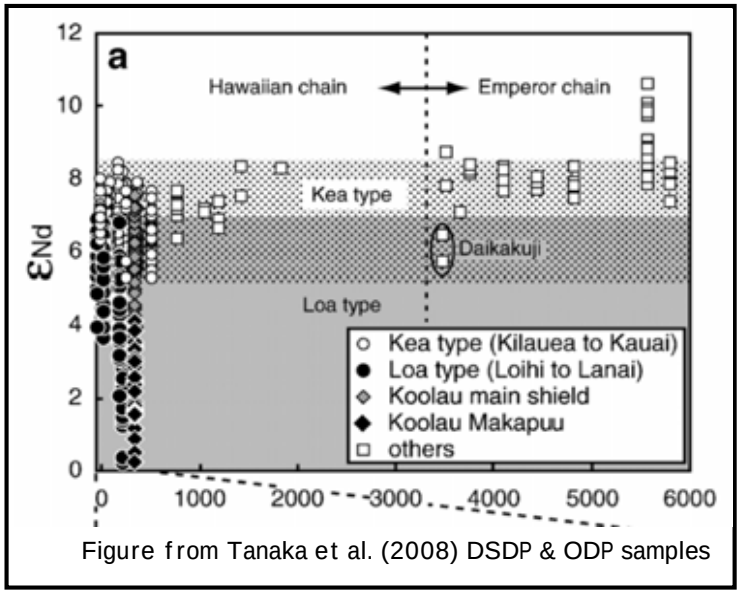
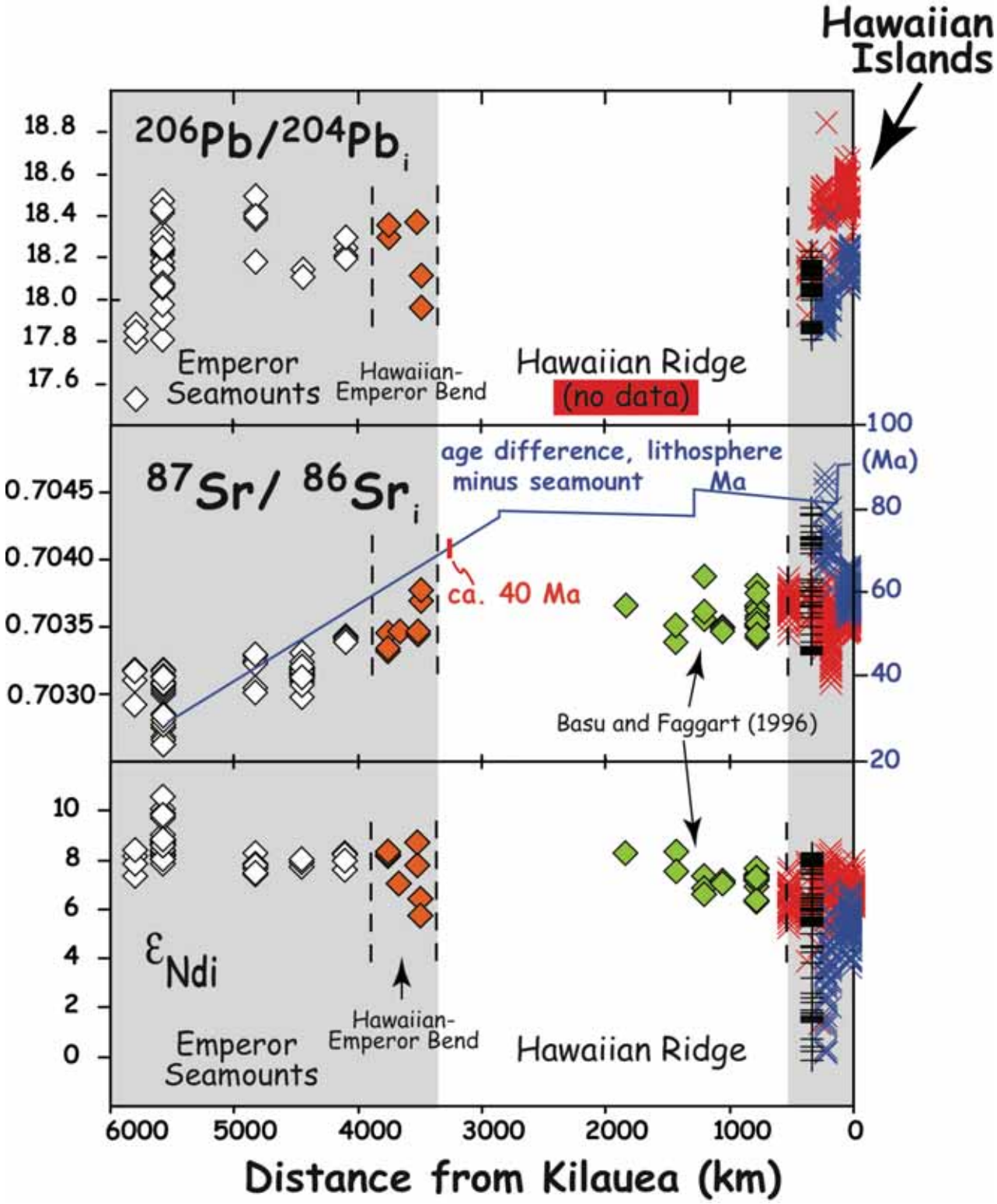
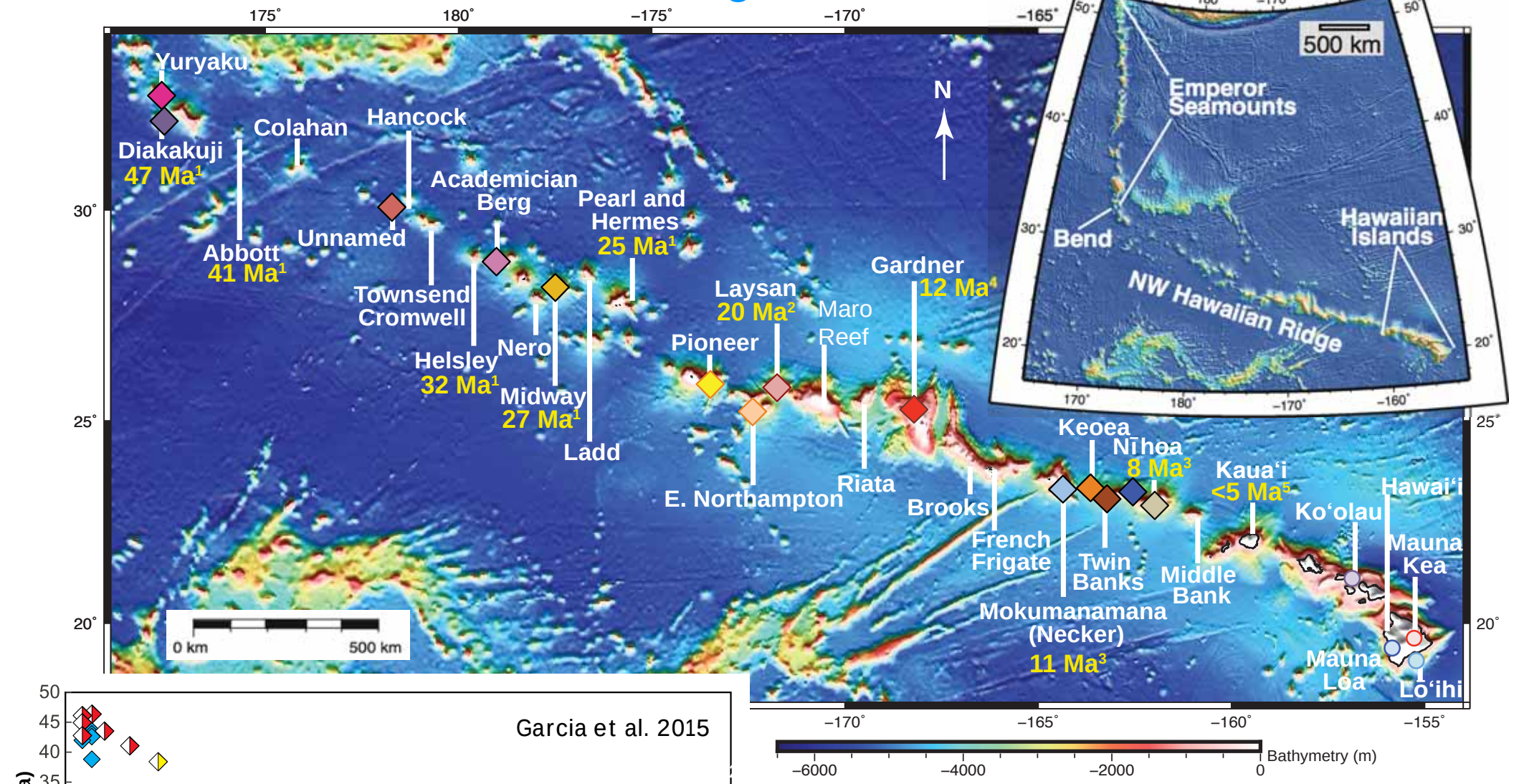
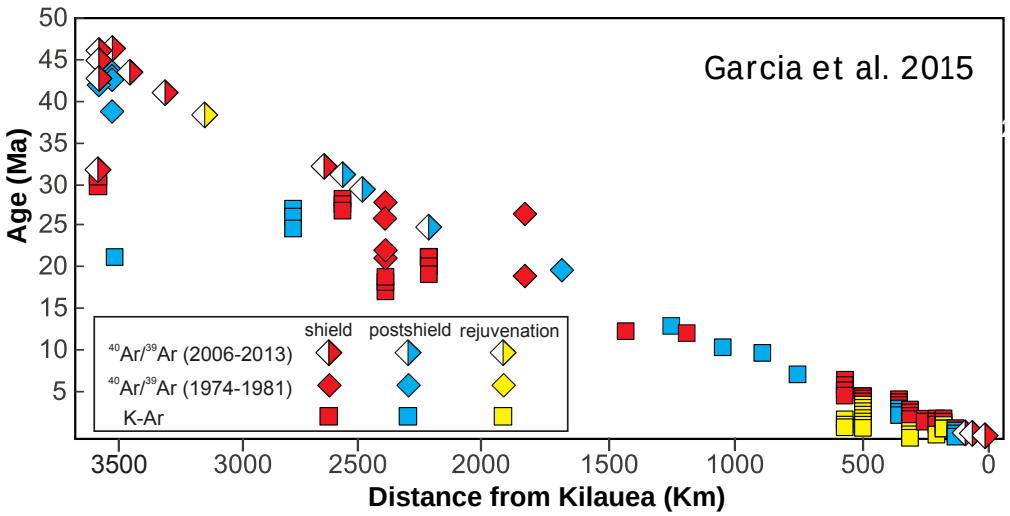


