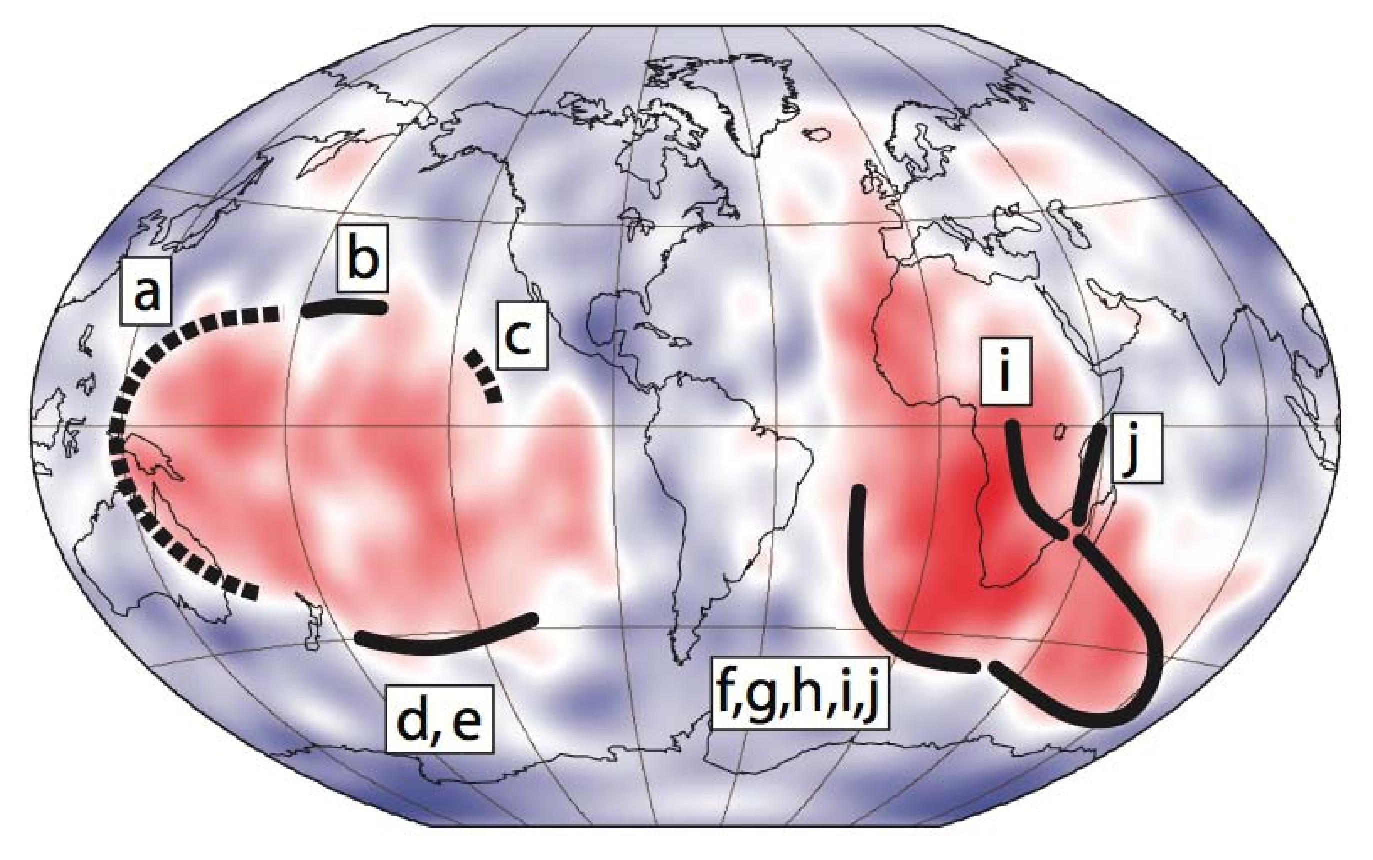
Formation of mantle domains in the Hadean and Archaean: Evidence for deep mantle preservation in oceanic lavas

Matt Jackson

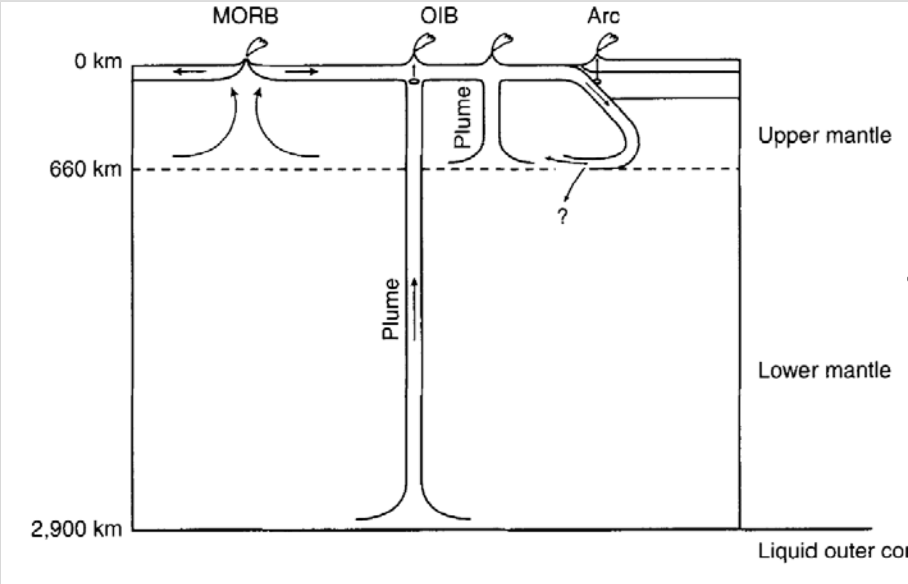
Boston University



Garnero et al. (2007)

BOSTON UNIVERSITY

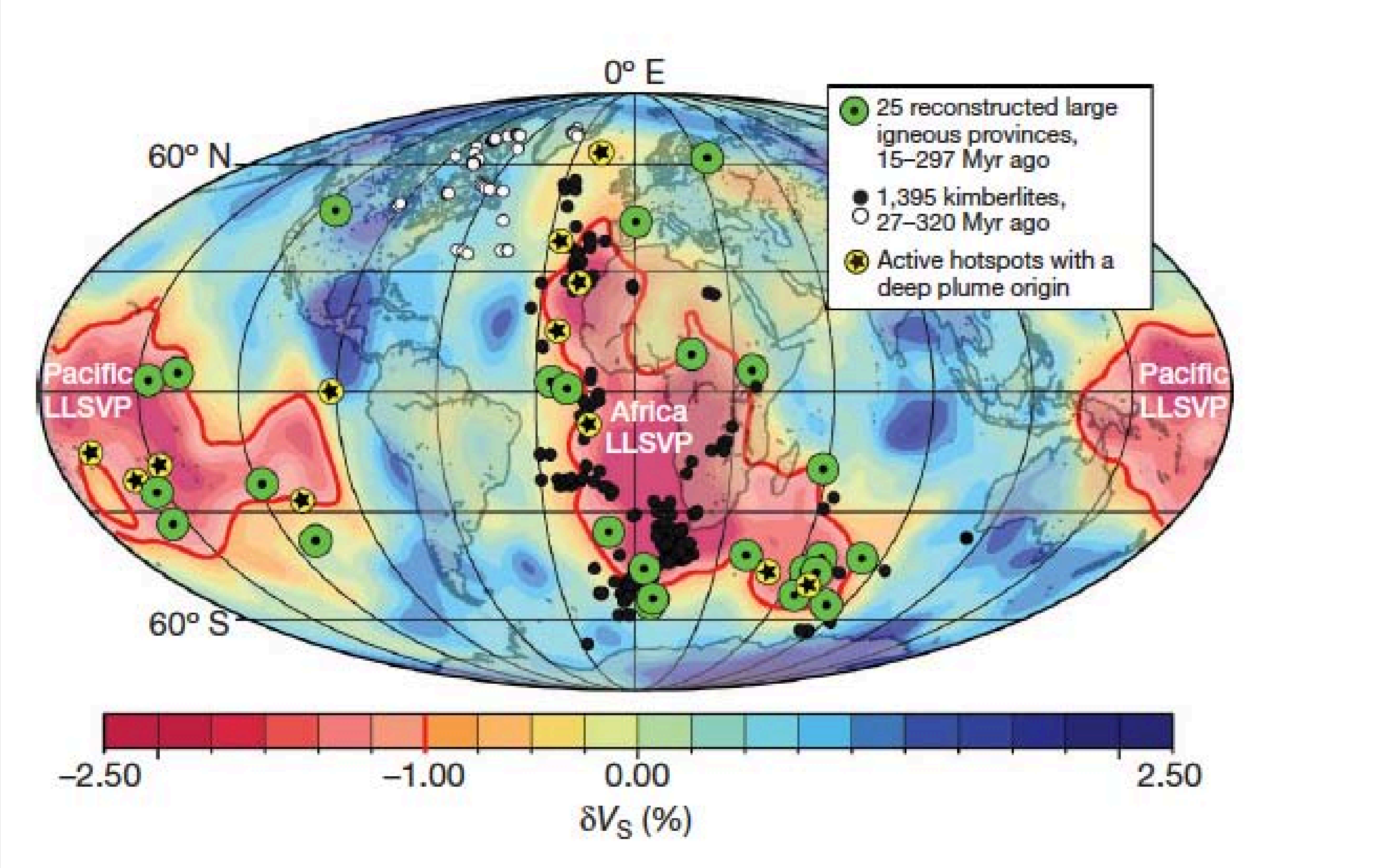
Ocean island lavas provide a "window" to the mantle, an otherwise virtually inaccessible reservoir



Hofmann, 1997

Fundamental objective: Use composition of lavas erupted at surface to say something about composition of (deep) mantle.

LLSVP’s

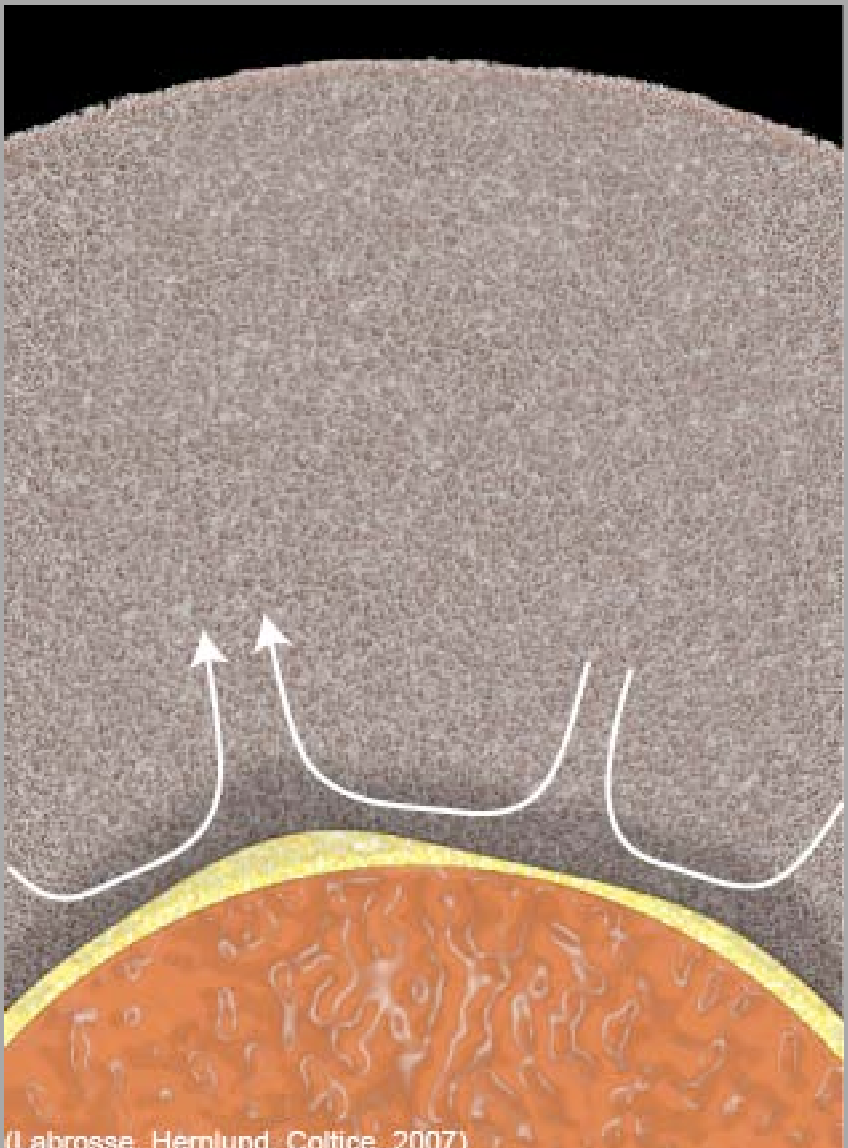


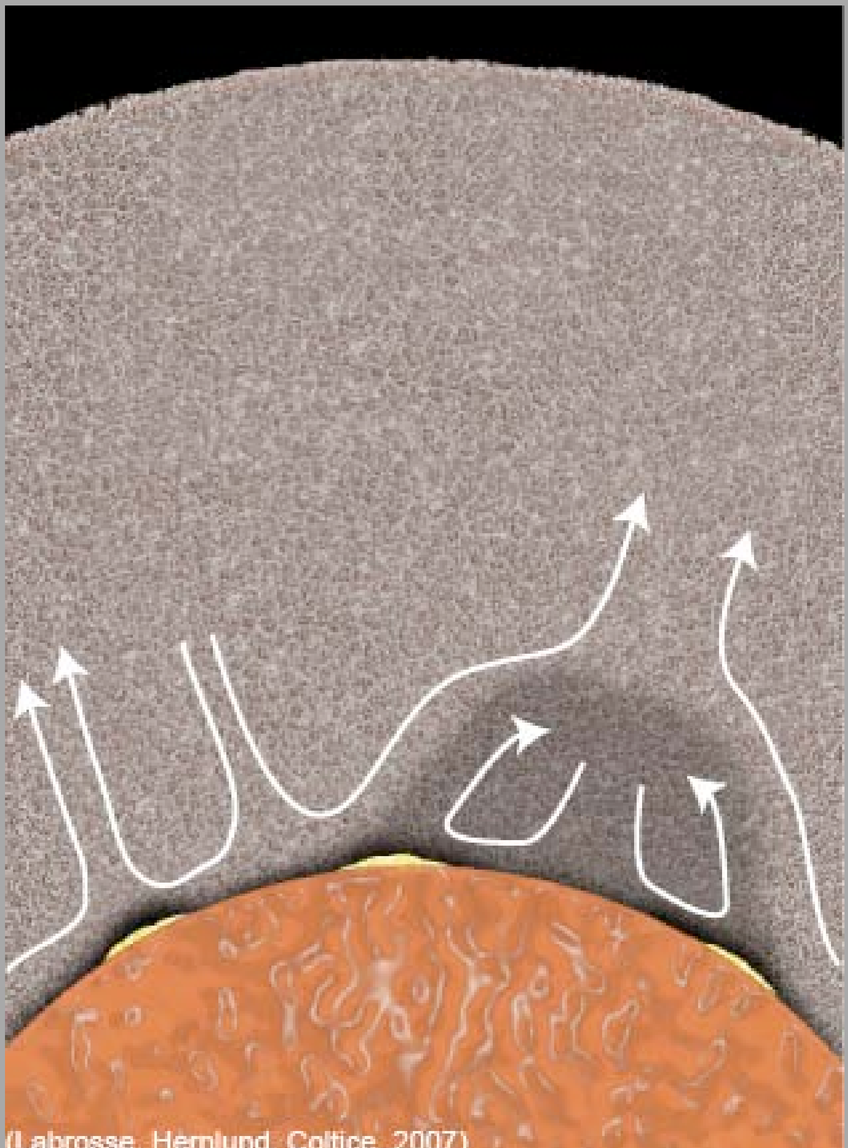
Torsvik et al. (Nature, 2010)

Make-up of LLSVP’s, 2 primary hypotheses:
-LLSVP’s host primitive mantle material.
-LLSVP’s are host to slab “graveyard”.

A crystallizing dense magma ocean at the base of the Earth's mantle

S. Labrosse[1], J. W. Hernlund[2]† & N. Coltice[1,3]





Crystallization of a basal magma ocean recorded by Helium and Neon

Nicolas Coltice [a,*], Manuel Moreira [b,d], John Hernlund [c], Stéphane Labrosse [a,d]

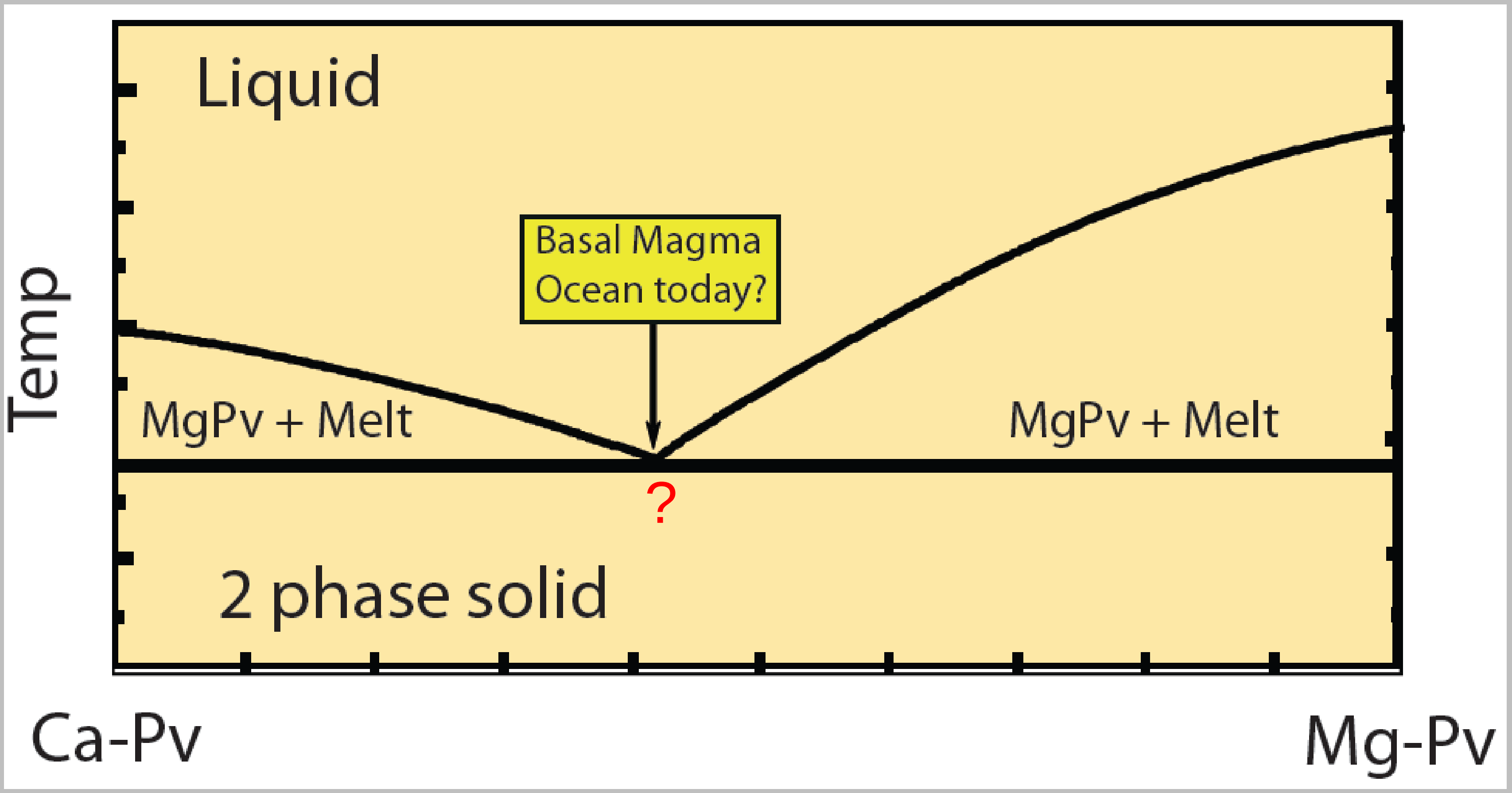
- Primordial He and Ne in the LLSVP’s?
- Can we link He and Ne to the deepest mantle?
- If so, how old are the LLSVP’s?

Primordial helium in Earth's mantle?

- Helium in the Earth's mantle:
  - -Two isotopes: ^3He (lower abundance) and ^4He (greater abundance)
  - -U and Th decay to Pb via alpha decay (^4He nuclei production)
  - -Little ^3He produced in the earth (mostly primordial)
  - -Therefore, $^3He/^4He$ in the earth decreases with time.
  - -Absolute $^3He/^4He$ ratios in the solar system are small (10^{-3} to 10^{-8}), so we normalize to $^3He/^4He$ ratio in atmosphere (Ra, 1.38×10^{-6}).

- The sun (solar wind) and the atmosphere of Jupiter have high $^3He/^4He$. High $^3He/^4He$ is thought to be primordial.

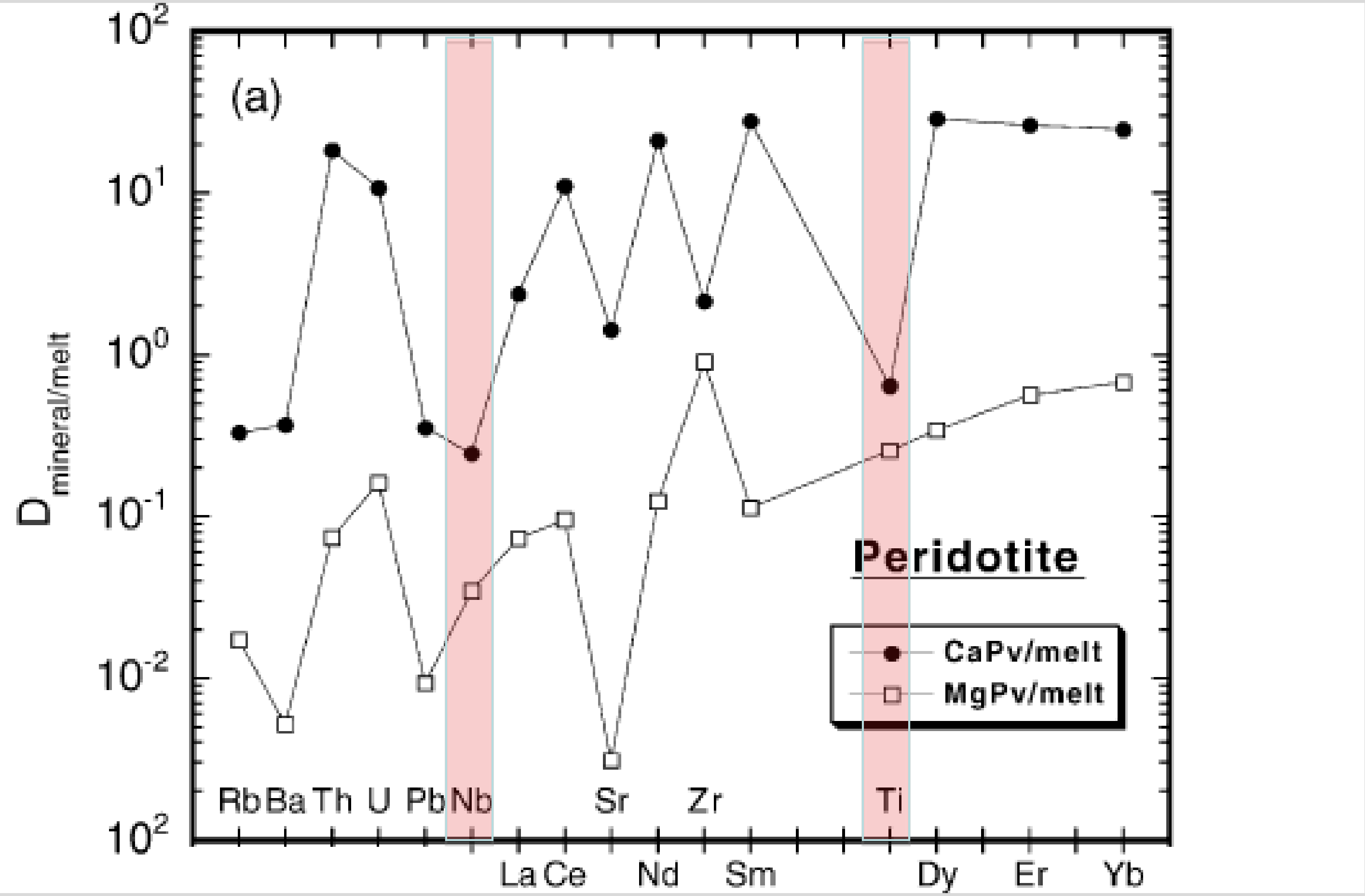
Eutectic between Ca-Pv and Mg-Pv?



Ca-perovskite is the primary carrier of geochemically important trace elements in the deep mantle and has key “fingerprints”.

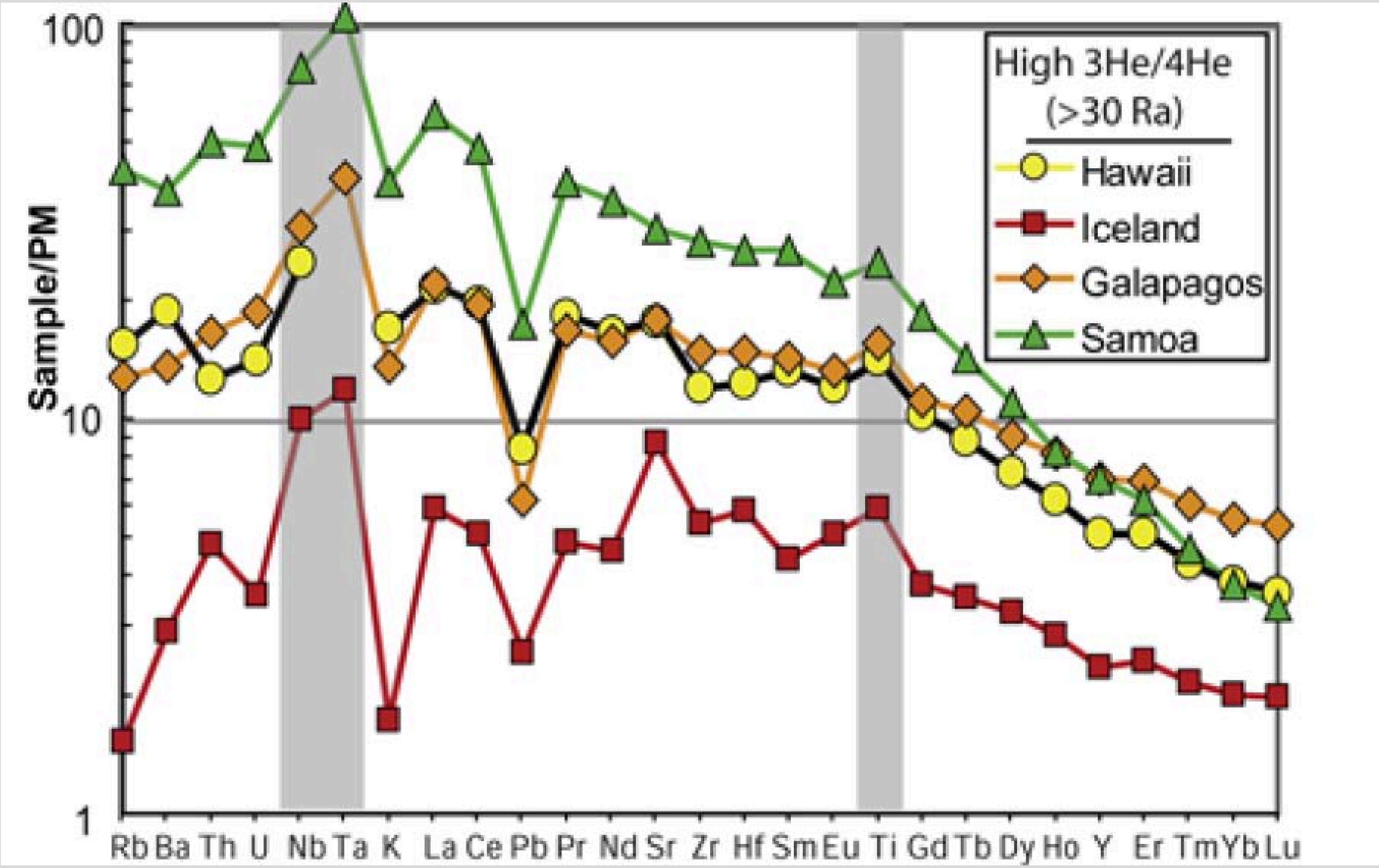
Trace element partitioning in Earth's lower mantle and implications for geochemical consequences of partial melting at the core–mantle boundary

Kei Hirose[a,*], Nobumichi Shimizu[b], Wim van Westrenen[c,d], Yingwei Fei[c]



Melt equilibrated with Ca-perovskite could have positive Ti, Nb (and Ta) anomalies

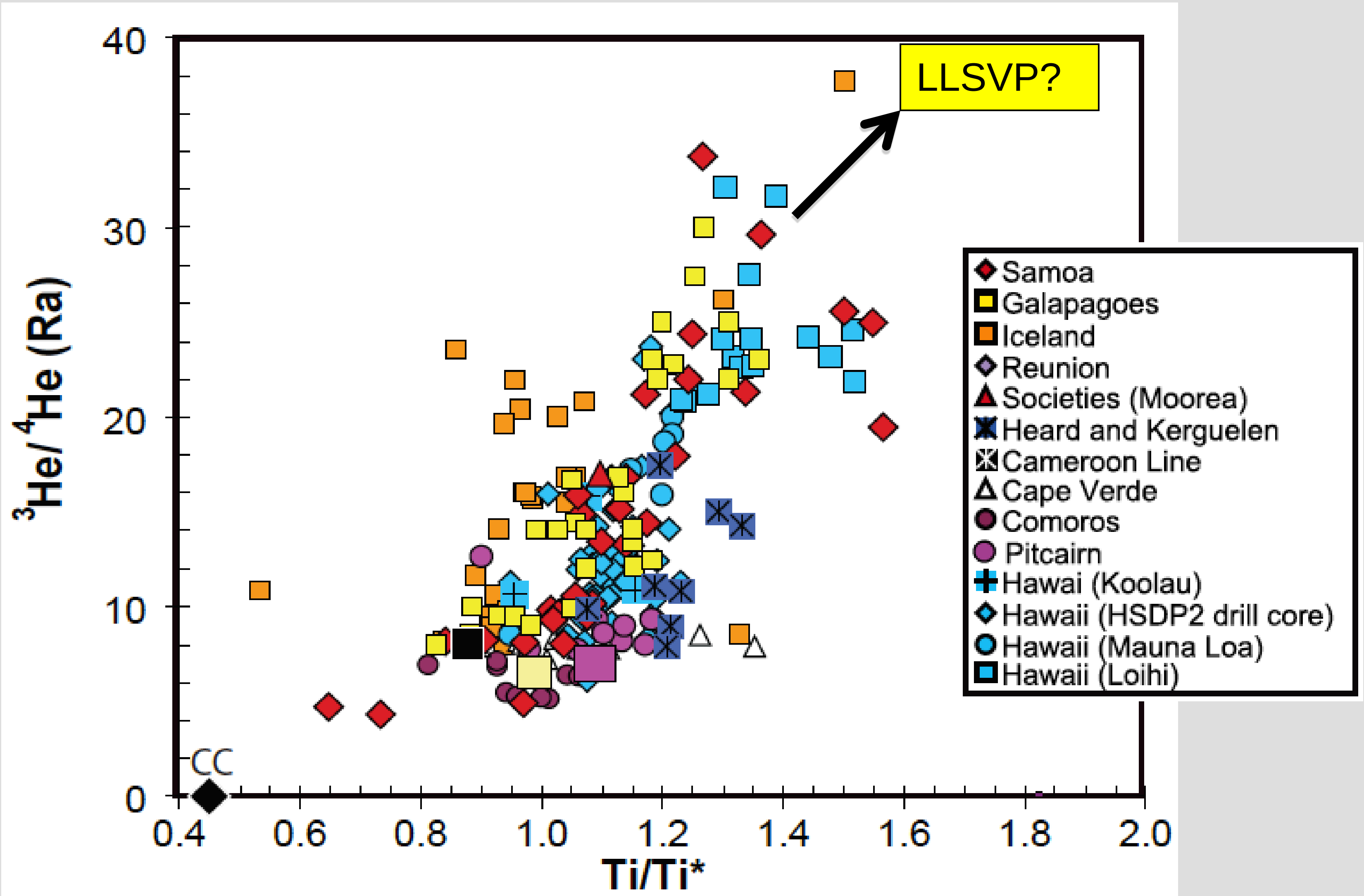
Globally elevated titanium, tantalum, and niobium (TITAN) in ocean island basalts with high $^3He/^4He$



Jackson et al, G-cubed 2008

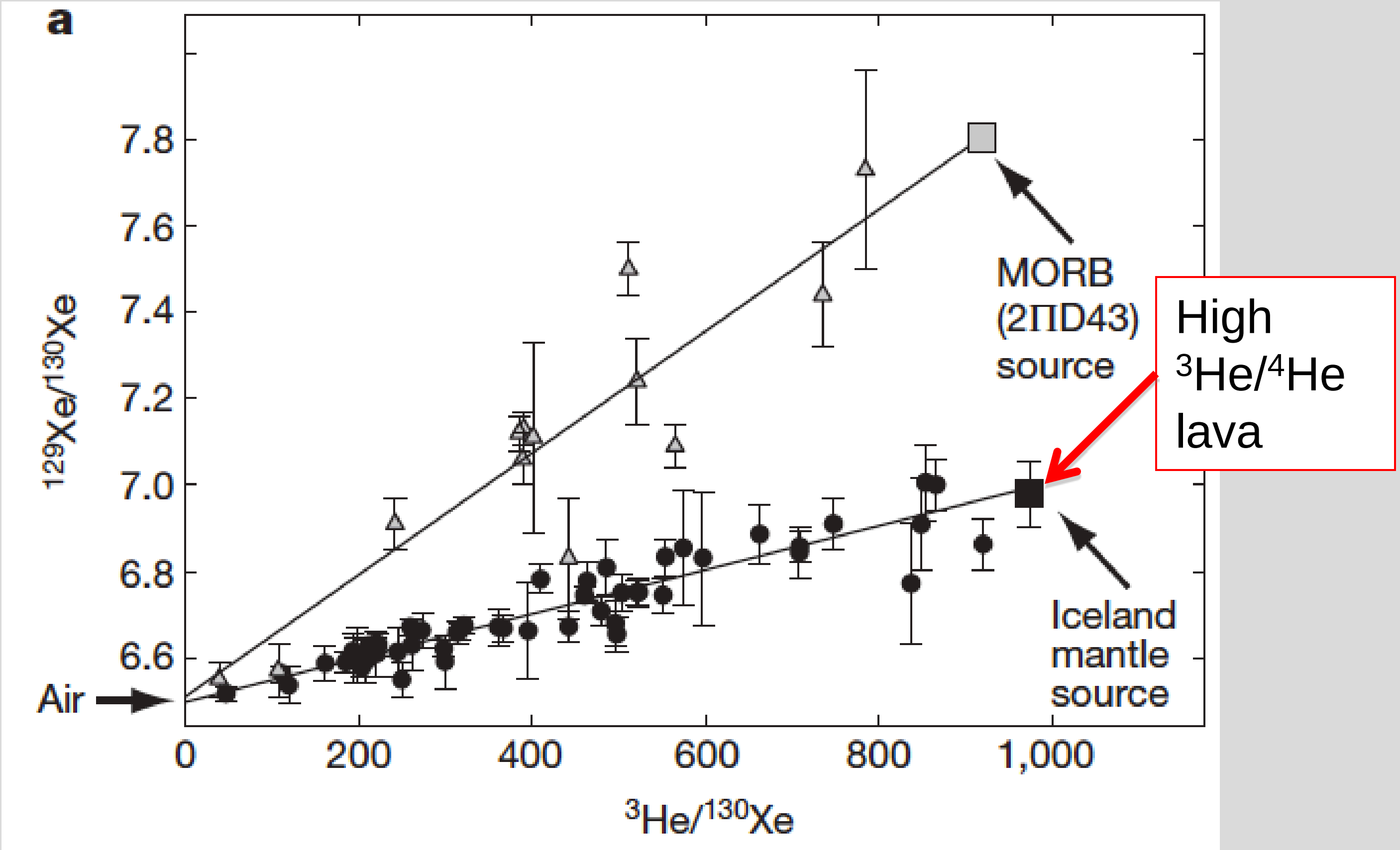
TITAN by partitioning between lower mantle phases?

Jackson et al. (G-cubed, 2008)



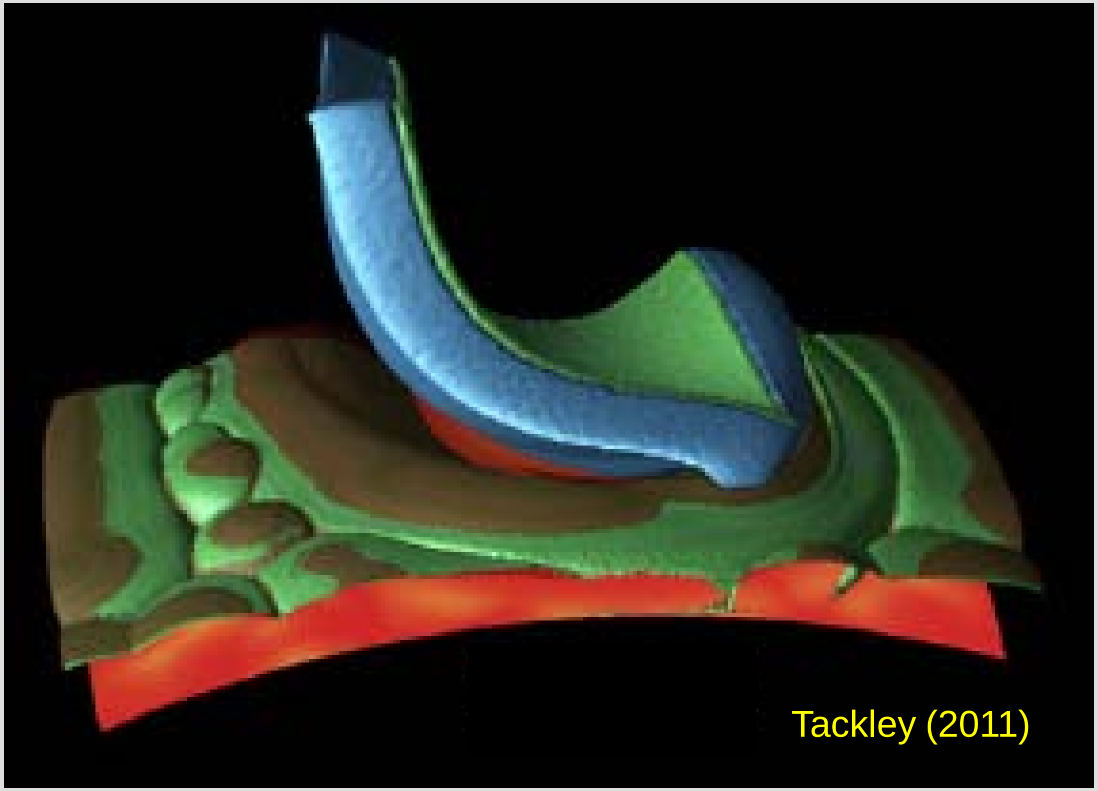
LLSVP's…..How old?

- -- $^{129}I \rightarrow {}^{129}Xe$ (half life = 16 Ma).
- -- ^{129}I is effectively extinct after 5 of 6 half-lives (~100 Ma).
- -- $^{129}Xe/^{130}Xe$ variability in the mantle made early (>4.45 Ga)!
- -- If LLSVP's have high $^{3}He/^{4}He$, they are OLD



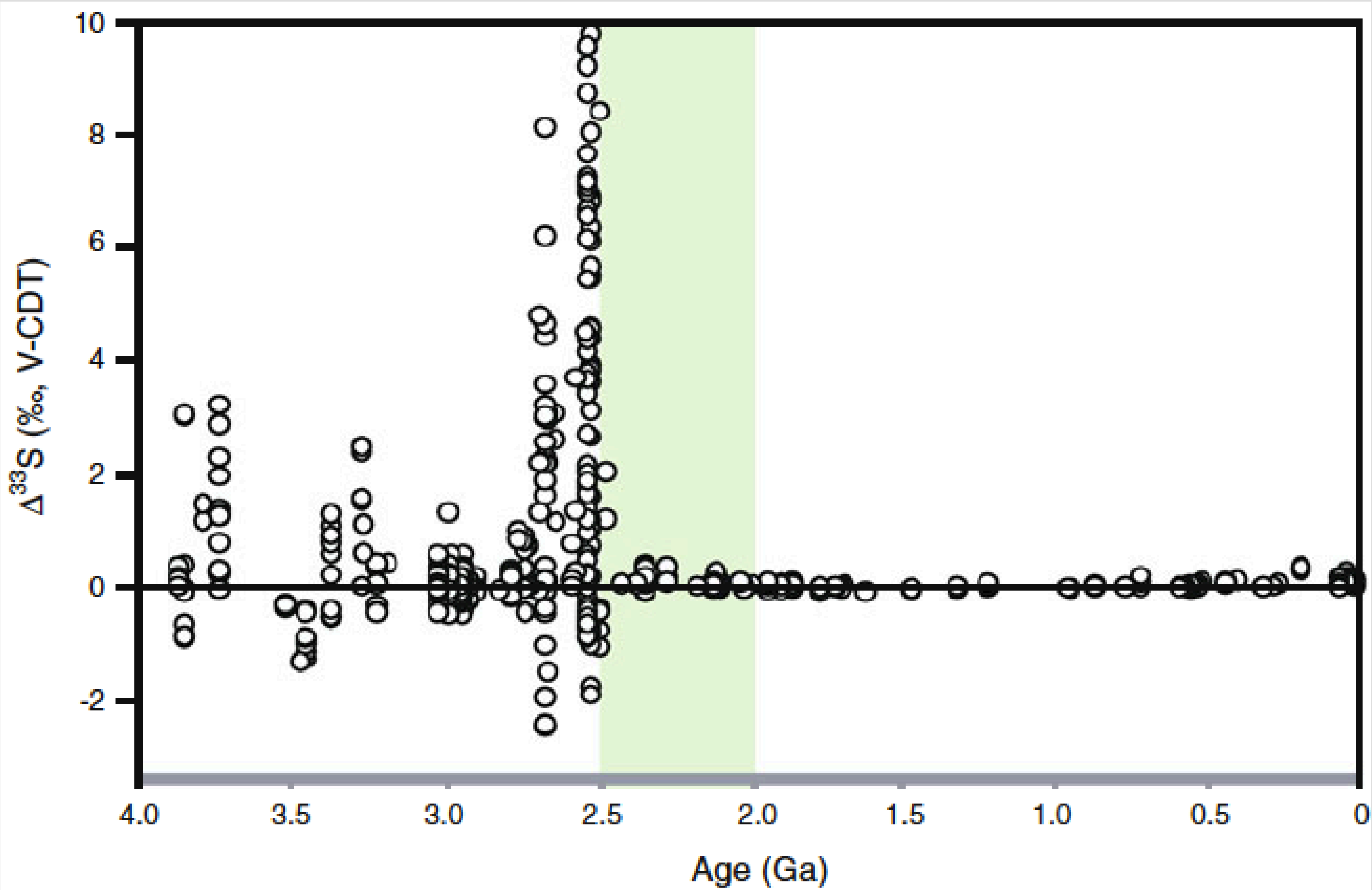
Mukhopadhyay, 2012

Slab Graveyard?



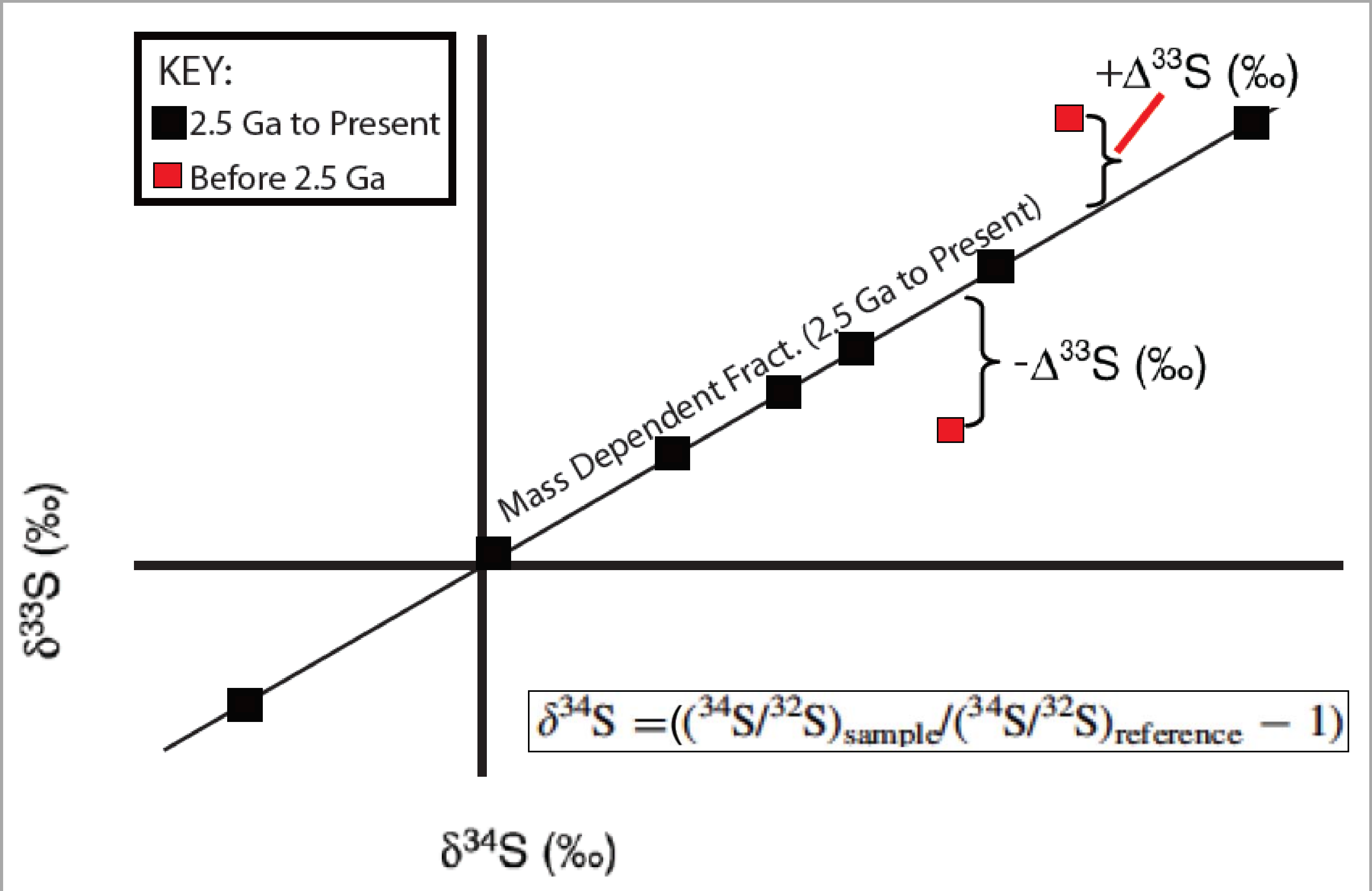
Evidence from hotspot lavas that plumes sample materials that were once at the Earth's surface?