Figure from Tanaka et al. (2008) DSDP & ODP samples



Northwestern Hawaiian Ridge

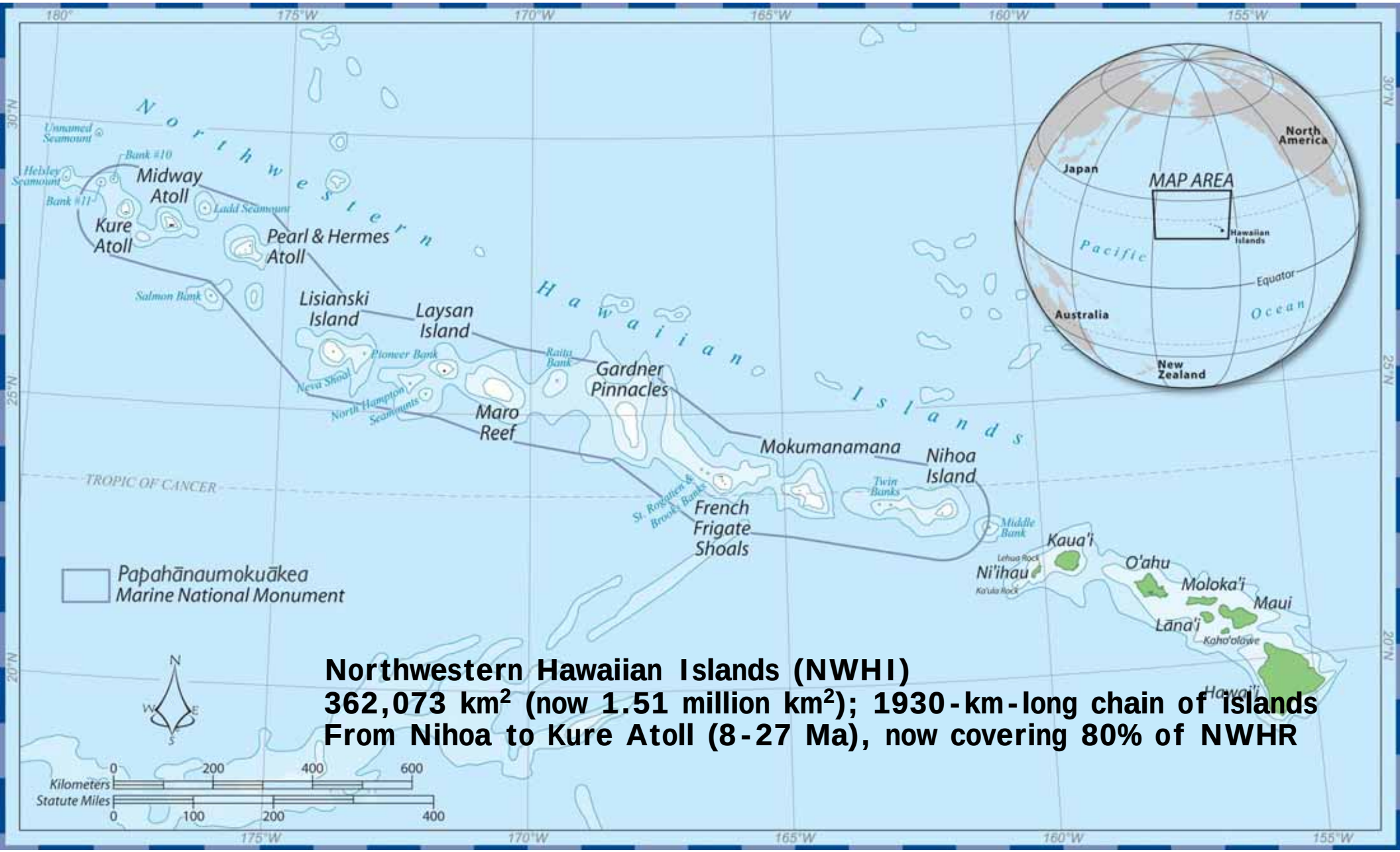




42 myr from the bend to the islands
24 shield-stage samples from
13 volcanoes

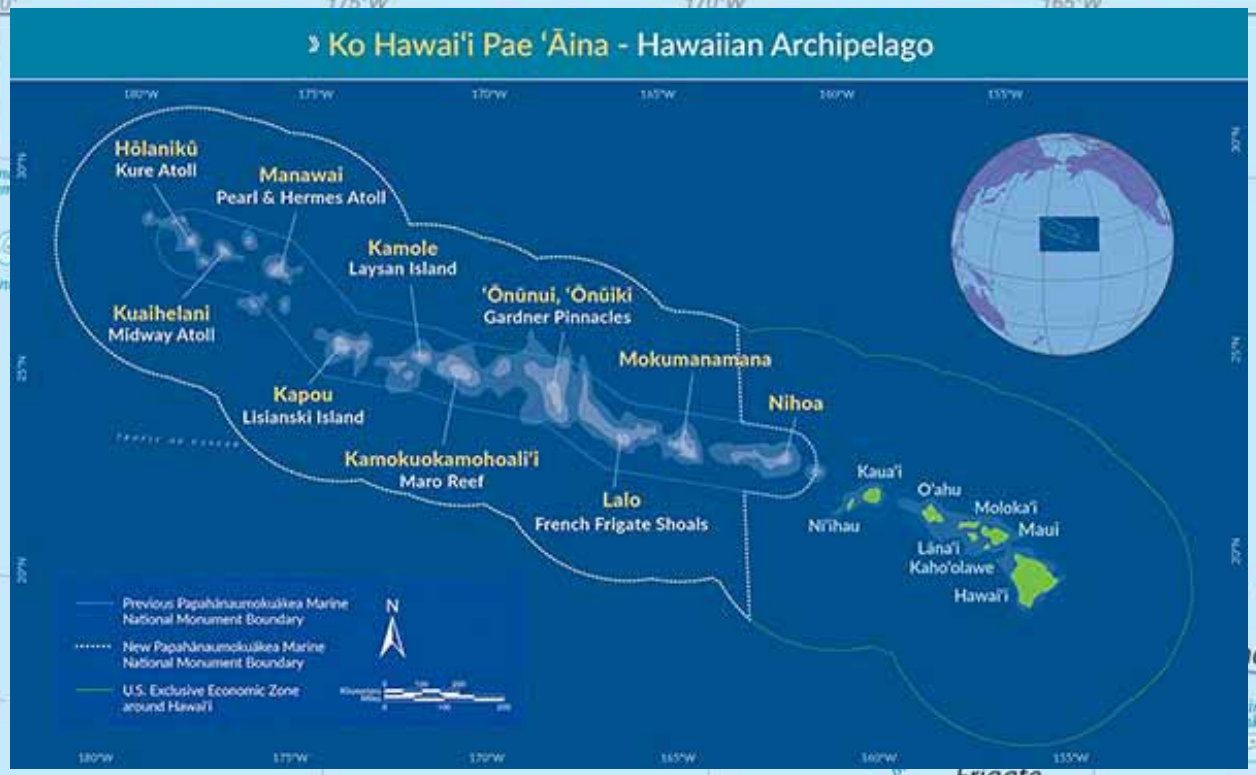
L. Harrison PhD Thesis

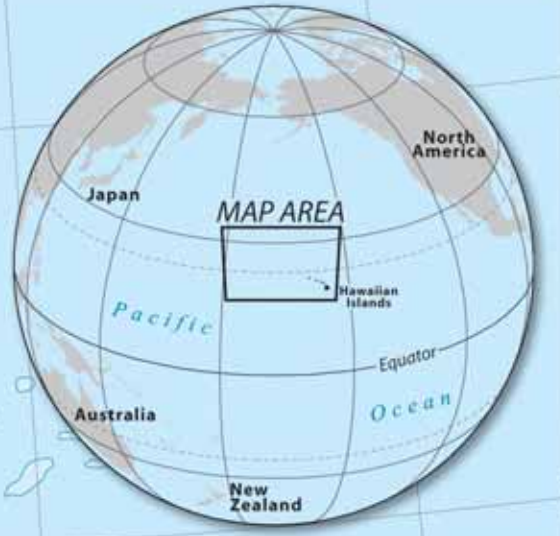
Papahānaumokuākea Marine National Monument
UNESCO World Heritage Site



Northwestern Hawaiian Islands (NWHI)
362,073 km² (now 1.51 million km²); 1930-km-long chain of islands
From Nihoa to Kure Atoll (8-27 Ma), now covering 80% of NWHR

Papahānaumokuākea Marine National Monument
UNESCO World Heritage Site





Papahānaumokuākea
Marine National Monument

Nihoa Island

Frigate Shoals

Middle Bank

Kaua'i

Ni'ihau

O'ahu

Moloka'i

Maui

Lāna'i

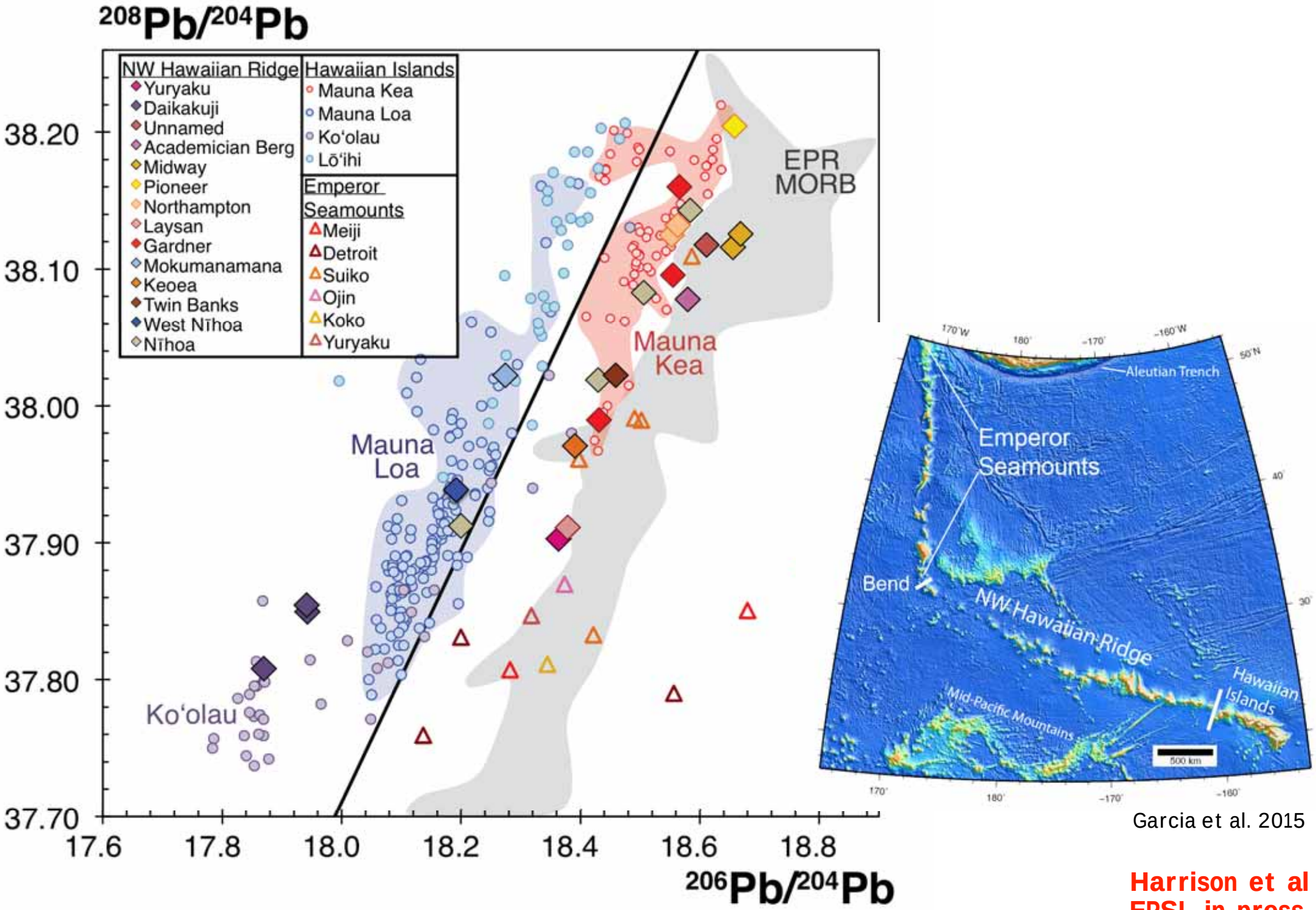
Kaho'olawe

Hawai'i

Northwestern Hawaiian Islands (NWHI)
362,073 km² (now 1.51 million km²); 1930-km-long chain of islands
From Nihoa to Kure Atoll (8-27 Ma), now covering 80% of NWHR