Clues from “Brimstone”



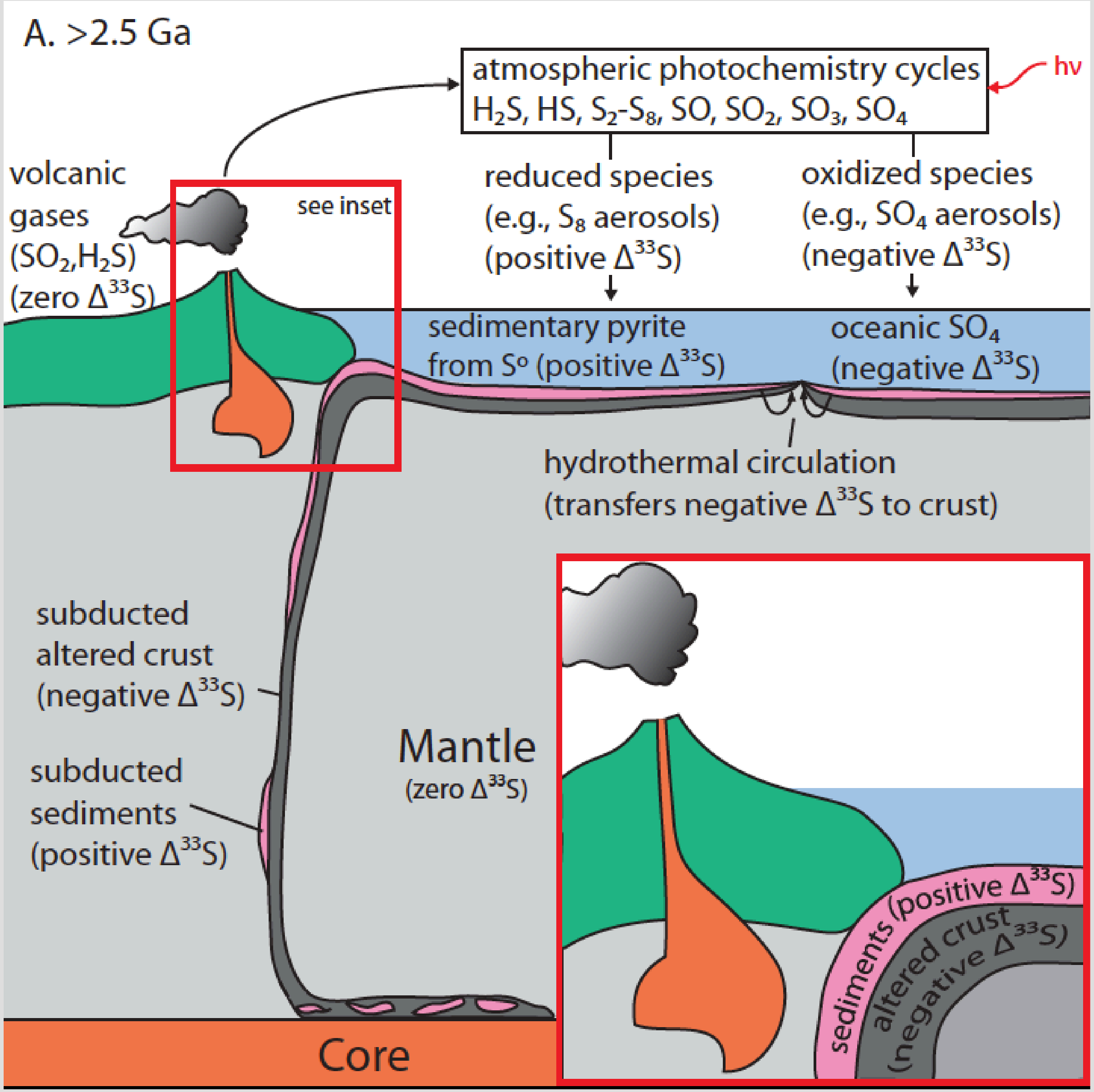
Farquhar et al. (2010, Photosynth Res)

$\Delta^{33}S$ Mass Independent Fractionation (MIF)



The origin of these anomalous $\Delta^{33}S$ values is attributed to atmospheric photochemistry involving sulfur dioxide in a primitive atmosphere with reduced oxygen and ozone and increased ultraviolet transparency (Farquhar et al., 2000)

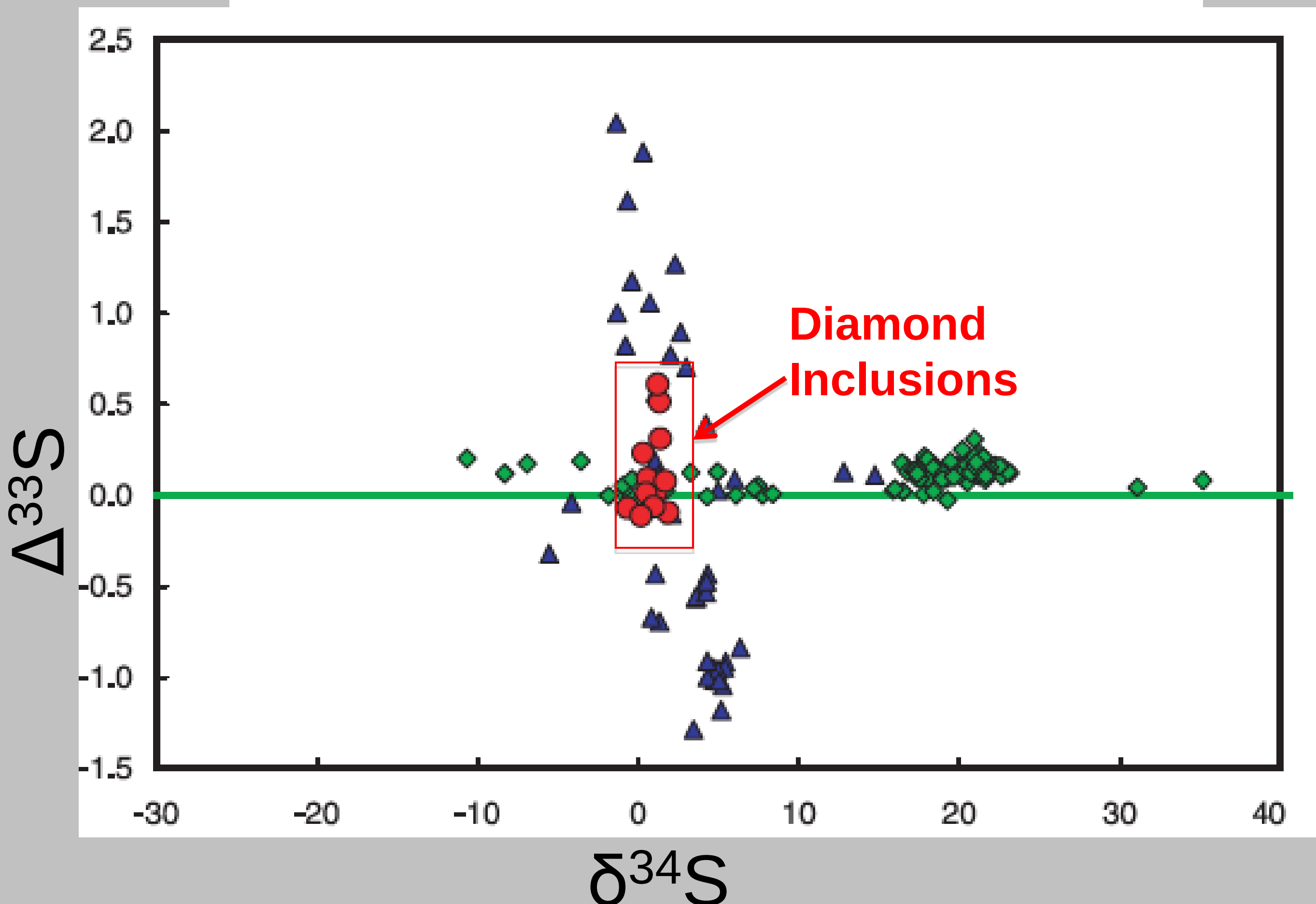
Deep Sulfur Cycle: Sulfur from the Archean



Mass-Independent Sulfur of Inclusions in Diamond and Sulfur Recycling on Early Earth

J. Farquhar,[1] B. A. Wing,[1] K. D. McKeegan,[2] J. W. Harris,[3]
P. Cartigny,[4] M. H. Thiemens[5]

SCIENCE VOL 298 20 DECEMBER 2002



--Positive $\Delta^{33}S$ in diamond sulfides also associated with Archean continental crust sediments.

--Farquhar (2002) hypothesized the subducted Archean oceanic crust would host negative $\Delta^{33}S$.

--The community has long thought that HIMU lavas sample subducted oceanic crust…..

The Cook Islands

Mangaia is the oldest ocean island in the Pacific (~20 Ma)

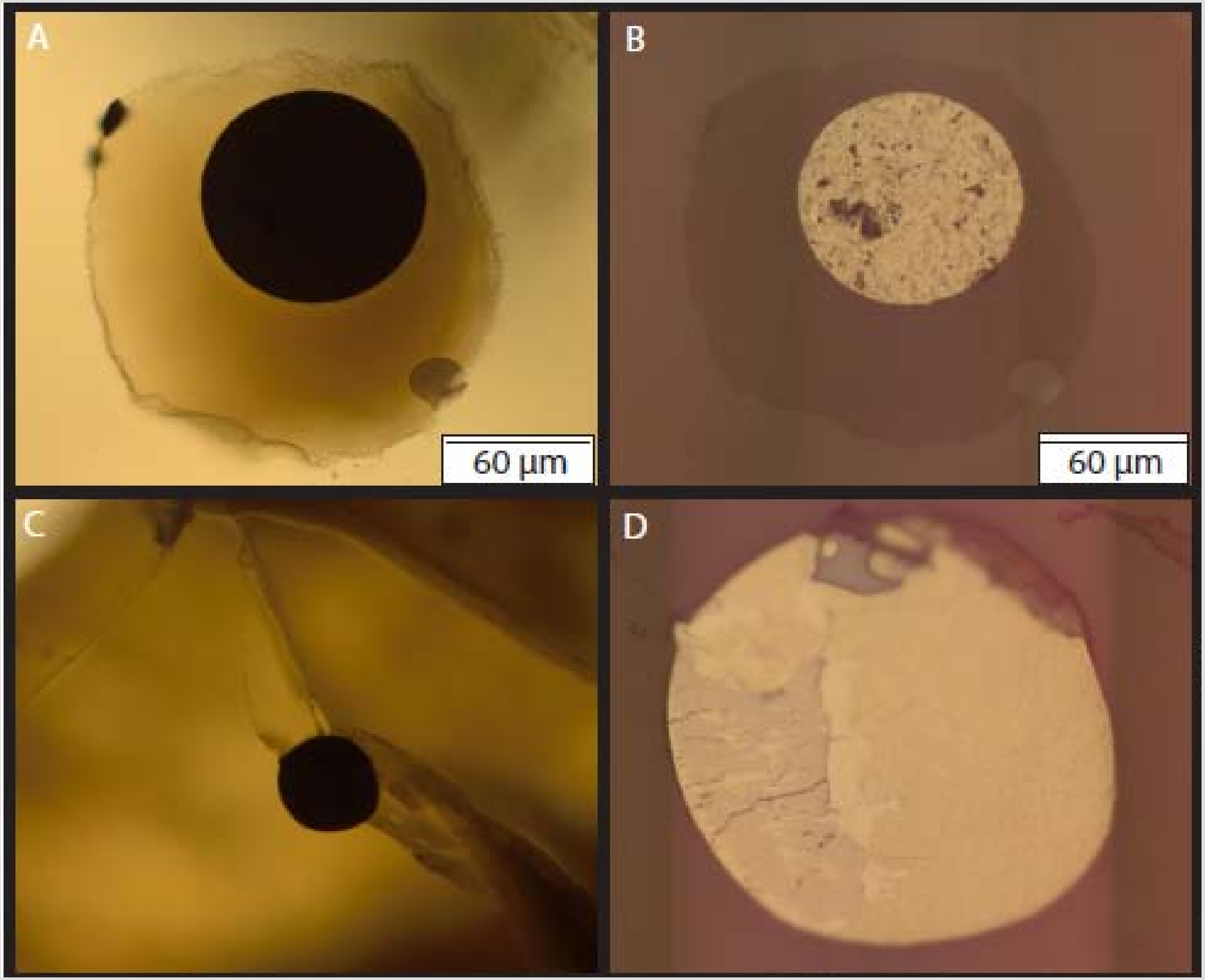
Total expedition

This study

Jungle Geology

Slide courtesy of Rita Cabral

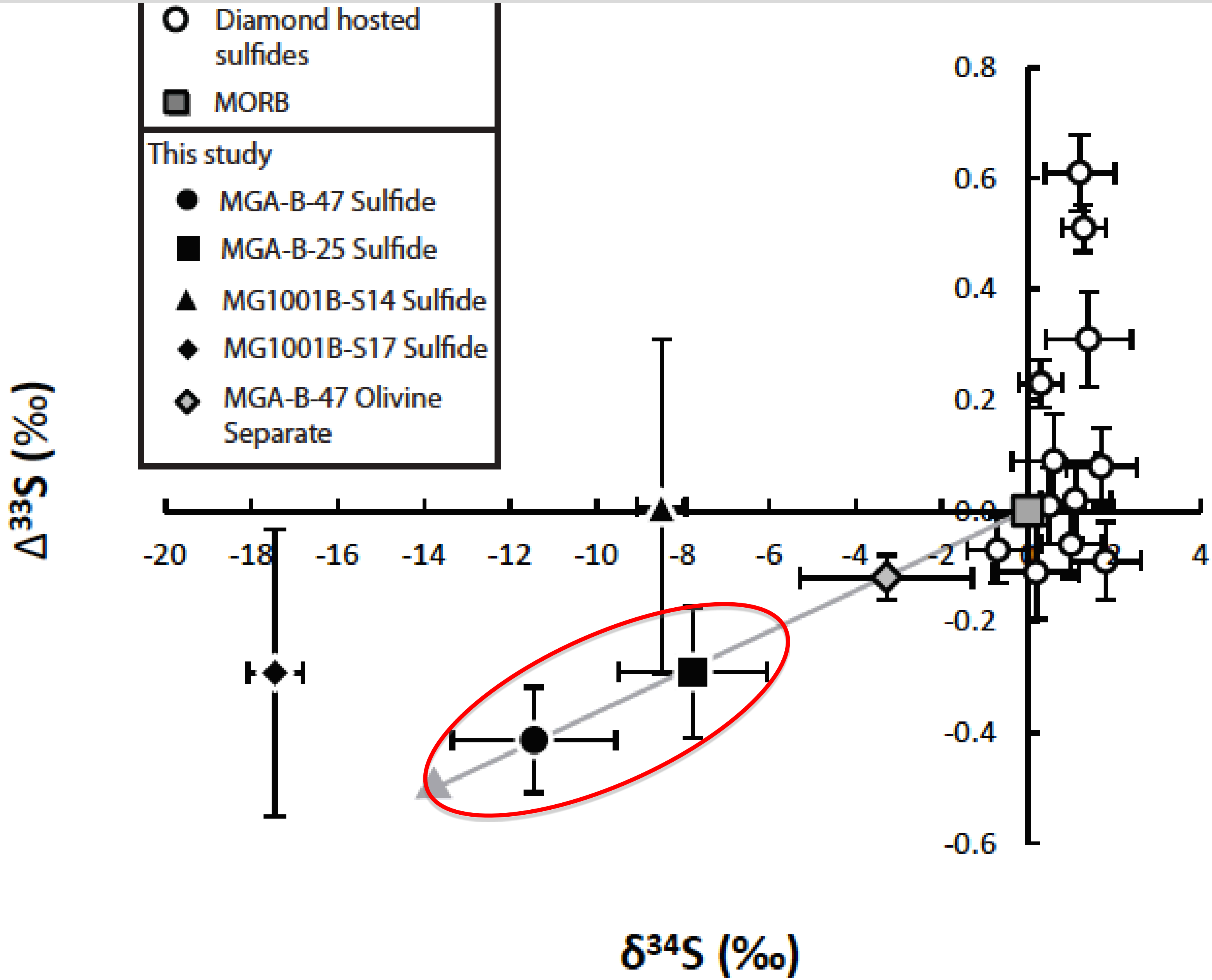
Olivine-hosted sulfides in Mangaia lavas



SIMS Cameca 1280 ion microprobe

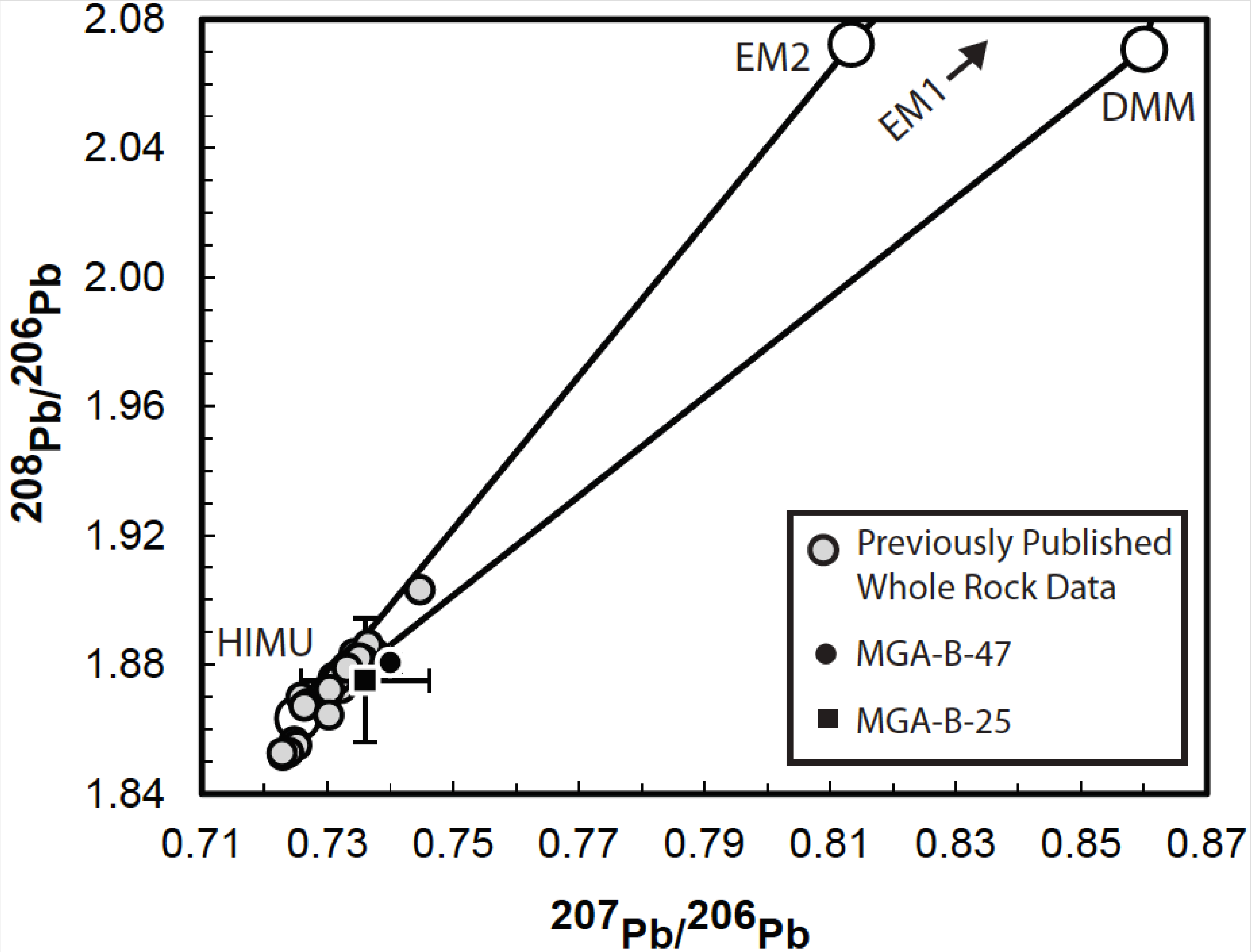
- Multiple faraday collection: $^{32}S^{-}$, $^{33}S^{-}$, $^{34}S^{-}$

Nordsim laboratory
Swedish Museum of Natural History
Stockholm, Sweden



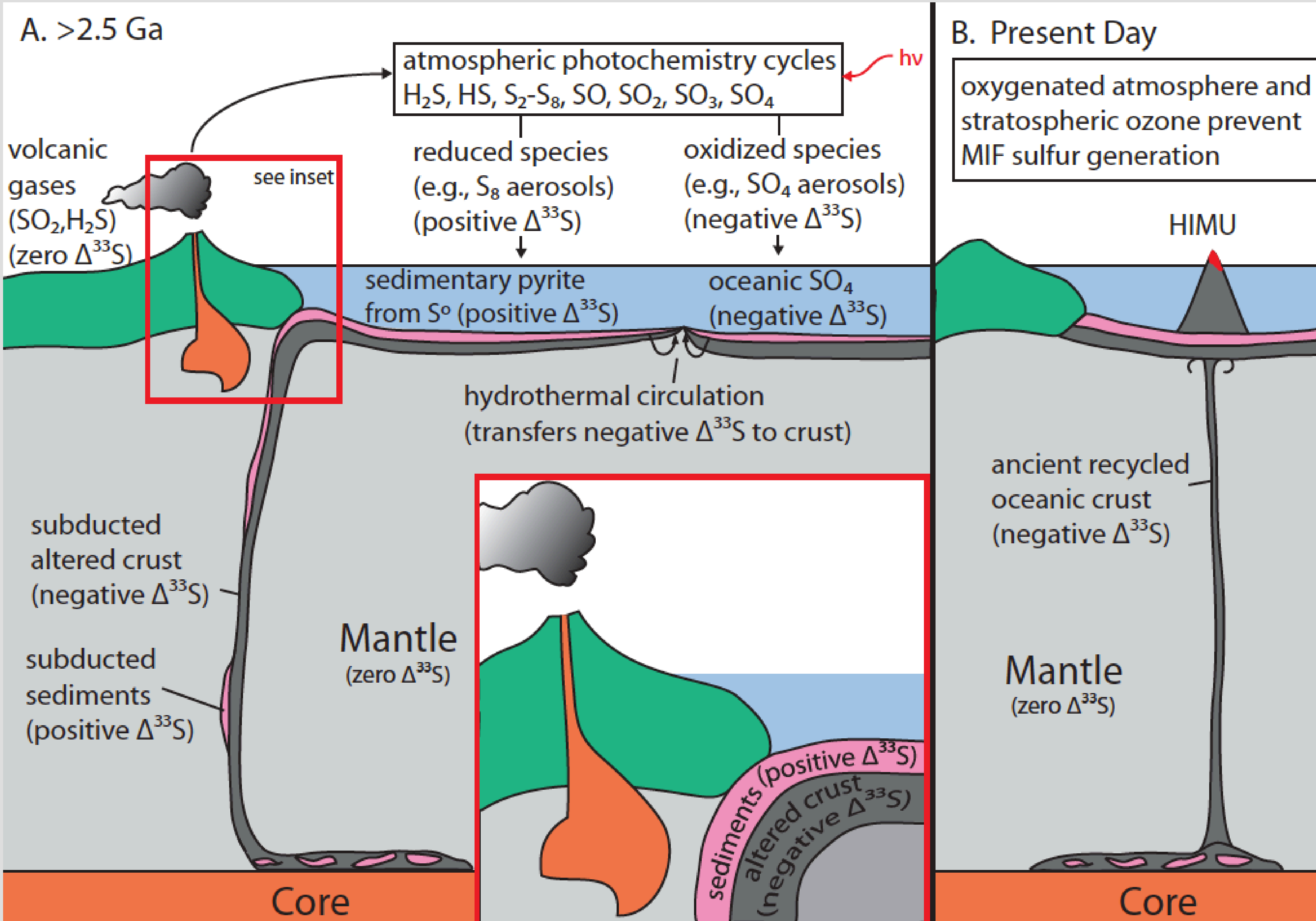
Cabral et al., 2012

Mangaia sulfides are “HIMU”



Cabral et al. (2012)

Mangaia lavas host sulfur once at the surface >2.45 Ga



Cabral et al. (to be submitted Friday)

Farquhar et al. (2002)

- Transfer of the negative ^{33}S signature from the oceanic sulfate reservoir, through sulfate reduction during basalt alteration and subsequent subduction of the altered basalt, may provide a mechanism, however, that satisfies mass balance constraints.

…..the recognition of potential **deep-mantle lithospheric graveyards** leads to the possibility that these regions contain the missing ^{33}S-depleted component.

The presence of ^{33}S-enriched mantle domains with sedimentary affinities and ^{33}S-depleted mantle domains with oceanic affinities remains to be tested.

Summary

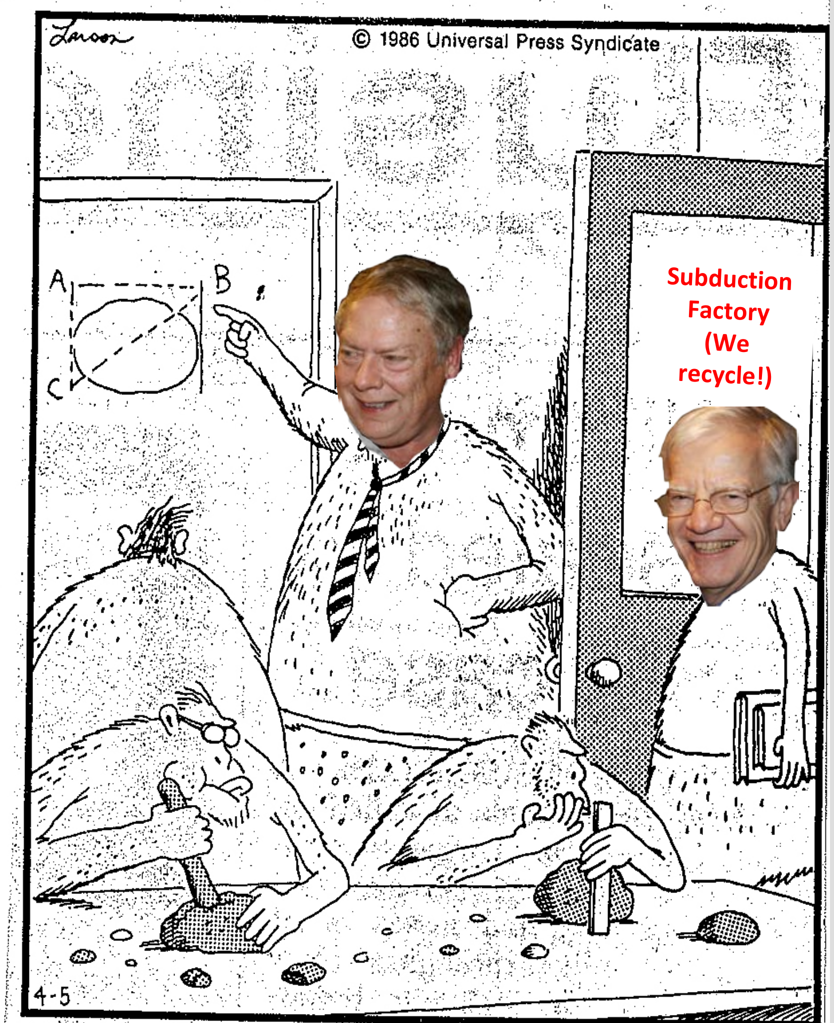
- Trace element partitioning between Ca-Pv and melt can generate key geochemical "fingerprints" (e.g., TITAN). These fingerprints can be used to link high $^3He/^4He$ hotspot lava compositions to basal magma ocean/LLSVP.

- Sulfur isotopes indicate that Archaean atmospheric sulfur was subducted and is returned to the surface in hotspot lavas. A "convenient" location for long-term storage may be the LLSVP's?

In God's kitchen

Part 1: How did the mantle become heterogeneous?

THE FAR SIDE



Rock Shop 101

30-year anniversary of the Recycling hypothesis: Crustal materials injected into the mantle at subduction zones, and this material is returned to the surface in upwelling mantle plumes.

Mantle plumes from ancient oceanic crust

Albrecht W. Hofmann * and William M. White *

Nature Vol. 296 29 April 1982

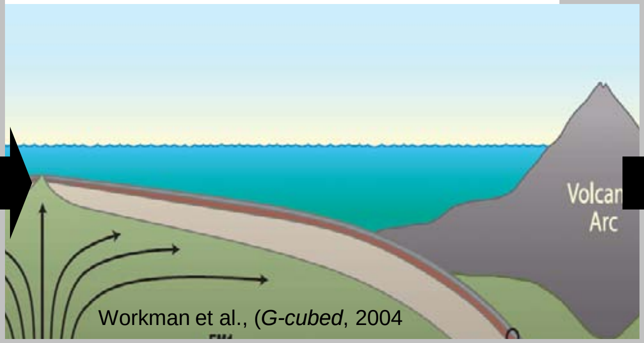
Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution

W. M. White*†‡§ & A. W. Hofmann*‡§

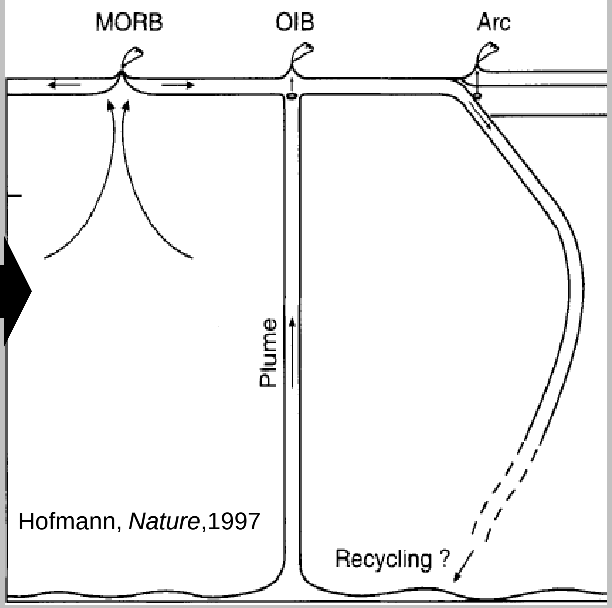
Recycling hypothesis

1. Oceanic plates (crust and sediment) enter the mantle at subduction zones.
2. They are returned to the surface in mantle upwellings (plumes?)
3. Crust and sediment are melted beneath hotspots.

Rivers contribute > 85% of ocean floor sediment



Workman et al., (*G-cubed*, 2004



Hofmann, *Nature*,1997

Sediment (continental) and oceanic crust subduction over time

- **Oceanic crust:** ~20 km^3 subducted annually.

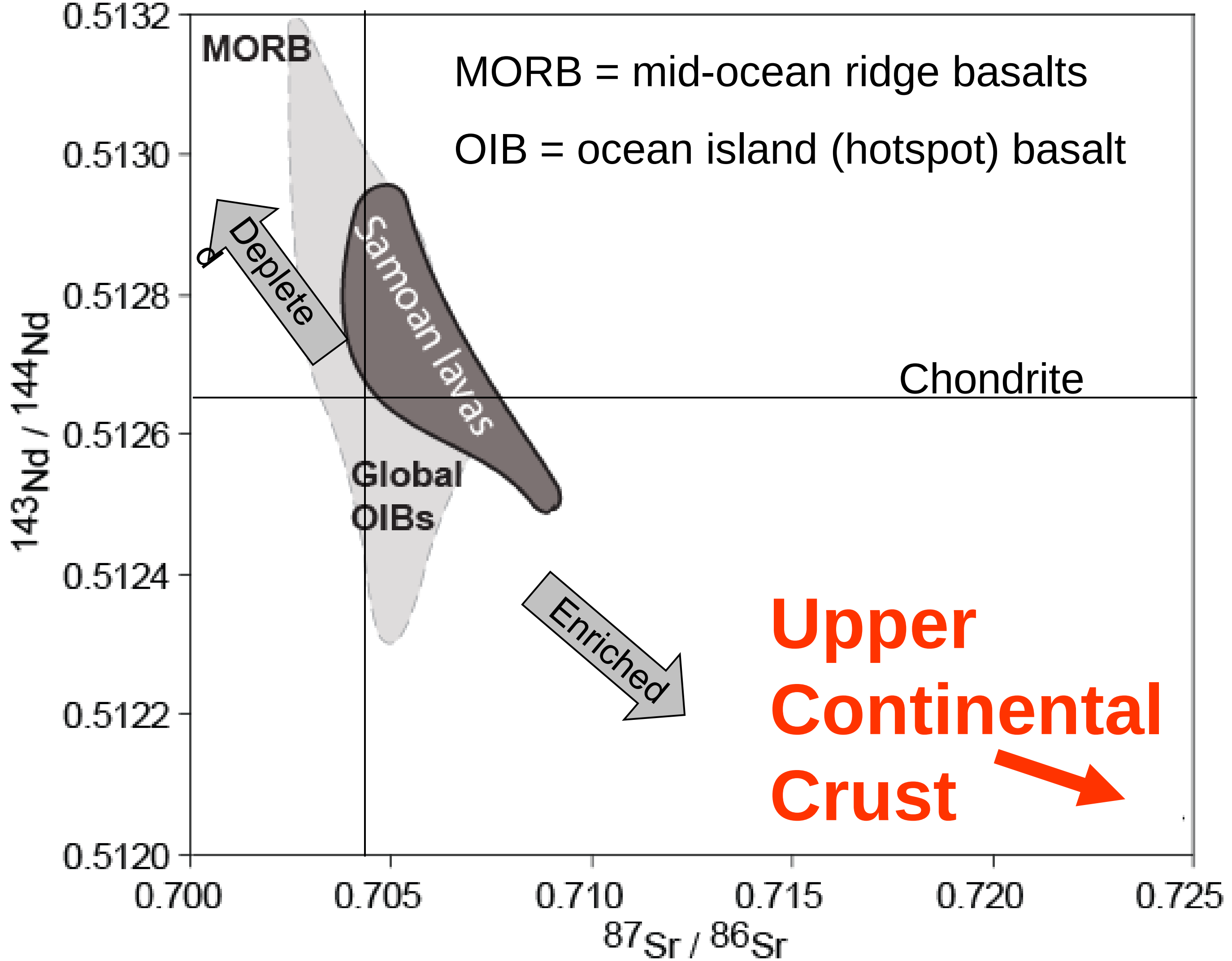
--In 3 Ga of subduction, that's 60 billion km^3, or ~5% of mantle's mass!

- **Sediment (mostly continental)**: 0.5 - 0.7 km^3 of sediment subducted annually.

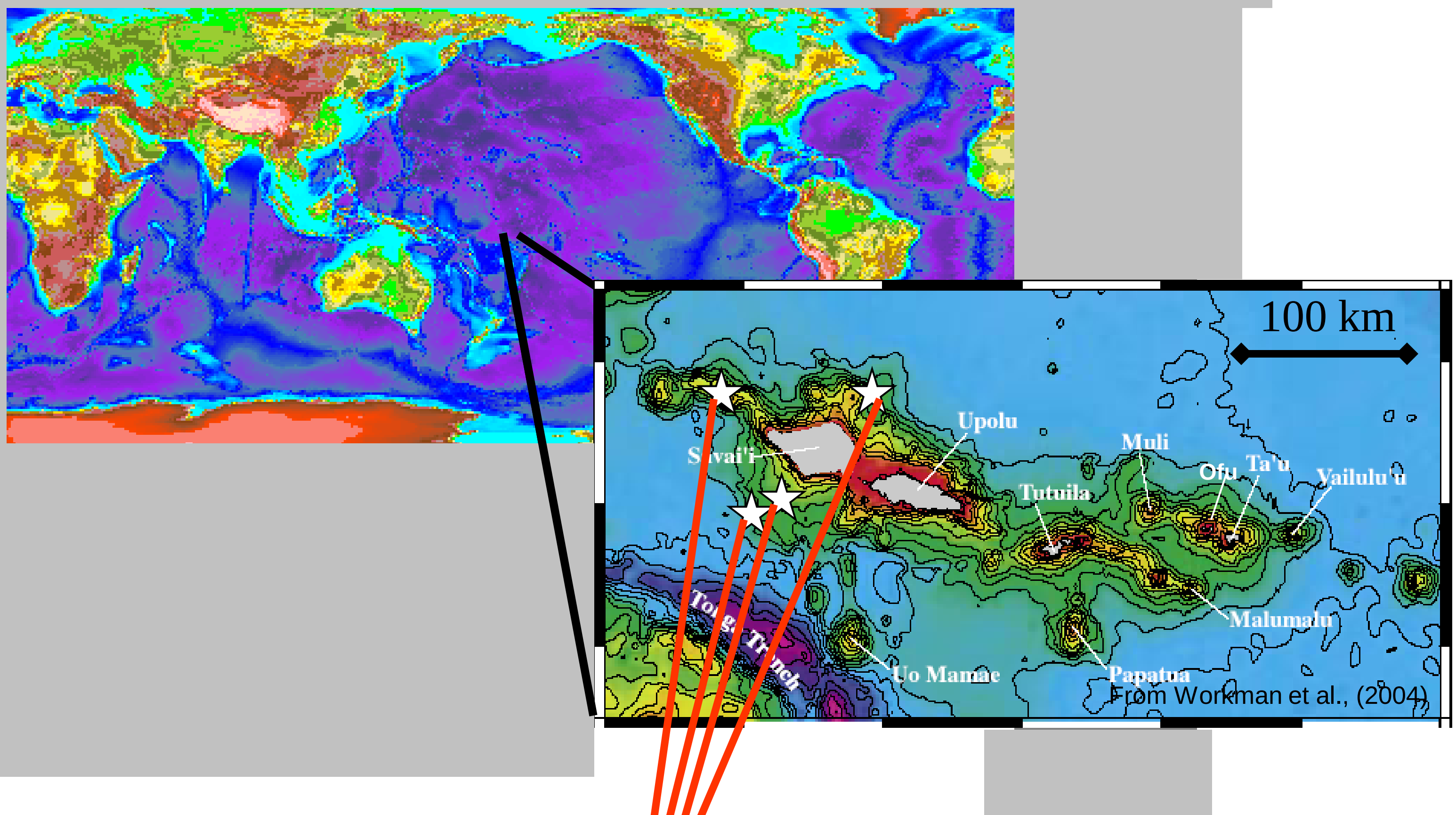
--In 3 Ga, that's a lot of sediment! 1/3 size of modern continents: Africa + S. America.

What is the fate of this crust/sediment? Where is it now? Do we ever see it again?

Samoa historically an example of a hotspot that samples a recycled sediment component, but….



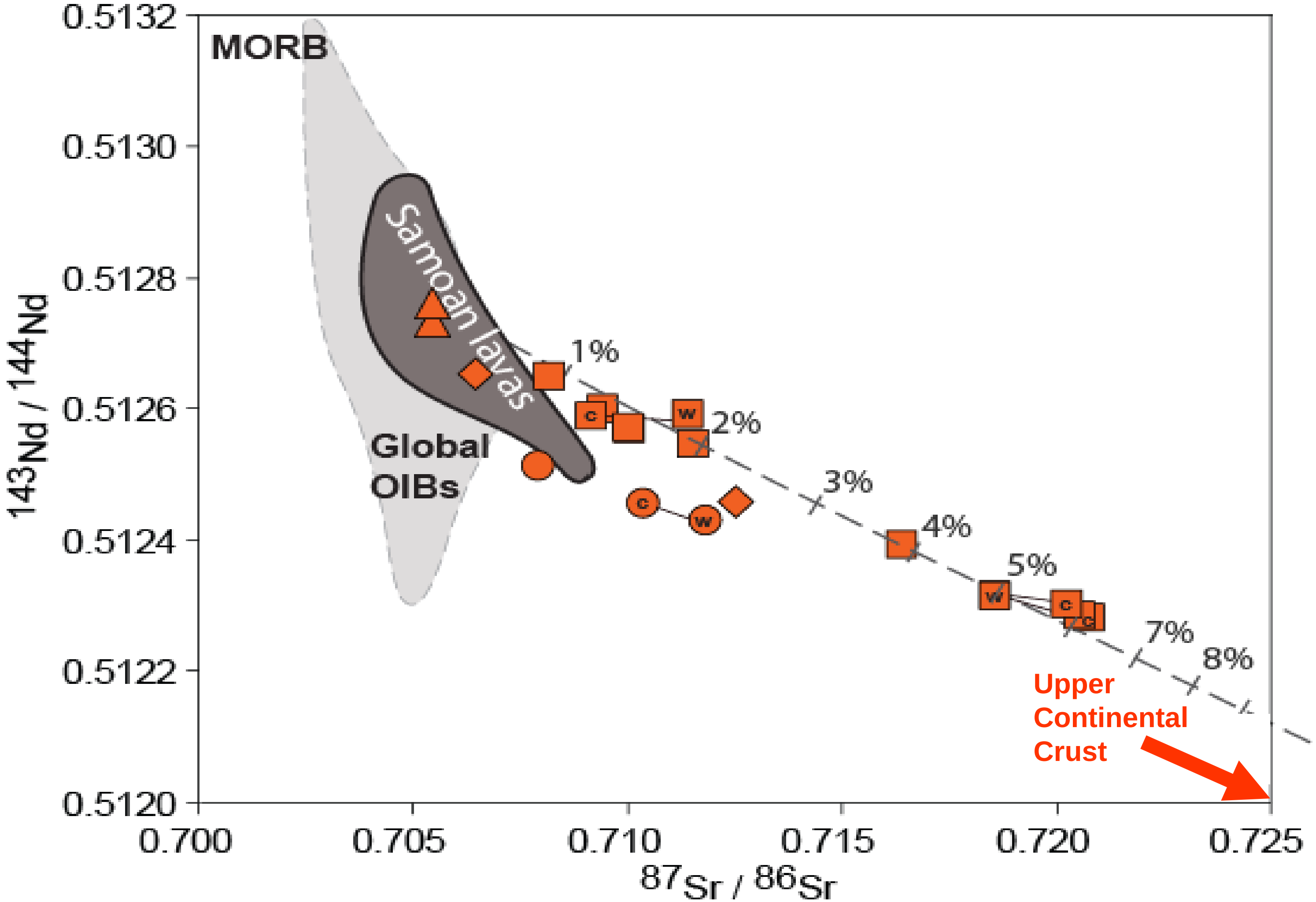
Study Site:
Savai'i Island (Independent Samoa)



Submarine Savai'i lavas

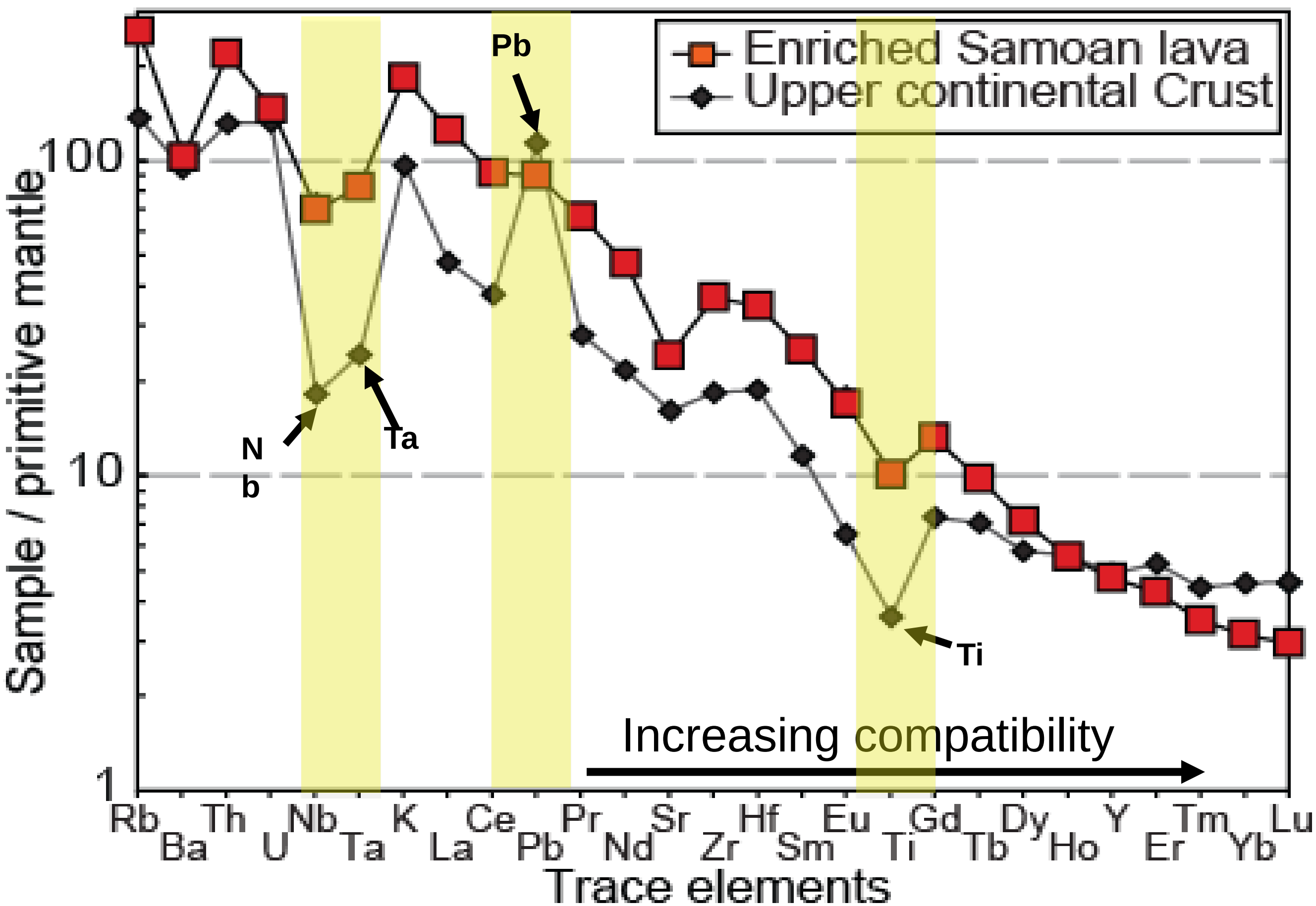
“High tech” dredging in the 21^{st} century

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data: Consistent with upper continental crust!



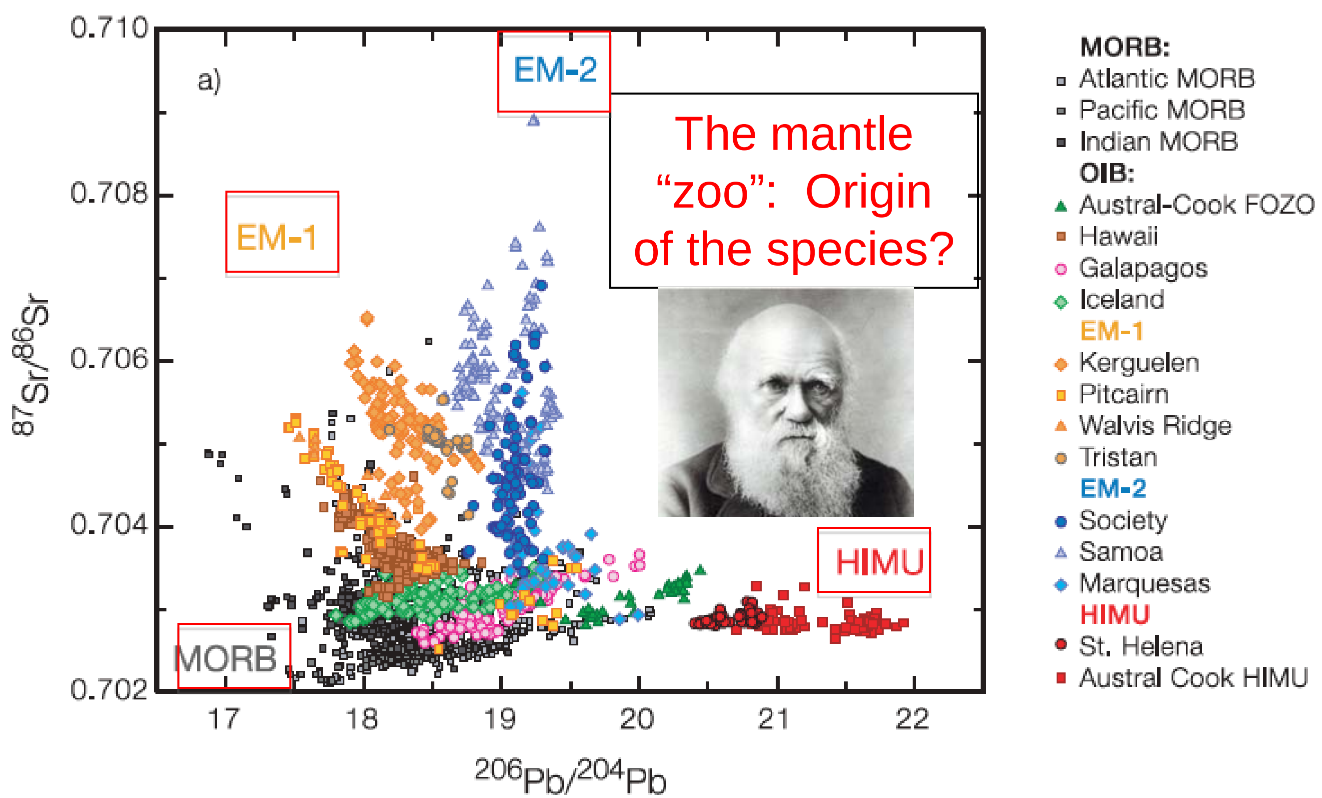
Jackson et al. (2007)

Continental crust has unique trace element “fingerprints”



Jackson et al. (2007)

But what about the other components?



Willbold and Stracke, G-cubed, 2002

- **<u>HIMU:</u>** Recycled oceanic crust? Requires a lot of "fiddling" with the crust in the subduction zone. Niu & O'Hara (2003) suggest "metasomatism".
- **<u>EM1:</u>** A real "dog's breakfast" of proposed origins: Pelagic sediment, lower continental crust, sub-continental lithosphere, "metasomatism", etc., etc.

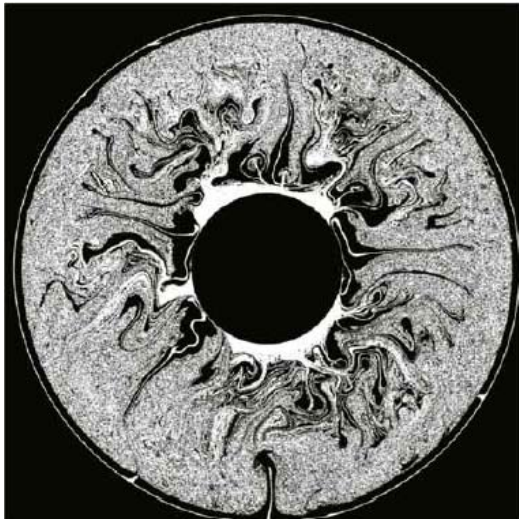
Part 3: Zoned plumes

Marble Cake à la Starbucks

Ocean island petrology/geochemistry: Probes of the Earth's deep interior

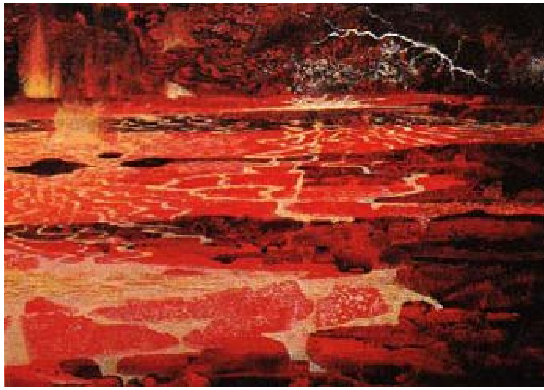
The observation that the mantle is heterogeneous leads to some of the most important questions in the study of the deep Earth:

Part 1: Where are the geochemical mantle reservoirs located in the mantle (LLSVP)?



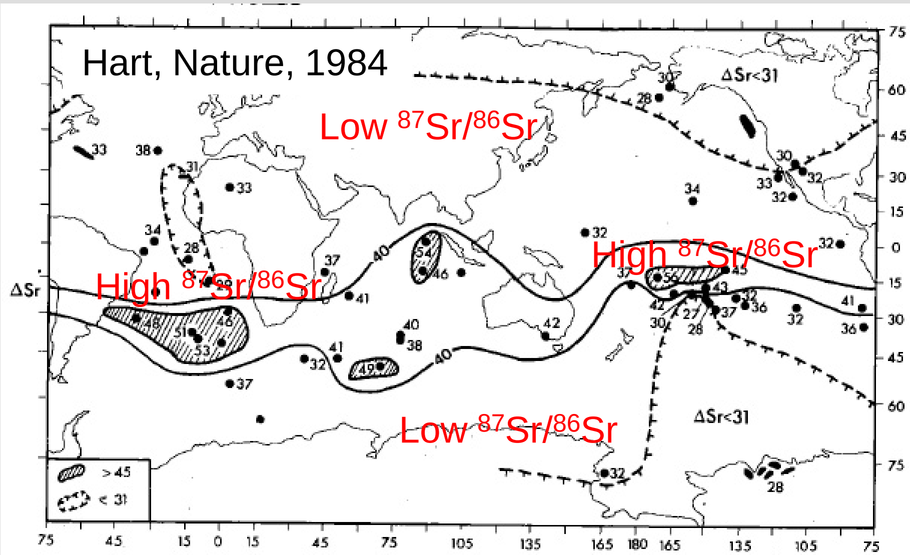
Brandenburg et al. (EPSL 2008)

Part 2: How old are geochemical mantle reservoirs?