Kilometers 0 200 400 600
Statute Miles 0 100 200 400

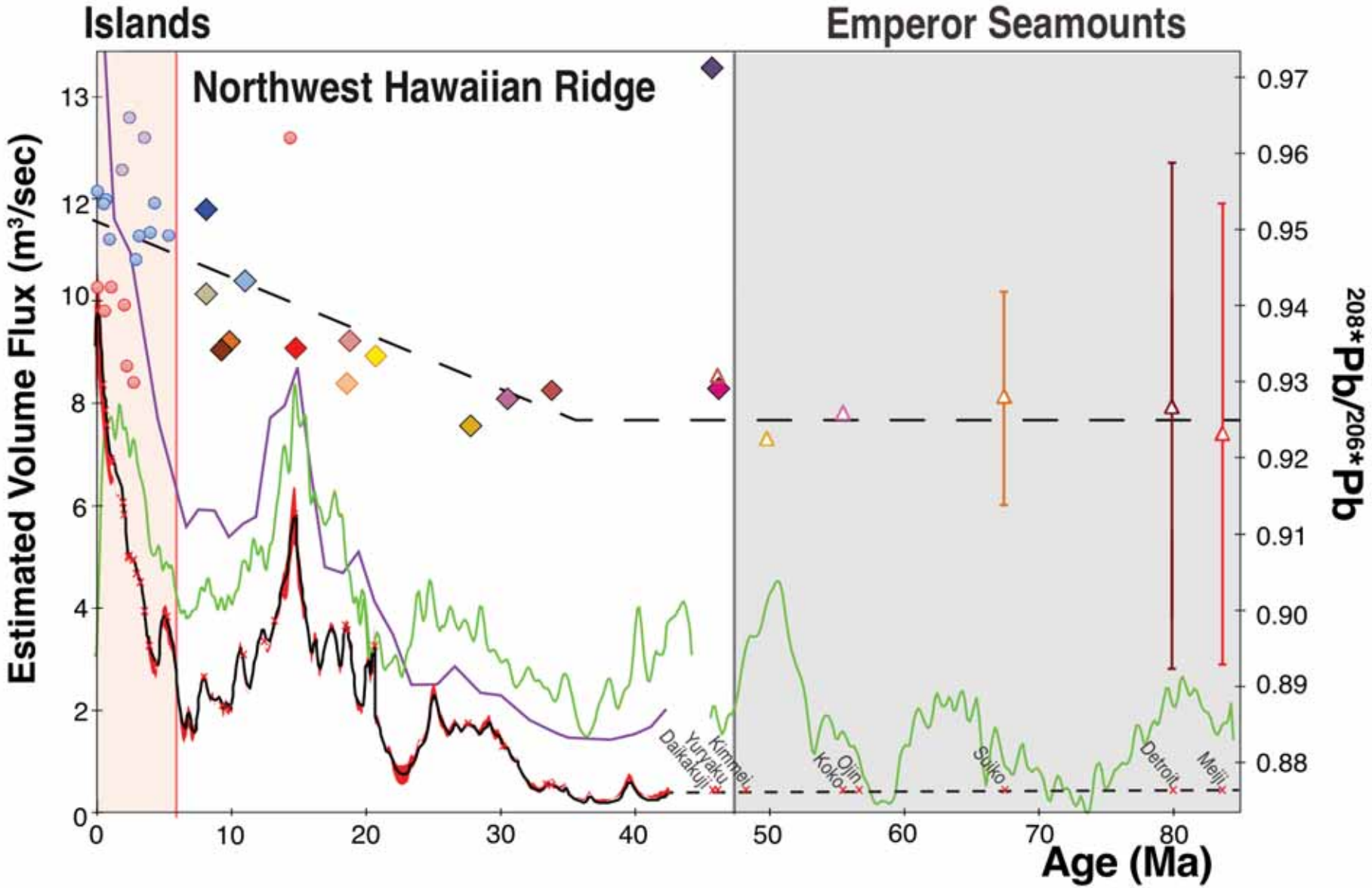
NWHR: Pb Isotope Systematics



Garcia et al. 2015

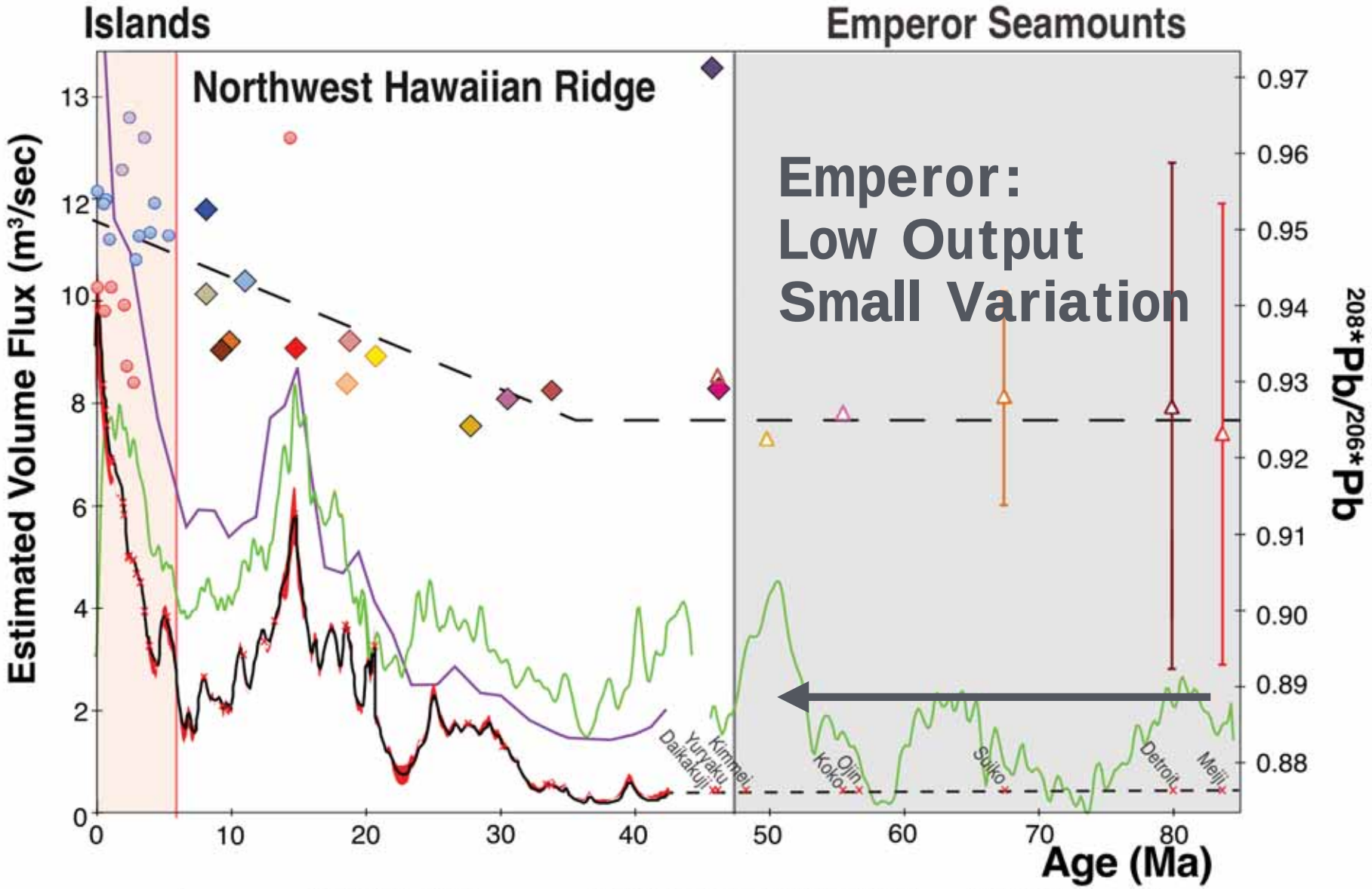
Harrison et al EPSL in press

NWHR: Pb Isotope Variations with Plume Magmatic Flux and Distance from Kilauea



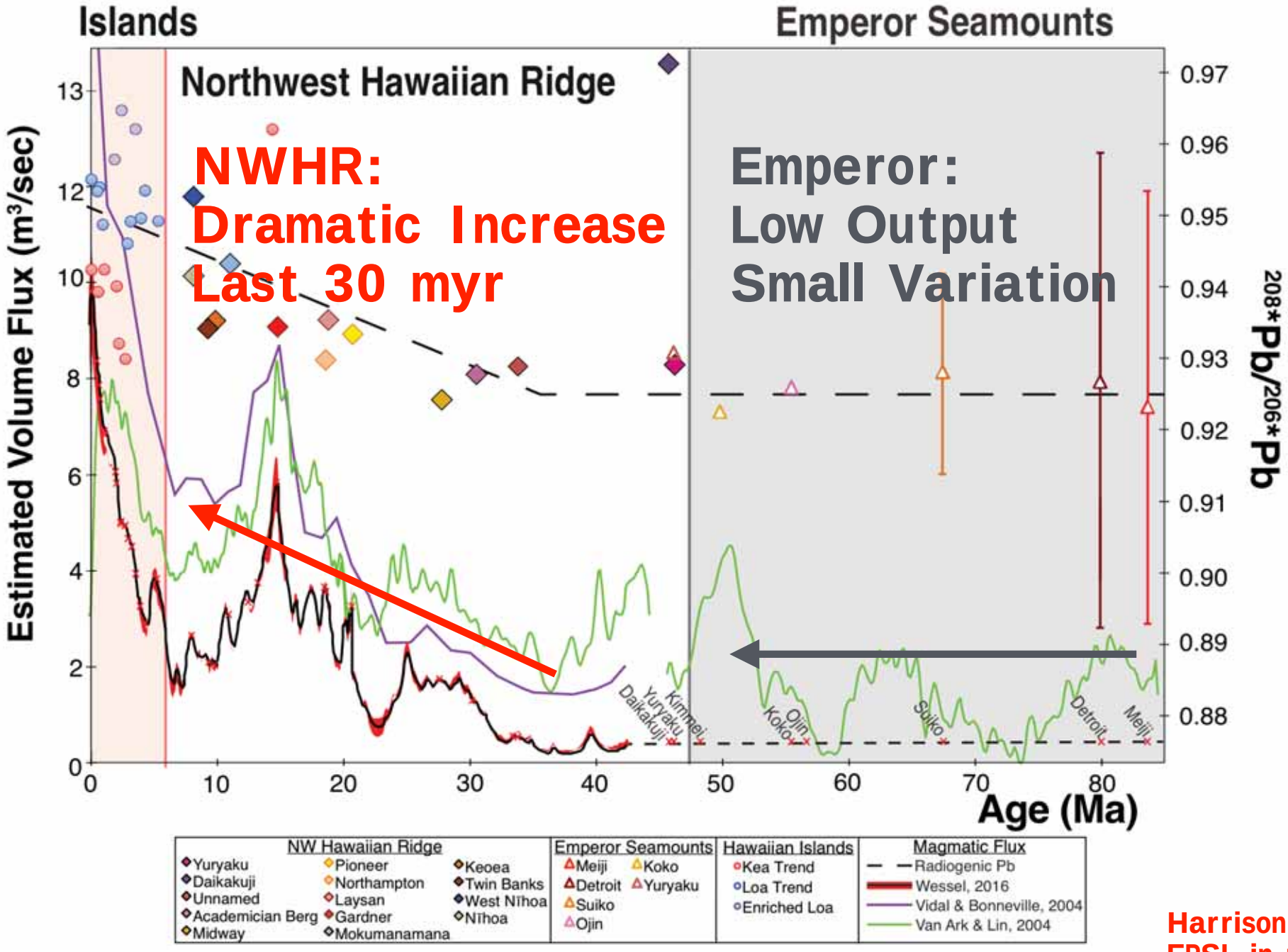
Harrison et al
EPSL in press

NWHR: Pb Isotope Variations with Plume Magmatic Flux and Distance from Kilauea



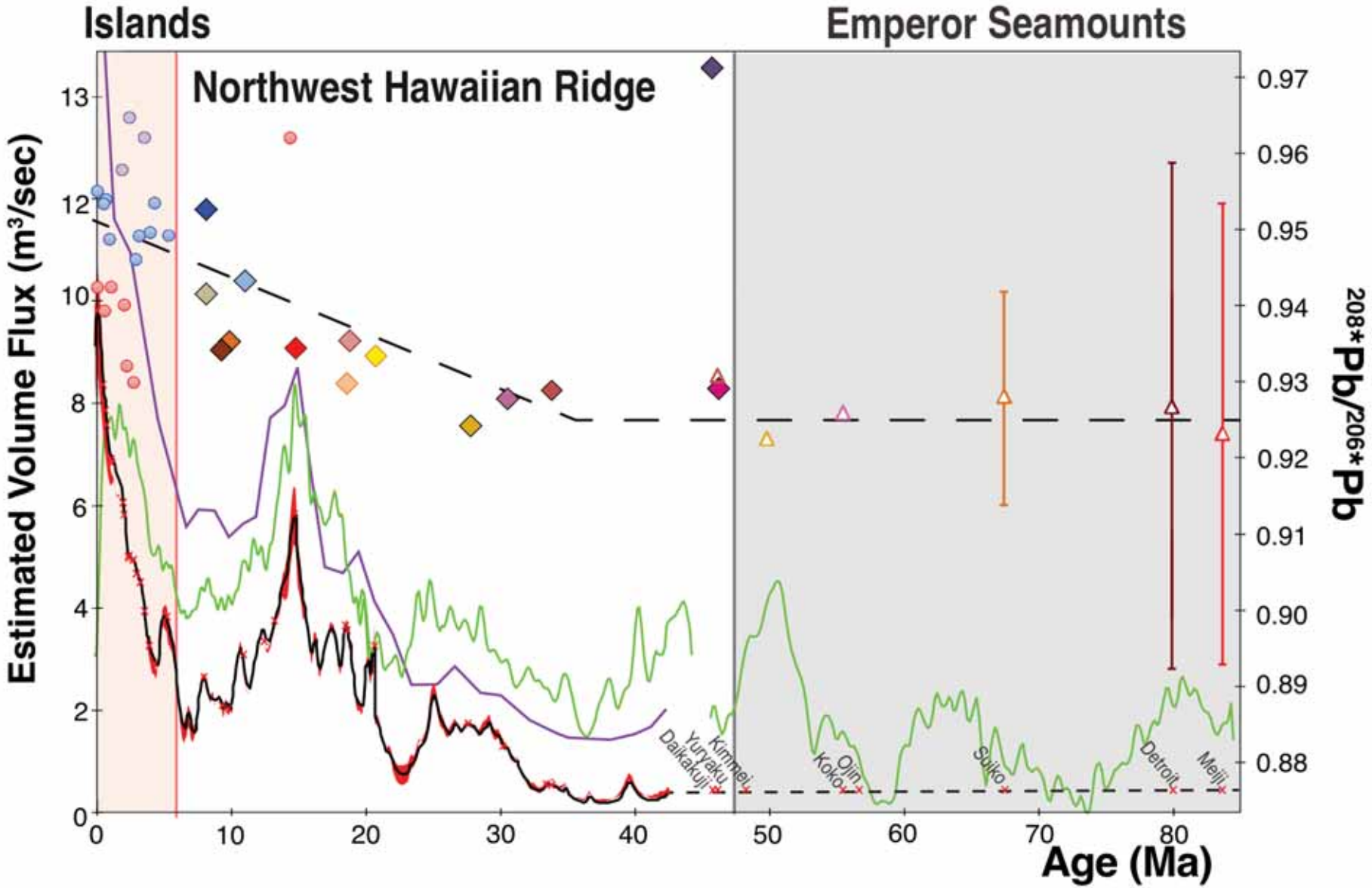
Harrison et al
EPSL in press

NWHR: Pb Isotope Variations with Plume Magmatic Flux and Distance from Kilauea



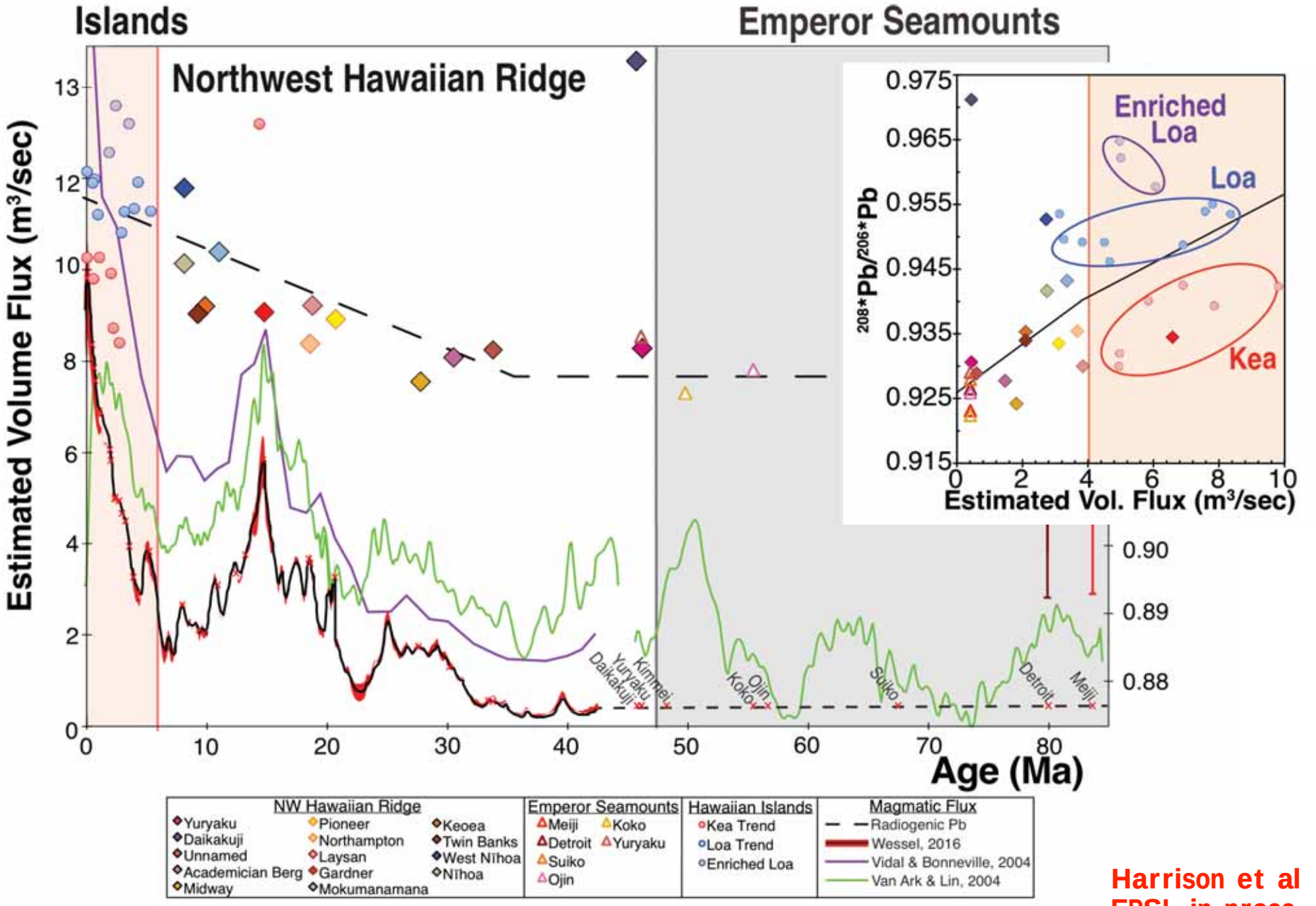
Harrison et al
EPSL in press

NWHR: Pb Isotope Variations with Plume Magmatic Flux and Distance from Kilauea



Harrison et al
EPSL in press

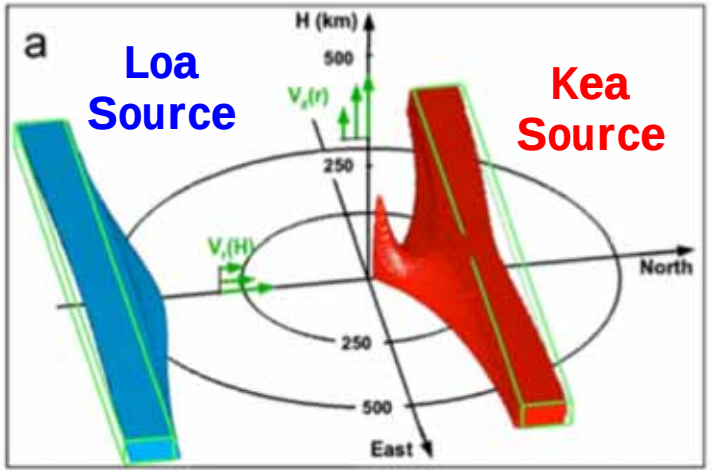