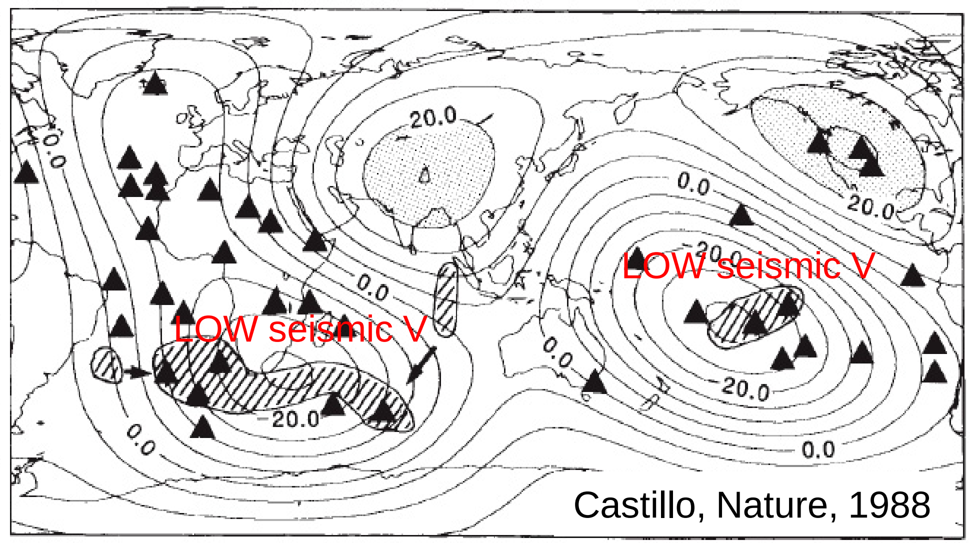


Distribution of mantle heterogeneities inferred from ocean islands

DUPAL anomaly



DUPAL vs. seismic low velocity anomaly



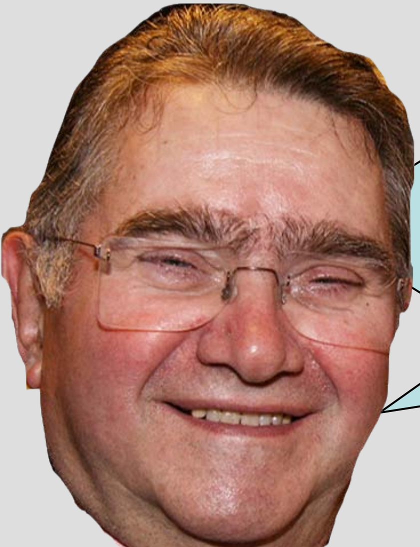
--The DUPAL anomaly is a globe encircling feature of isotopic enrichment in southern hemisphere OIBs. Largest isotopic feature in the Earth's mantle.

--**Key observation: surface geochemistry associated with seismic low velocity anomalies (LLSVP's) at depth.**

DUPAL = **Dup**ré+**All**ègre **LLSVP** = **L**arge **L**ow **S**hear-wave **V**elocity **P**rovince

How to generate hemispheric heterogeneity in the first place?

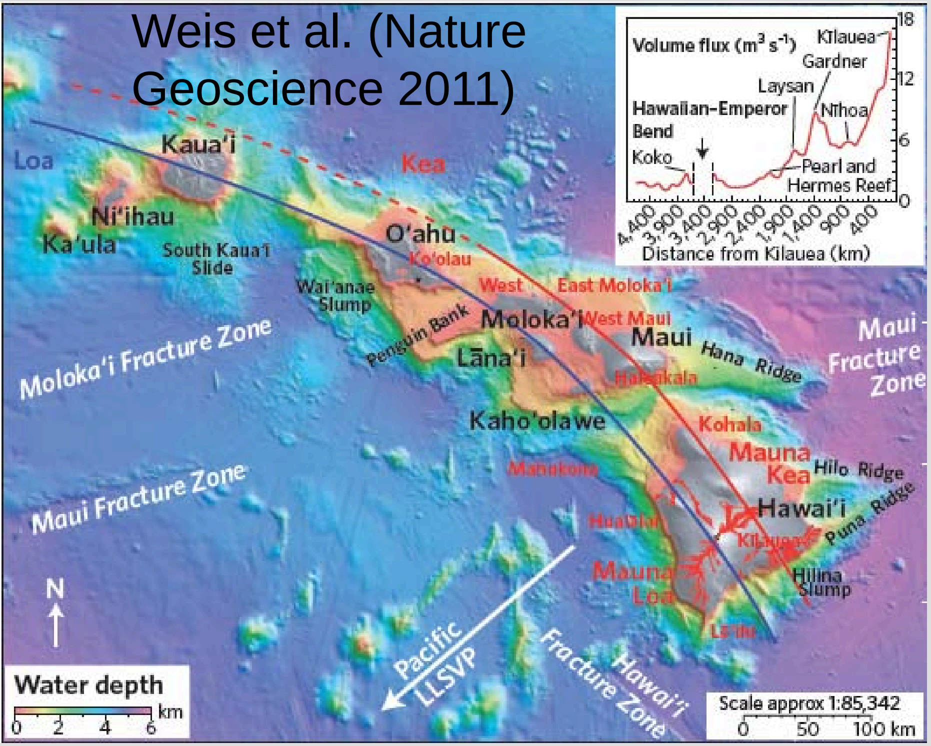
Focused subduction around
the perimeter of a supercontinent?

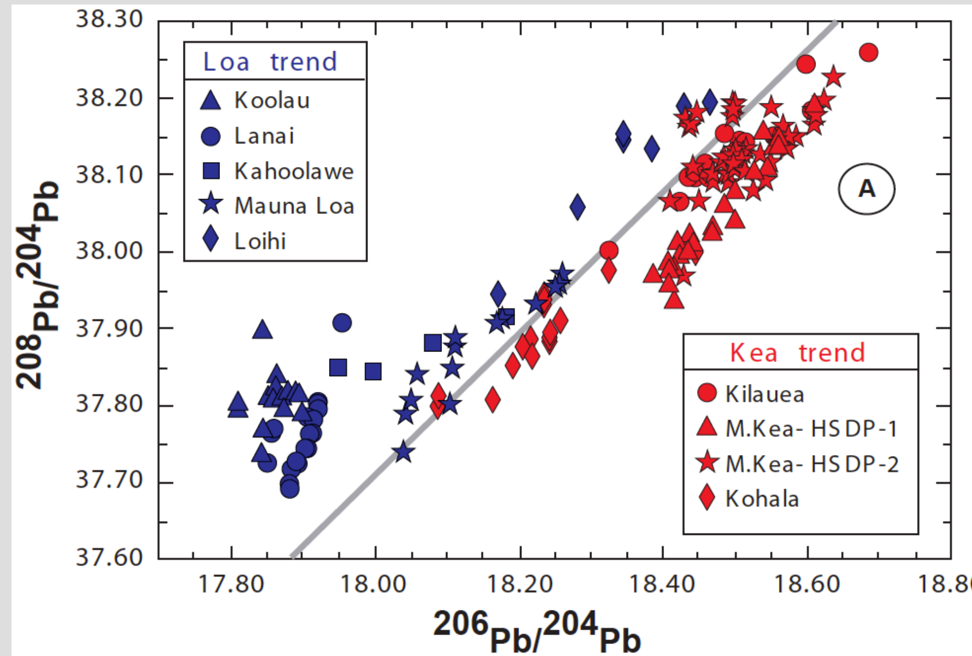


“Indeed, what *can* be proved in the Earth Sciences?”

-C. Allègre
Phil. Trans. R. Soc. Lond. A
vol. 360, 2002

The zoned Hawaiian plume: The Loa & Kea volcanic trends

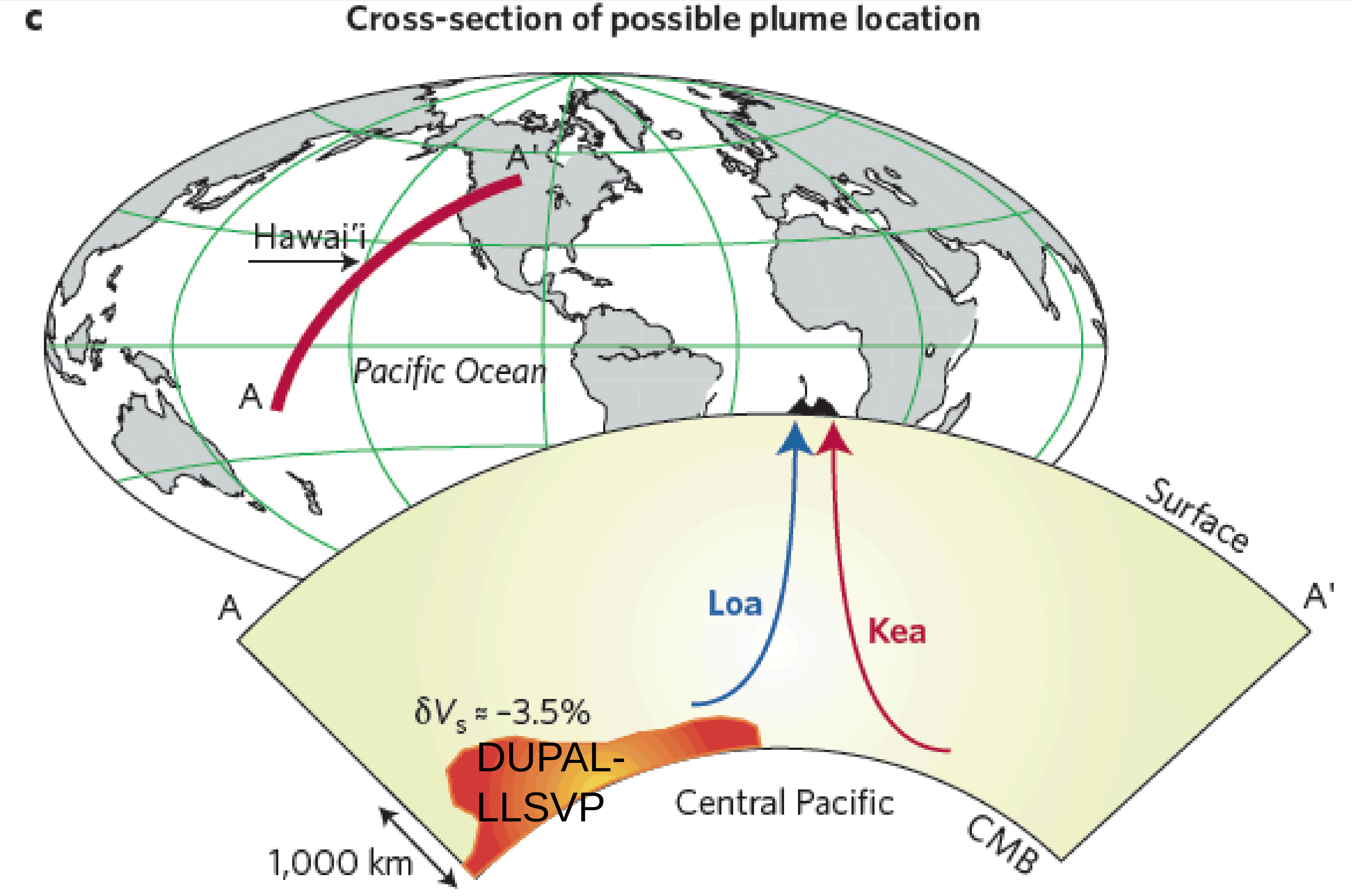




Abouchami et al. (Nature, 2005)

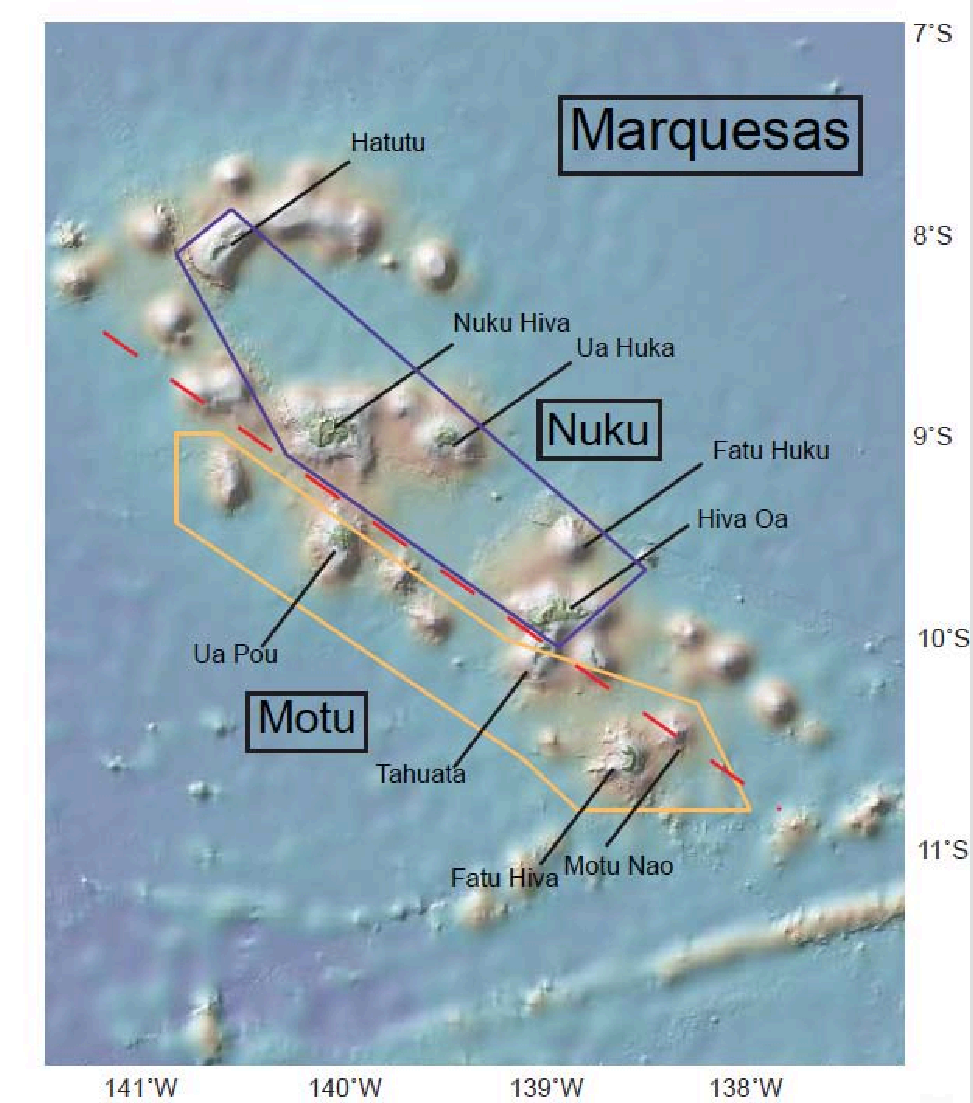
- Two volcanic trends the separate geographically and geochemically.
- The southern (Loa) trend more enriched than the northern (Kea) trend. Why?!

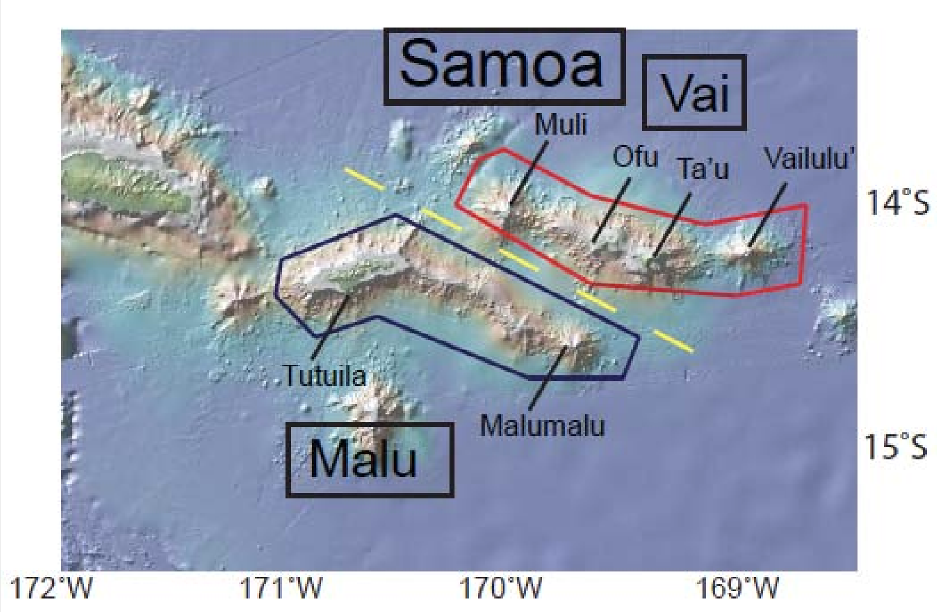
Weis et al. (2011) model: Hawaiian plume conduit preserves geometry of lower mantle geochemistry

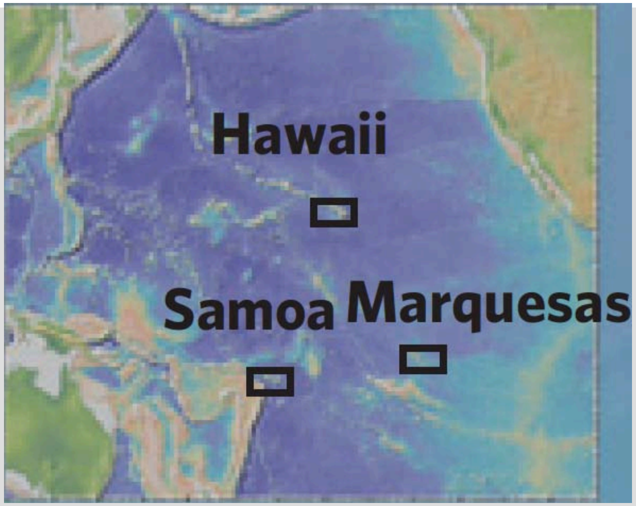


Weis et al. (Nature Geoscience, 2011)

Loa-Kea trends not unique: Evidence from Marquesas and Samoa

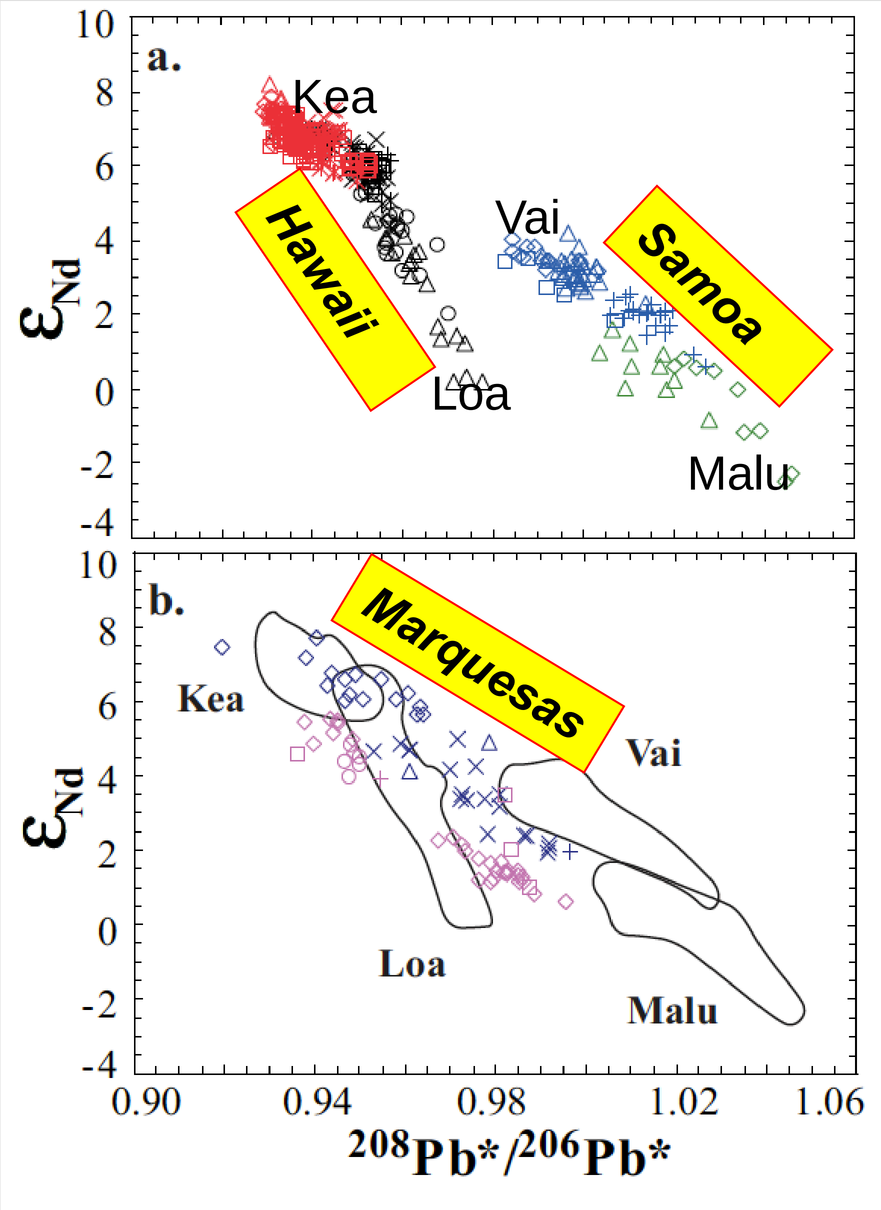


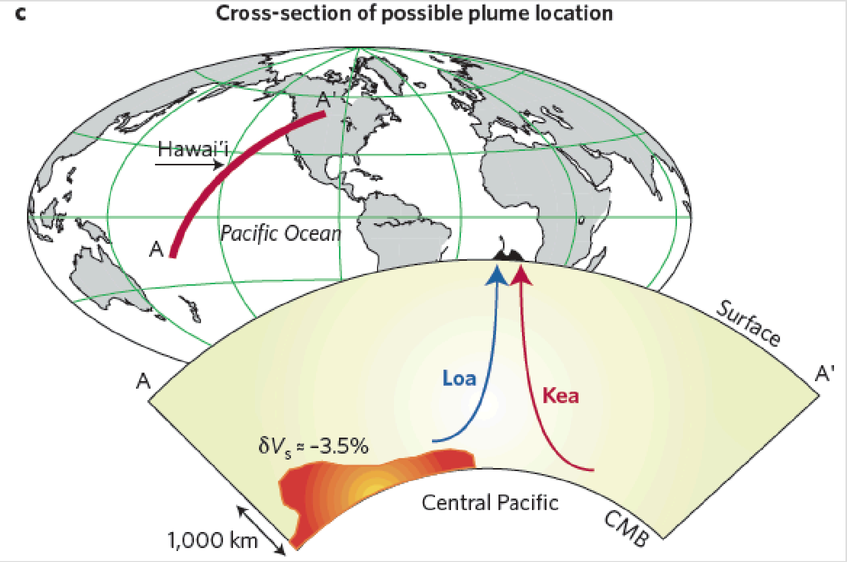




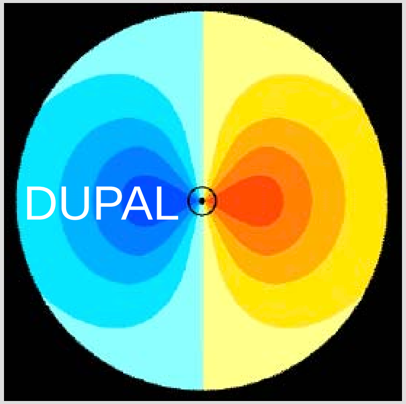
Huang, Hall, Jackson (Nature Geoscience, 2011)

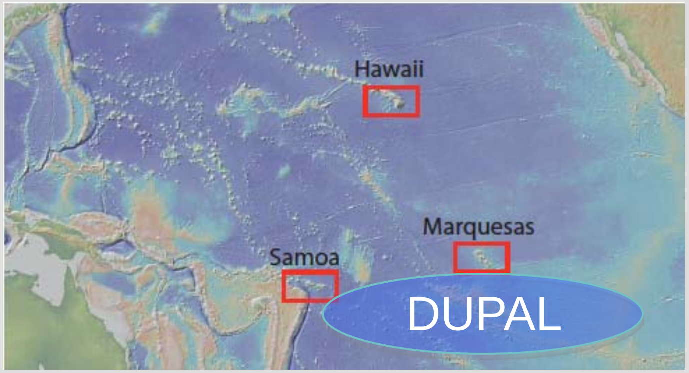
The southern volcanic trend is more enriched at Hawaii ("Loa"), Samoa ("Malu"), and Marquesas ("Motu")

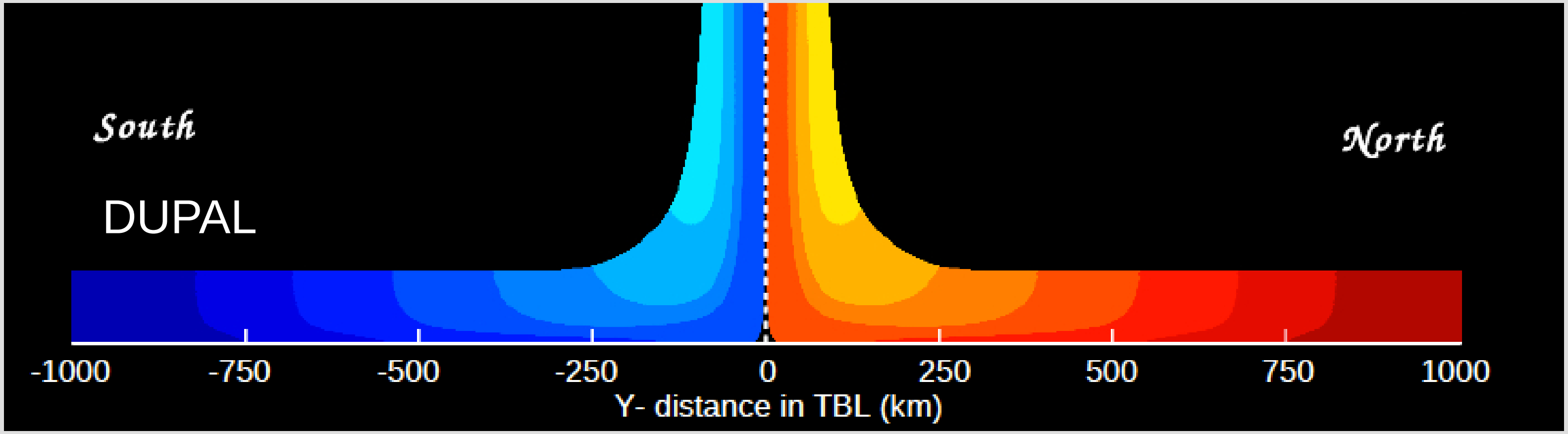




Dynamic models: Geochemical structure of deep mantle preserved in plume conduits





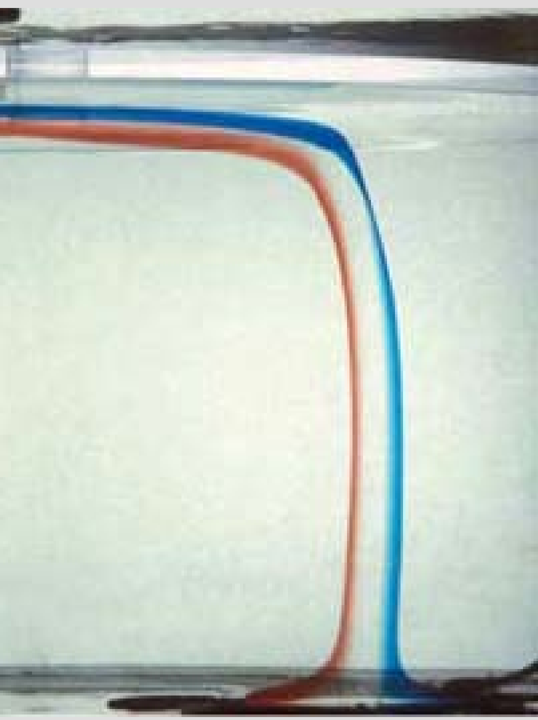


Farnetani

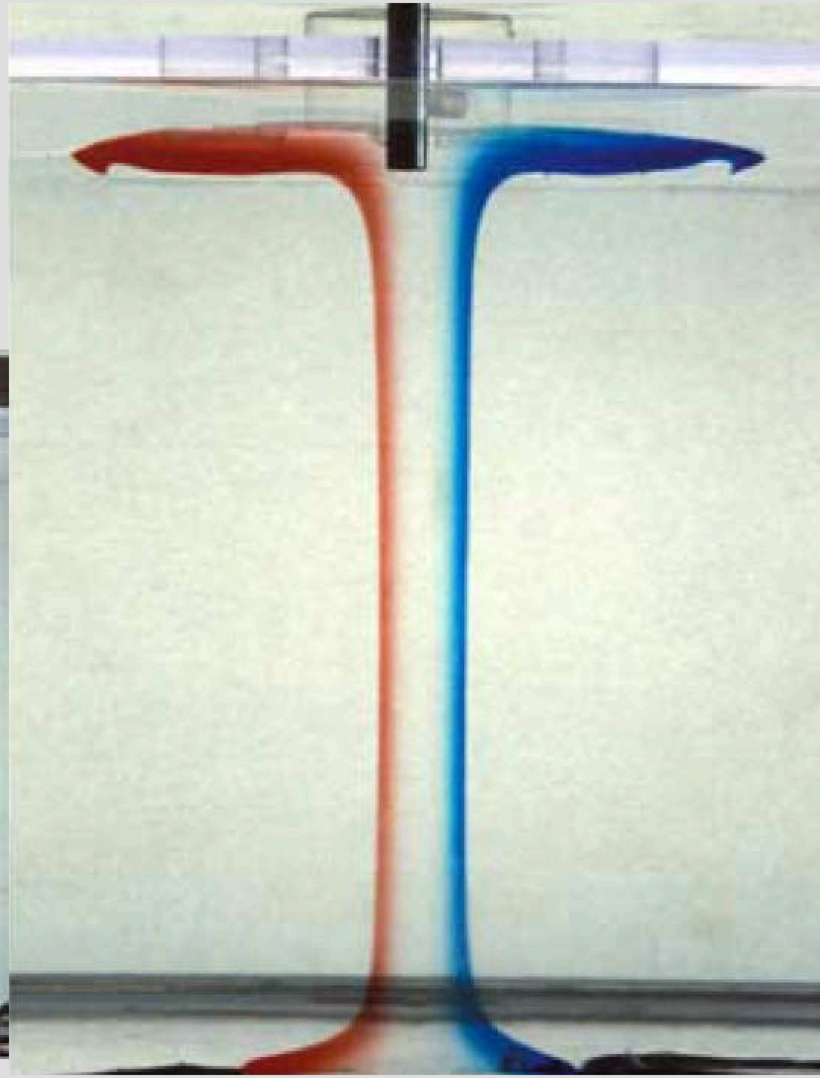
Prediction: A plume south of the low velocity zone will be enriched on the north side. Indeed, we have discovered such a plume….

Tank experiments: Geochemical structure of deep mantle preserved in plume conduits

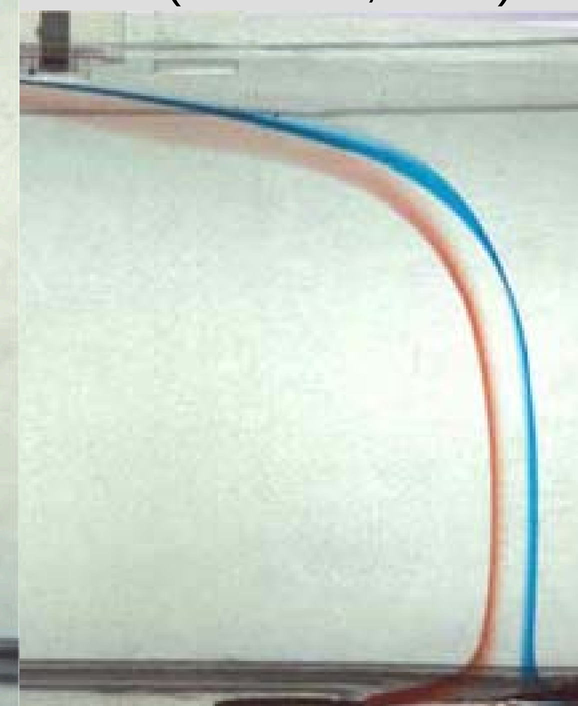
Kerr and Mériaux
(G-cubed, 2004)



Moderate shear

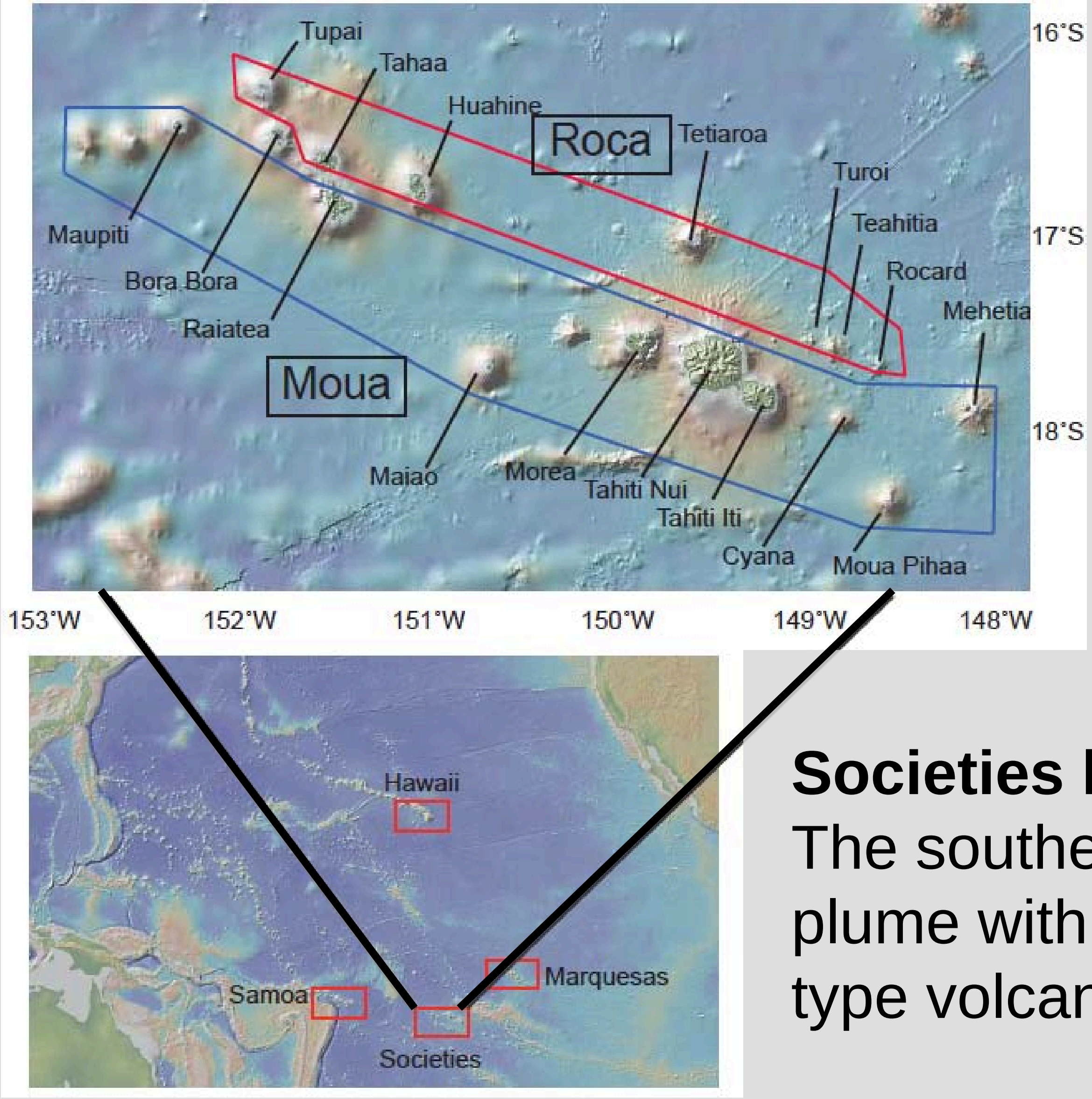


No shear



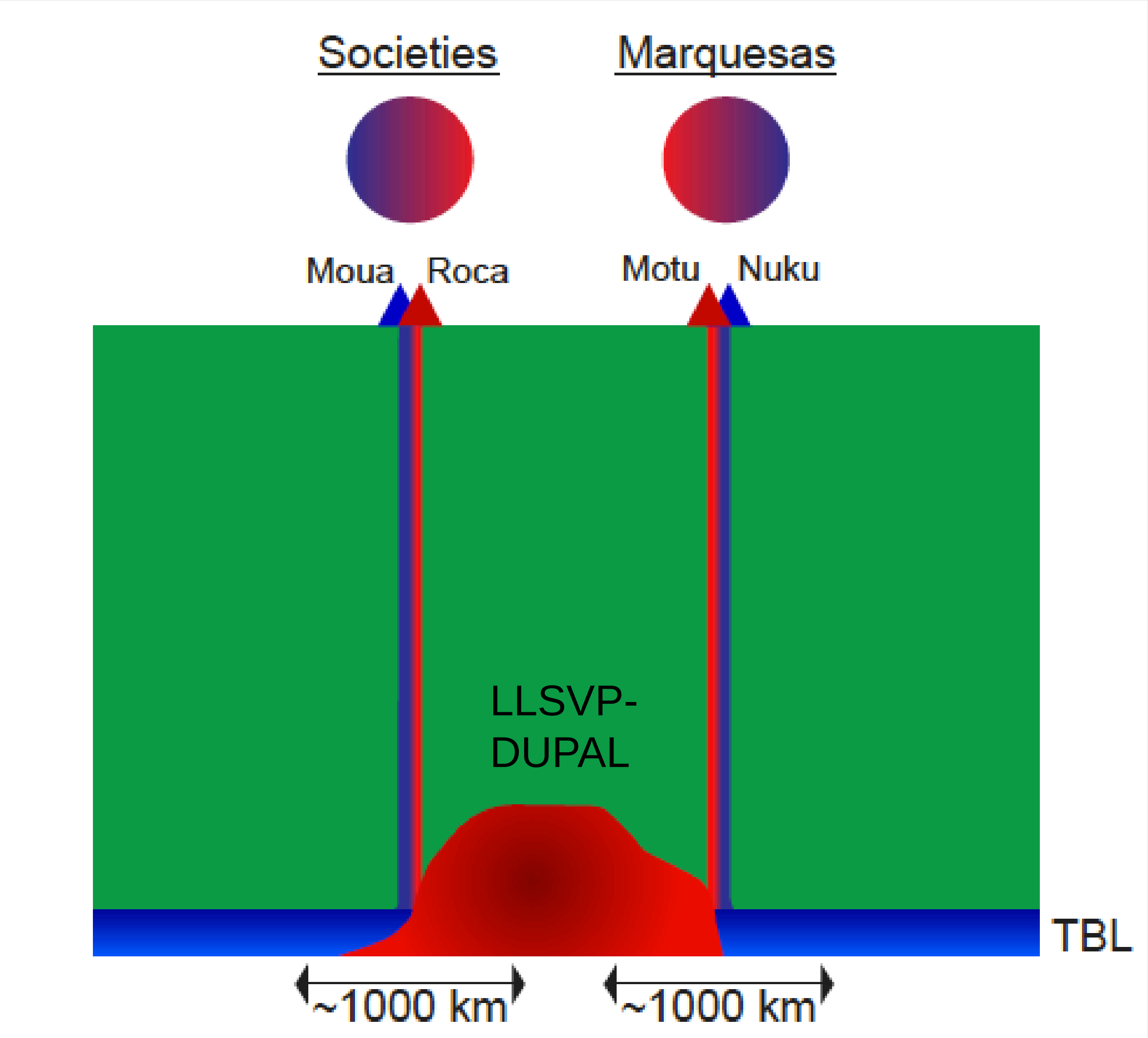
High shear

Test the hypothesis: A plume south of the DUPAL-LLSVP will have north-side enrichment



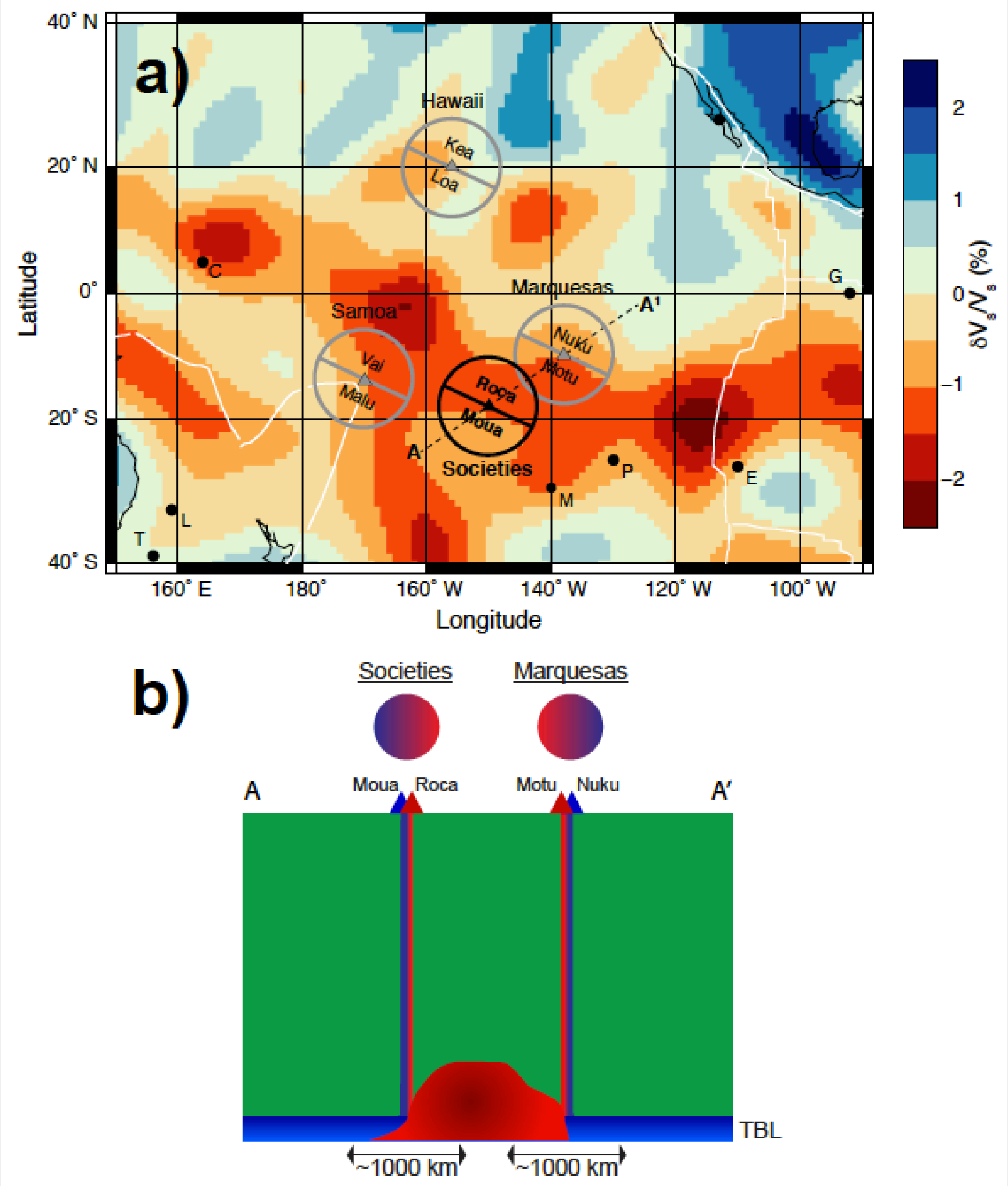
Societies hotspot: The southernmost plume with Loa-Kea type volcanism

If Societies south of DUPAL-LLSVP, then north side of plume should be enriched



Payne, Jackson, Hall (Geology, in press)

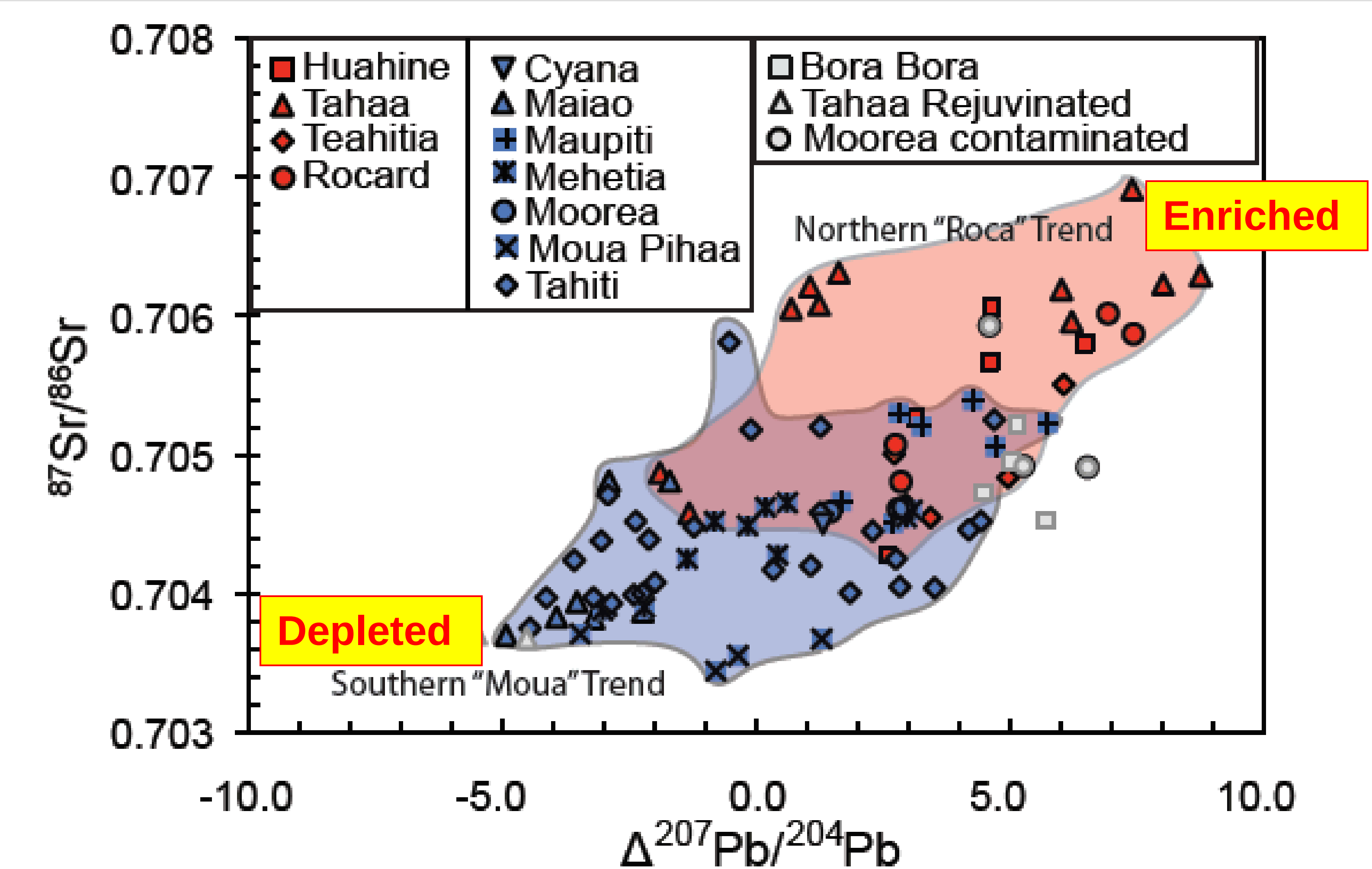
Societies vs. Marquesas: Mantle “mirror images”



SAW642AN model of Panning and Romanowicz (2006) at 2800 km

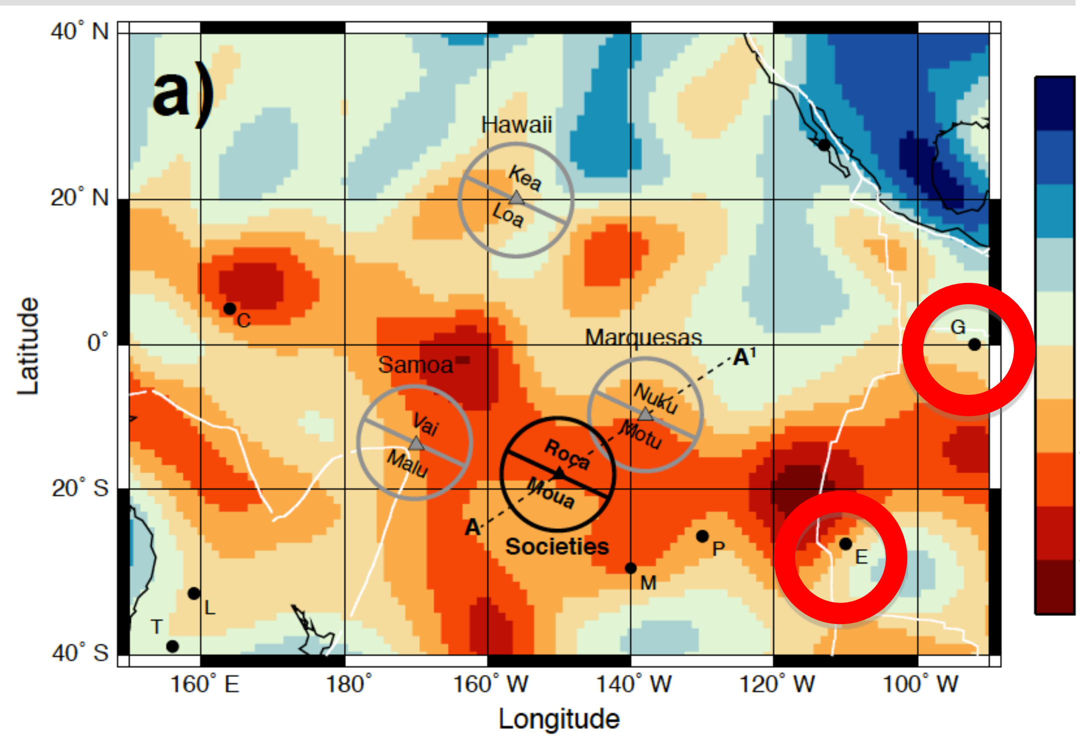
Payne, Jackson, Hall (Geology, in press)

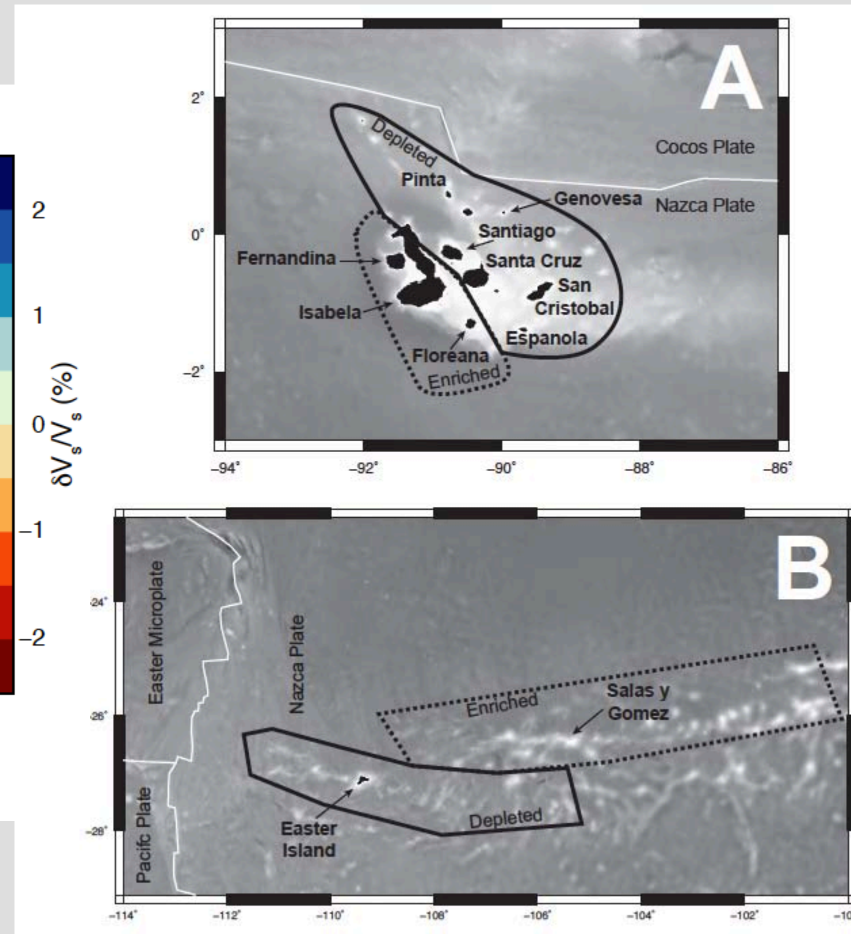
Societies: North side enrichment!