NWHR: Pb Isotope Variations with Plume Magmatic Flux and Distance from Kilauea



Harrison et al
EPSL in press

Sampling lower mantle heterogeneity accounts for Loa trend arrival

2.5 Ma



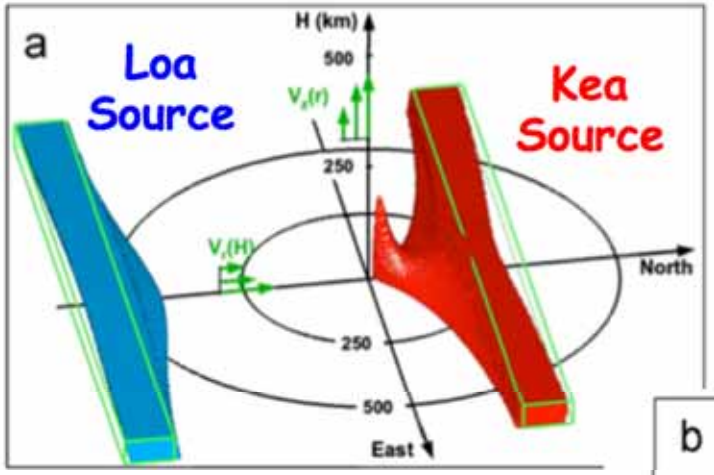
Pacific LLSVP

Ambient Pacific Mantle

Figure modified from Farnetani et al., 2012

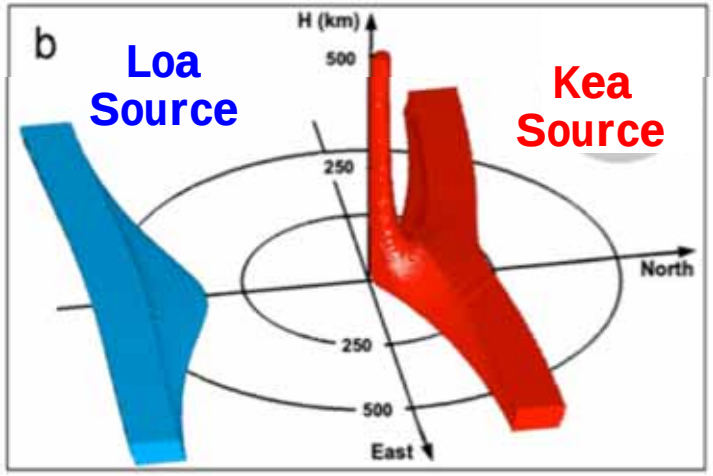
Sampling lower mantle heterogeneity accounts for Loa trend arrival