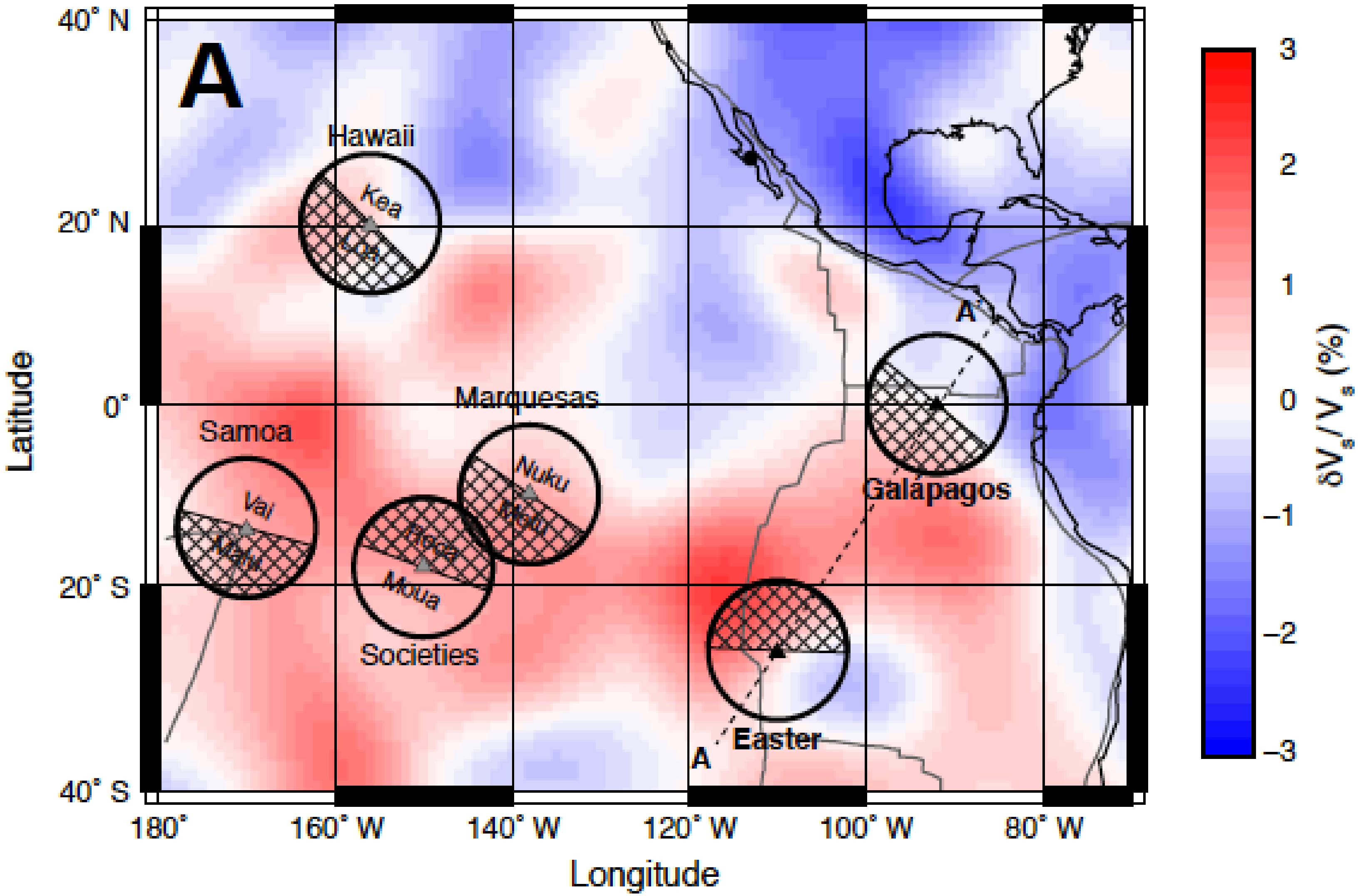
Payne, Jackson, Hall (Geology, in press)

Nazca Plate: Galapagos vs. Easter



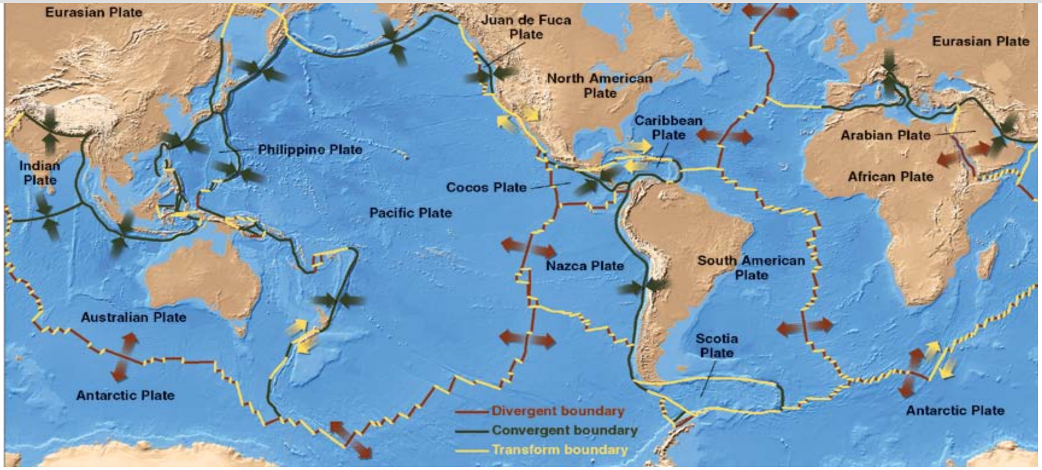


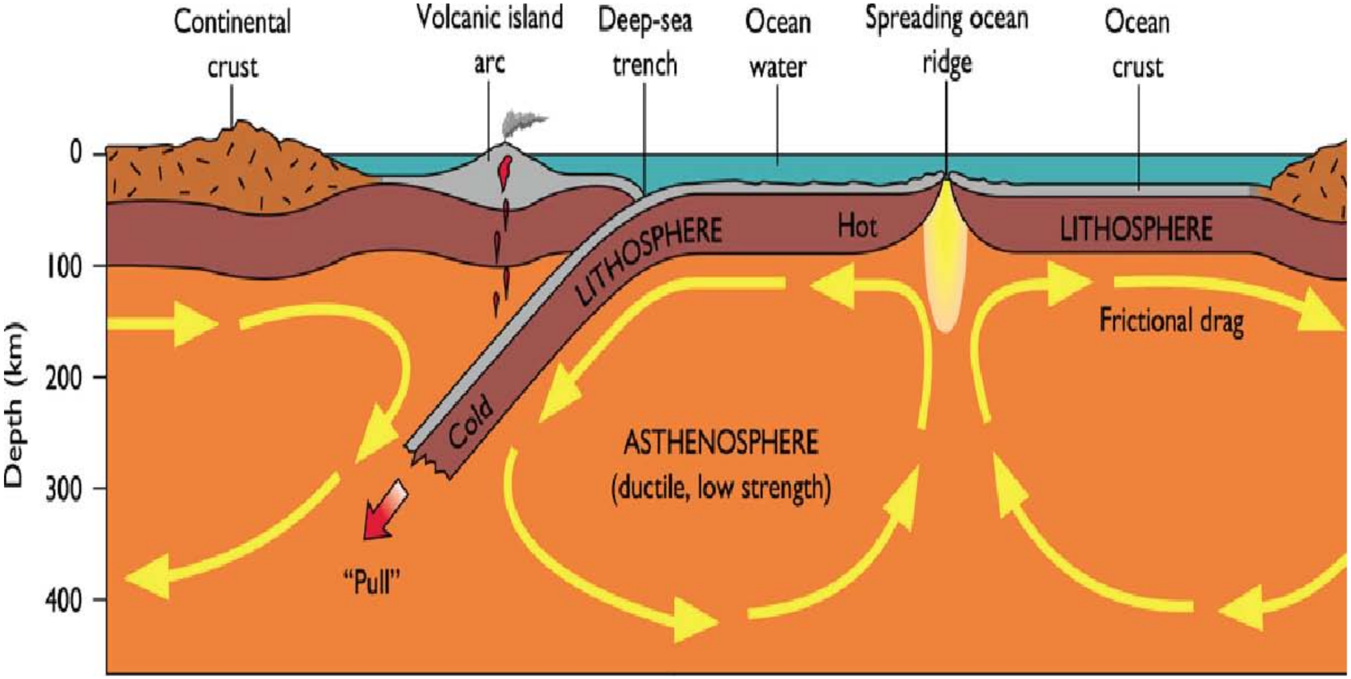
Harpp et al, in review at *Geology*



Harpp et al, in review at *Geology*

A Dynamic Earth





Lavas as probes of the mantle's composition:

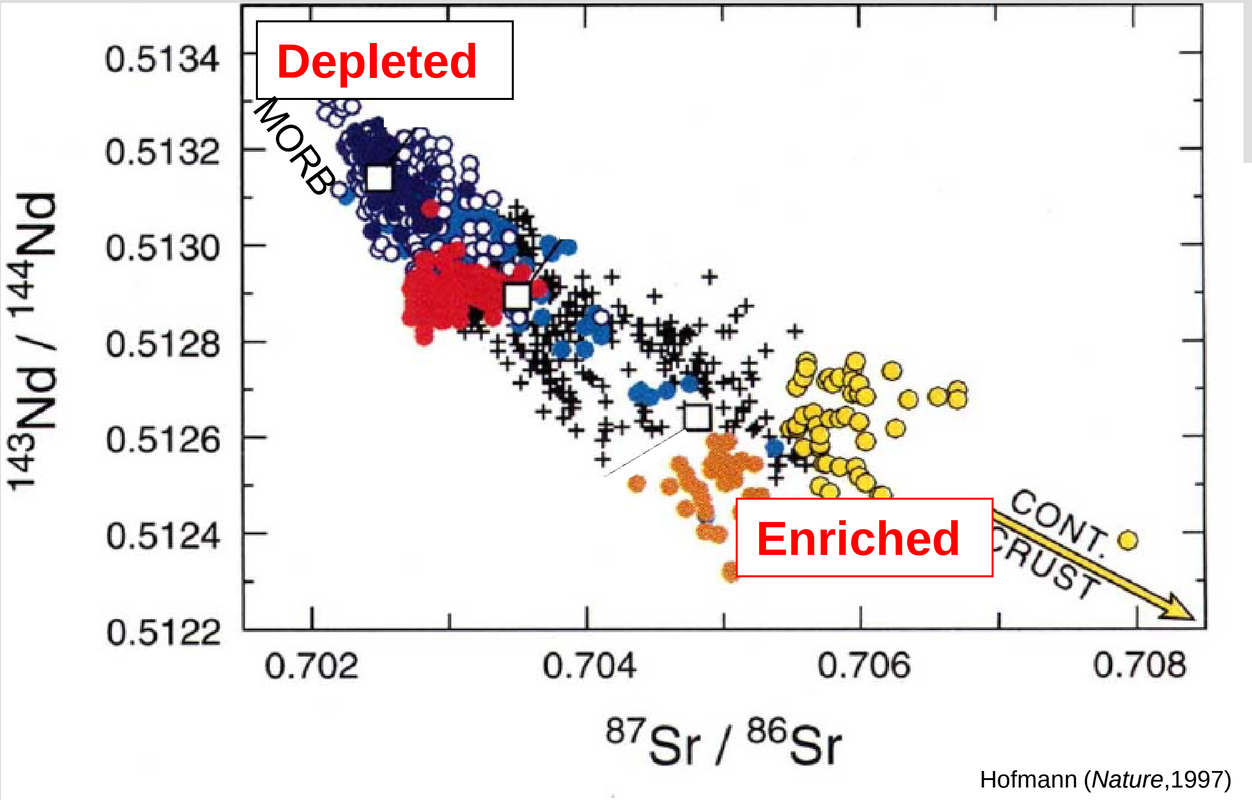
Radiogenic isotopes (e.g., $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$) and some trace element ratios <u>are not changed</u> between solid and melt.

$^{87}Sr/^{86}Sr$ solid mantle
(Peridotite)

=

$^{87}Sr/^{86}Sr$ melt
(Basalt)

Hotspot lavas reveal a heterogeneous mantle



Hofmann (*Nature*,1997)

Lavas erupted at hotspots are isotopically heterogeneous.
Therefore: ***The solid mantle sources of these lavas are heterogeneous.***

The $1 billion mission to reach the Earth's mantle - CNN

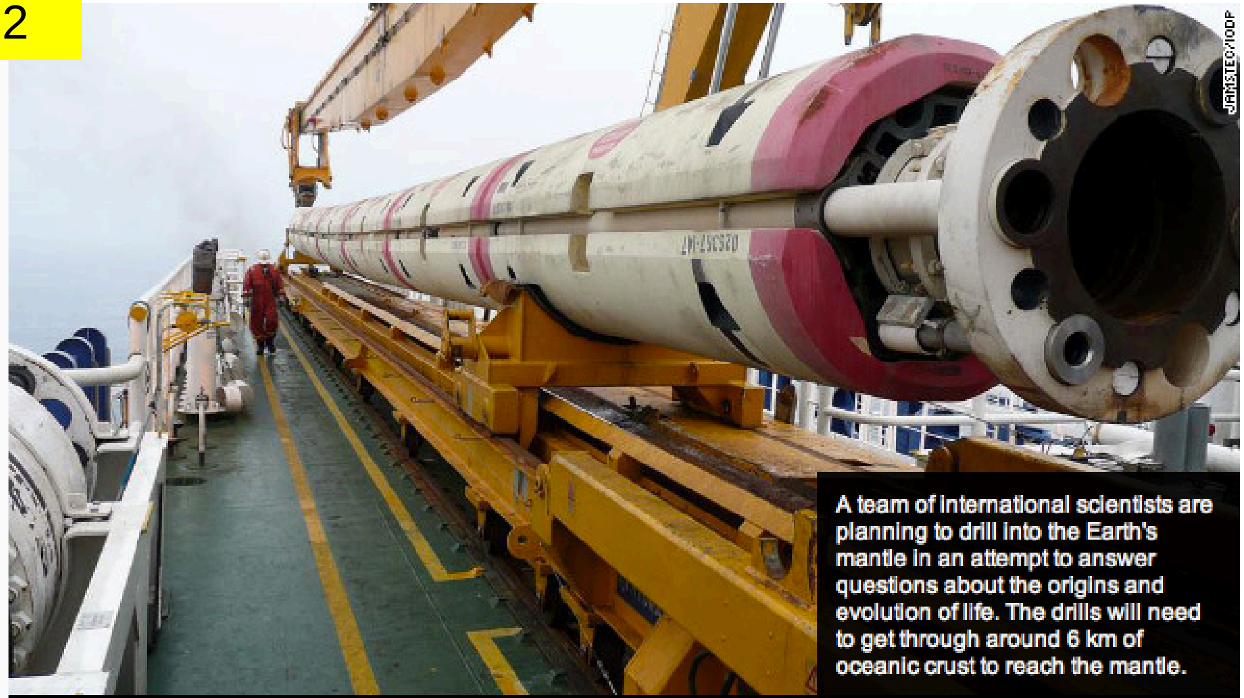
http://www.cnn.com/2012/10/01/tech/mantle-earth-drill-mission/index.html?hpt=hp_c2

Apple Yahoo! Google Maps YouTube Wikipedia News (1,155) Popular

The $1 billion mission to reach the Earth's mantle

By **Tom Levitt**, for CNN
updated 2:54 PM EDT, Tue October 2, 2012 |

Oct 2, 2012



A team of international scientists are planning to drill into the Earth's mantle in an attempt to answer questions about the origins and evolution of life. The drills will need to get through around 6 km of oceanic crust to reach the mantle.

HIDE CAPTION

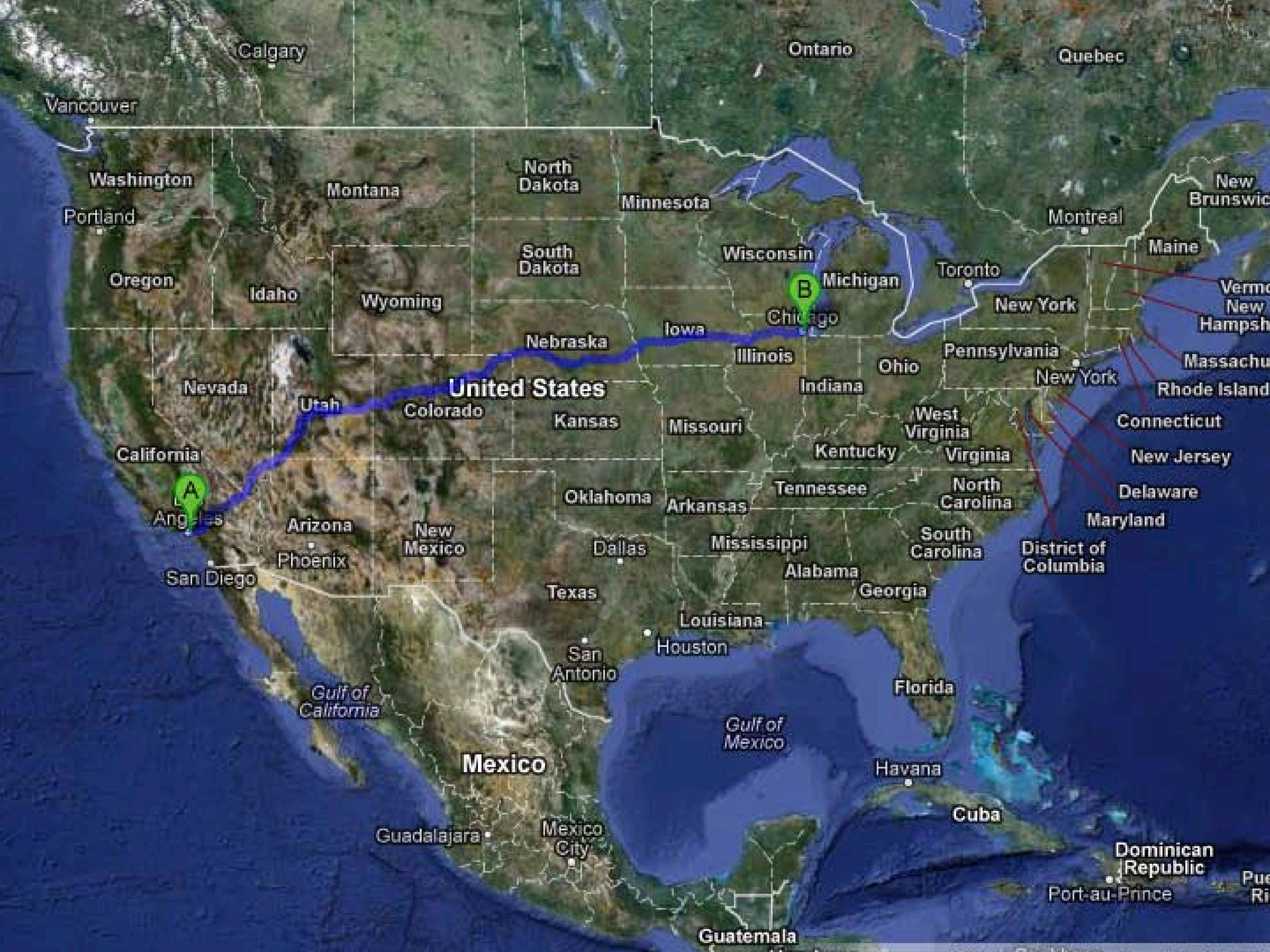
Mission impossible?

<< < 1 2 3 4 5 > >>

STORY HIGHLIGHTS

- Scientists planning mission to drill down to Earth's mantle and

(CNN) -- Humans have reached the moon and are planning to return samples from Mars, but when it comes to exploring the land deep beneath our feet, we have only scratched the surface of our


Calgary
Ontario
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Washington
Montana
North Dakota
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Portland
New Brunswic
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Idaho
Wyoming
South Dakota
Wisconsin
Michigan
Toronto
B
Chicago
New York
Vermo
New Hampsh
Iowa
Nebraska
Illinois
Pennsylvania
Ohio
Massachu
Nevada
Utah
United States
Colorado
Indiana
New York
Rhode Island
Kansas
Missouri
West Virginia
Connecticut
California
Kentucky
Virginia
New Jersey
A
Oklahoma
Tennessee
North Carolina
Delaware
Arkansas
Maryland
Arizona
New Mexico
South Carolina
District of Columbia
Phoenix
Dallas
Mississippi
San Diego
Alabama
Georgia
Texas
Louisiana
Houston
San Antonio
Florida
Gulf of California
Gulf of Mexico
Mexico
Havana
Cuba
Guadalajara
Mexico City
Dominican Republic
Port-au-Prince
Guatemala

A virtually inaccessible interior

- It’s hard to constrain the compositional variability of the inside Earth’s interior.
- Why? Because it’s hard to dig deep holes…we’ve barely “scratched” the surface!
- The Soviet “Kola” drill hole (1970-1992), 12.3 km deep.

$\Delta^{33}S$

$$\Delta^{33}S = (^{33}S/^{32}S)_{sample}/(^{33}S/^{32}S)_{reference} - [(^{34}S/^{32}S)_{sample}/(^{34}S/^{32}S)_{reference}]^{0.515}$$

- Cs^+ primary beam using critical focusing, 10kV acceleration potential with 2~2.5 nA intensity, Field aperture is at 3000 micron, with auto centering on, contrast aperture is at 400 micron, entrance slit = 85 micron, exit slit = 250 micron, 5 micron raster, MRP = 4850. Counts are collected in 16 cycles with 4s counting for each cycle. Counts are corrected for background and yield.

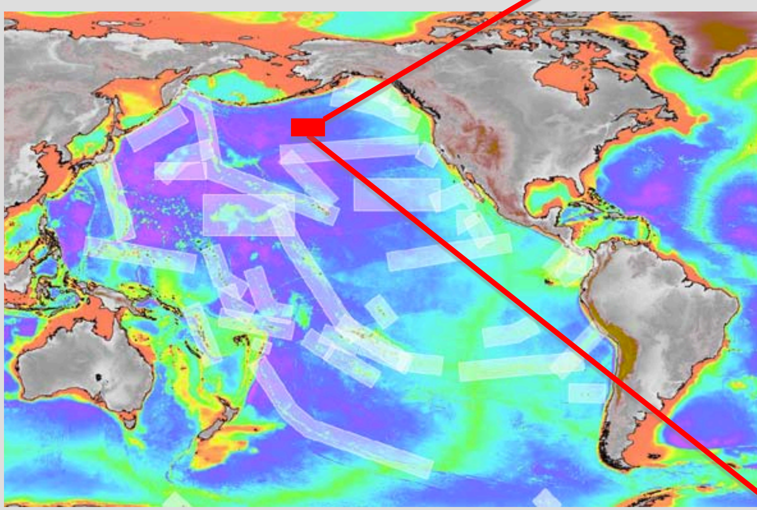
<u>Key issues:</u>

- Measurements of isotope ratios are done essentially by the standard-sample-standard bracketing in principle. In the measurements presented for the manuscript, Ruttan pyrite is used as a calibration standard to correct for $^{34}S/^{32}S$ and $^{33}S/^{32}S$ ratios of secondary standards and samples. Ruttan pyrite is trusted because of its homogeneity inferred from a long term analytical data set.

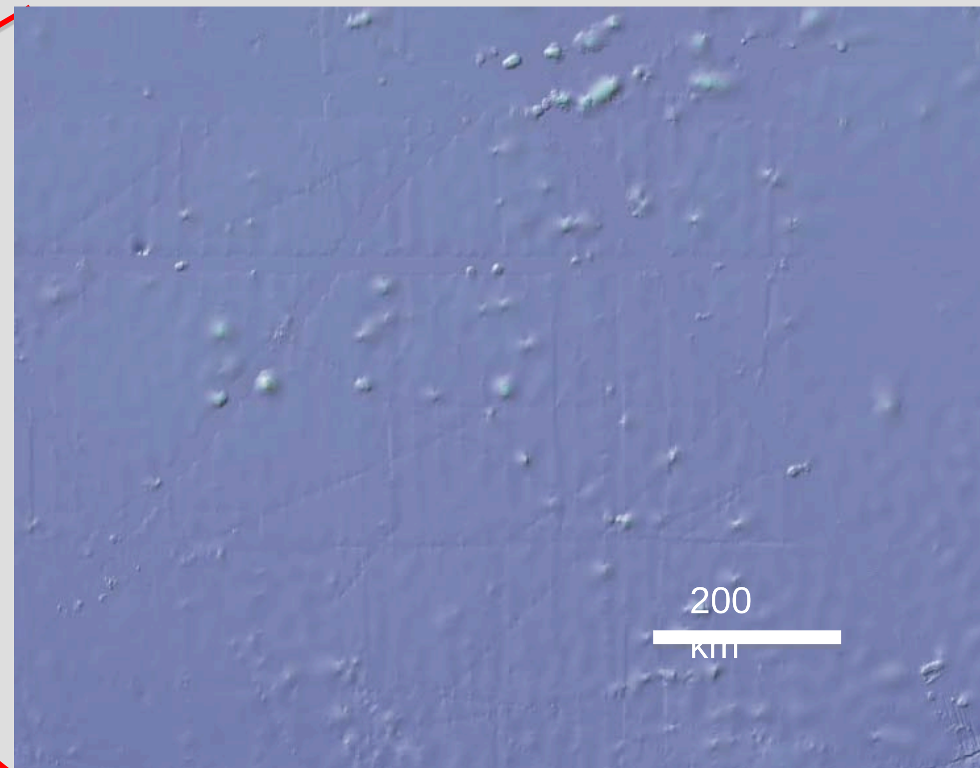
- The mass fractionation line (slope ≈ 0.515) is drawn by through the origin minimizing the dispersion among measurements of standard (Ruttan) and secondary standard (Balmat) which are supposedly $\mathbf{\Delta}^{33}S=0$. This is considered to give better accuracy for $\mathbf{\Delta}^{33}S$ values than imposing an assumed slope (0.515) passing through the origin of a $\delta^{34}S$- $\delta^{33}S$ plot. In any case, the fitted slope would pass through the origin within 0.512 +/- 0.003.

Looking ahead….

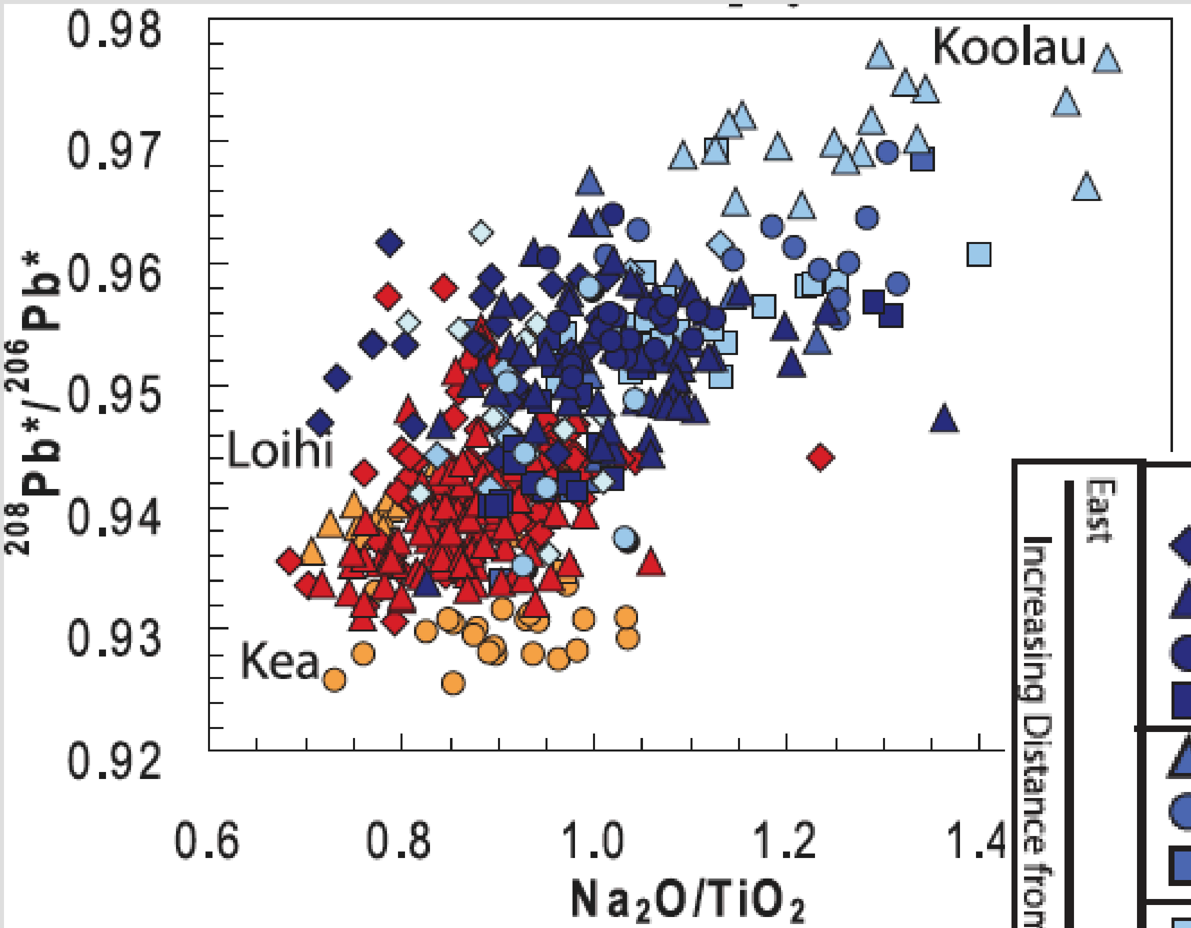
100,000 seamounts >1km high (*National Geographic*, Sept ‘12)

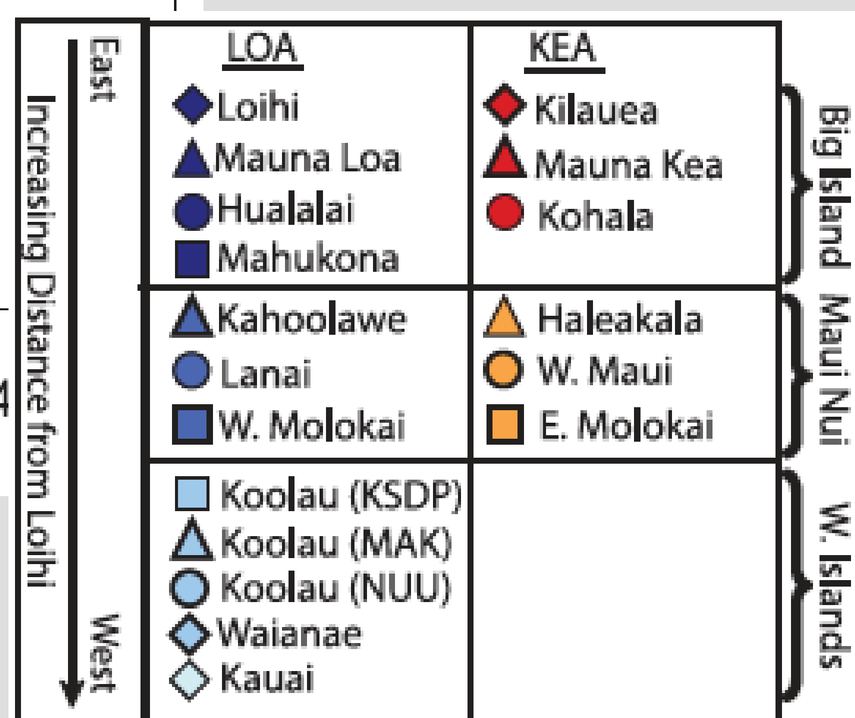


EarthRef Seamount Catalogue



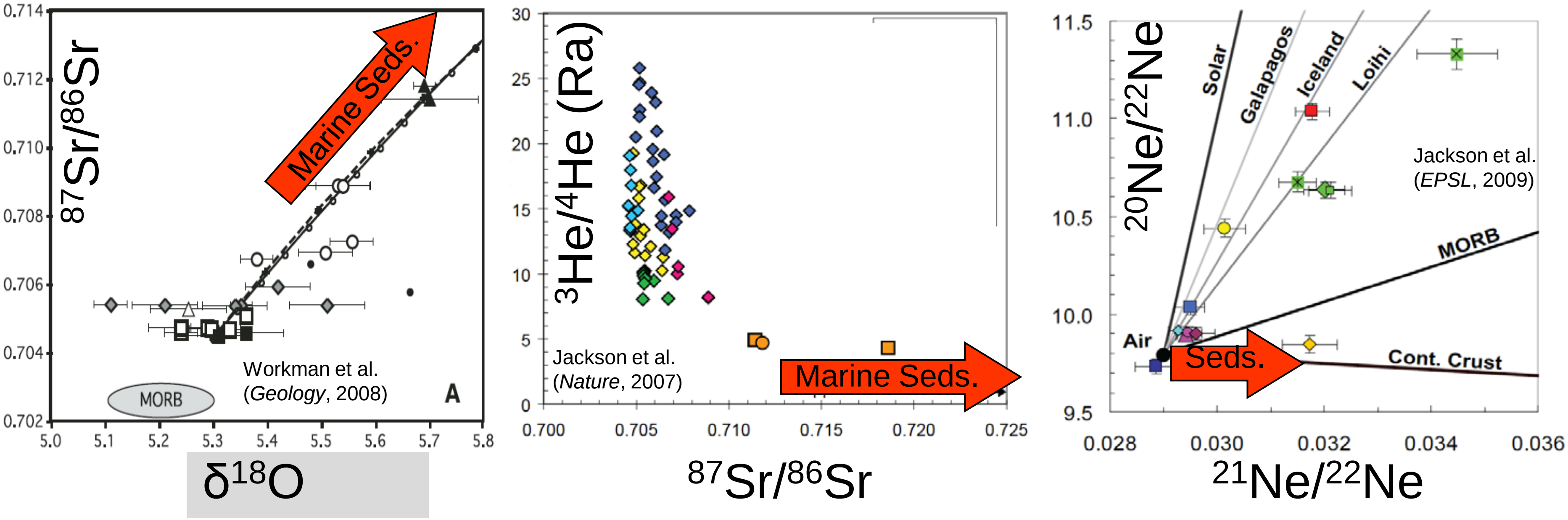
Loa vs. Kea: Different major elements





Jackson et al. (G-cubed, 2012)

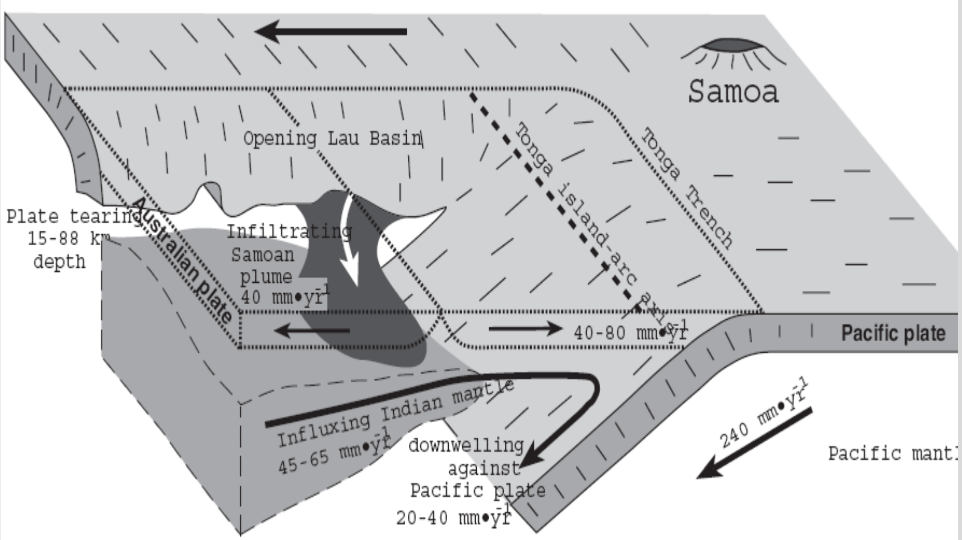
Multiple isotopic systems consistent with recycled sediment



And $^{187}Os/^{188}Os$, $^{176}Hf/^{177}Hf$ ……

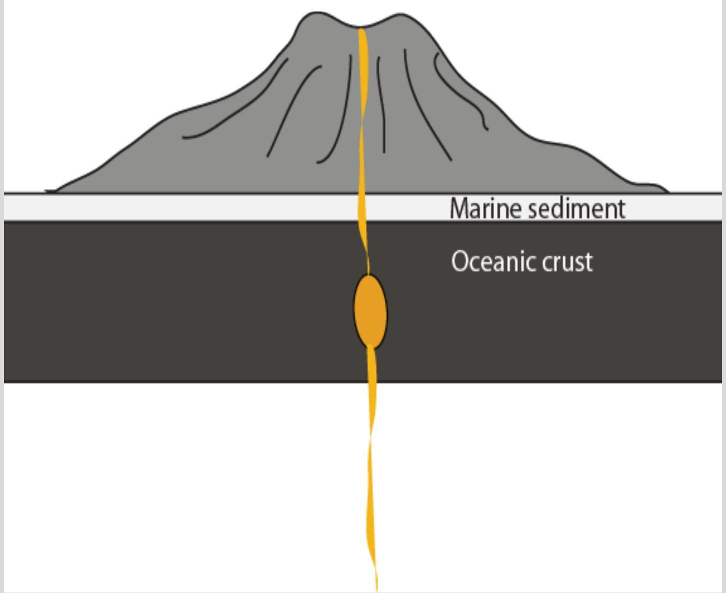
Recap: Strong geochemical evidence for a sediment signature in Samoan lavas, but….

Rapid-cycled sediment from the Tonga trench?

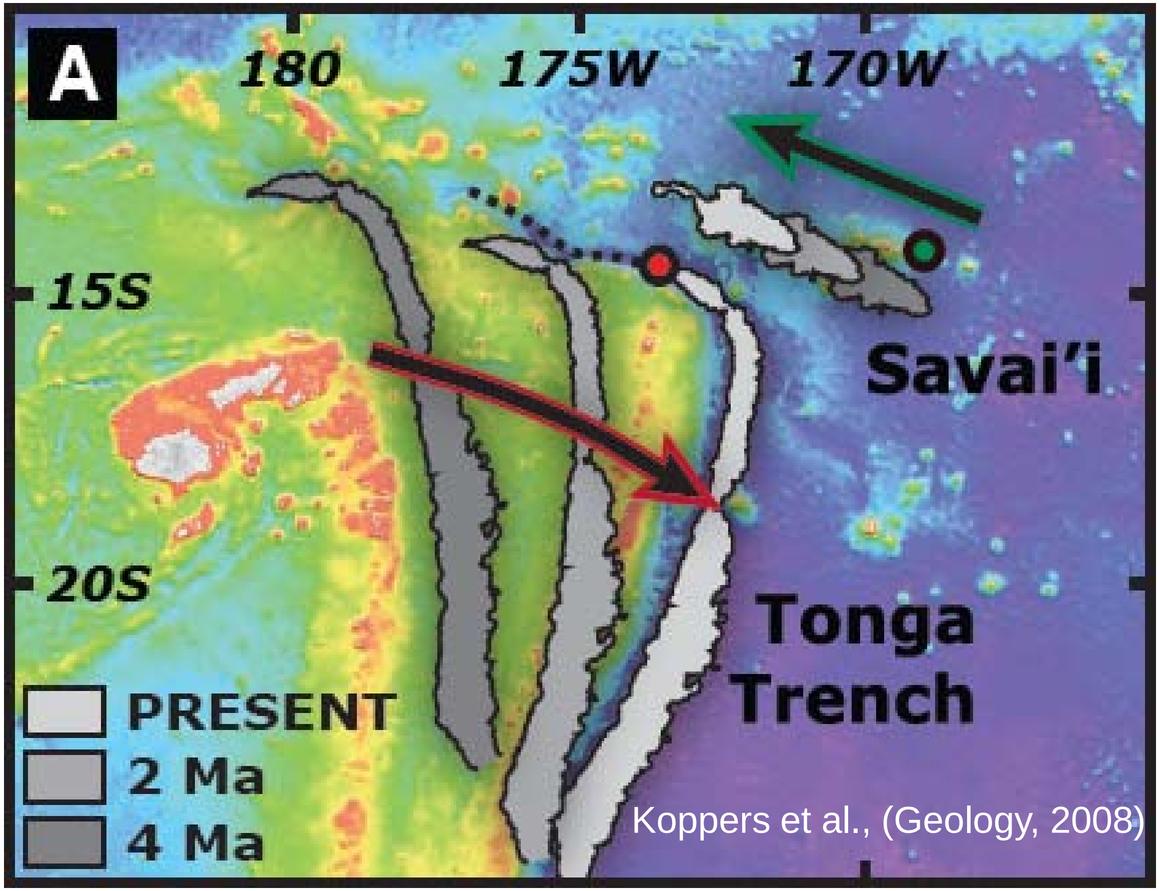


Turner and Hawkesworth, *Geology* 1998

Shallow-level assimilation of marine sediment?

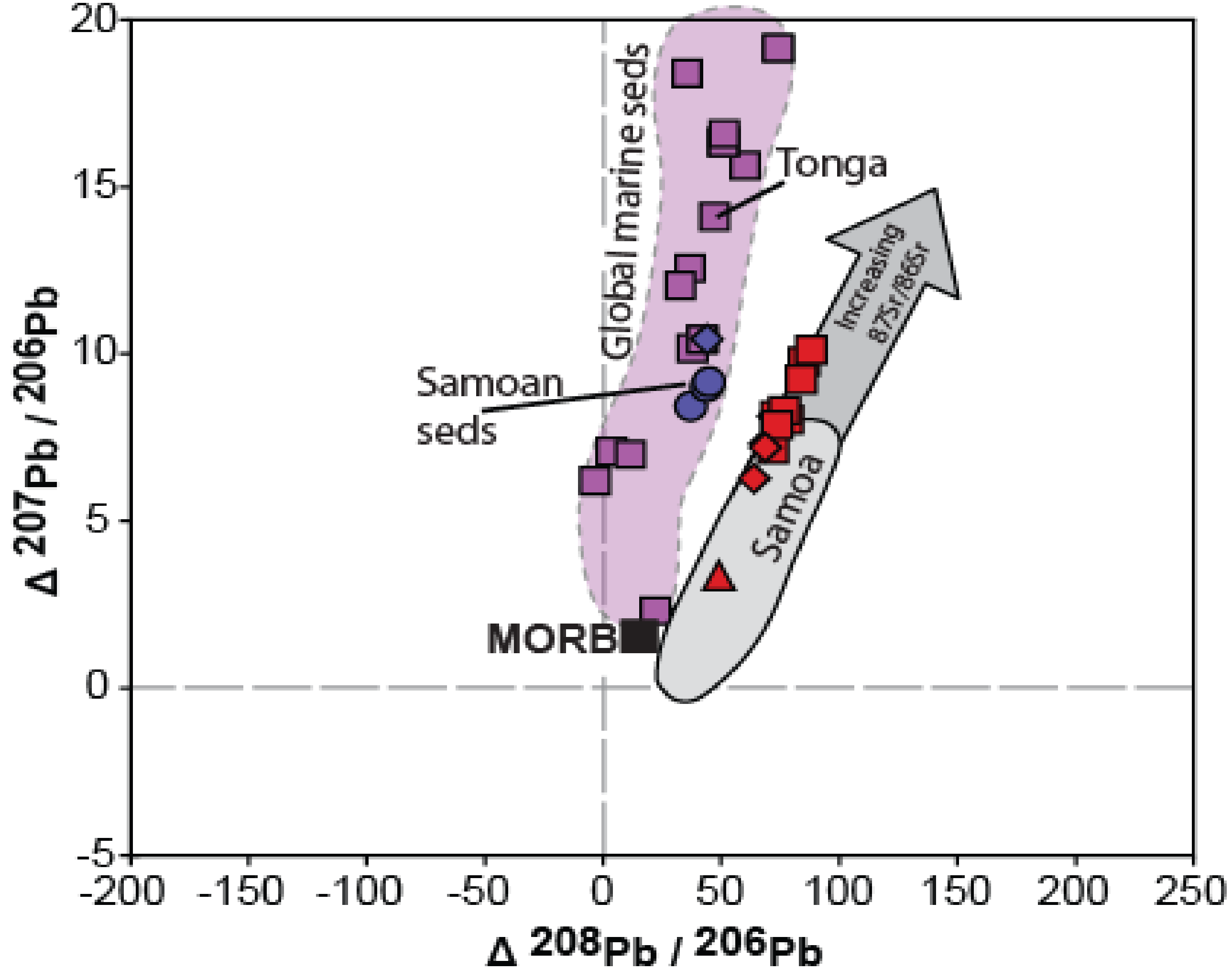


Rule out contamination by sediments from the Tonga trench



Tonga trench – Savai'i convergence rate = 24 cm/year !

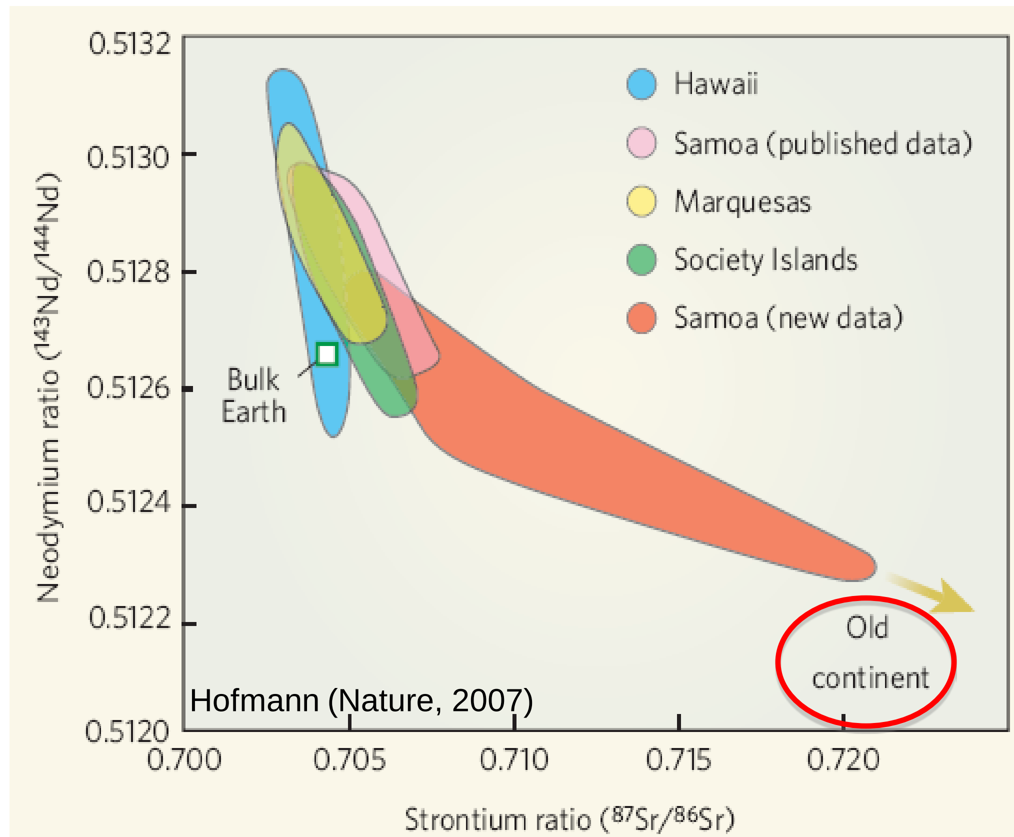
Rule out contamination by shallow modern marine sediments



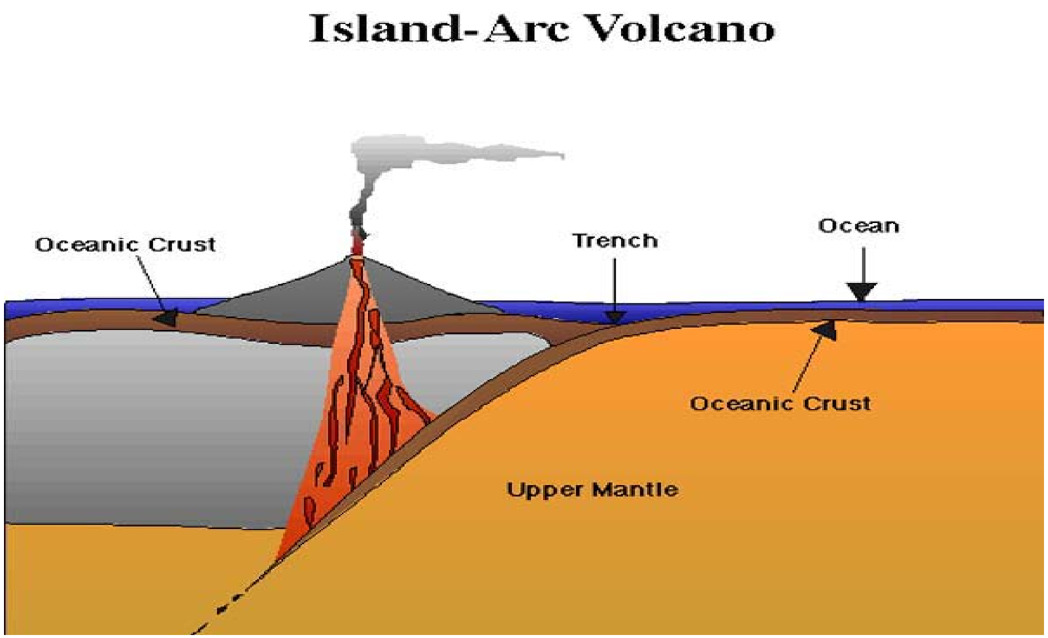
Recycled sediment signatures in hotspot lavas are rare…

- Large quantities of sediment enter the mantle.
  Africa AND S. America in 3 Ga !

- **Why is recycled sediment so rare in hotspot lavas? It took >30 years of looking!**



Sediment melted during subduction and "short-circuited" back to the surface?



Tracing trace elements from sediment input to volcanic output at subduction zones

Terry Plank* & Charles H. Langmuir
NATURE · VOL 362 · 22 APRIL 1993

"Mass balance indicates that ~20% of the element budget in subducted sediment is recycled to the arc. …… a larger fraction of subducted sediment may continue to descend with the plate into the deeper mantle."

Or, sediment is subducted and subsequently mixed to “smithereeens”?

Australian-
Indian plate

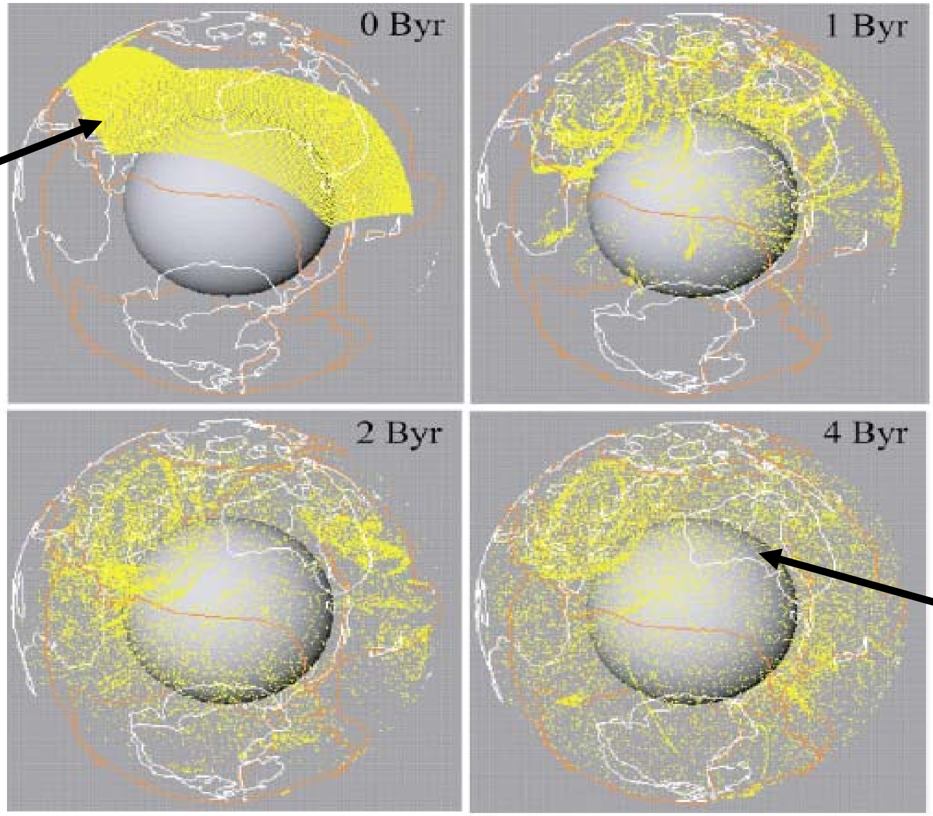
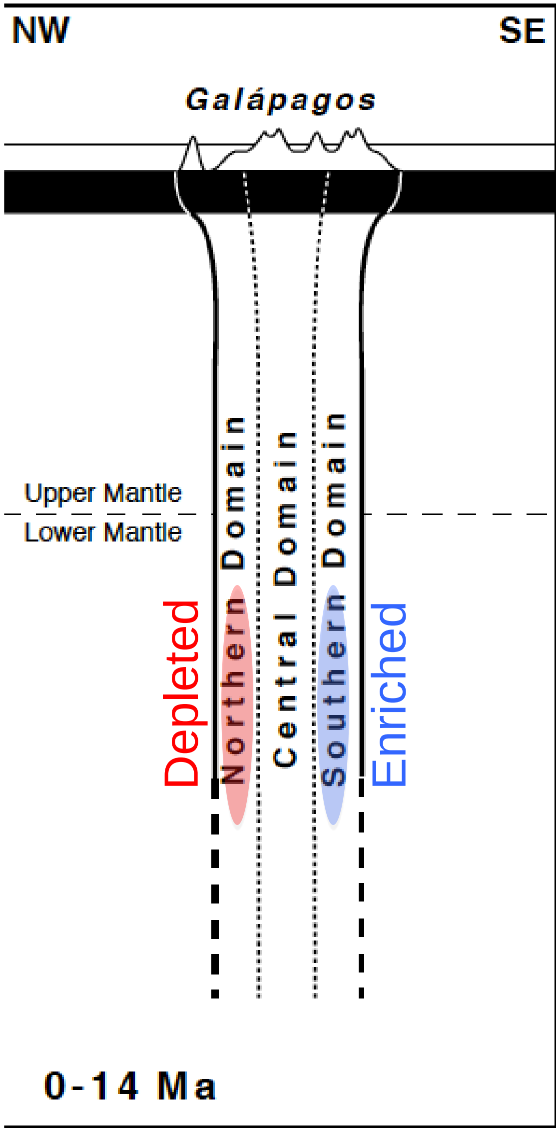


Figure 11 Evolution of the Australian-Indian plate in the steady state mixing model of Van Keken & Zhong (1999). Snapshots of the particles that composed the plate at time 0 are shown at 1, 2, and 4 Ga.

Van Keken et al. (*Ann. Rev. Earth Planet. Sci.*, 2002)

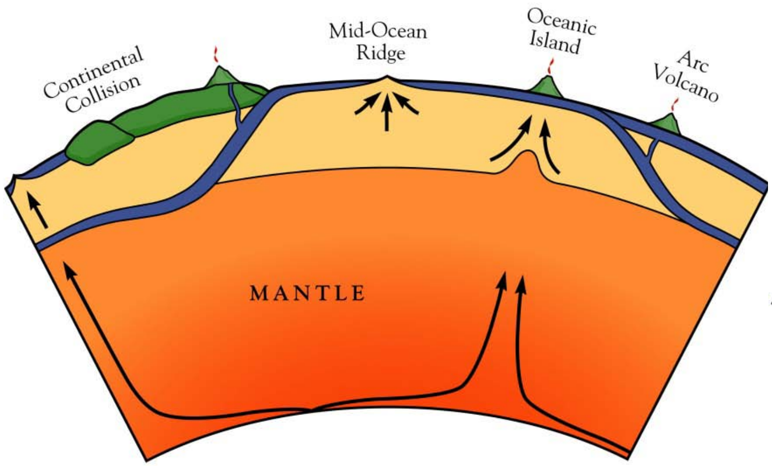
Thin sediment veneers would be “destroyed” by mixing.

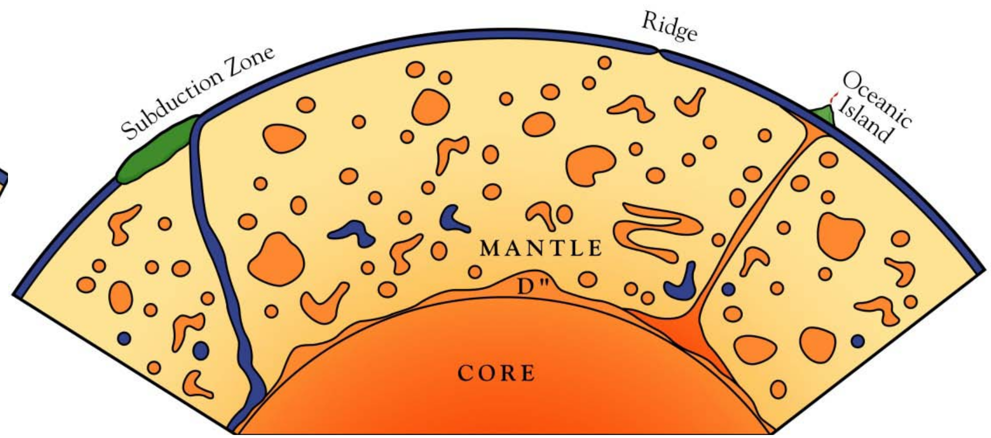
The mantle is a big place: Mass of subducted continents is only **0.1%** of the mantle.

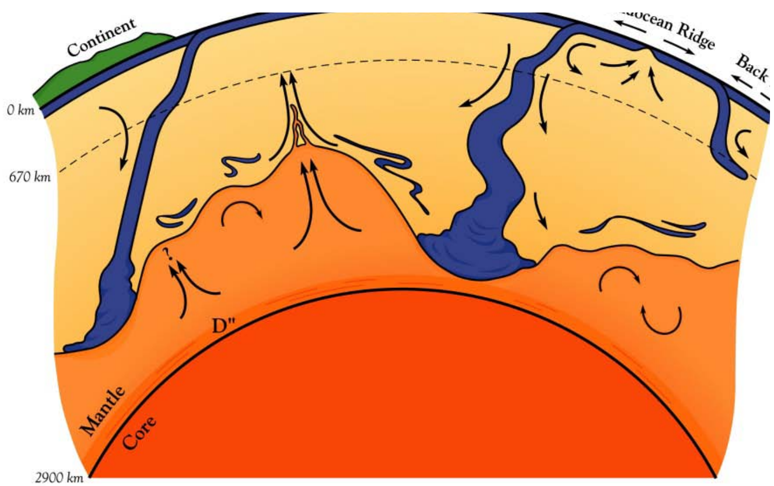


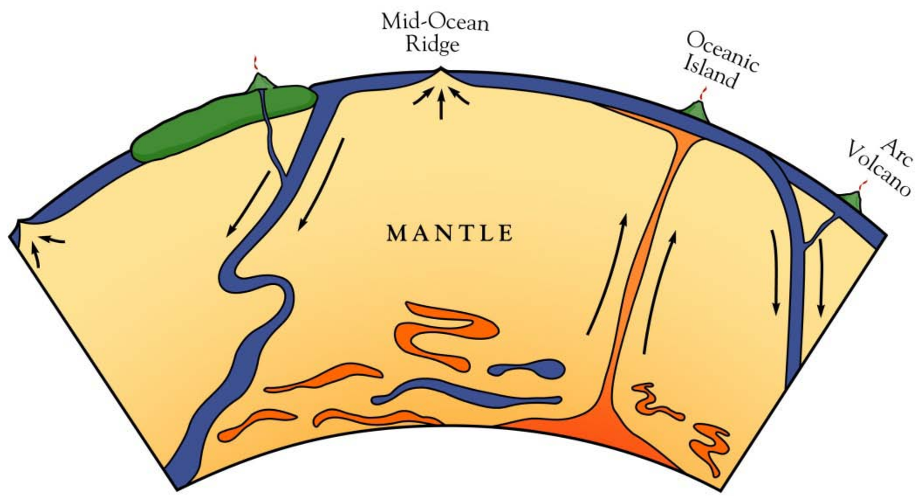
Hoernle et al., 2000

Models of mantle convection and distribution of heterogeneities



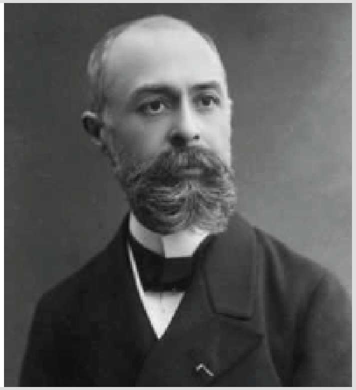




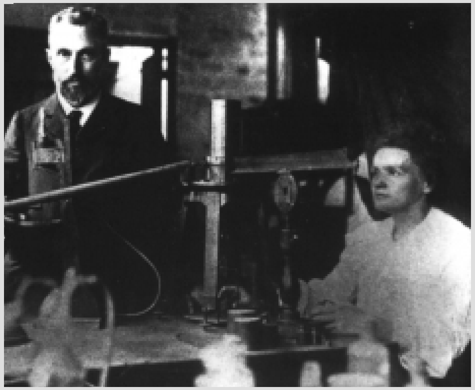


In the span of 1 human life….
(oldest living person born in 1896)

Becquerel



Curies



Rutherford

Soddy

Boltwood

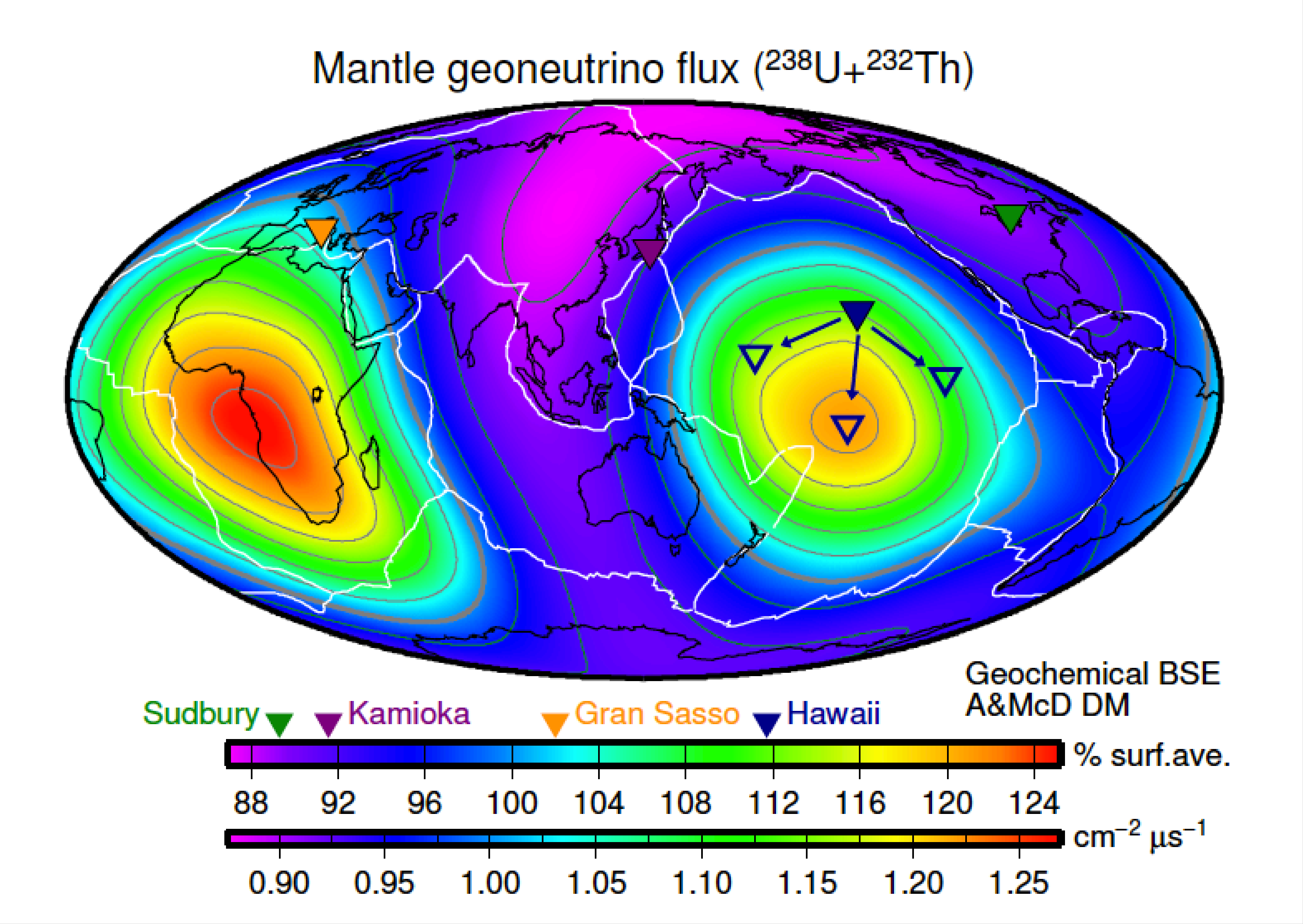
1896. Discovered radioactivity accidentally. Phosphorescent U-salts exposed photographic plates

1903. Nobel Prize in physics in 1903 for their work on "radioactivity" – a term coined by Marie Curie.

1903-1910. Demonstrated existence of isotopes and that radioactivity follows an exponential law. Hypothesized that it might be used as a clock.

1907. Dated first rock, acting on suggestion from Rutherford. Got ages from 400 to 2200 million years.

Geoneutrinos to “map out” mantle chemical heterogeneities



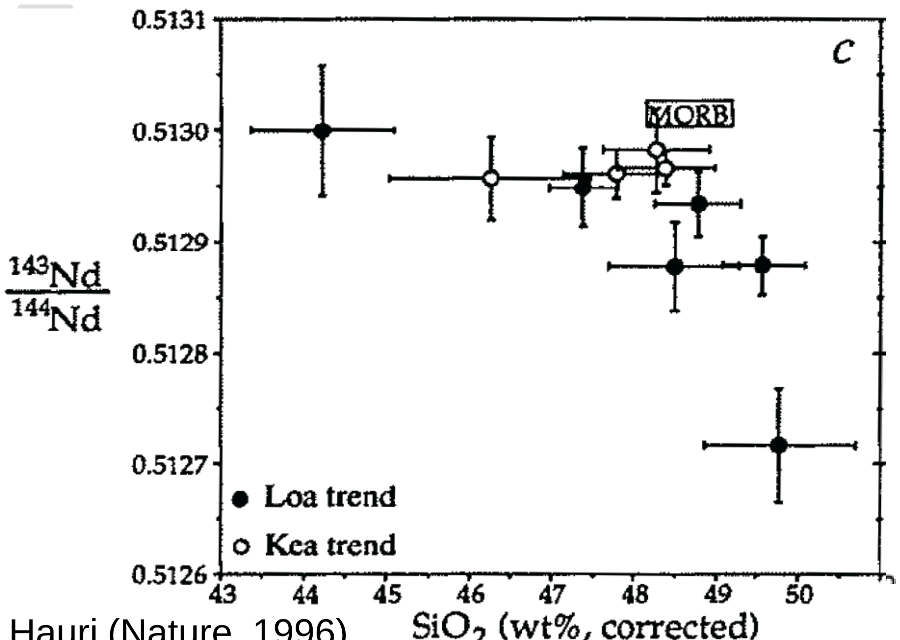
Sramek et al. (2012)

Major-element variability in the Hawaiian mantle plume

Erik H. Hauri

Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015, USA

Major element (lithological?) heterogeneity accumulates in the mantle owing to subduction over time



Hauri (Nature, 1996)

“HOLY GRAIL”

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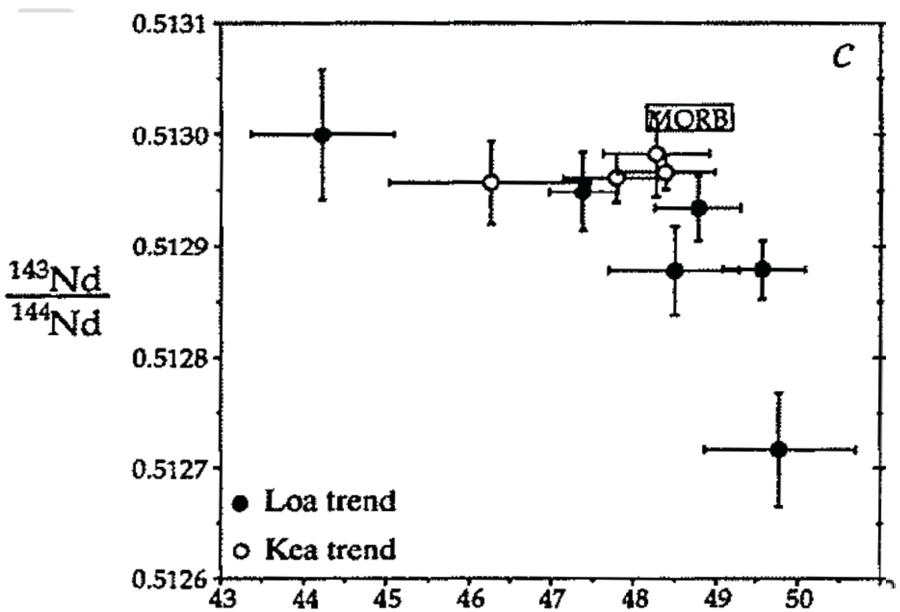
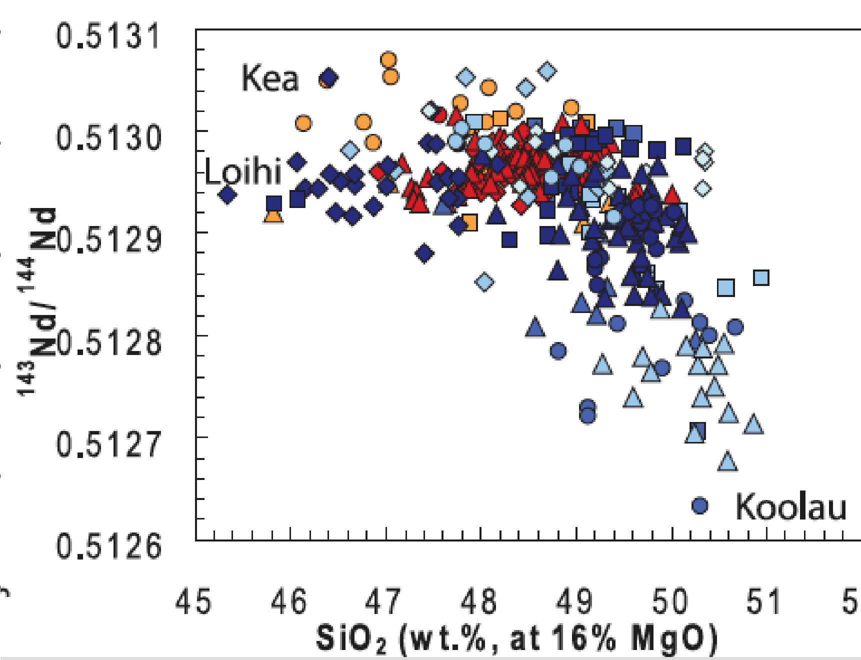


Hauri (Nature, 1996)



Jackson, Weis, Huang (G-Cubed, 2012)

ARTICLES

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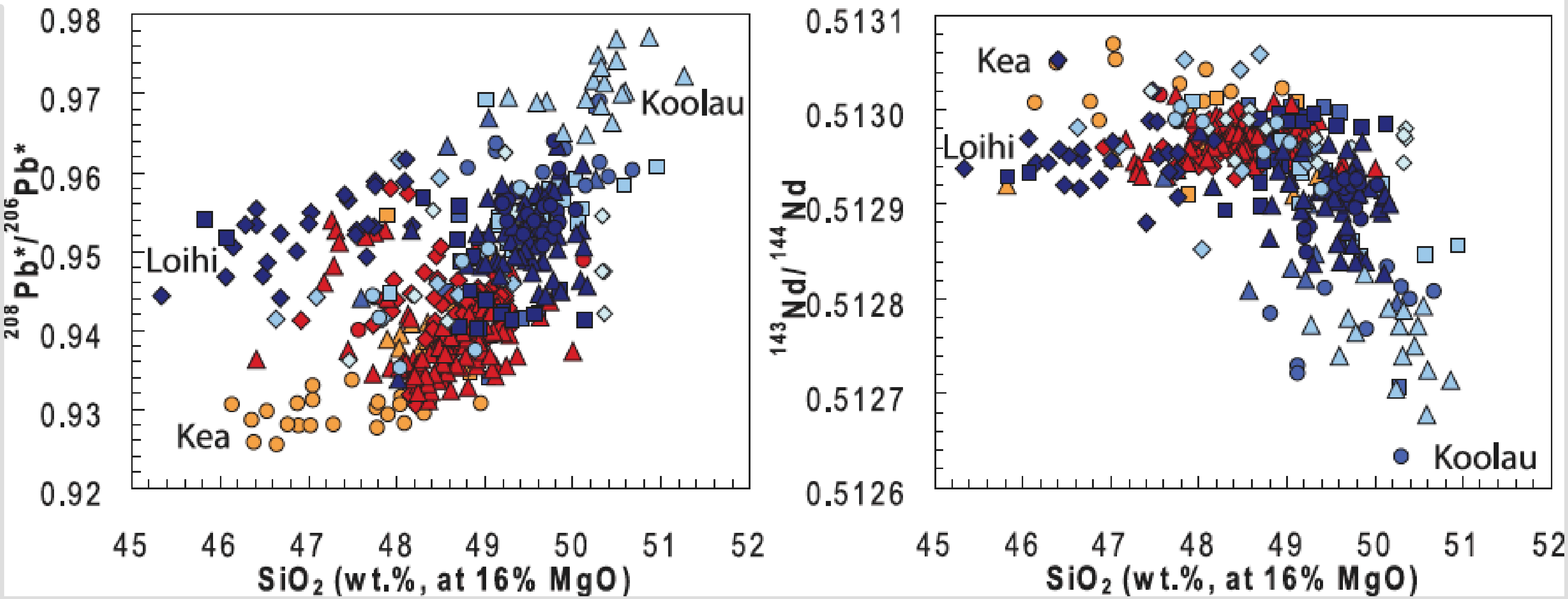

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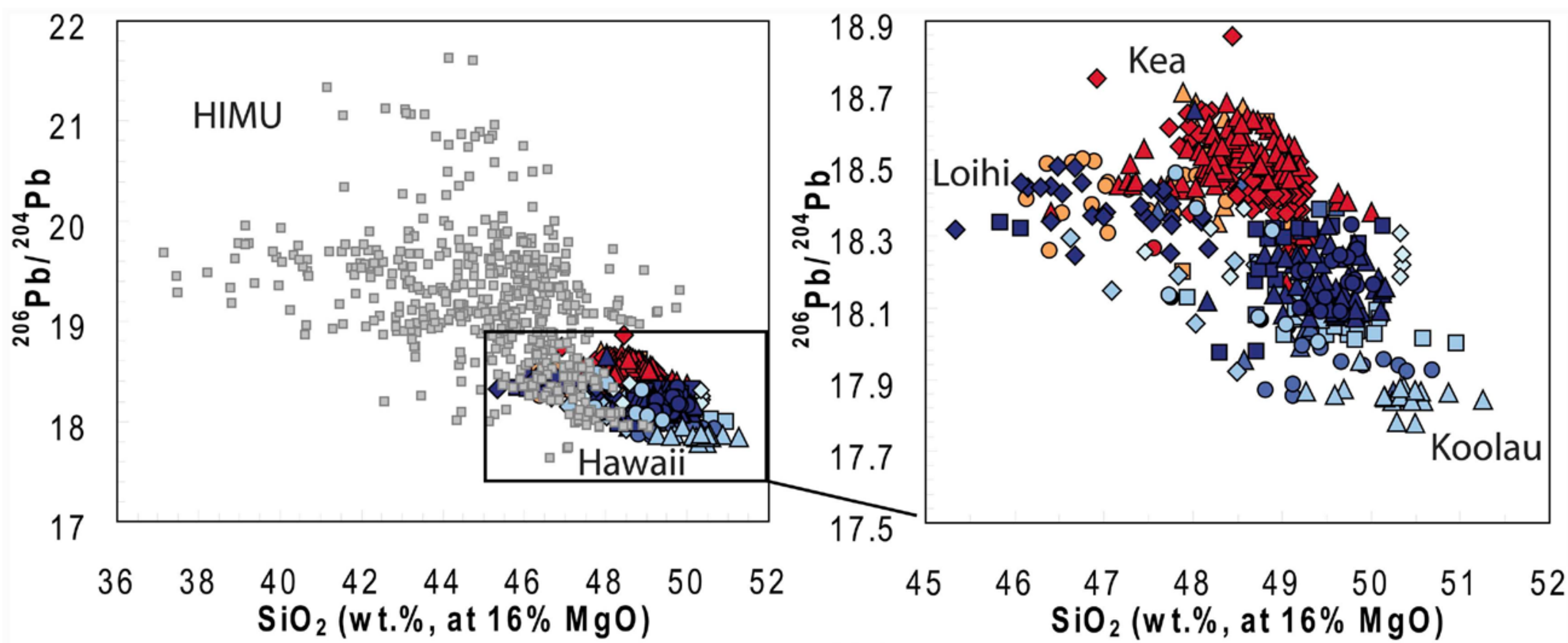
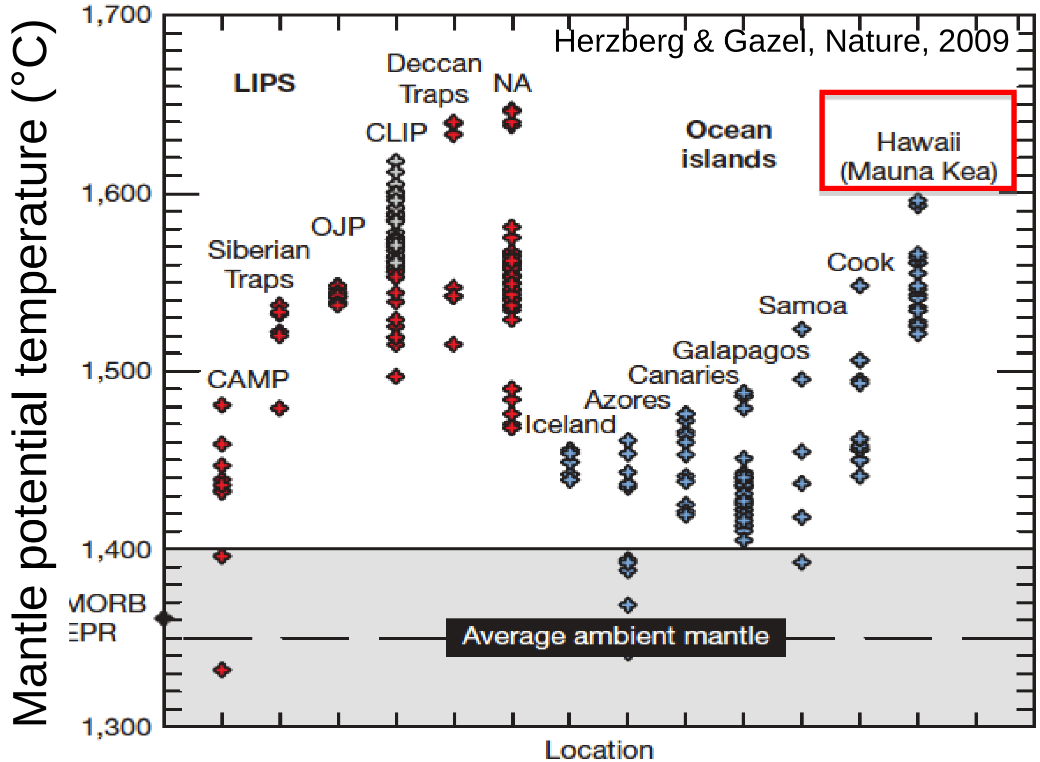


Pinpointing specific major element compositions for the different isotopic reservoirs will allow experimentalists to better constrain source lithologies

Mantle plumes: Are they hot or not?

Current petrological thermometers require that **<u>olivine and orthopyroxene</u>** co-exist in the mantle source of the melts.



Problem: Olivine may not always be a phase in the source of oceanic lavas.

An olivine-free mantle source of Hawaiian shield basalts

Alexander V. Sobolev[1,2], Albrecht W. Hofmann[1], Stephan V. Sobolev[3,4] & Igor K. Nikogosian[5,6]

Summary Part 1

Why do we care what is melting
(eclogite vs. peridotite) beneath Hawaii & other ocean islands?

Well, until we figure out what is melting beneath Hawaii, geochemists and petrologists can't do simple things like calculate mantle melting temperatures with any certainty.

Without temperature estimates, it's hard to argue for mantle plumes.

Without mantle plumes, we can't easily cool the Earth.

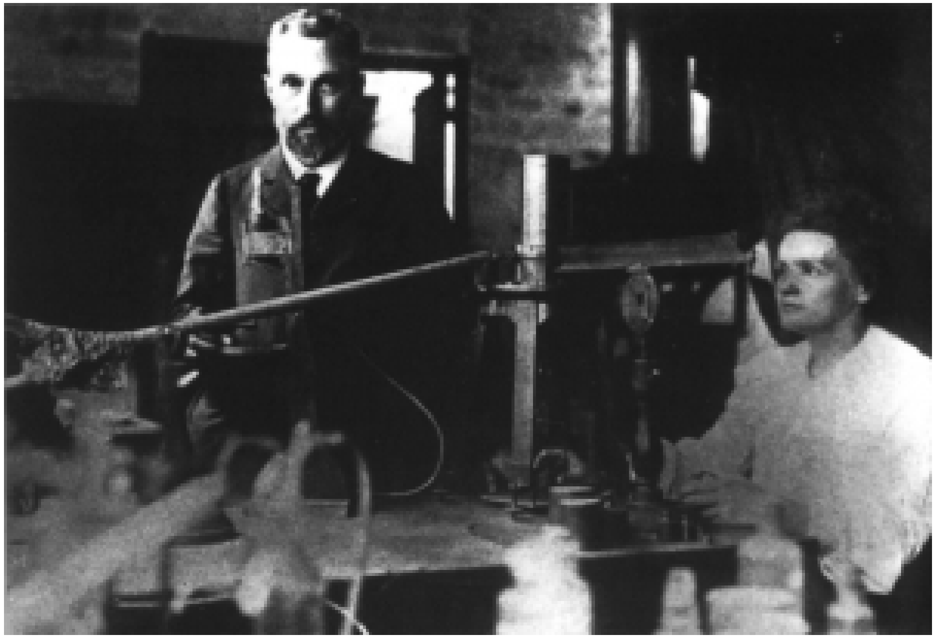
How can we model the thermal evolution of the Earth without a good idea of present-day temperature variations?

Radioactivity was discovered accidentally in 1896 by Henri Becquerel.

He was actually studying phosphorescence (the phenomenon whereby some minerals glow in the dark after exposure to light).

He noticed that certain phosphorescent U salts would blacken photographic places. However, he soon discovered that the plates would blacken even when the minerals weren't phosphorescing.

Pierre and Marie Curie, discovered that radioactivity was not confined to minerals of U.

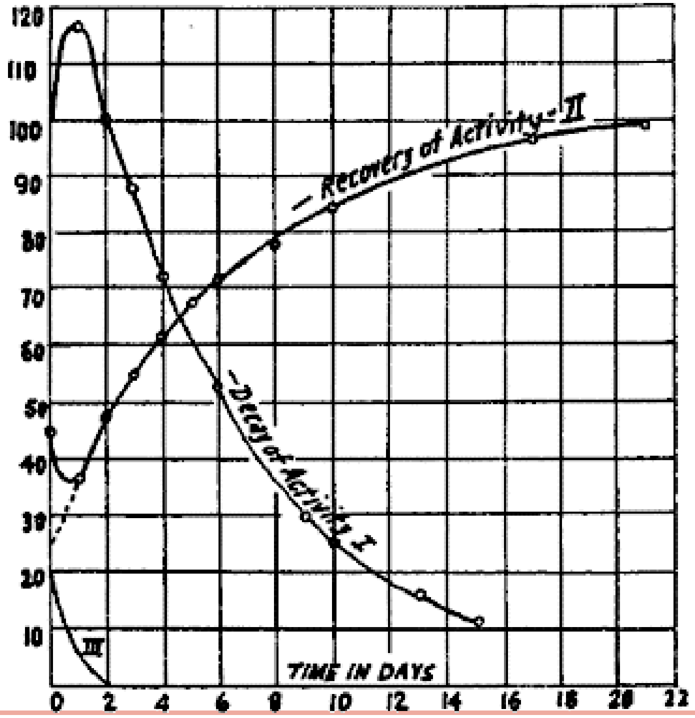


They won the Nobel Prize in physics in 1903 for their work on “radioactivity” – a term coined by Marie Curie.

Their research led to the discovery of new elements (in particular Po and Ra). Marie would win a second Nobel Prize (this time in chemistry) for the isolation of Ra. She was the first ever double Nobel Laureate, and one of only 2 double Laureates to have obtained the honour in different fields.

Ernest Rutherford and Frederick Soddy

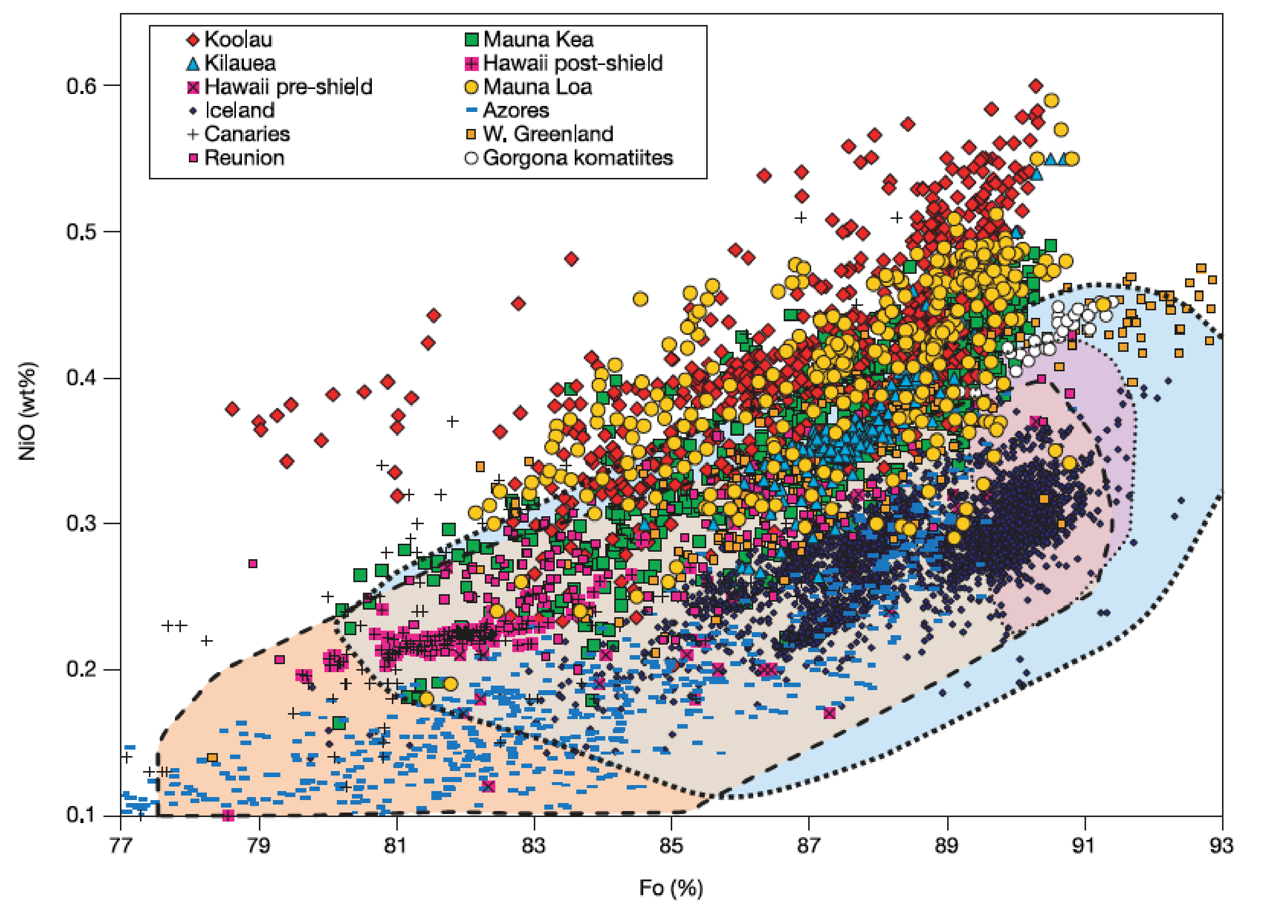
Demonstrated that radioactivity follows an exponential law (more on this later) and hypothesised that it might be used as a clock.



Lithological heterogeneity?

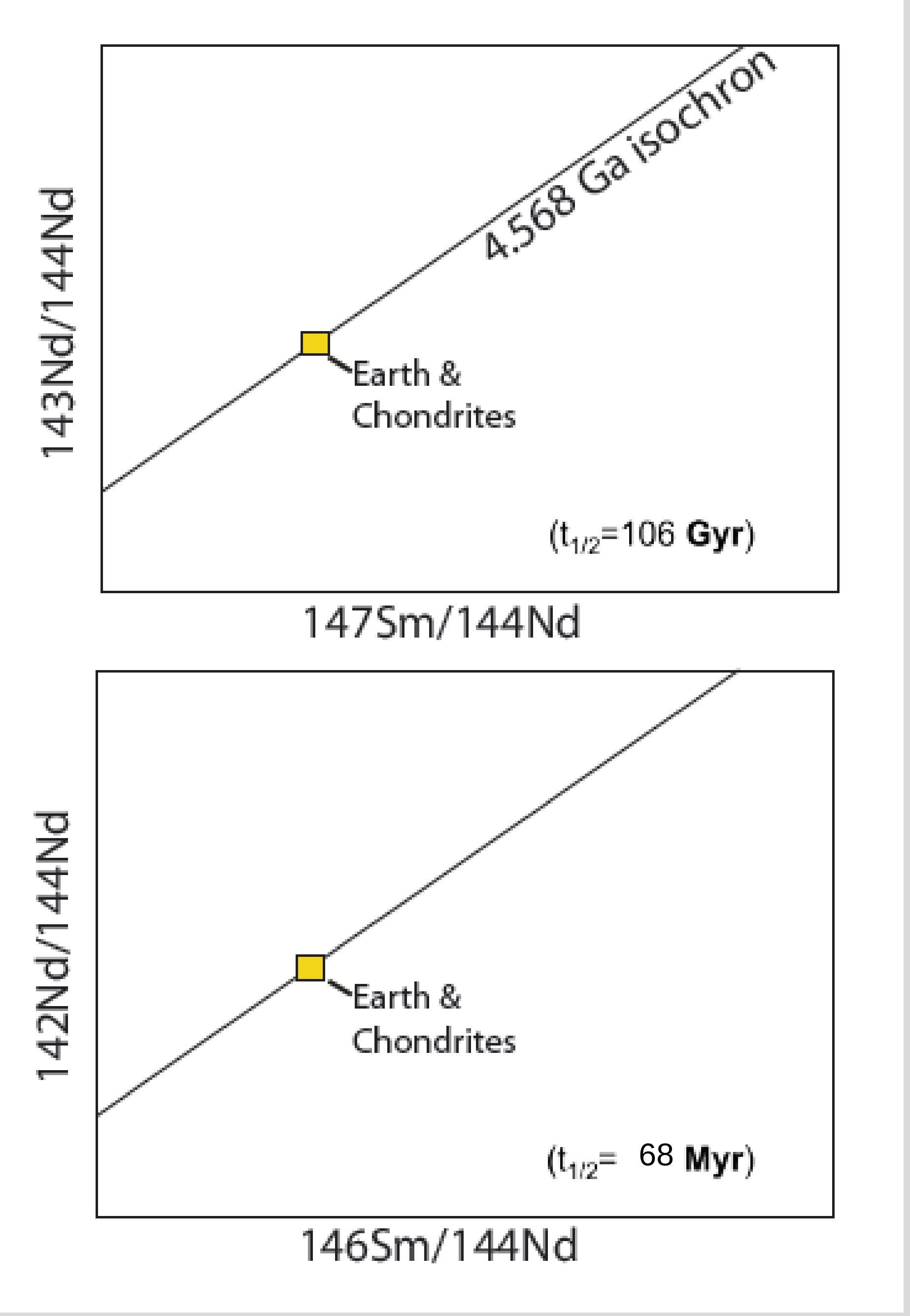
An olivine-free mantle source of Hawaiian shield basalts

Alexander V. Sobolev[1,2], Albrecht W. Hofmann[1], Stephan V. Sobolev[3,4] & Igor K. Nikogosian[5,6]

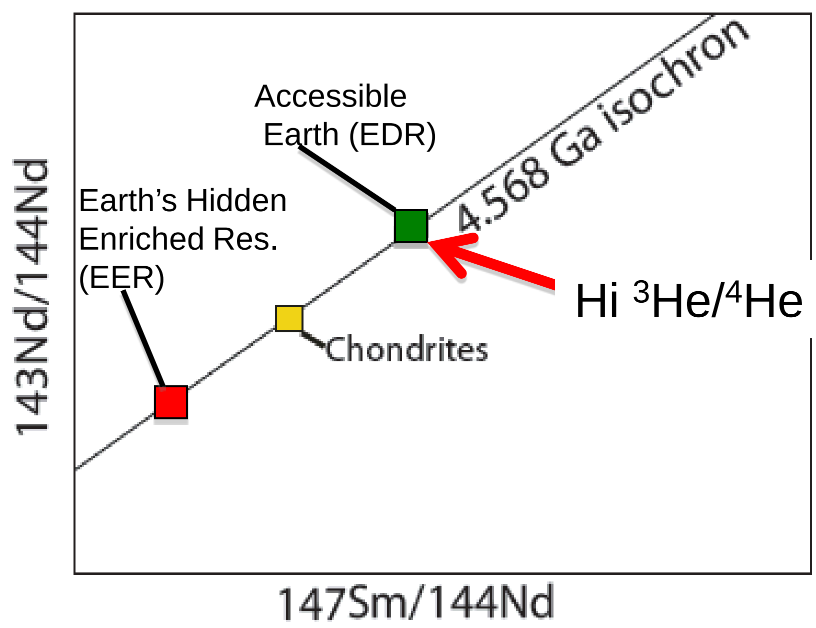


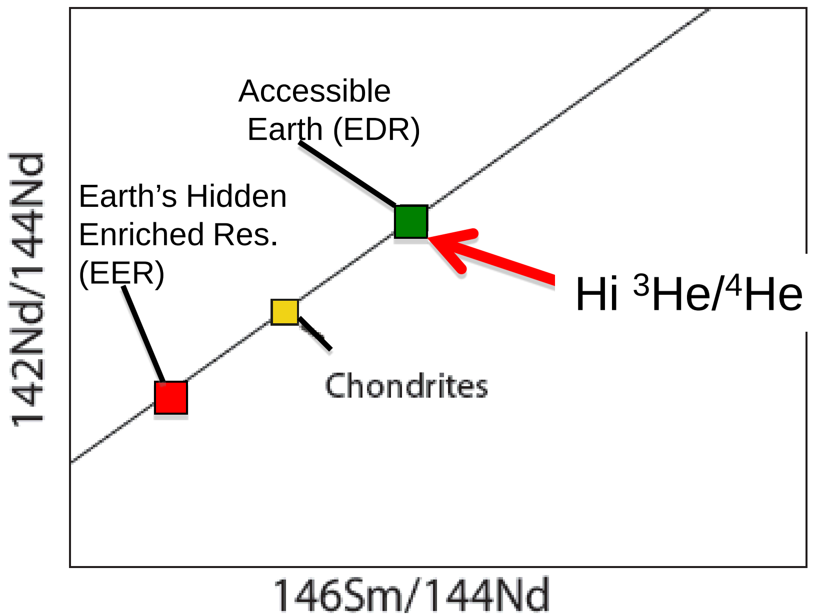
- **Standard Model (Earth is Chondritic)**

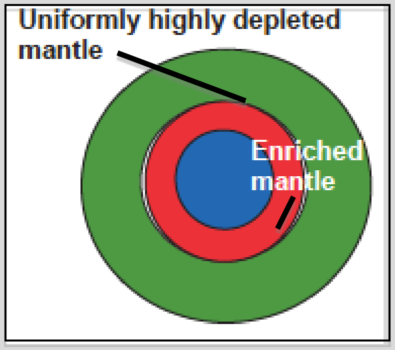
1. Earth and chondrites have same Sm/Nd.
2. **Isochrons 101:** Therefore, Earth and chondrites have the same $^{143}Nd/^{144}Nd$ and $^{142}Nd/^{144}Nd$.