2.5 Ma



Pacific LLSVP | **Ambient Pacific Mantle**

4.5 Ma



Pacific LLSVP | **Ambient Pacific Mantle**

Figure modified from Farnetani et al., 2012

Sampling lower mantle heterogeneity accounts for Loa trend arrival

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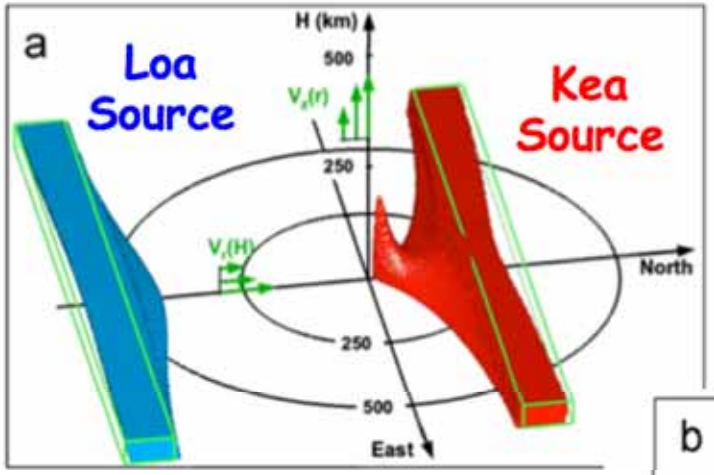
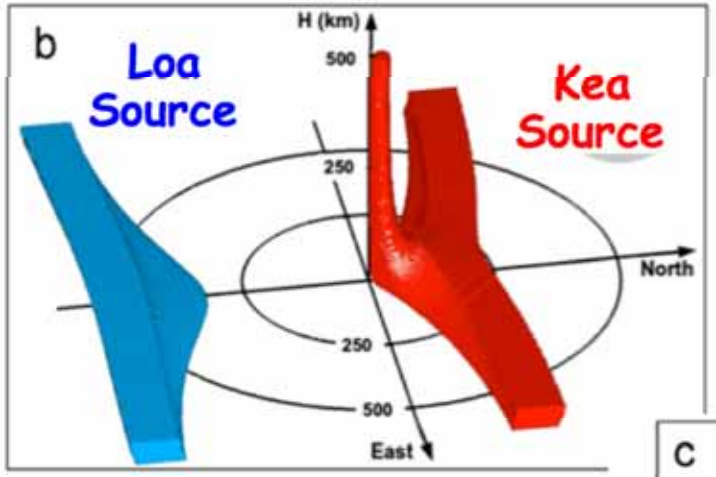


Pacific LLSVP | **Ambient Pacific Mantle**

4.5 Ma



Pacific LLSVP | **Ambient Pacific Mantle**

11 Ma

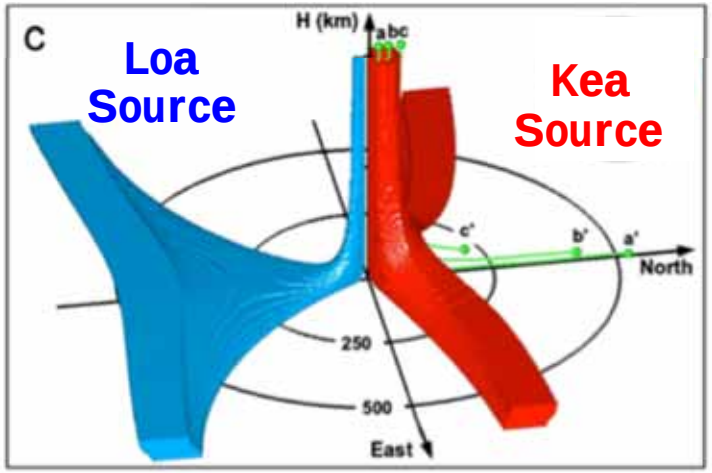
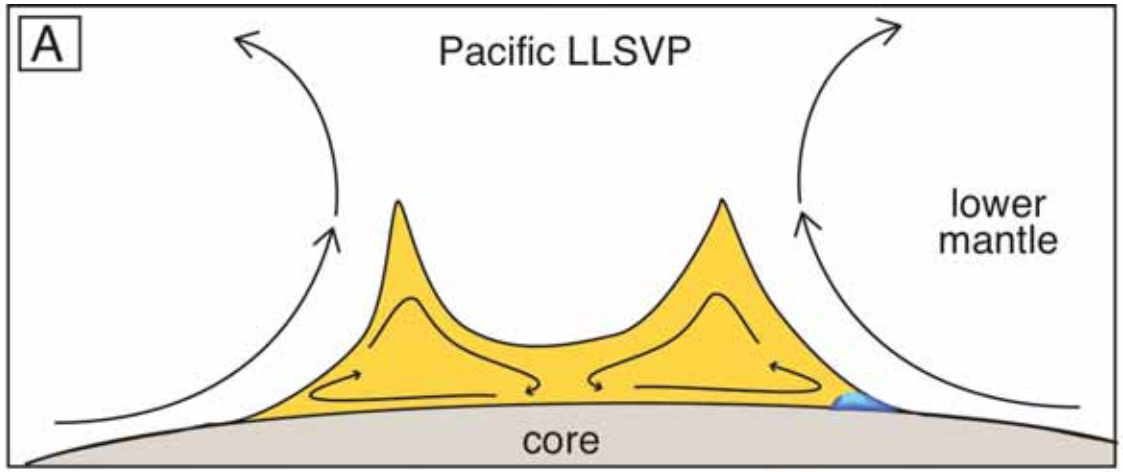


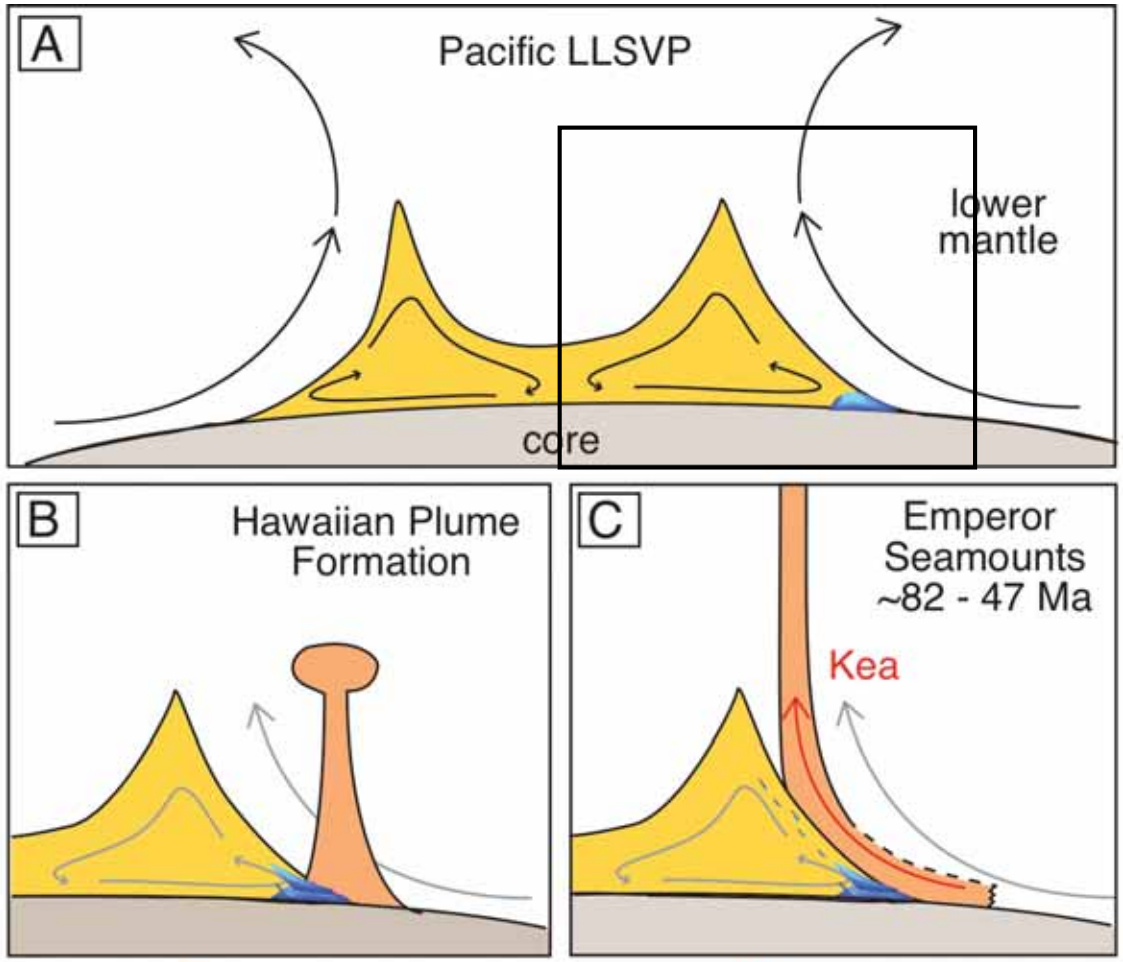
Figure modified from Farnetani et al., 2012