Preserving the Chondrite model

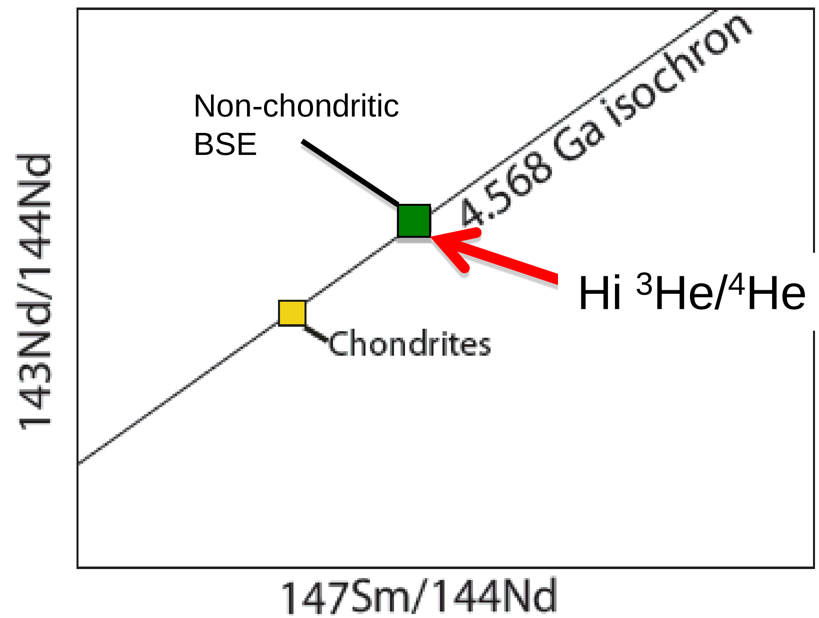


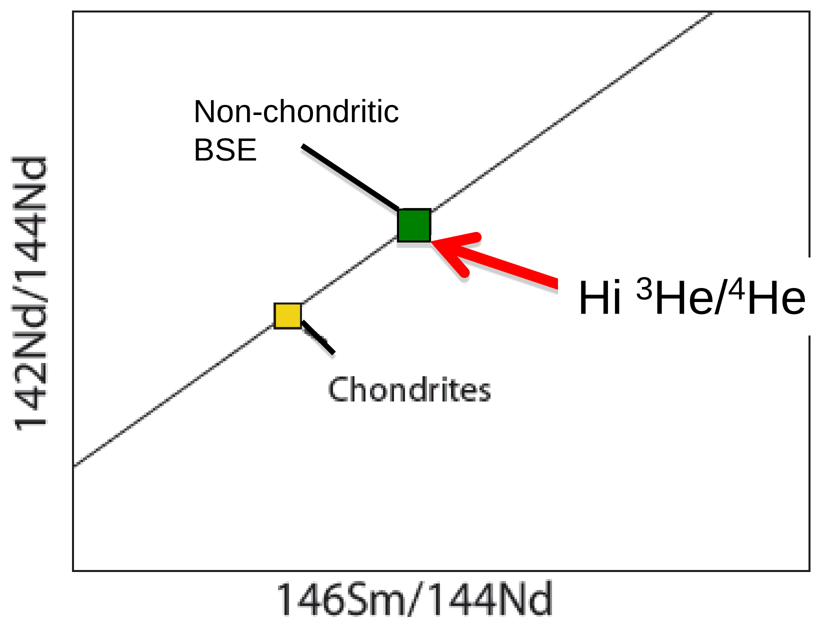




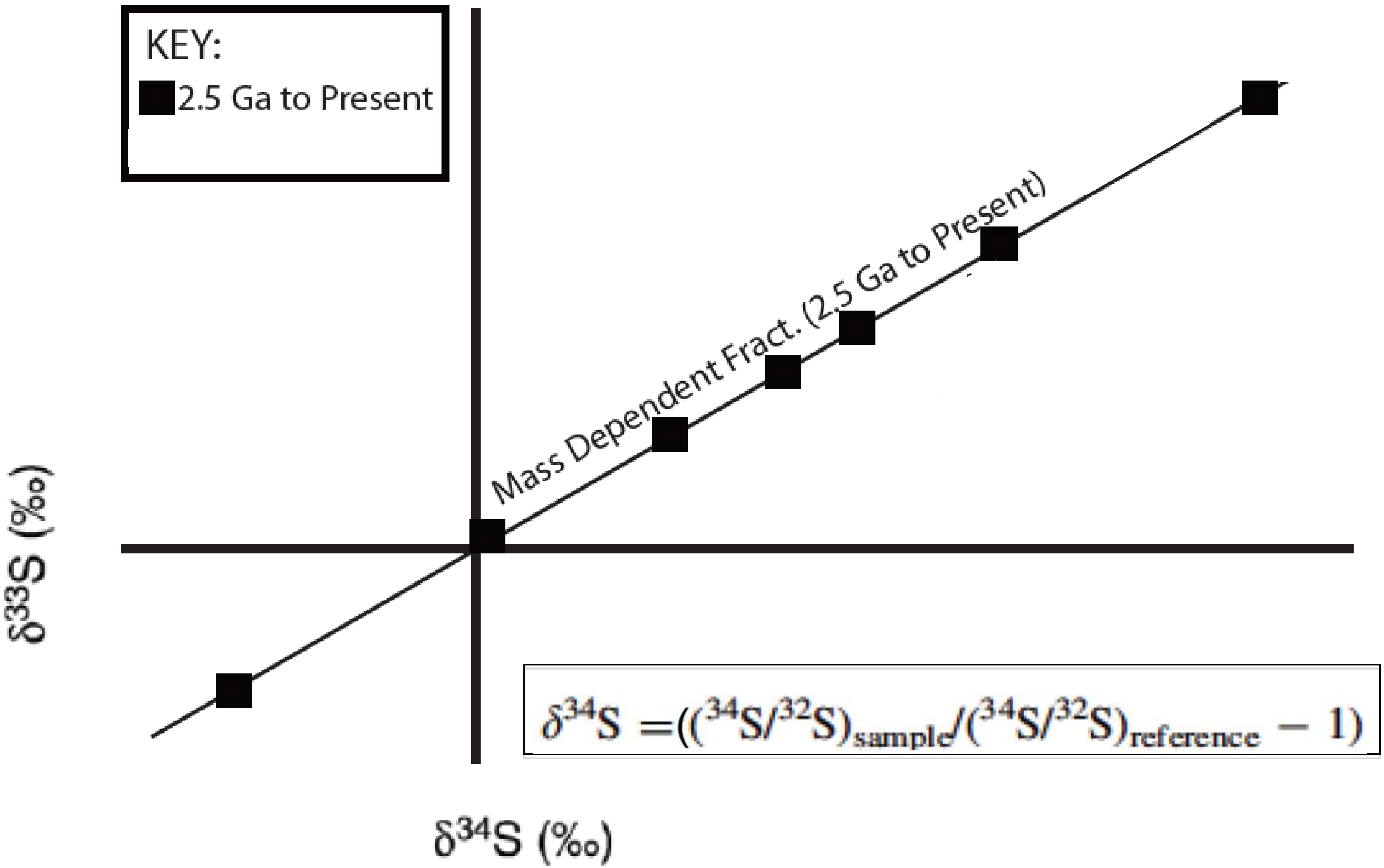
Non-chondritic Earth model

NO HIDDEN RESERVOIR





Δ33S ?!

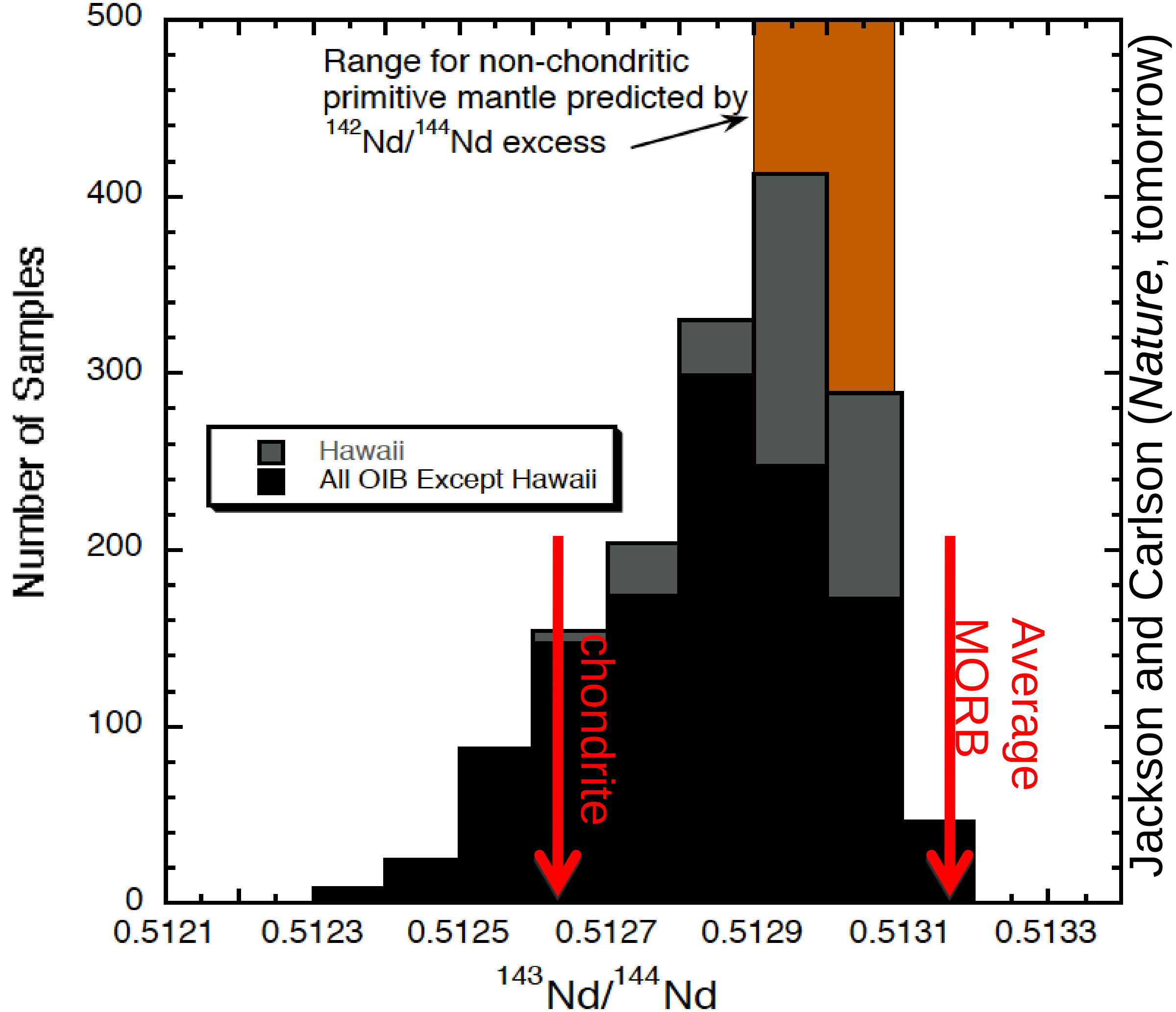

KEY:
2.5 Ga to Present
Mass Dependent Fract. (2.5 Ga to Present)
$\delta^{34}S = ((^{34}S/^{32}S)_{sample}/(^{34}S/^{32}S)_{reference} - 1)$
$\delta^{33}S$ (‰)
$\delta^{34}S$ (‰)

To paraphrase a useful quotation…

- ~~Astrophysicicists~~ Geochemists are always wrong, but never in doubt. …

-RP Kirshner

PREMA (Prevalent Mantle)

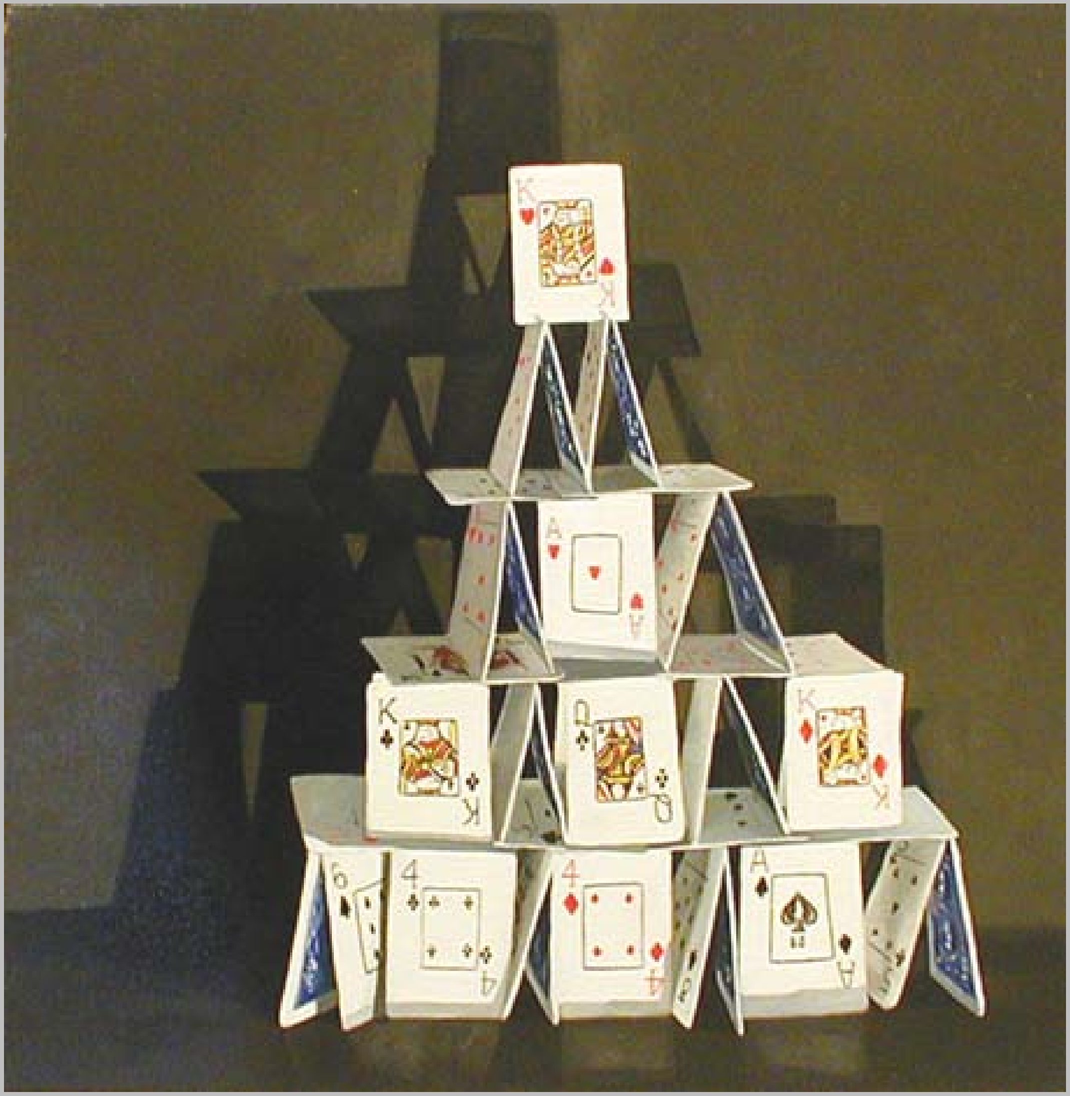


If the large proportion of OIB lavas with present-day $^{143}Nd/^{144}Nd$ near 0.5130 reflects a high proportion of non-chondritic primitive material in the mantle, then primitive material must comprise a substantial portion of the modern terrestrial mantle.

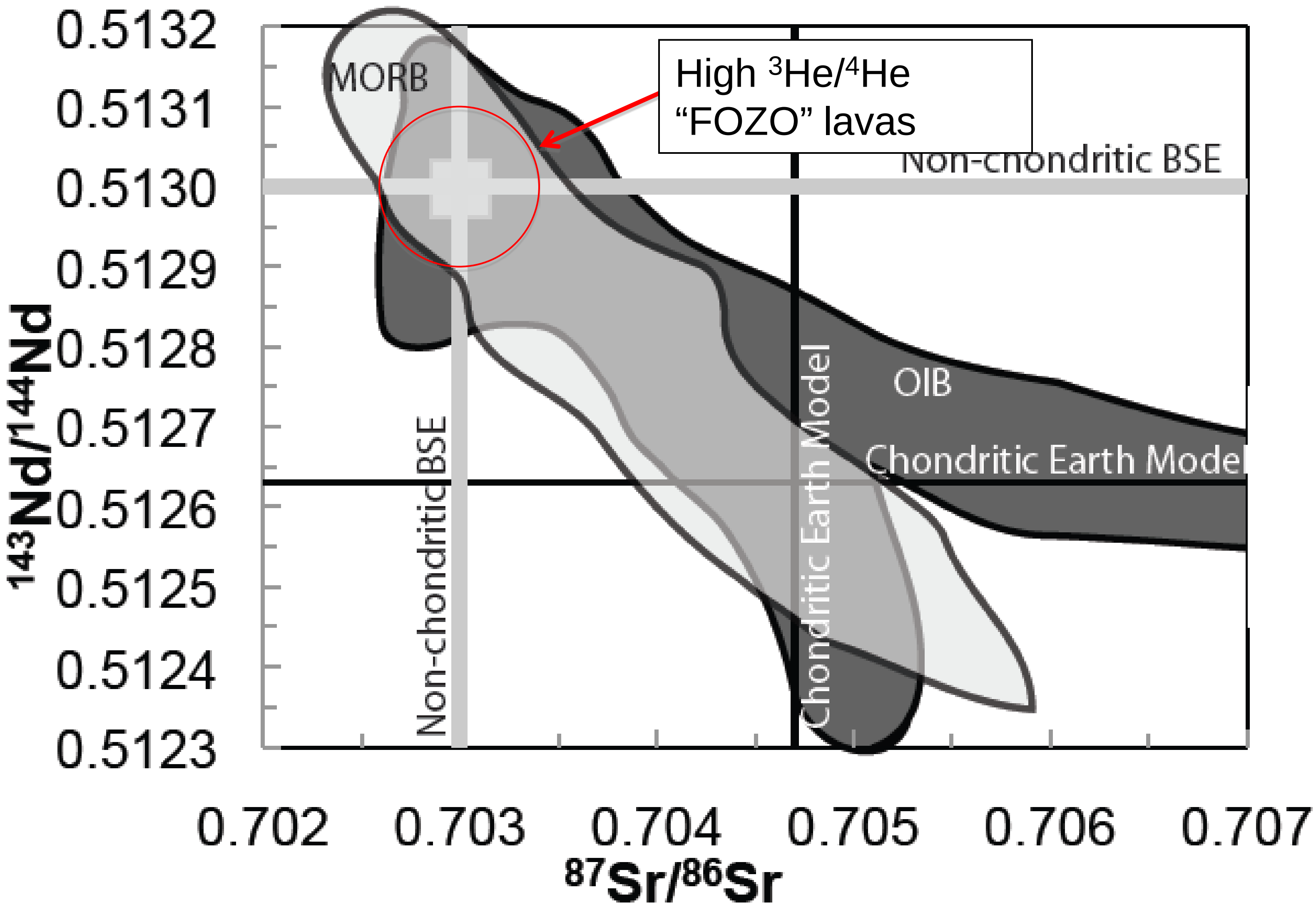
Part II: Building a new Bulk Silicate Earth (BSE) composition

- The new compositional model relies on the *difference* in $^{142}Nd/^{144}Nd$ between Earth and chondrites.
- Fundamental assumption of model: Sm/Nd of Earth is ~6% higher than chondrites.
- **Non-chondritic BSE (Bulk Silicate Earth) has an isotopic composition like high $^{3}He/^{4}He$ lavas (FOZO).**

Use many of the assumptions used in the chondrite-based model

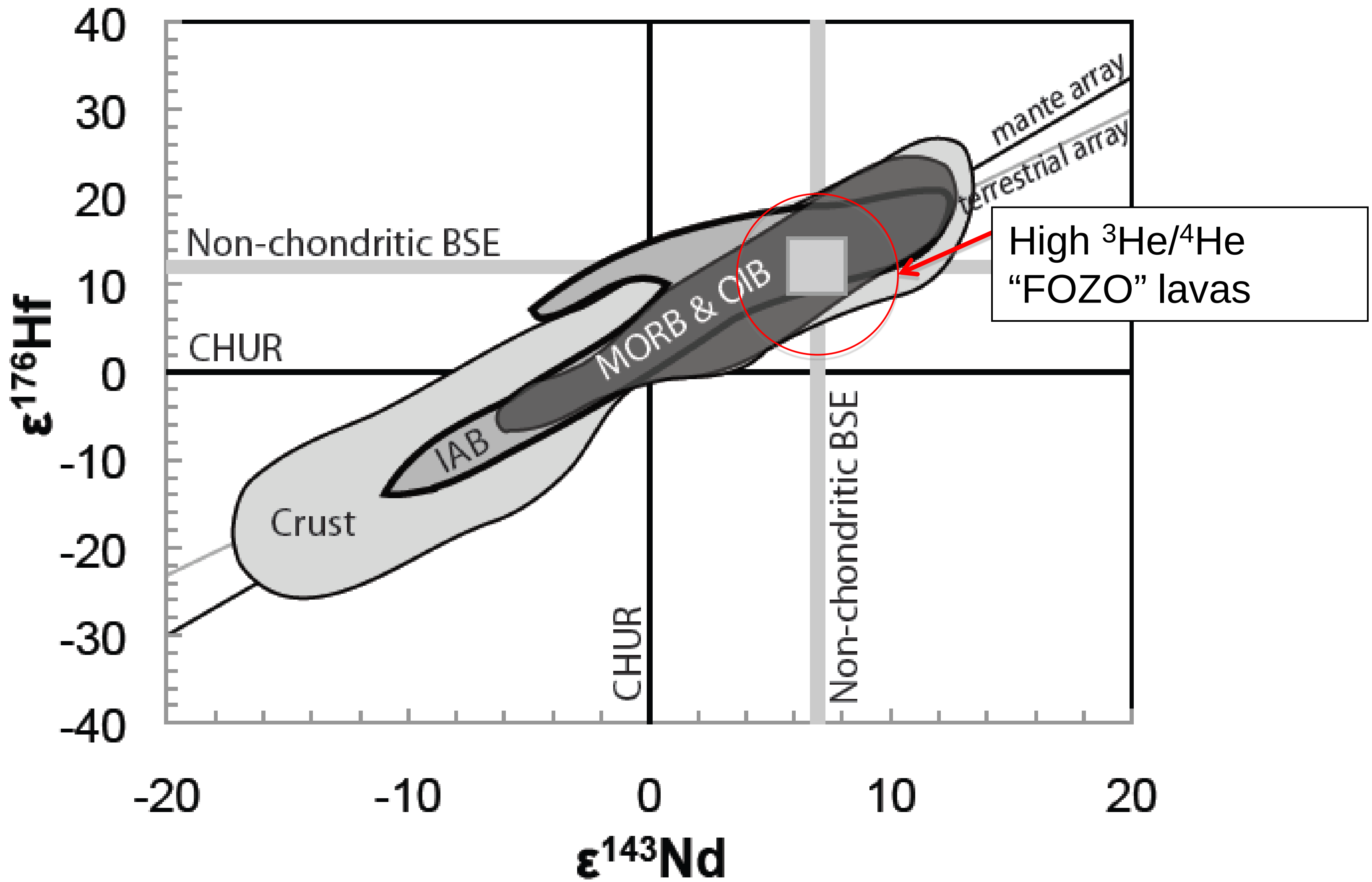


$^{87}Sr/^{86}Sr$ of BSE decreases from 0.7047 to 0.7030: Rb/Sr of BSE is 30% lower in new model



After Caro and Bourdon (2010)

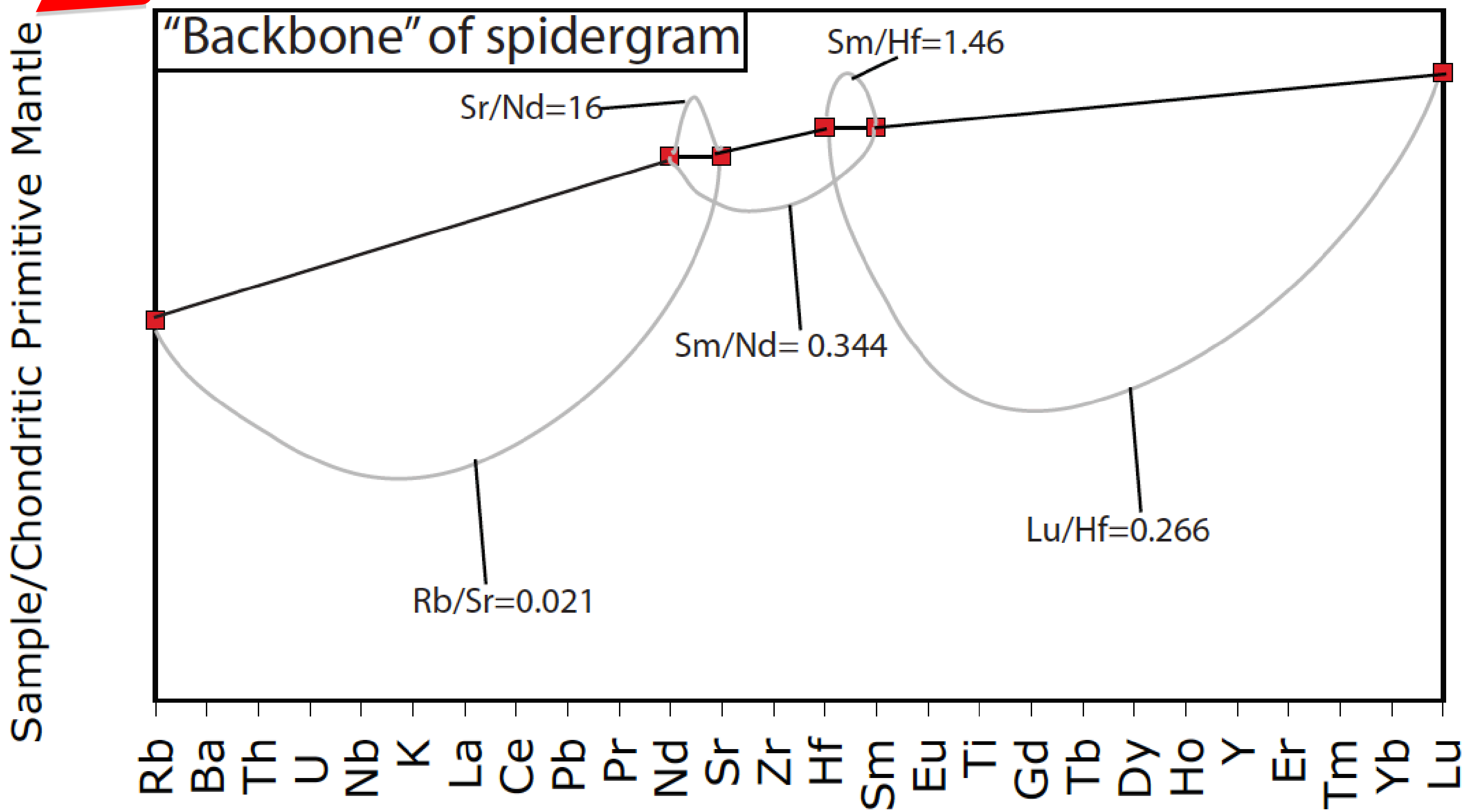
$^{176}Hf/^{177}Hf$ of BSE increases 12 epsilon units: Lu/Hf of BSE is 12% higher in new model



After Caro and Bourdon (2010)

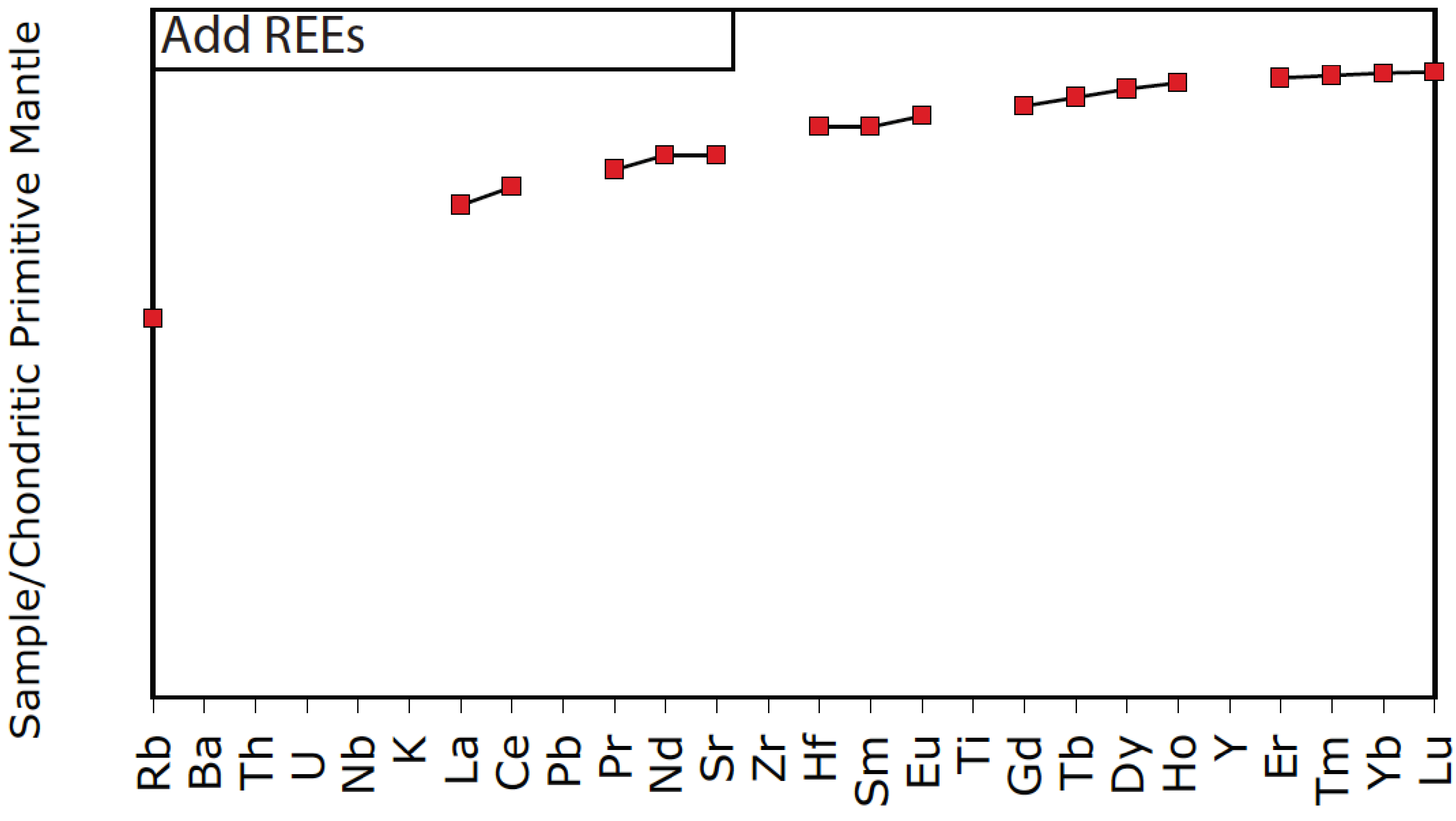
“Backbone” of trace element pattern: Link the segments with Sr/Nd and Sm/Hf

McDonough and Sun (1995)



Jackson & Jellinek, 2012

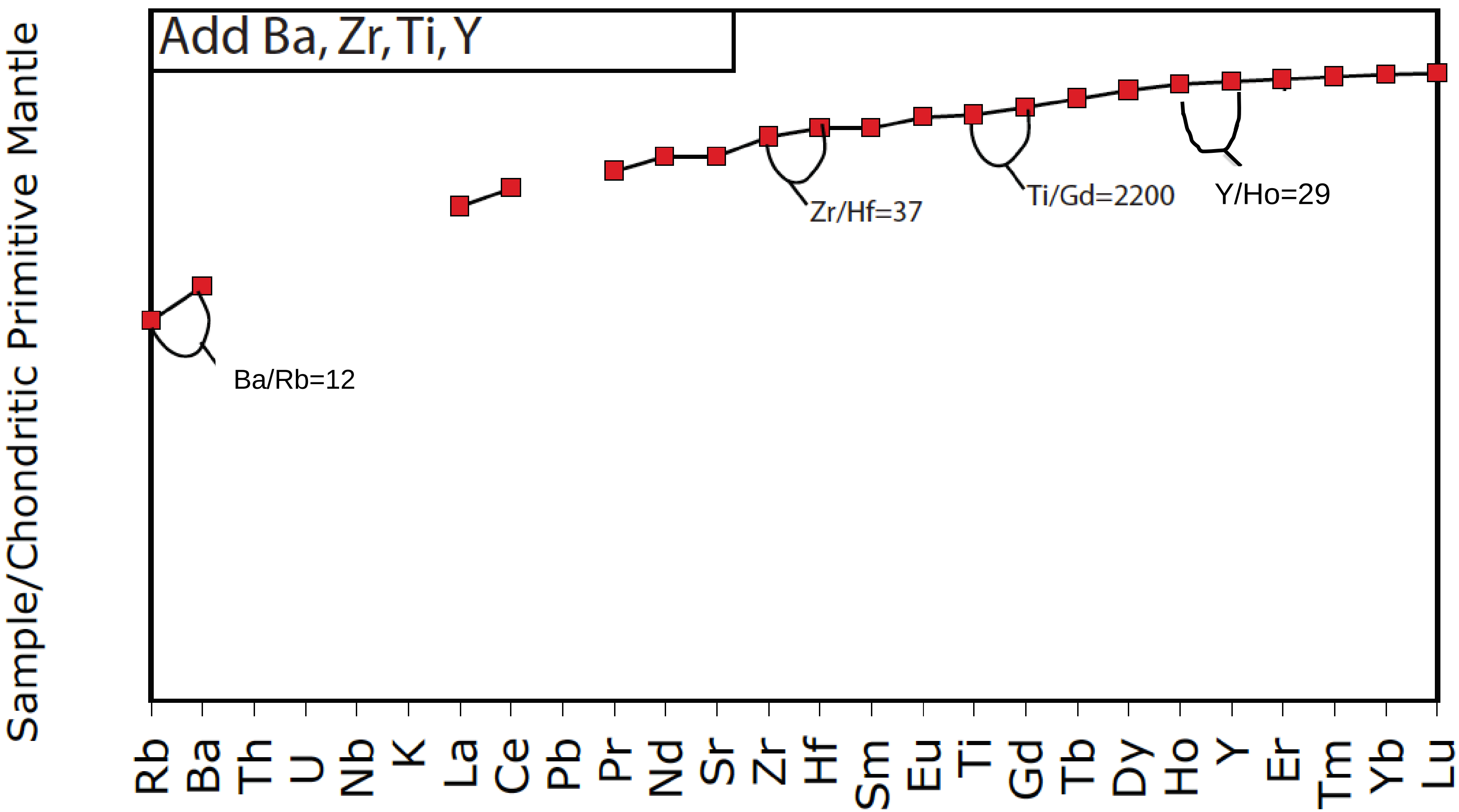
“Splice” in the Rare Earth’s



Jackson & Jellinek, 2012

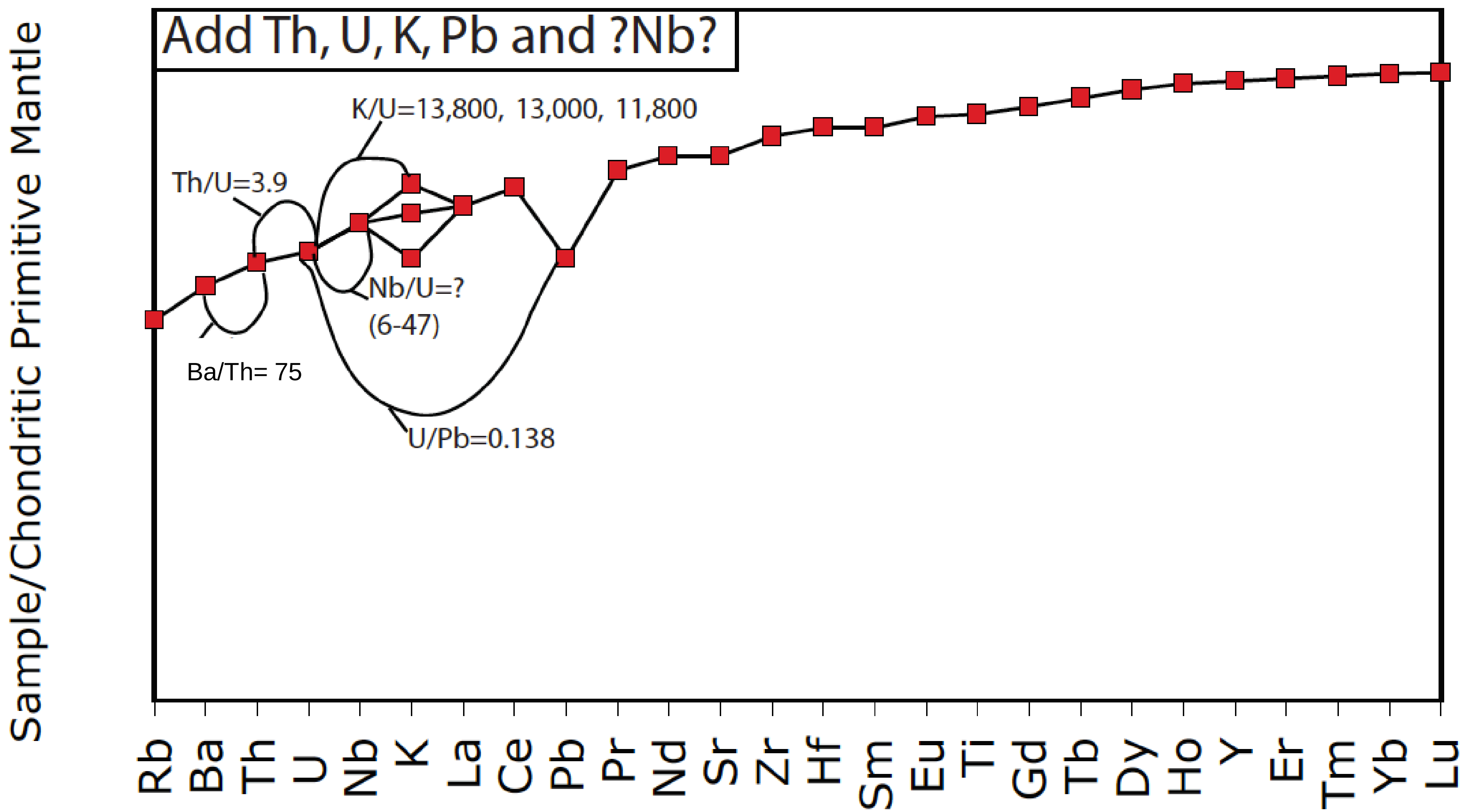
Ba, Zr, Ti, Y

(Use canonical ratios, which are similar in MORBs and continents)



Jackson & Jellinek, 2012

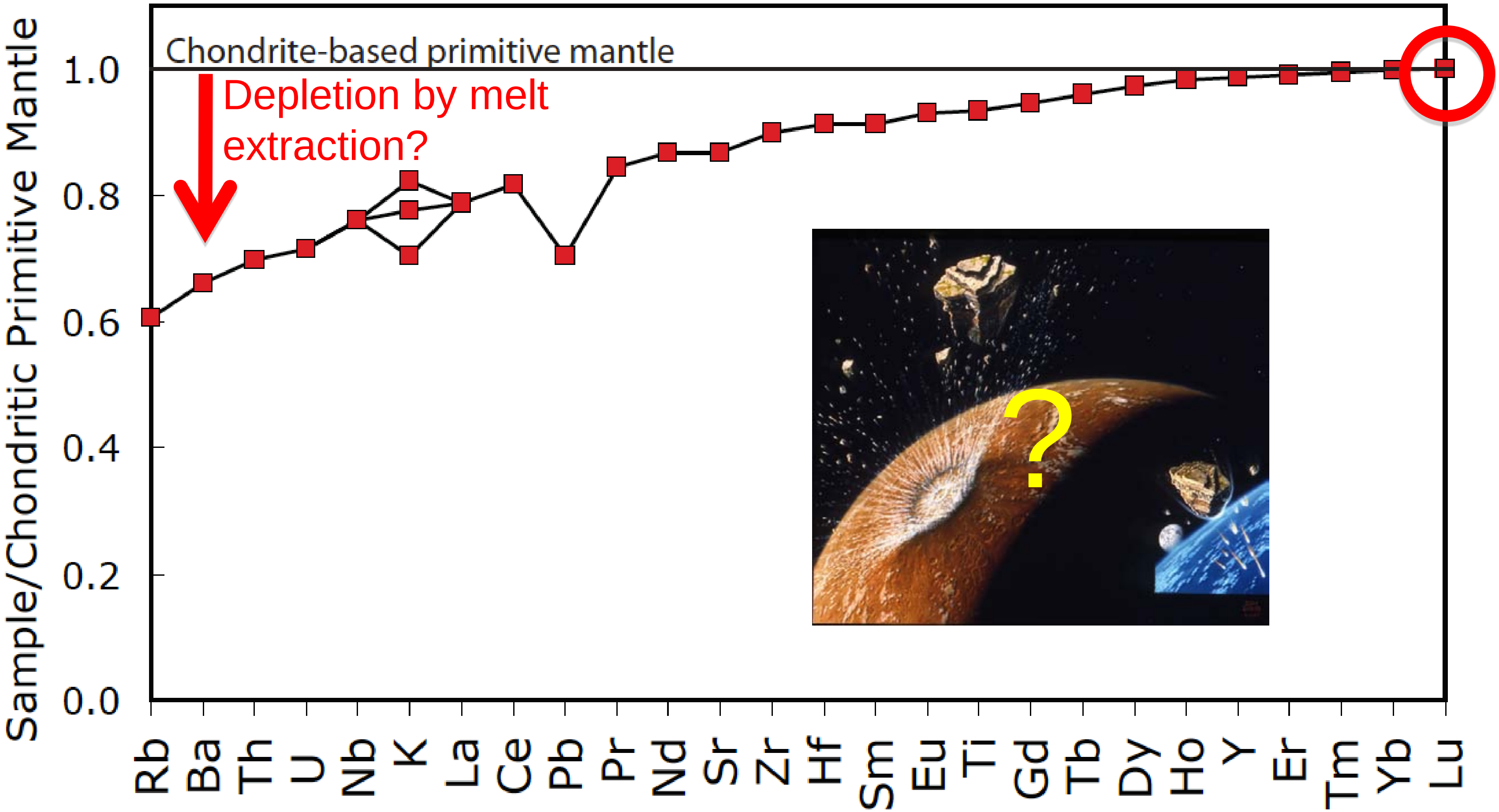
Th-U-K-Pb and Nb



Jackson & Jellinek, 2012

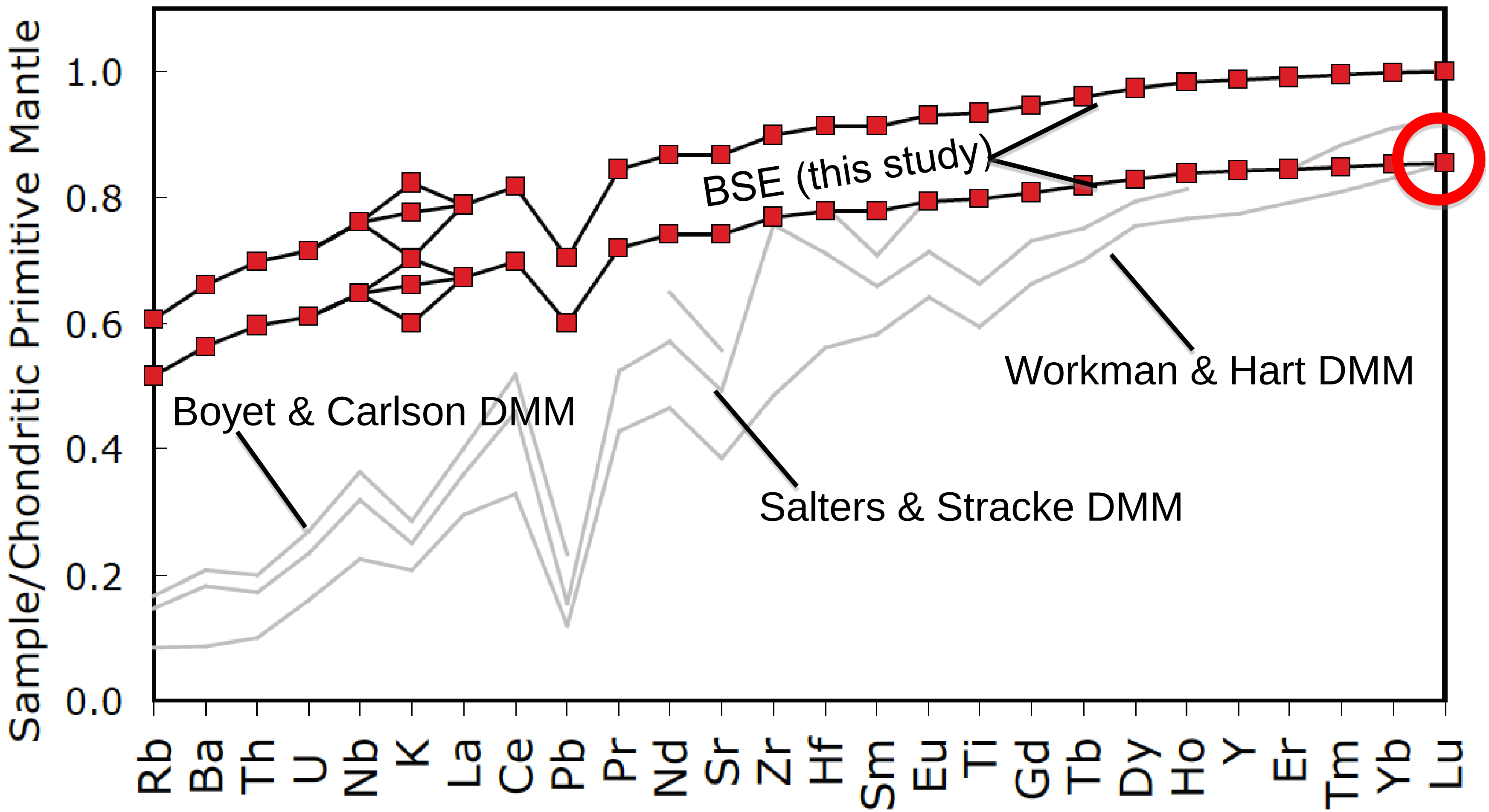
-Spidergram has a shape, but no absolute concentrations.

-Can't be more enriched than chondrite-based model………"   **So, anchor to Lu!**



Jackson & Jellinek, 2012

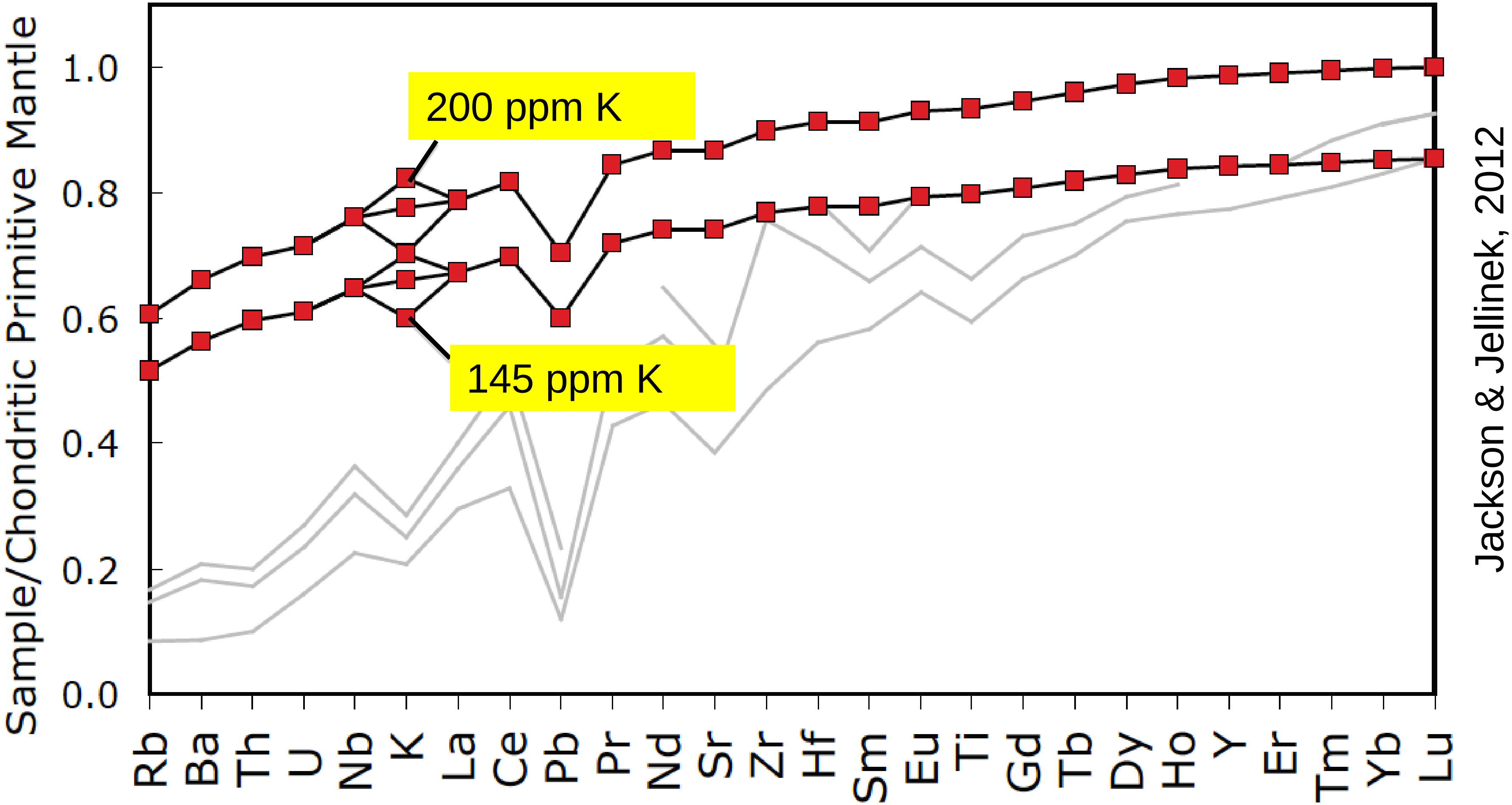
Can't be more depleted than DMM (upper and lower limits established)



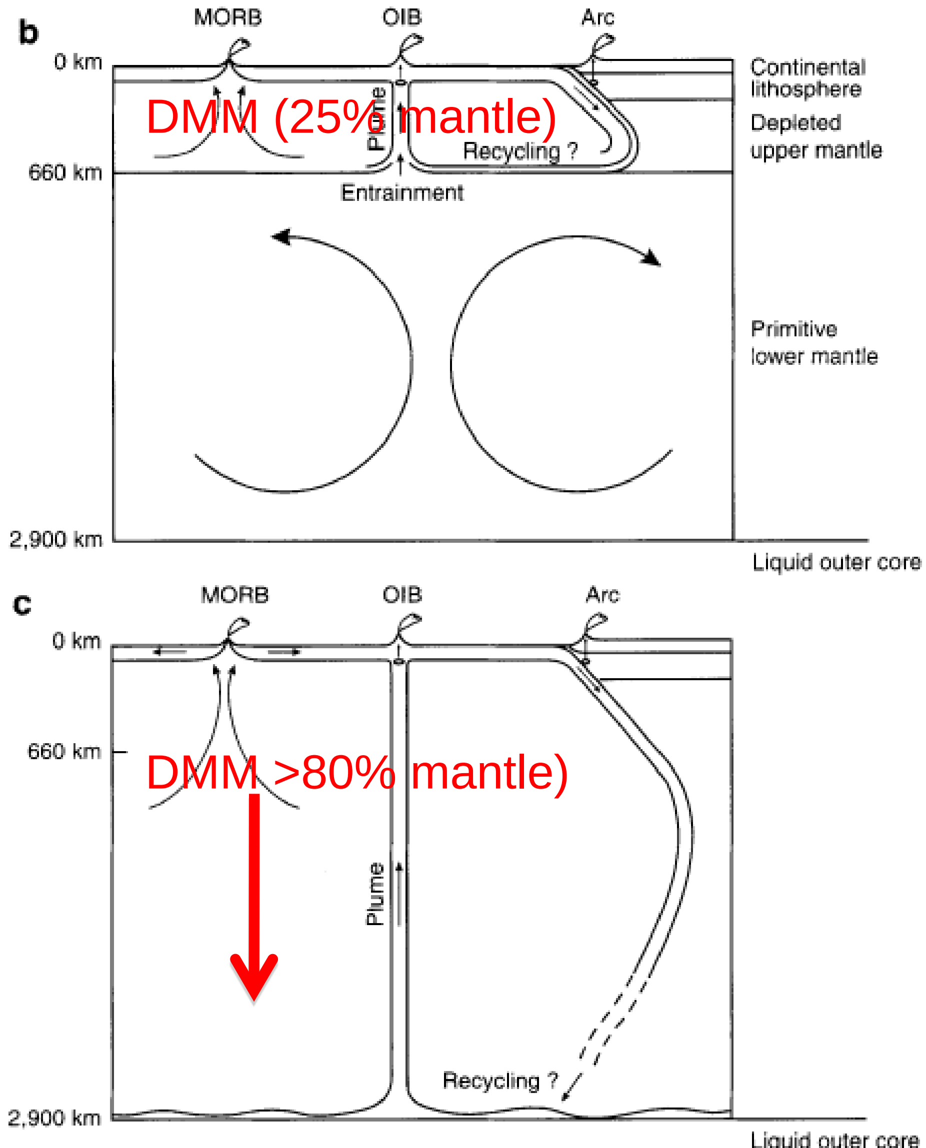
Jackson & Jellinek, 2012

Solution to “missing” Ar?

The ^{40}Ar in atmosphere, DMM and continental crust ($8.7\text{-}11.5 \times 10^{16}$ kg) is supported by 155-205 ppm K



Continental crust extraction? Requires >80% of mantle!



Hofmann, Nature (1997)

Thermal budgets of a non-chondritic Earth

- U, Th and K abundances in the Earth are 30-35% lower than the standard model.
- So, 30-35% less radiogenic heat than the standard model. Lower Urey ratio (radiogenic heat/total heat)
- The Earth produces 46 TW.

-- Standard model: ~20 TW is radiogenic heat

-- New model: ~13 TW is radiogenic heat.

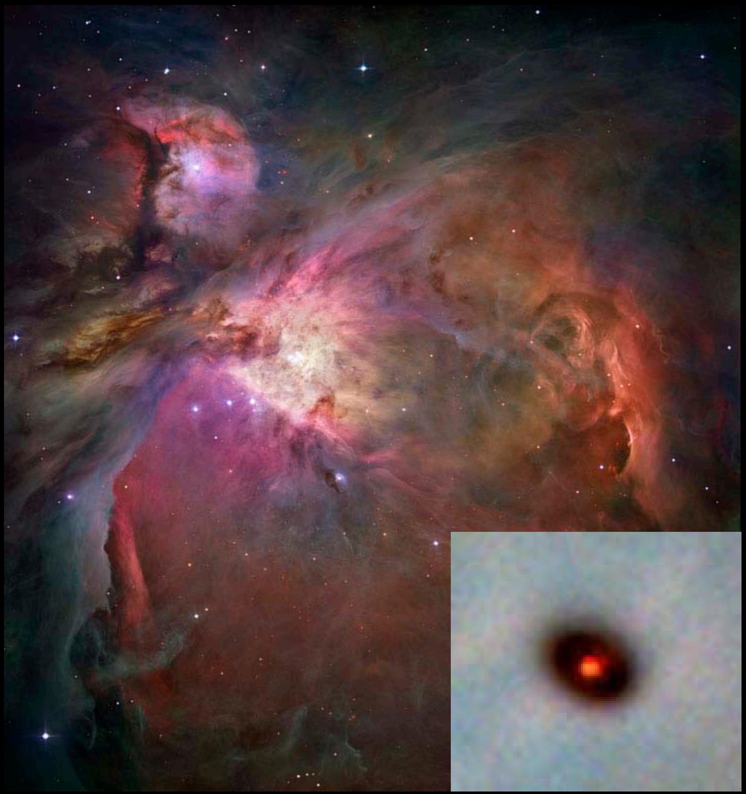
- The rest is primordial heat. Is there enough uncertainty in primordial heat that we can make a non-chondritic Earth "work"?

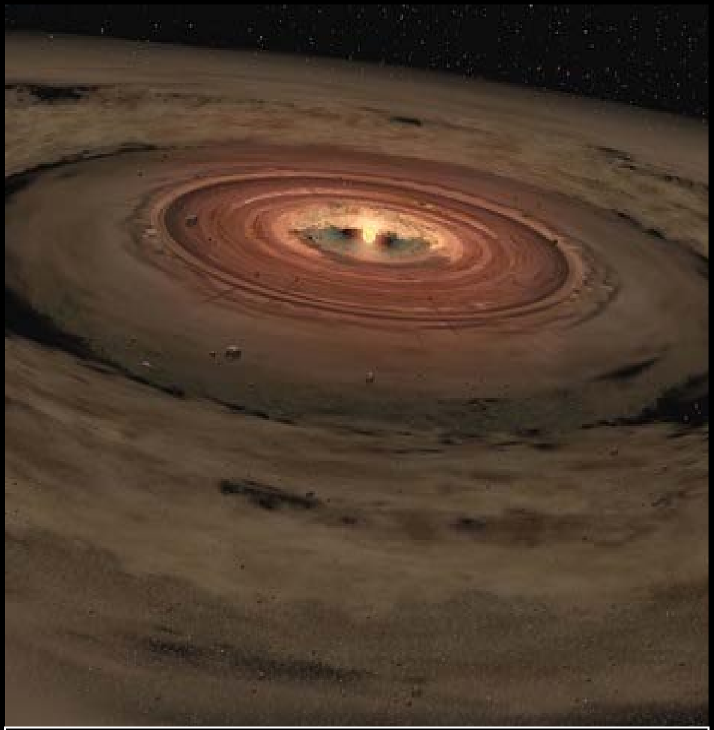
Earth and Planetary Science Letters 310 (2011) 380–388

On the relative influence of heat and water transport on planetary dynamics

John W. Crowley [a,*], Mélanie Gérault [b,c], Richard J. O'Connell [a]

In the beginning….





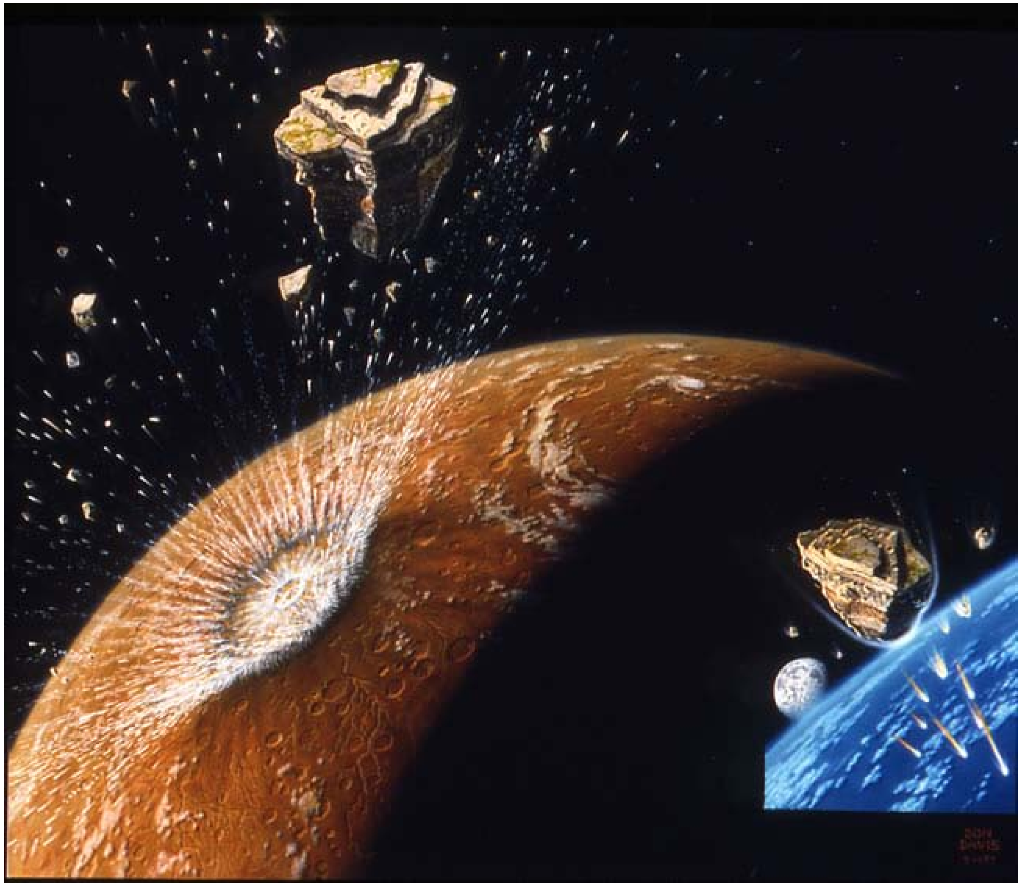
Courtesy of NASA/JPL-Caltech

4.568 Ga (Bouvier & Wadhwa, 2010)

Solar Nebula Theory:

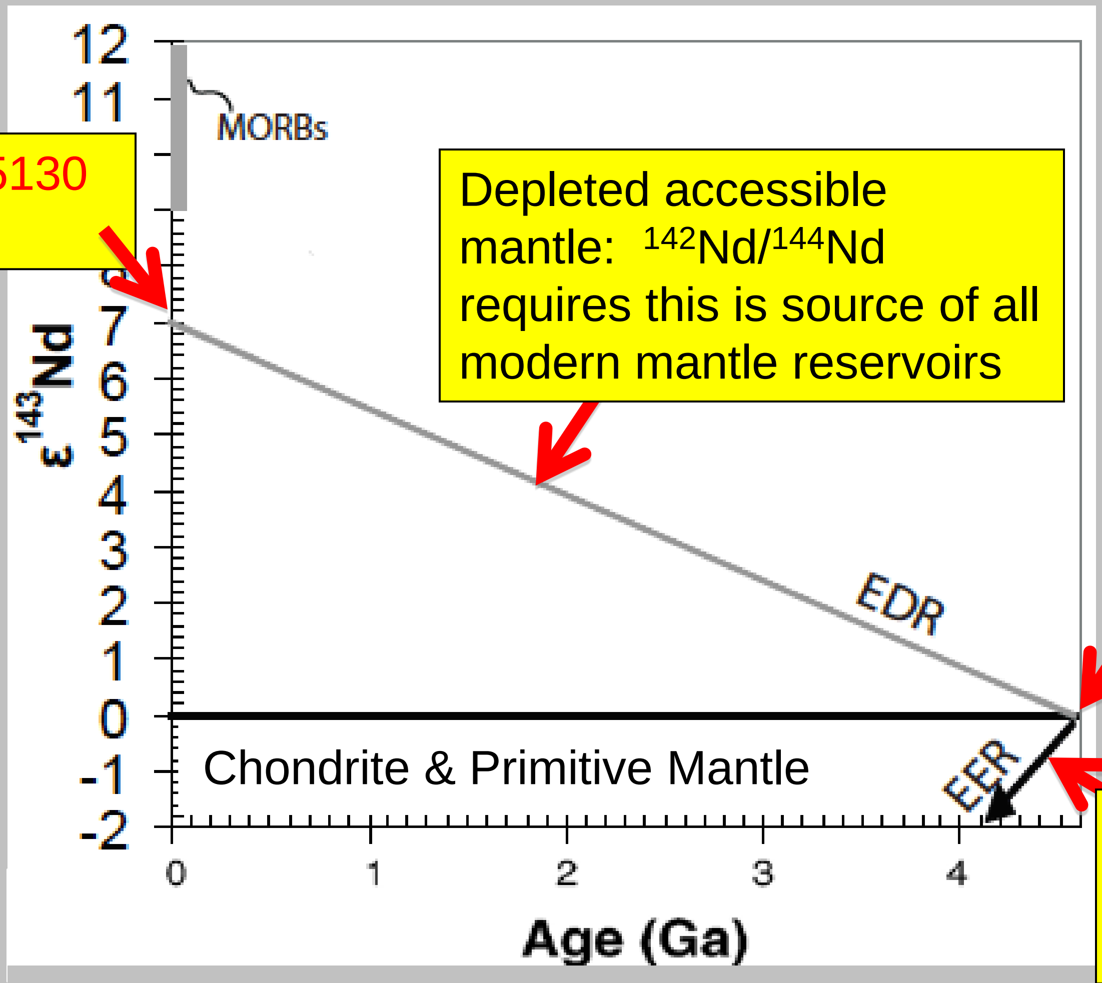
1. Cloud of gas and dust
2. Rotating disk
3. Gravitational collapse
4. Solar nebula with young sun
5. Planets accrete from rotating cloud

Impact erosion: Lessons from Martian meteorites



Early enriched crust "blasted" into space, leaving behind a depleted (non-chondritic) mantle (O'Neill and Palme, 2008)

How did the accessible Earth get higher Sm/Nd than chondrites?
Early differentiation?



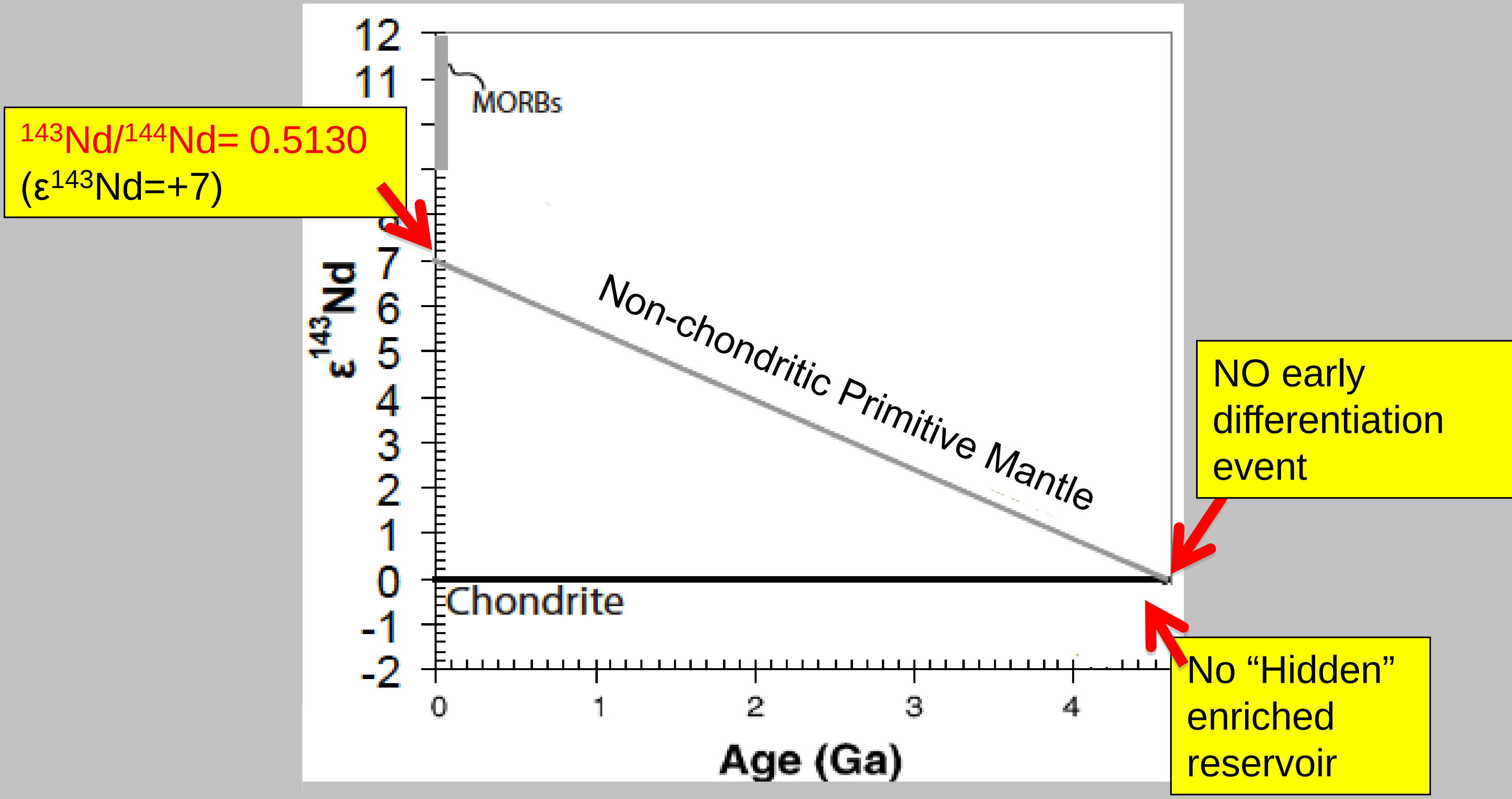
^{143}Nd/^{144}Nd= 0.5130 (ε^{143}Nd=+7)

Depleted accessible mantle: ^{142}Nd/^{144}Nd requires this is source of all modern mantle reservoirs

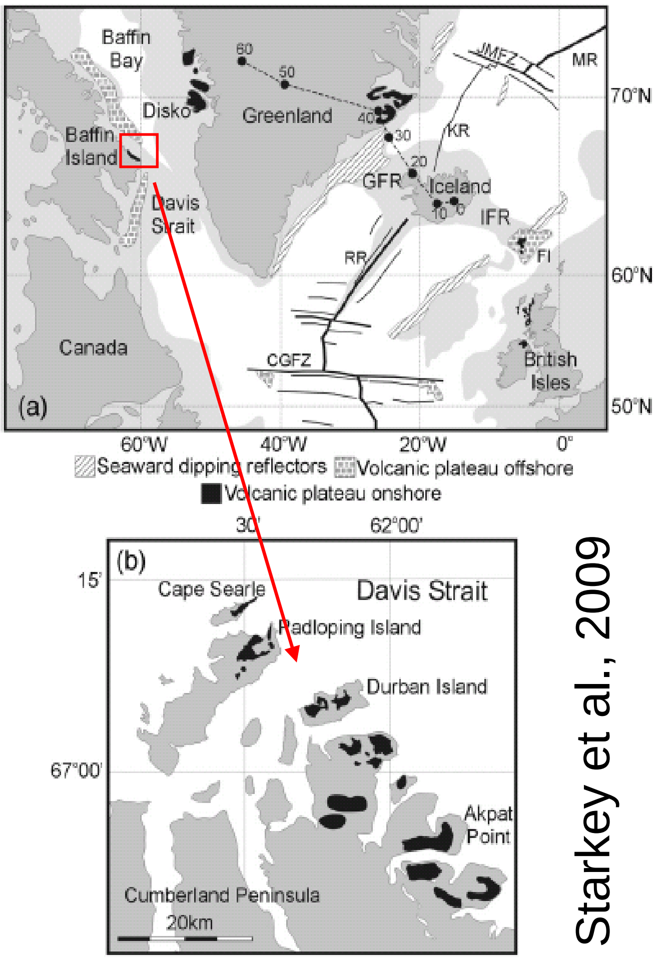
Early differentiation (melting) event

“Hidden” early enriched reservoir

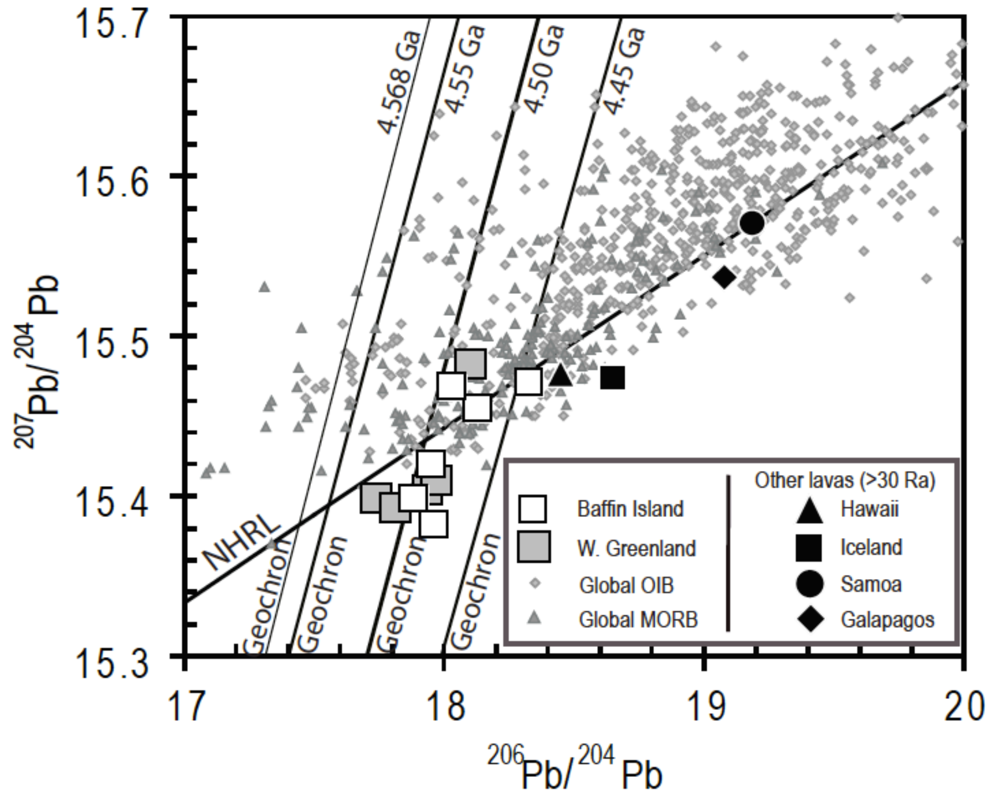
The Bulk Earth has non-chondritic Sm/Nd



Baffin and West Greenland picrites plot near the Geochron



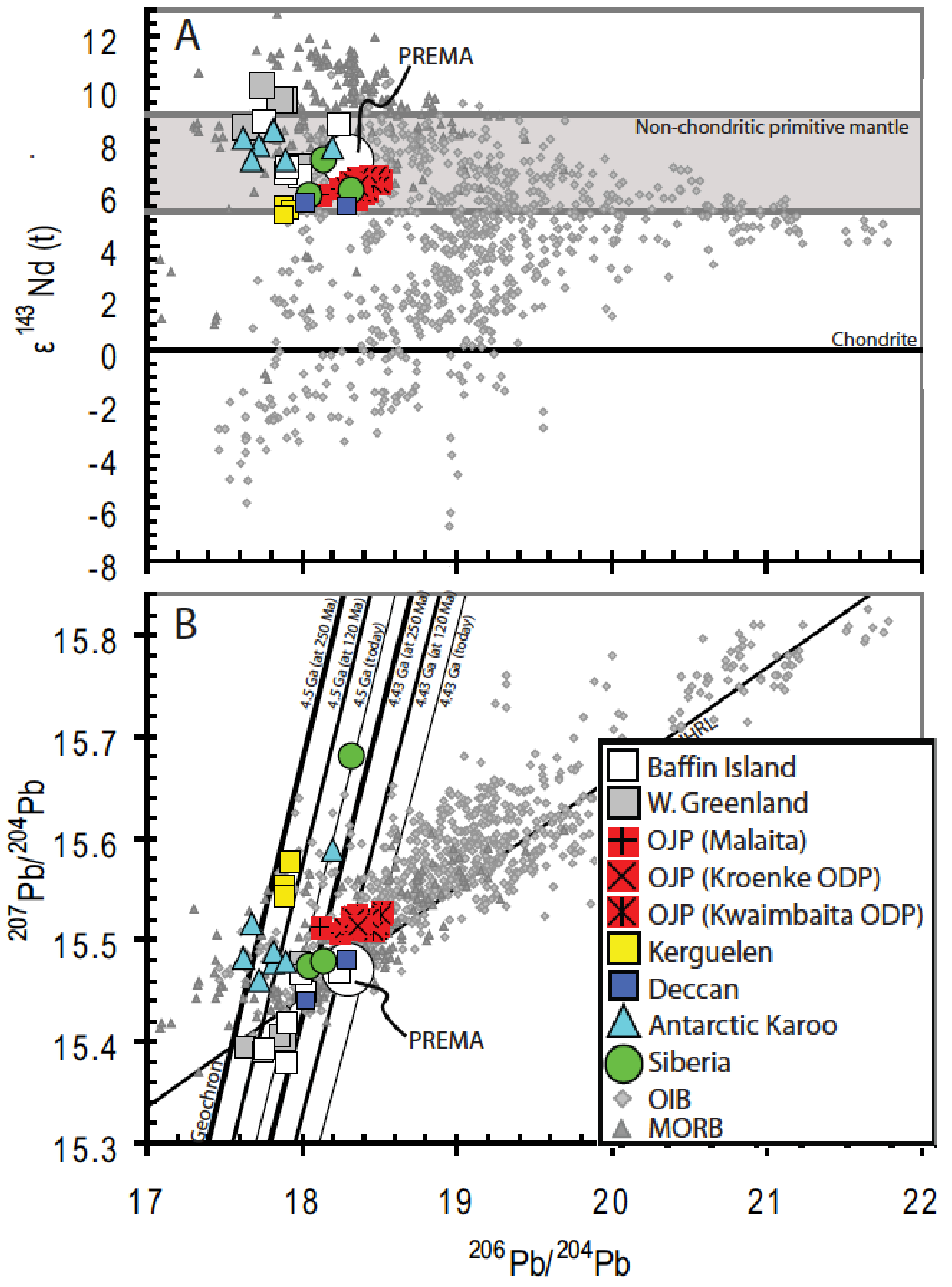
Starkey et al., 2009



Jackson et al. (*Nature*, 2010)

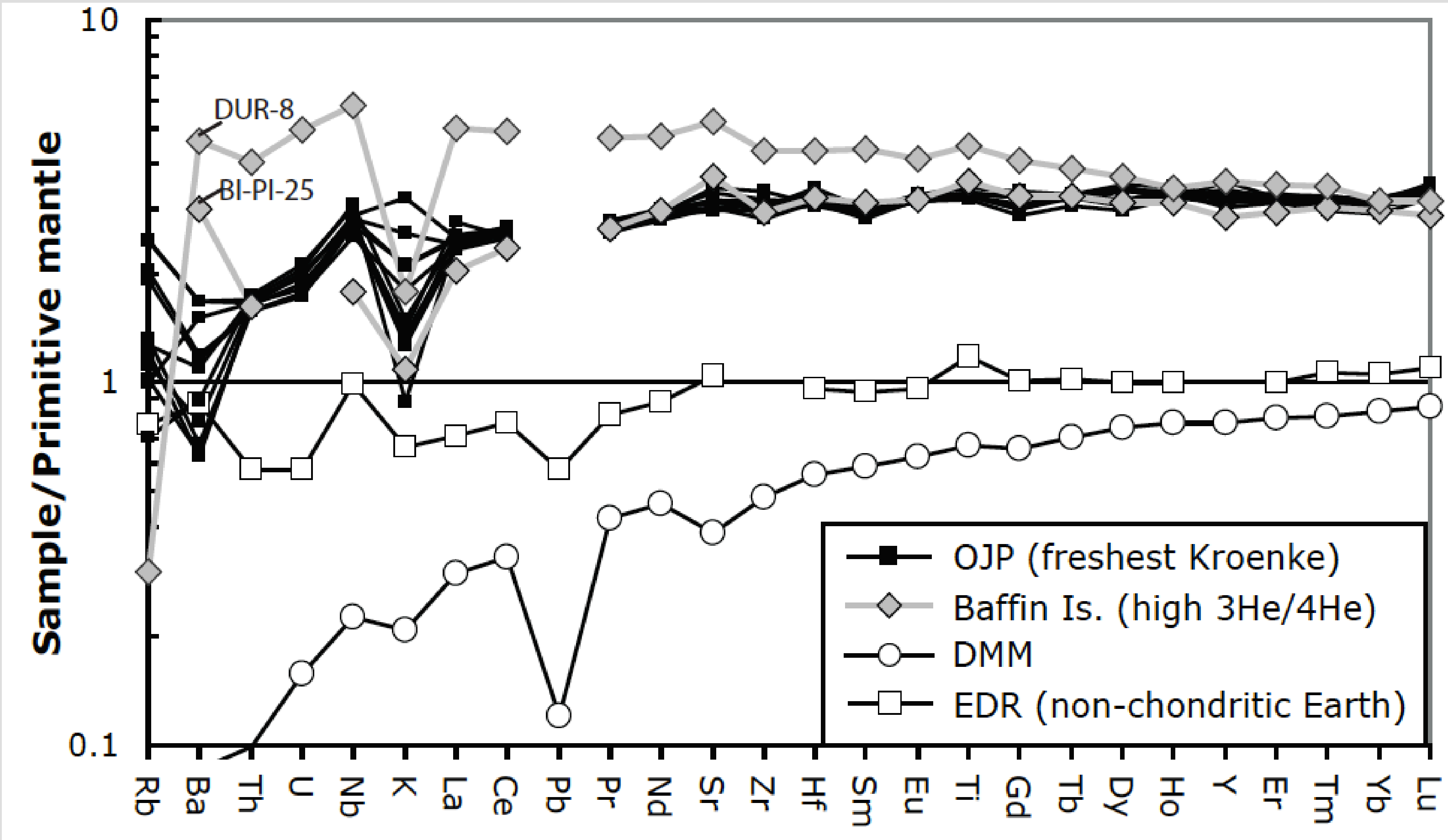
Global?

- Baffin Island is a flood basalt.
- Do other flood basalts have similar geochem signatures?



Jackson and Carlson (Nature, 2011)

Highest $^{3}He/^{4}He$ Baffin Island lavas bracket the OJP

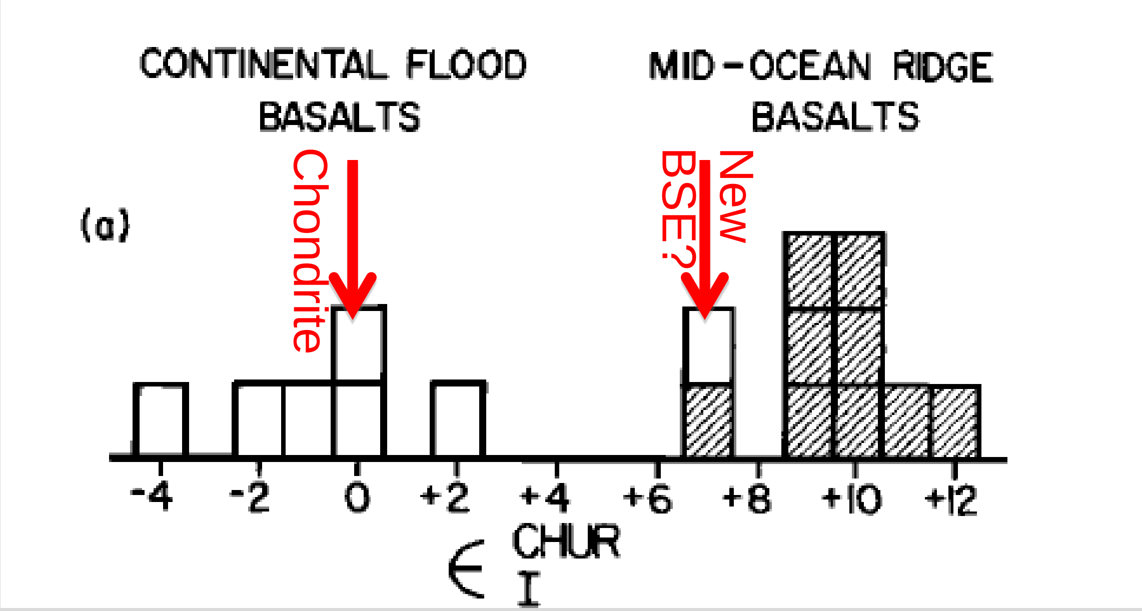


Jackson and Carlson (Nature, 2011)

Was the OJP derived from a huge (almost) primitive mantle reservoir?

M. L. G. TEJADA[1], J. J. MAHONEY[2], P. R. CASTILLO[3], S. P. INGLE[4,5], H. C. SHETH[2,6] & D. WEIS[4,7]

Old Reservoir, Old Idea (new possibilities)

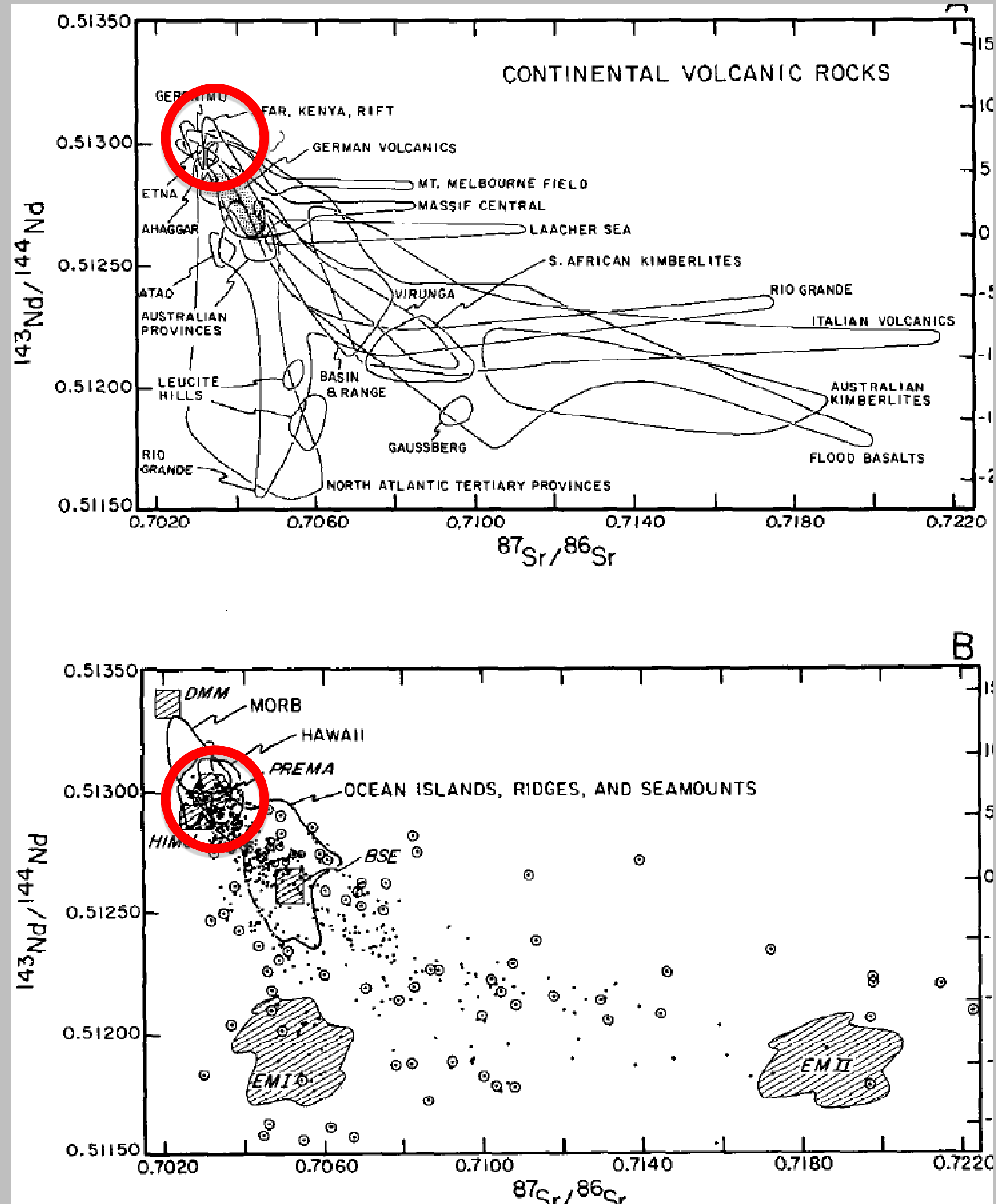


“The nominal value of $\varepsilon^{CHUR} \approx 0$ for the continental flood basalts indicates they are derived from a reservoir which has maintained an unfractionated, chondritic Sm/Nd throughout the history of the earth.”

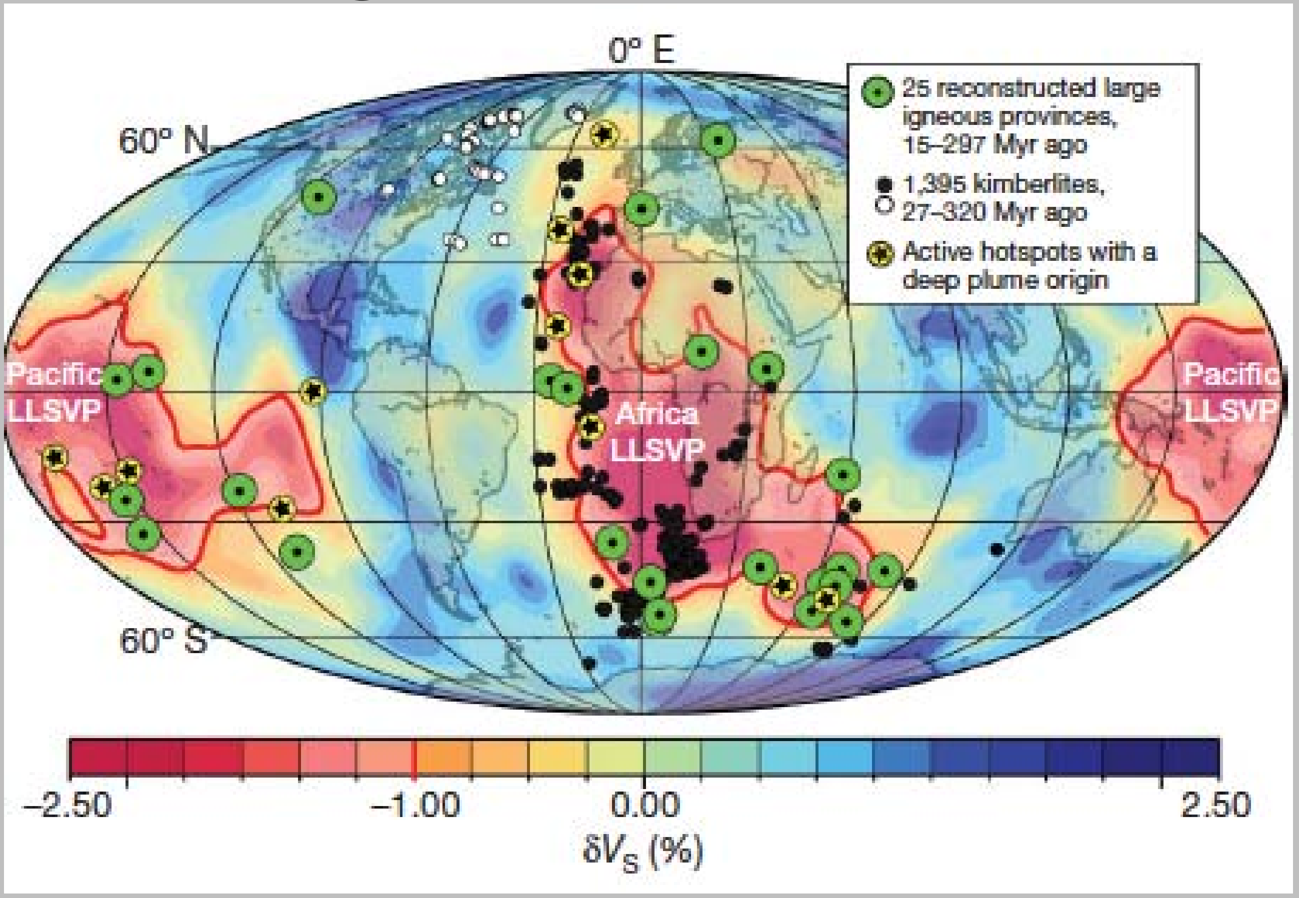
-DePaolo & Wasserburg, GRL 1976

PREMA and LIP's

- Zindler & Hart, '86
- PREMA and uncontaminated LIP's…

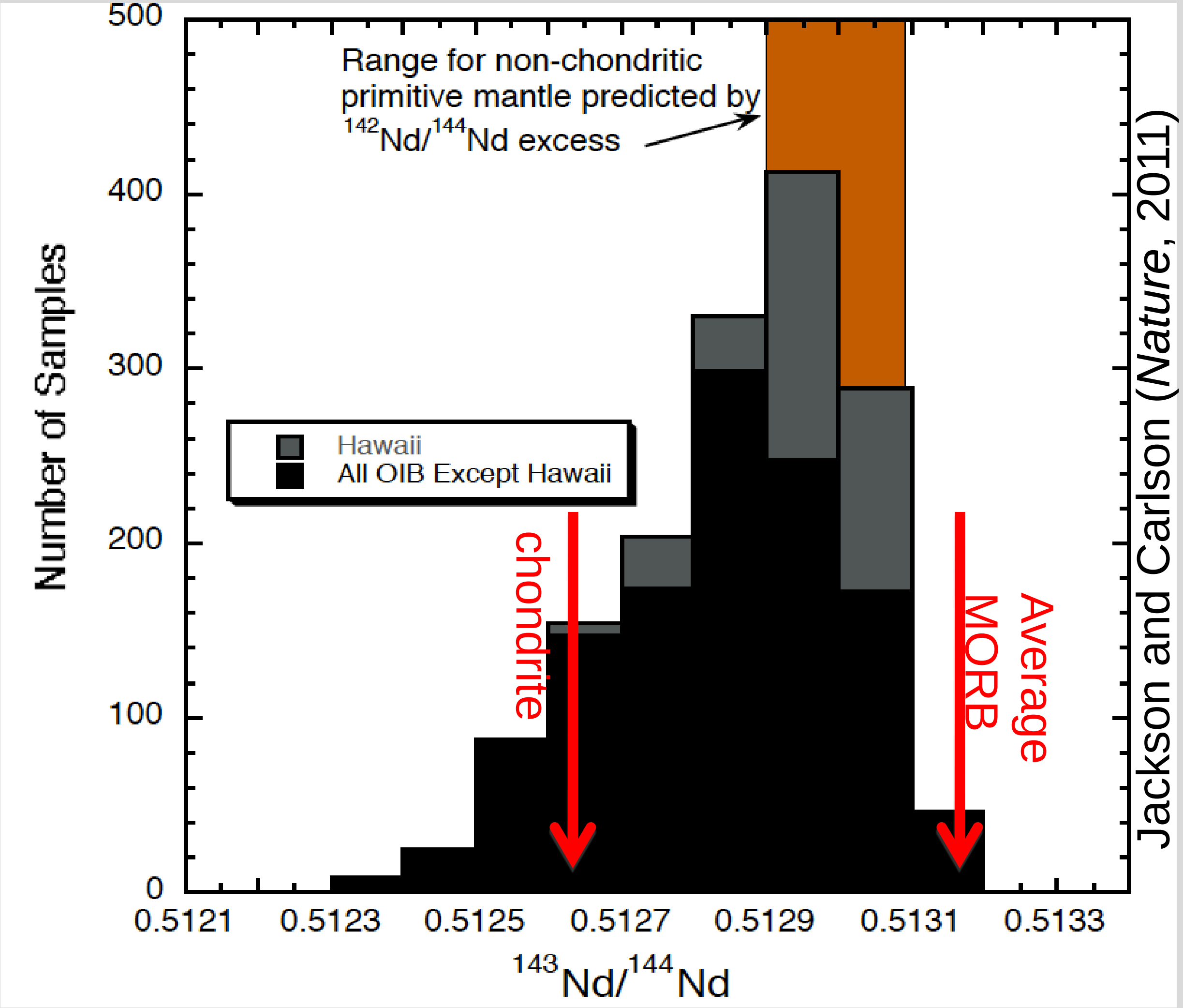


LIP's (mostly) erupted on margins of LLSVP's



- LIP's also have common geochemical signature associated with non-chondritic primitive mantle

PREMA (Prevalent Mantle) = BSE?



The large proportion of OIB lavas with present-day $^{143}Nd/^{144}Nd$ near 0.5130 may reflect a high proportion of non-chondritic primitive material in the mantle.

Standard (chondrite) model for K in the Earth: "Hidden" Ar reservoir

- K volatile, lost during accretion, so BSE abundance is unknown.
- U is refractory, so it's abundance can be estimated from chondrites. ~20 ppb.
- K/U in Earth known from basalts (~1.2x10^4).
- Calc K abundance in chondritic primitive mantle is >250 ppm.
- ^{40}K decays to ^{40}Ar ($t_{1/2}$=1.3 Ga).
- All ^{40}Ar in the Earth is radiogenic, accumulated since accretion.
- There should be ~14x10^{16} kg ^{40}Ar Earth.
- Only ~8.7-11.5x10^{16} kg ^{40}Ar Earth accounted for (**atm,CC,DM**).
- Ergo, a "hidden" reservoir in the Earth hosts the "missing" ^{40}Ar!

$$M\left({}^{40}\mathrm{Ar}\right)_{PM} = M\left({}^{40}\mathrm{Ar}\right)_{atm} + M\left({}^{40}\mathrm{Ar}\right)_{CC} + M\left({}^{40}\mathrm{Ar}\right)_{DM} + M\left({}^{40}\mathrm{Ar}\right)_{hidden}$$

Lyubetskaya & Korenaga (2007)

Use ^{40}Ar in Earth to "pin" primitive mantle K concentration

- Turn the problem of "missing" Ar into a solution:

  What we see is what we get: no missing Ar reservoir!

- Three ^{40}Ar reservoirs:

1. Atmosphere: 6.6×10^{16} kg ^{40}Ar (Turekian, 1959)

2. Continental Crust: $0.1\text{-}1.0\times10^{16}$ kg ^{40}Ar

3. Depleted Mantle (2 independent estimates):

A. Assume K in DM: $2.8\text{-}3.9\times10^{16}$ kg ^{40}Ar (50-68 ppm K)

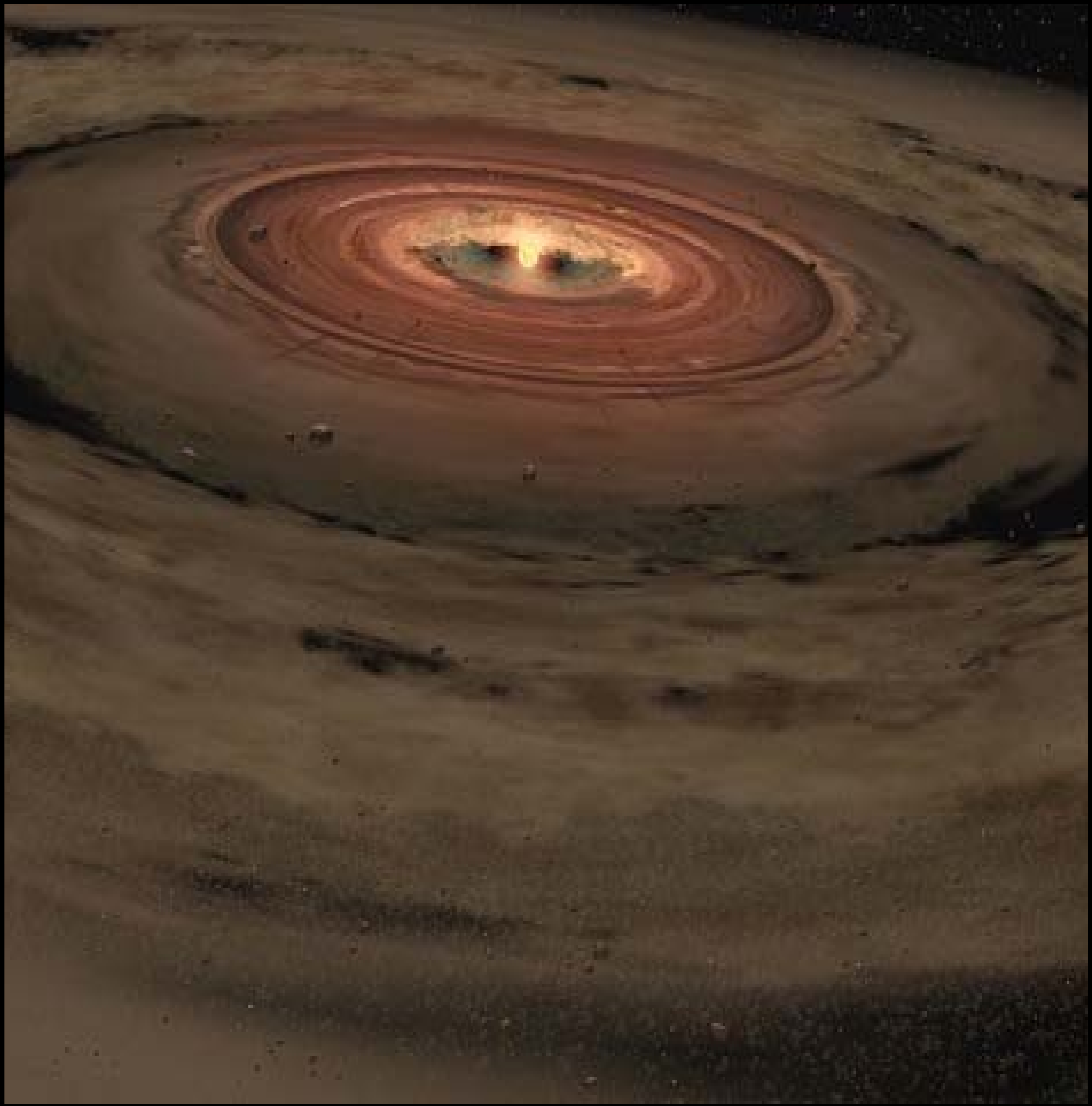
B. ^{40}Ar flux at ridges: 2.0×10^{16} kg ^{40}Ar ("popping" rock ^{4}He/^{40}Ar=1.5)

- Total ^{40}Ar in Earth: $8.7\text{-}11.5\times10^{16}$ kg
- Therefore, **155-205 ppm K** in the Earth.