Evolution of the Hawaiian Plume Source at the CMB



Harrison et al
EPSL in press

Evolution of the Hawaiian Plume Source at the CMB



Harrison et al
EPSL in press

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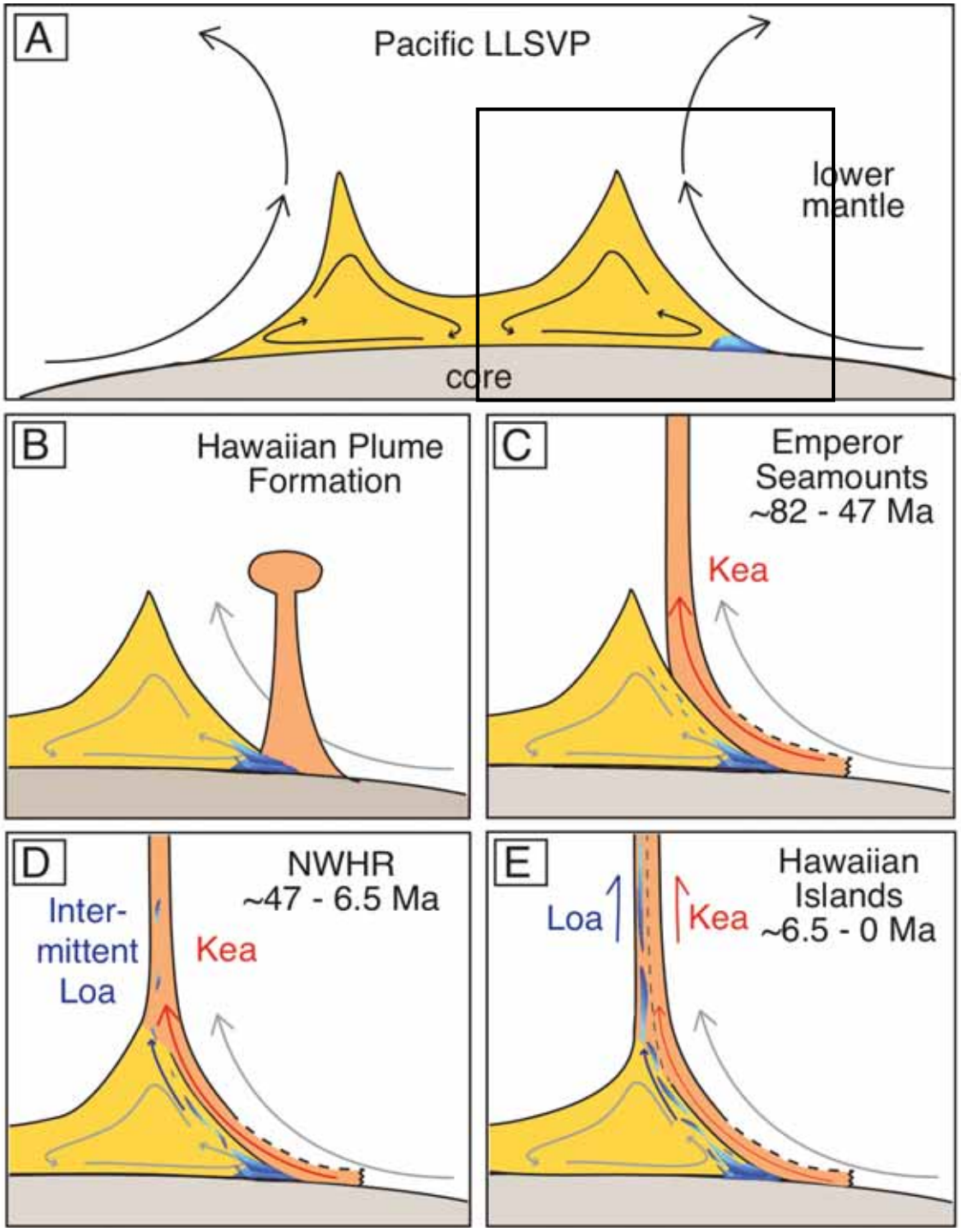
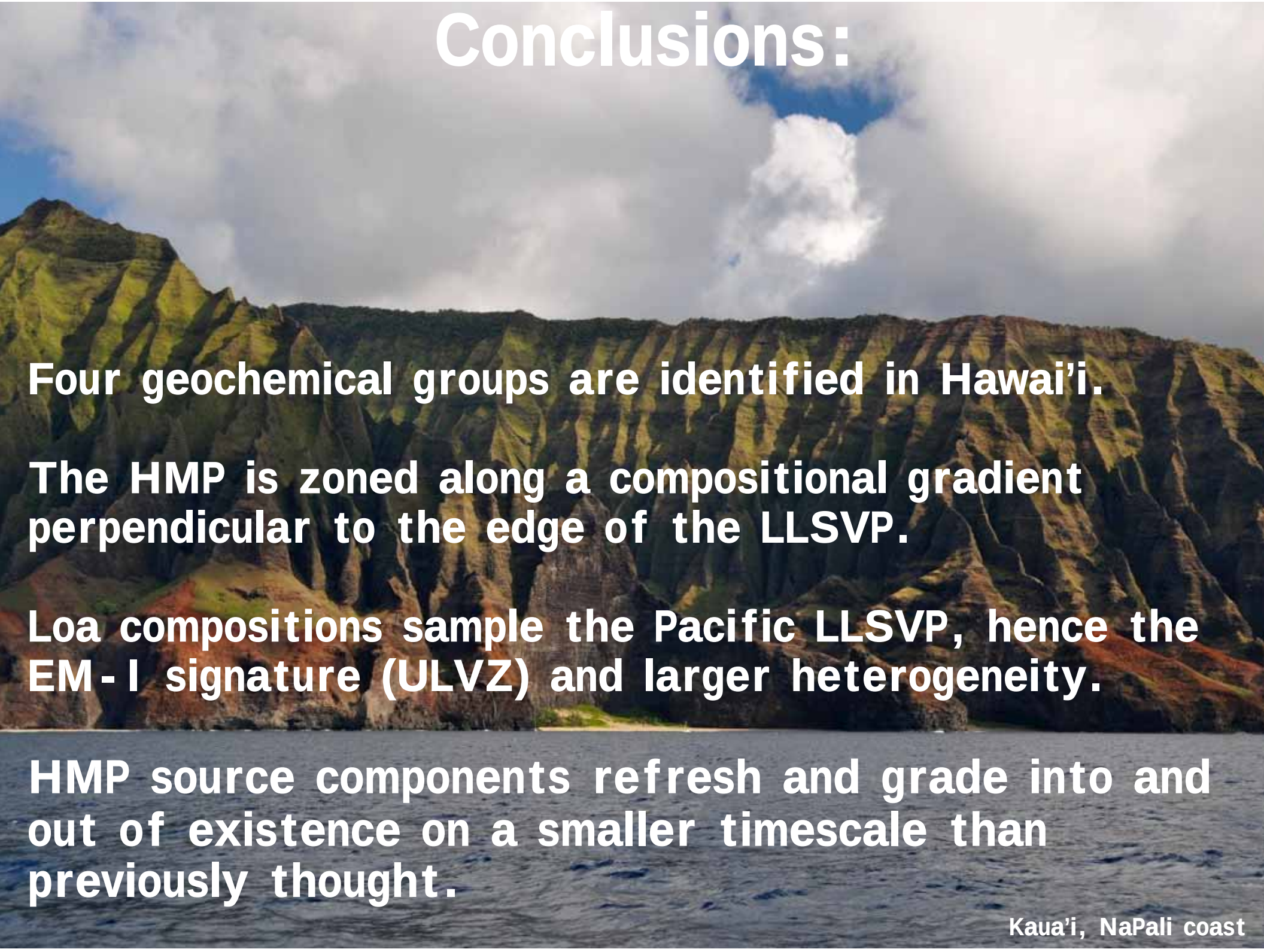


Harrison et al
EPSL in press

Conclusions:



Four geochemical groups are identified in Hawai'i.

The HMP is zoned along a compositional gradient perpendicular to the edge of the LLSVP.

Loa compositions sample the Pacific LLSVP, hence the EM-I signature (ULVZ) and larger heterogeneity.

HMP source components refresh and grade into and out of existence on a smaller timescale than previously thought.

Kaua'i, NaPali coast

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Thank You !

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