Impact erosion: Lessons from Martian meteorites

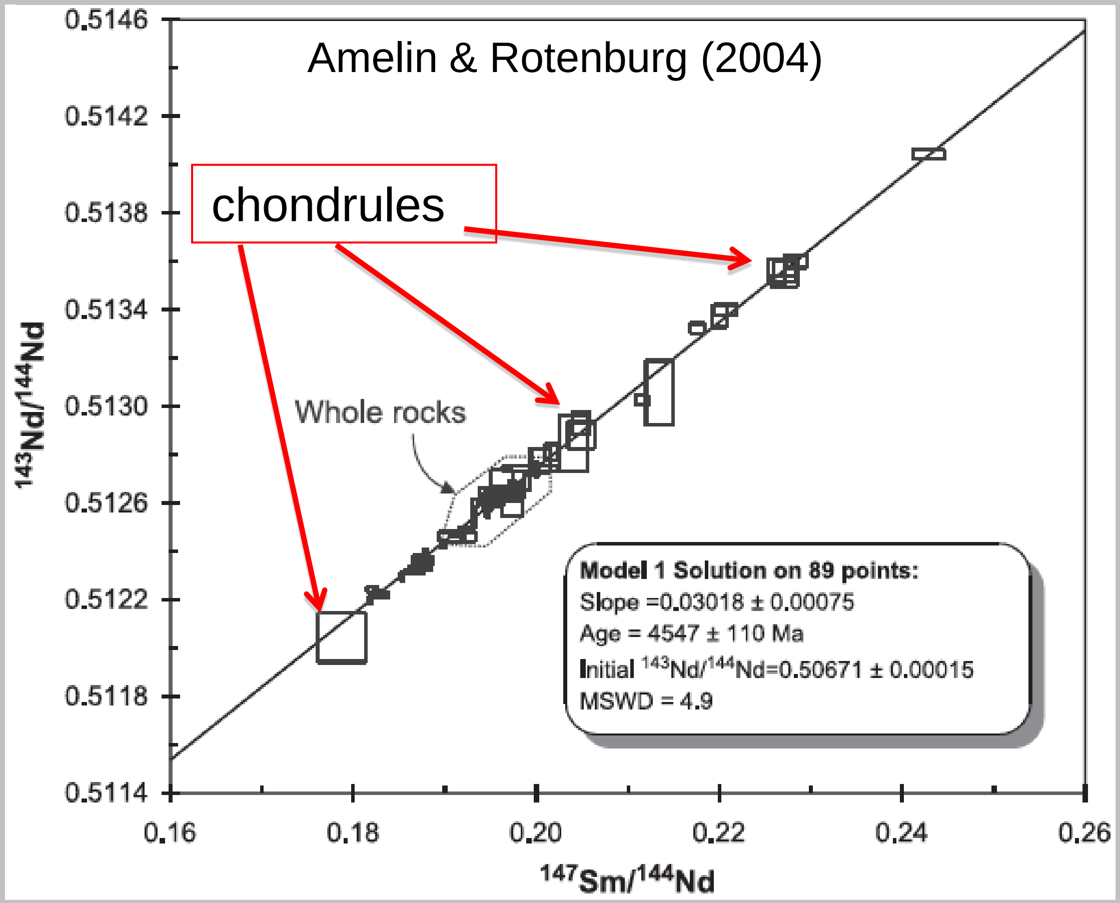
Early enriched crust “blasted” into space, leaving behind depleted (non-chondritic) mantle (O’Neill and Palme, 2008)

Homogeneous?



Courtesy of NASA/JPL-Caltech

In detail, chondrites aren't "chondritic"



Is the Earth chondritic?

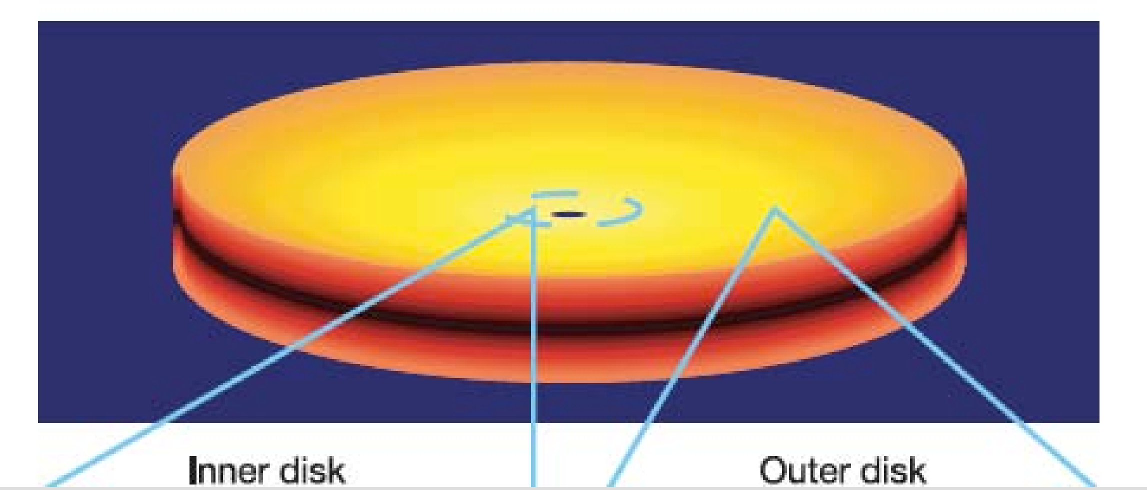
Chondrules in *primitive* chondrites have highly variable $^{143}Nd/^{144}Nd$.

Are other protoplanetary disks homogeneous?

The building blocks of planets within the 'terrestrial' region of protoplanetary disks

R. van Boekel[1,2], M. Min[1], Ch. Leinert[3], L.B.F.M. Waters[1,4], A. Richichi[2], O. Chesneau[3], C. Dominik[1], W. Jaffe[5], A. Dutrey[6], U. Graser[3], Th. Henning[3], J. de Jong[5], R. Köhler[3], A. de Koter[1], B. Lopez[7], F. Malbet[6], S. Morel[2], F. Paresce[2], G. Perrin[8], Th. Preibisch[9], F. Przygodda[3], M. Schöller[2] & M. Wittkowski[2]

Nature, 2004.



(0-2 AU)

(2-20 AU)

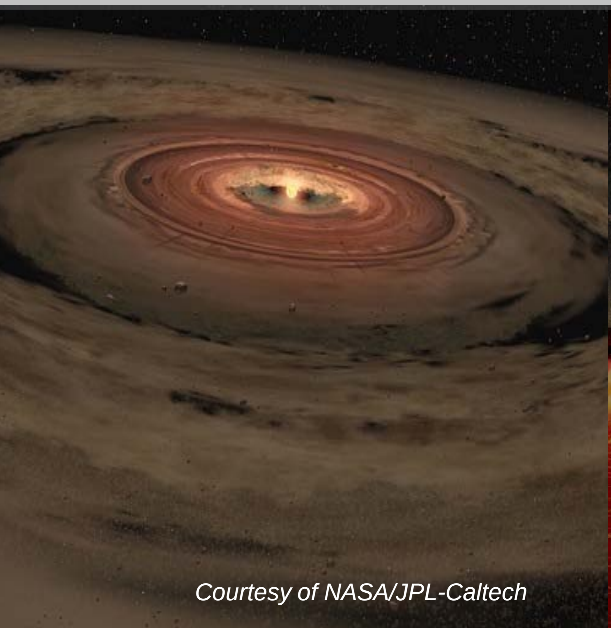
Table 1 **Dust properties in the inner and outer disk**

	Crystallinity (%)		Fraction of large grains (%)		Crystalline olivine to pyroxene ratio	
	Inner disk	Outer disk	Inner disk	Outer disk	Inner disk	Outer disk
HD 163296	40^{+20}_{-20}	15^{+10}_{-10}	95^{+5}_{-10}	65^{+20}_{-20}	$2.3^{+3.7}_{-0.5}$	–
HD 144432	55^{+30}_{-20}	10^{+10}_{-5}	90^{+10}_{-10}	35^{+20}_{-20}	$2.0^{+1.8}_{-0.6}$	–
HD 142527	95^{+5}_{-15}	40^{+20}_{-15}	65^{+15}_{-10}	80^{+10}_{-30}	$\boxed{2.1^{+1.3}_{-0.7}}$	$\boxed{0.9^{+0.2}_{-0.1}}$

Part 2: “Prospecting” for primitive mantle: If Earth isn’t chondritic, what would surviving relics look like today?

1. Noble gas isotopes and abundances (high $^3He/^4He$)
2. A primitive, mantle reservoir should have predictable (superchondritic!) ratios of the refractory, lithophile elements (e.g., Sm/Nd).
3. Pb-isotopes will be on the Geochron, the locus of data in Pb-isotope space that have had the same U/Pb for ~4.5 Ga.

- **Any mantle-derived melts satisfying these three requirements?**



Courtesy of NASA/JPL-Caltech

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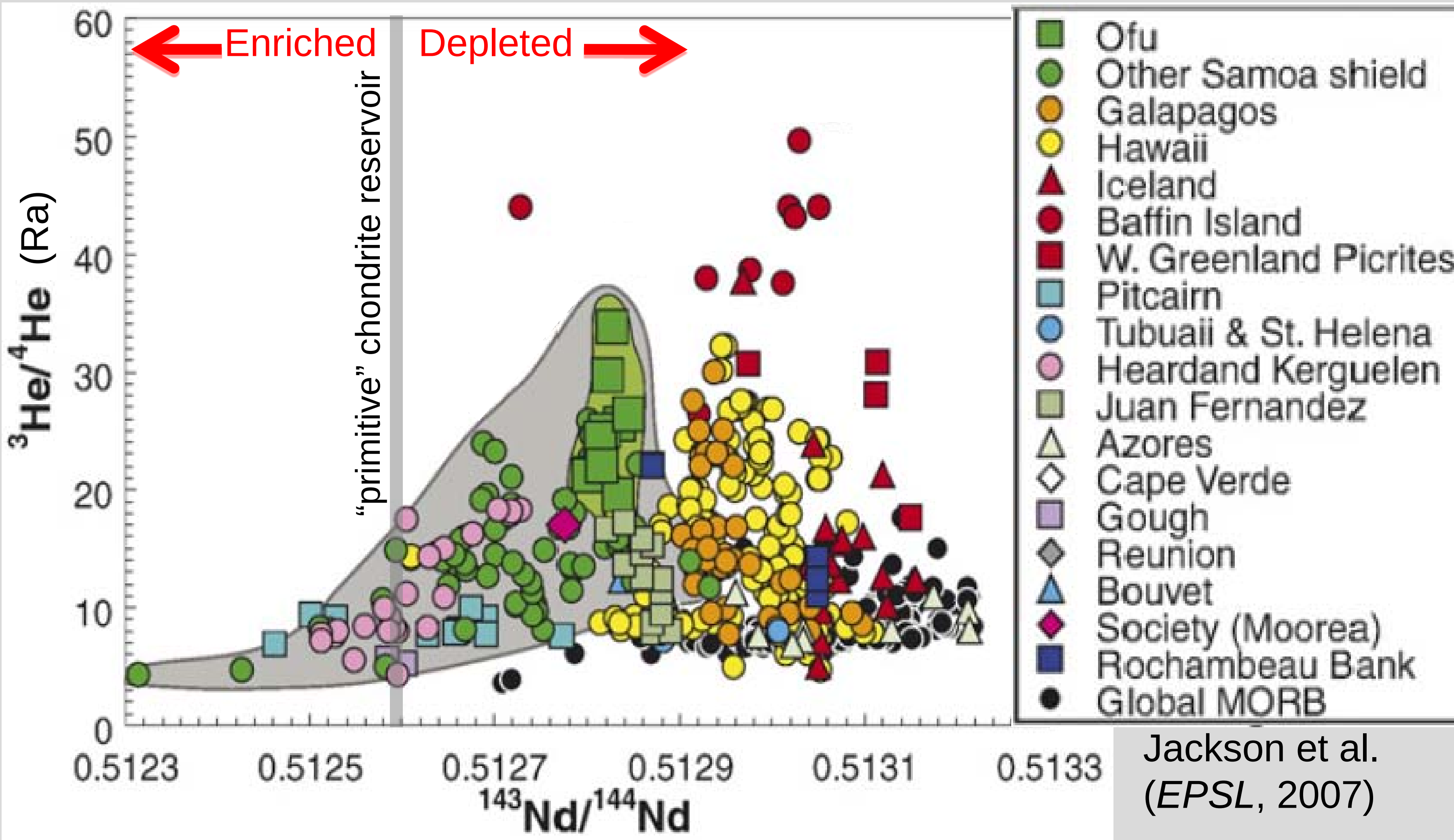
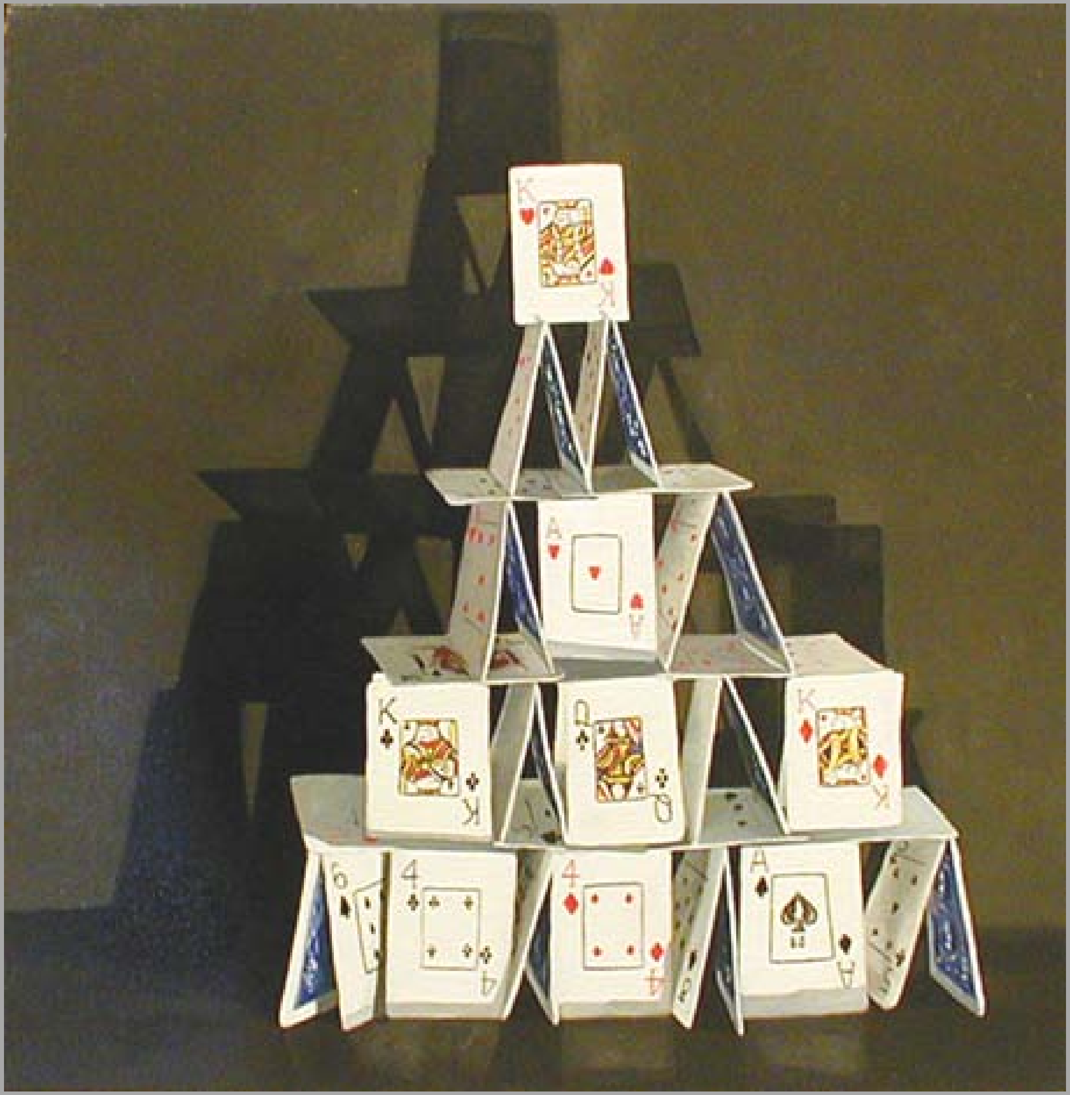
Brandenburg et al., EPSL 2008

Lavas with primordial $^3He/^4He$ don't have primitive chondritic $^{143}Nd/^{144}Nd$

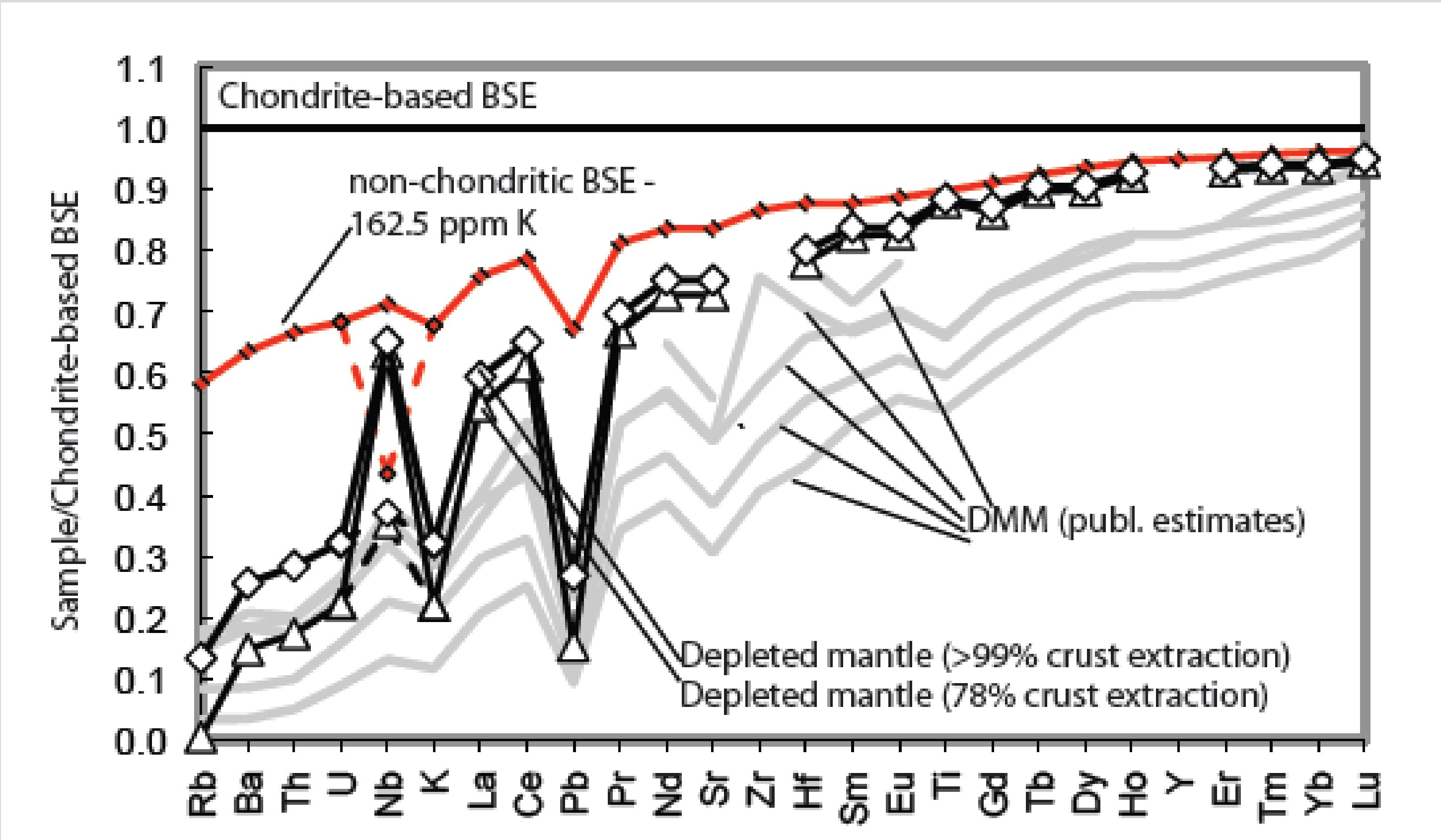


Jackson et al. (*EPSL*, 2007)



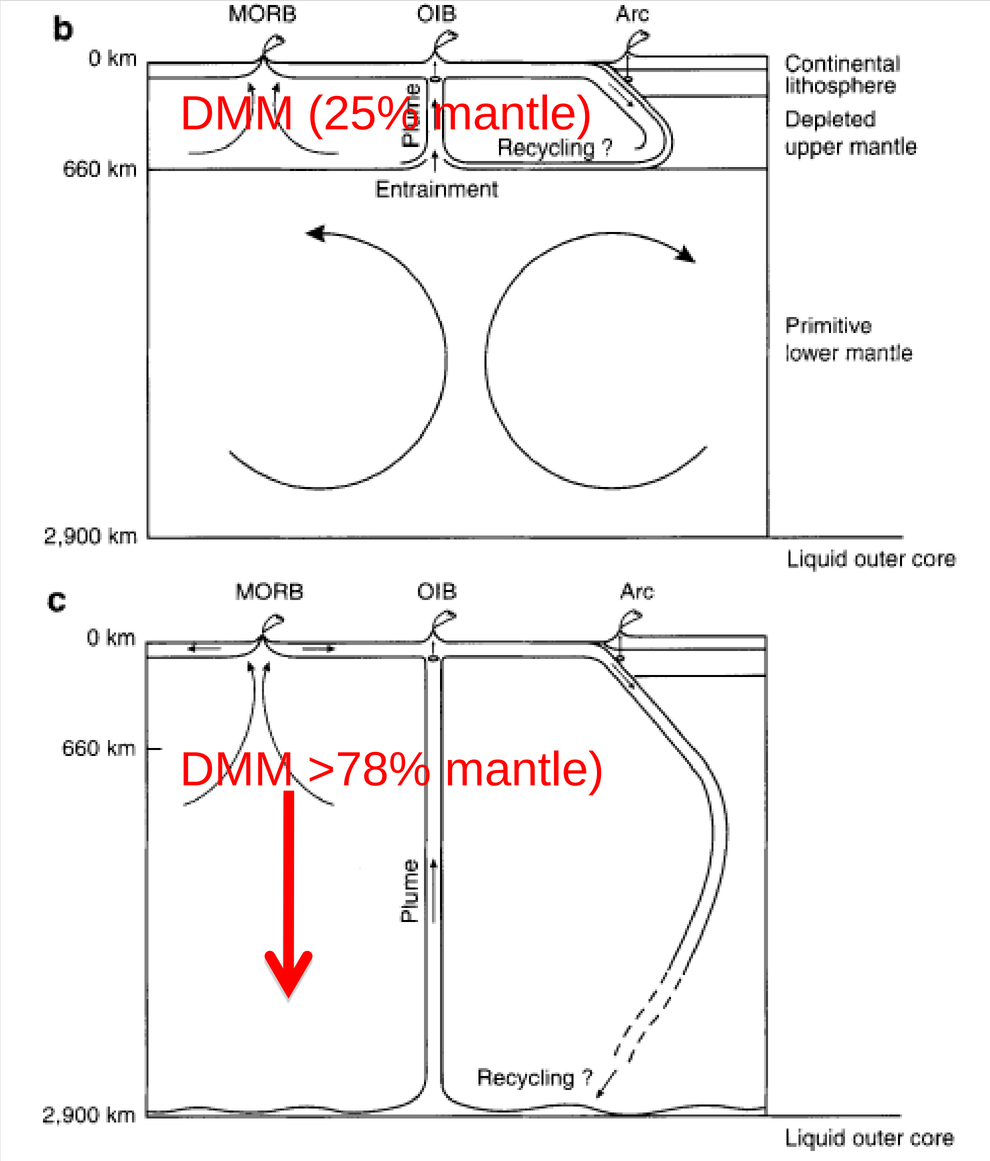
Can we extract continental crust from non-chondritic primitive mantle?

- Primitive Mantle = Continental Crust + Depleted Mantle
- New Primitive Mantle: Have to deplete >78% of the mantle to make Rudnick and Gao´s (2003) Continental Crust!



Jackson & Jellinek, 2012 (in review)

Layered Mantle? 660km of DMM? Not if the Earth is non-chondritic!



Hofmann, Nature (1997)

Thermal budgets of a non-chondritic Earth

- U, Th and K abundances in the Earth are 30-35% lower than the standard model.
- So, 30-35% less radiogenic heat than the standard model. Lower Urey ratio (radiogenic heat/total heat)
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- The rest is primordial heat. Is there enough uncertainty in primordial heat that we can make a non-chondritic Earth “work”?

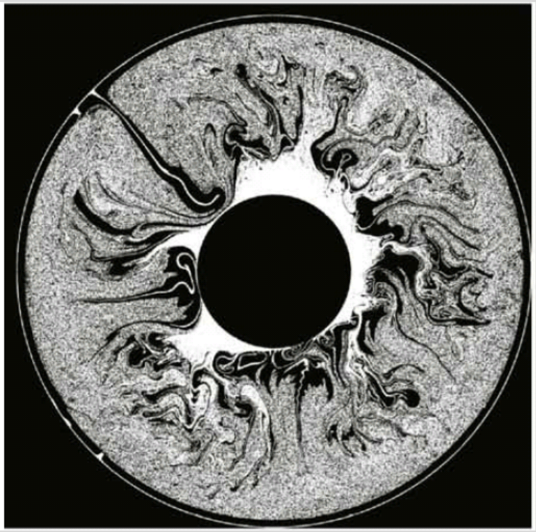
Earth and Planetary Science Letters 310 (2011) 380–388

On the relative influence of heat and water transport on planetary dynamics

John W. Crowley [a,*], Mélanie Gérault [b,c], Richard J. O'Connell [a]

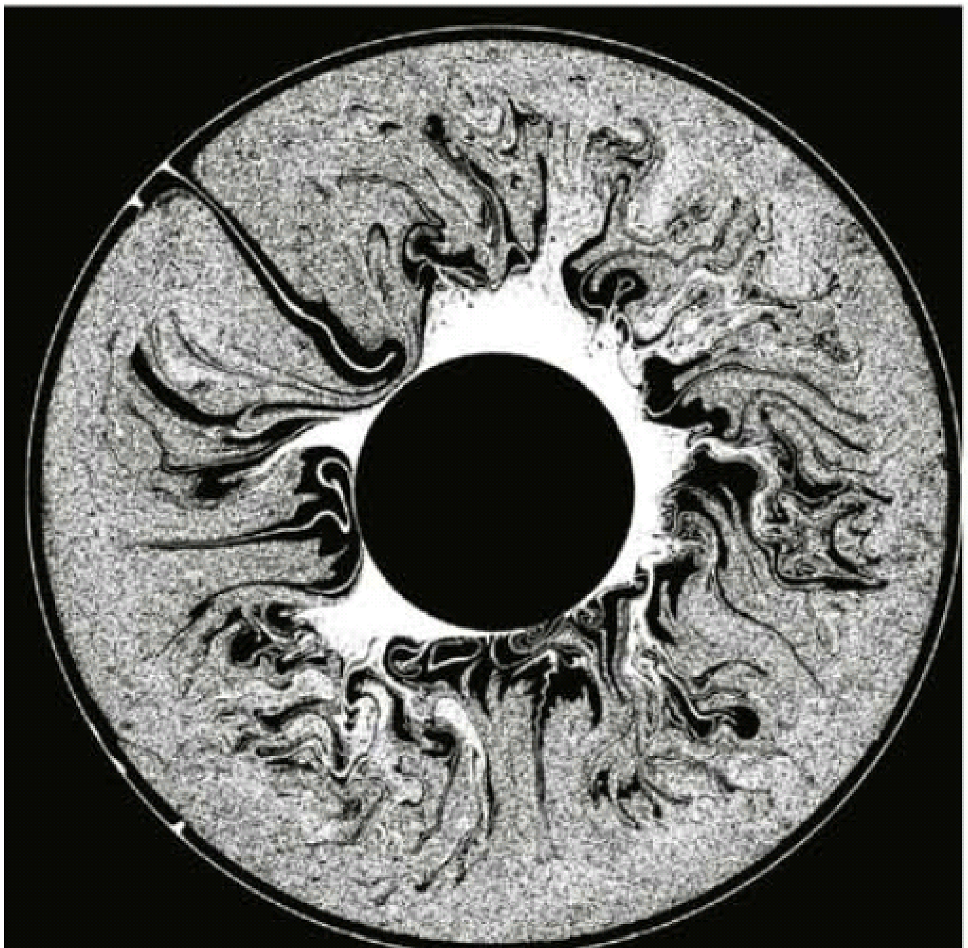
Summary

- The specter of a non-chondritic bulk earth? 0.5130 is Primitive Mantle? Closer to MORB than chondrite!
- Geochemical evolution of the mantle…a whole new family of models: Isotopic, compositional & thermal evolution.
- If the Earth isn't chondritic, then we don't know some of its fundamental properties (e.g., Urey ratio, etc.)



Brandenburg et al. (*EPSL*, 2008)

How does a portion of the mantle survive for ~4.5 Ga?



Brandenburg et al. (*EPSL*, 2008)

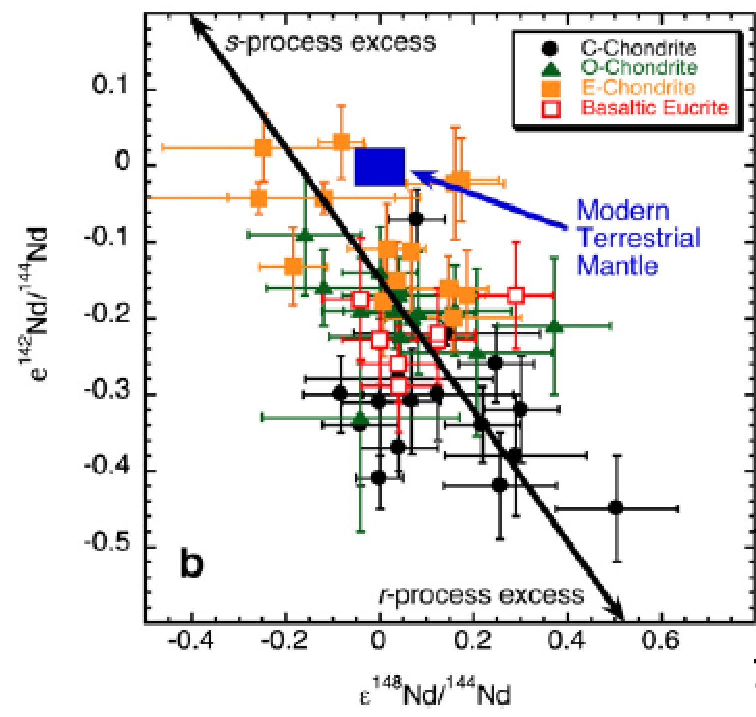
- Solid-state convective stirring is thought to process large portions of the mantle on geologic time-scales.
- Recent dynamic models suggest that pristine portions (up to 10-15%) of the mantle might have escaped differentiation and mixing over the age of the Earth (in convective "eddies"?).

Enstatite (E) chondrite model?

Earth and Planetary Science Letters 293 (2010) 259–268

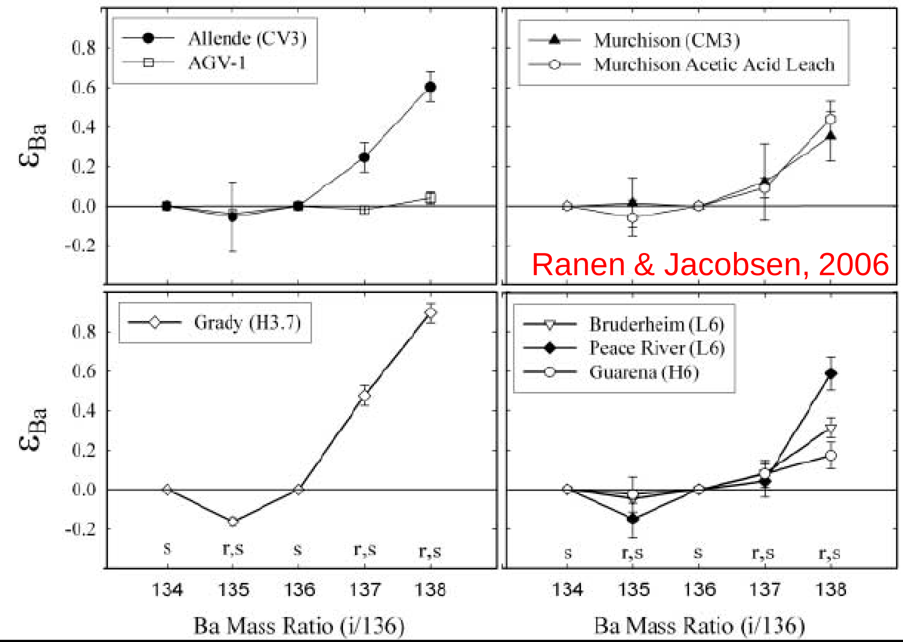
The chemical composition of the Earth: Enstatite chondrite models

M. Javoy [a], E. Kaminski [a,*], F. Guyot [a], D. Andrault [e], C. Sanloup [b], M. Moreira [a], S. Labrosse [d], A. Jambon [b], P. Agrinier [a], A. Davaille [c], C. Jaupart [a]



Qin et al., EPSL 2011

- Enstatite chondrites are Si-rich.
- Earth’s mantle is peridotitic (Si-poor)
- Have to “stuff” a lot of Si in the core to make the E-chondrite model work!



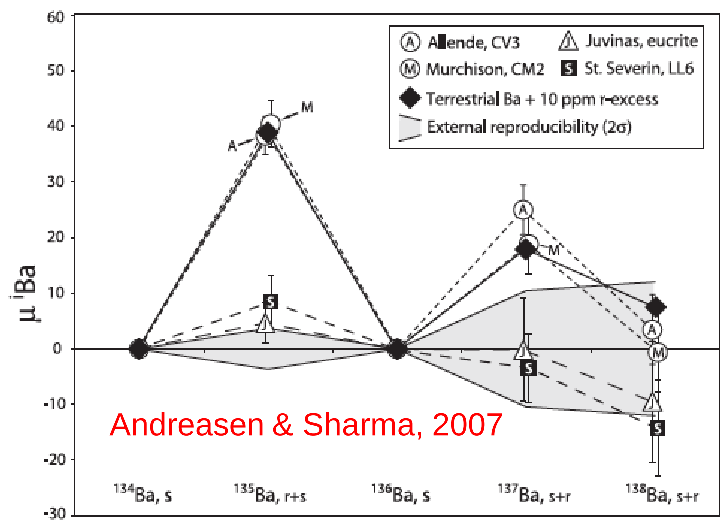


FIG. 2.—Deviations in Ba isotopic composition from that of terrestrial standard. Calculated deviation from terrestrial Ba plus 10 ppm *r*-process Ba, based on Arlandini et al. (1999), is shown as diamonds connected by a solid line. Data are fractionation-corrected using $^{134}Ba/^{136}Ba = 0.30774$ (McCulloch & Wasserburg 1978a), deviations for the low-abundance ^{130}Ba and ^{132}Ba are omitted for clarity due to their lower precision.

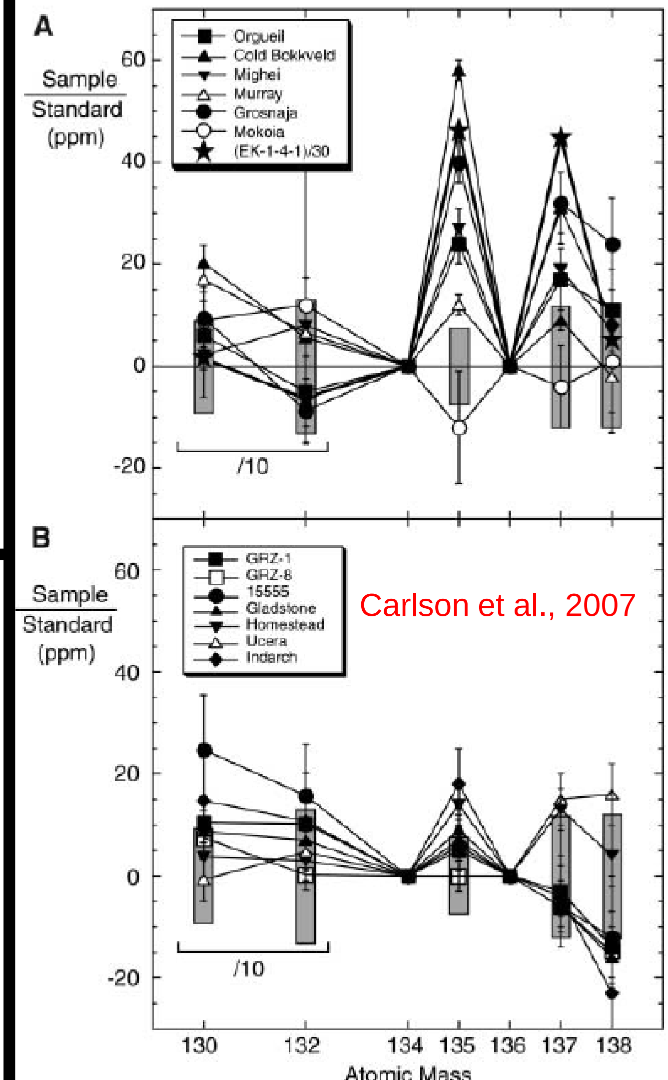


Fig. 1. Ba isotopic variation relative to the average value measured for the terrestrial standard. Gray boxes at each mass show the 2σ external reproducibility obtained on the standard. Both the values and the errors at ^{130}Ba and ^{132}Ba have been divided by 10 to plot on this scale. **(A)** Data for C-chondrites; **(B)** data for O- and E-chondrites and lunar and terrestrial samples. The pattern denoted by the large stars in (A) shows the isotopic composition measured in Allende CAI EK 1-4-1 (*16*) with the anomalies divided by 30 to plot on this scale.

Magma ocean solidification followed by homogenization

Michael C. Ranen* and Stein B. Jacobsen SCIENCE VOL 314 3 NOVEMBER 2006

Magma oceans almost certainly existed on the Moon and Mars and most likely existed on Earth as well. Although it is likely that early differentiation of a terrestrial magma ocean produced $^{142}Nd/^{144}Nd$ isotopic variations (*26*, *27*), it is also likely that, after ^{146}Sm became extinct (~500 My after the formation of the solar system), convection mixed the mantle well enough to destroy most of the heterogeneities caused by fractionation in a magma ocean (*28*).

26. C. L. Harper Jr., S. B. Jacobsen, *Nature* **360**, 728 (1992).
27. G. Caro, B. Bourdon, J. L. Birck, S. Moorbath, *Geochim. Cosmochim. Acta* **70**, 164 (2006).
28. S. B. Jacobsen, C. L. Harper Jr., *Geochim. Cosmochim. Acta* **60**, 3747 (1996).

Science 30 March 2012:
Vol. 335 no. 6076 pp. 1614-1617
DOI: 10.1126/science.1215510

REPORT

A Shorter ^{146}Sm Half-Life Measured and Implications for ^{146}Sm-^{142}Nd Chronology in the Solar System

N. Kinoshita[1], M. Paul[2,*], Y. Kashiv[3,*], P. Collon[3], C. M. Deibel[4,5], B. DiGiovine[4], J. P. Greene[4], D. J. Henderson[4], C. L. Jiang[4], S. T. Marley[4], T. Nakanishi[6], R. C. Pardo[4], K. E. Rehm[4], D. Robertson[3], R. Scott[4], C. Schmitt[3], X. D. Tang[3], R. Vondrasek[4], A. Yokoyama[6]

+ Author Affiliations

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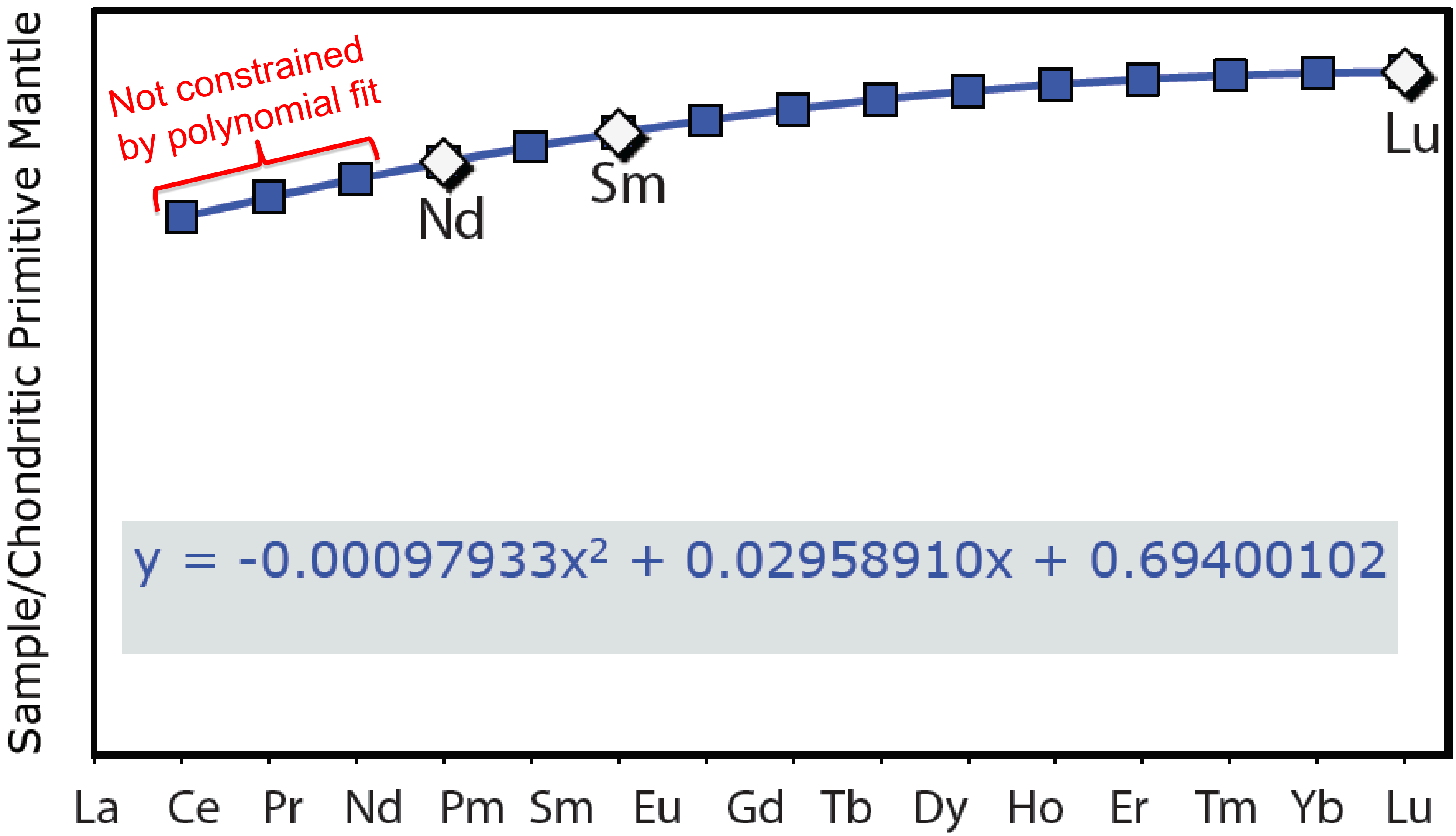
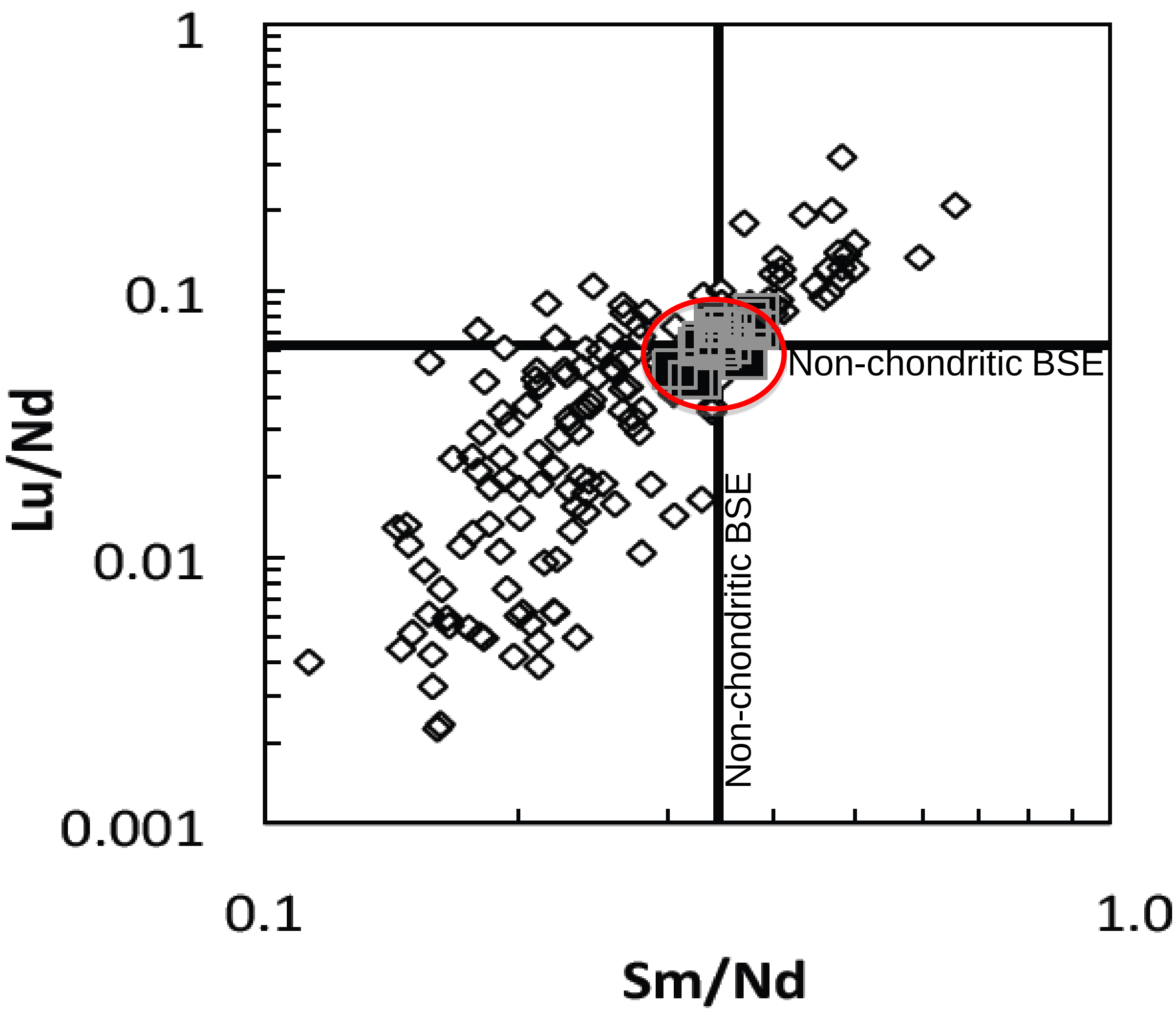
ABSTRACT

The extinct *p*-process nuclide ^{146}Sm serves as an astrophysical and geochemical chronometer through measurements of isotopic anomalies of its α-decay daughter ^{142}Nd. Based on analyses of ^{146}Sm/^{147}Sm α-activity and atom ratios, we determined the half-life of ^{146}Sm to be 68 ± 7 (1σ) million years, which is shorter than the currently used value of 103 ± 5 million years. This half-life value implies a higher initial ^{146}Sm abundance in the early solar system, $(^{146}\mathrm{Sm}/^{144}\mathrm{Sm})_0$ = 0.0094 ± 0.0005 (2σ), than previously estimated. Terrestrial, lunar, and martian planetary silicate mantle differentiation events dated with ^{146}Sm-^{142}Nd converge to a shorter time span and in general to earlier times, due to the combined effect of the new ^{146}Sm half-life and $(^{146}\mathrm{Sm}/^{144}\mathrm{Sm})_0$ values.

Rare Earth Elements



McDonough and Sun's peridotites: Select 20 most similar to non-chondritic BSE



Relationship between flood basalts and a primitive (non-chondritic) mantle

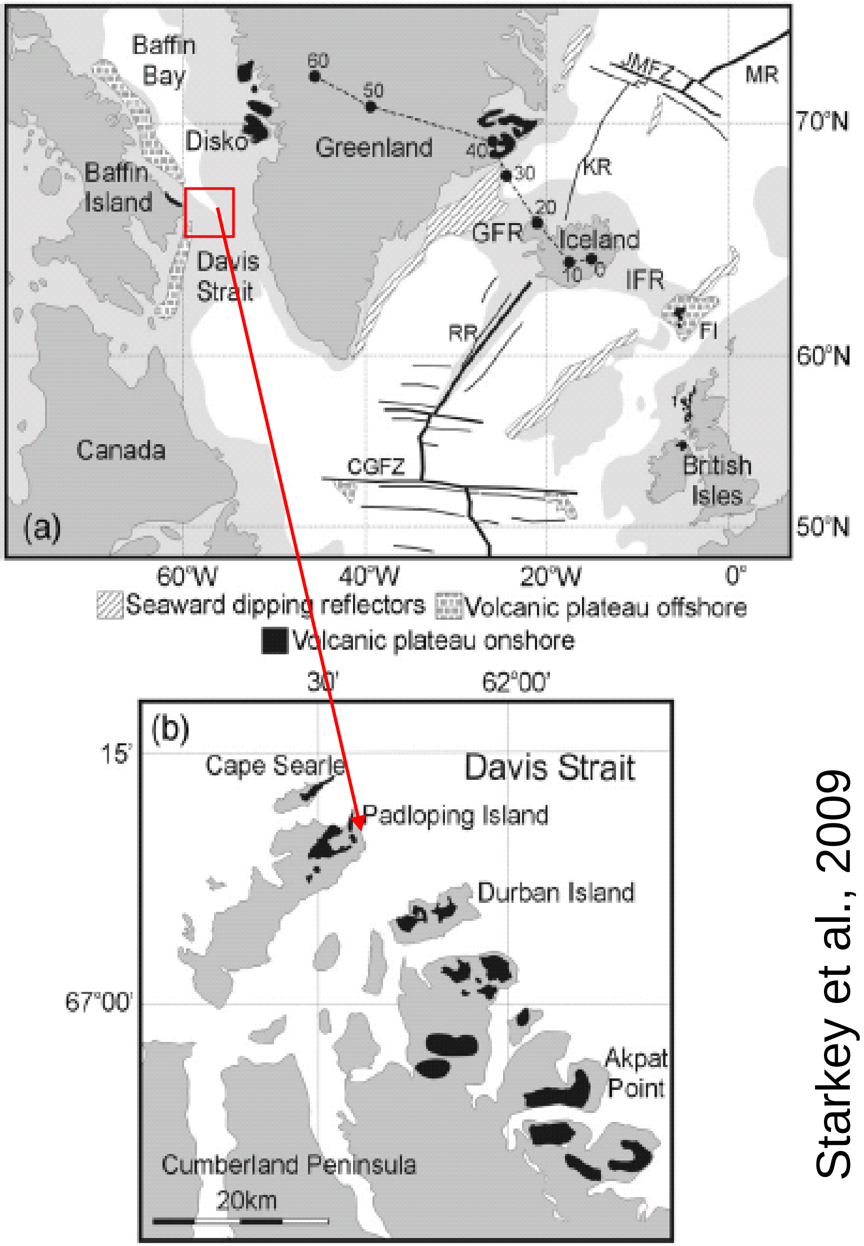
- Relics of the early Earth may not be so rare?
- Why would this reservoir be sampled by large igneous provinces?

A. Primitive Mantle produces more heat, melts more.

B. Primitive Mantle is more fusible, melts more.

A recipe for producing extraordinary volumes of melt?

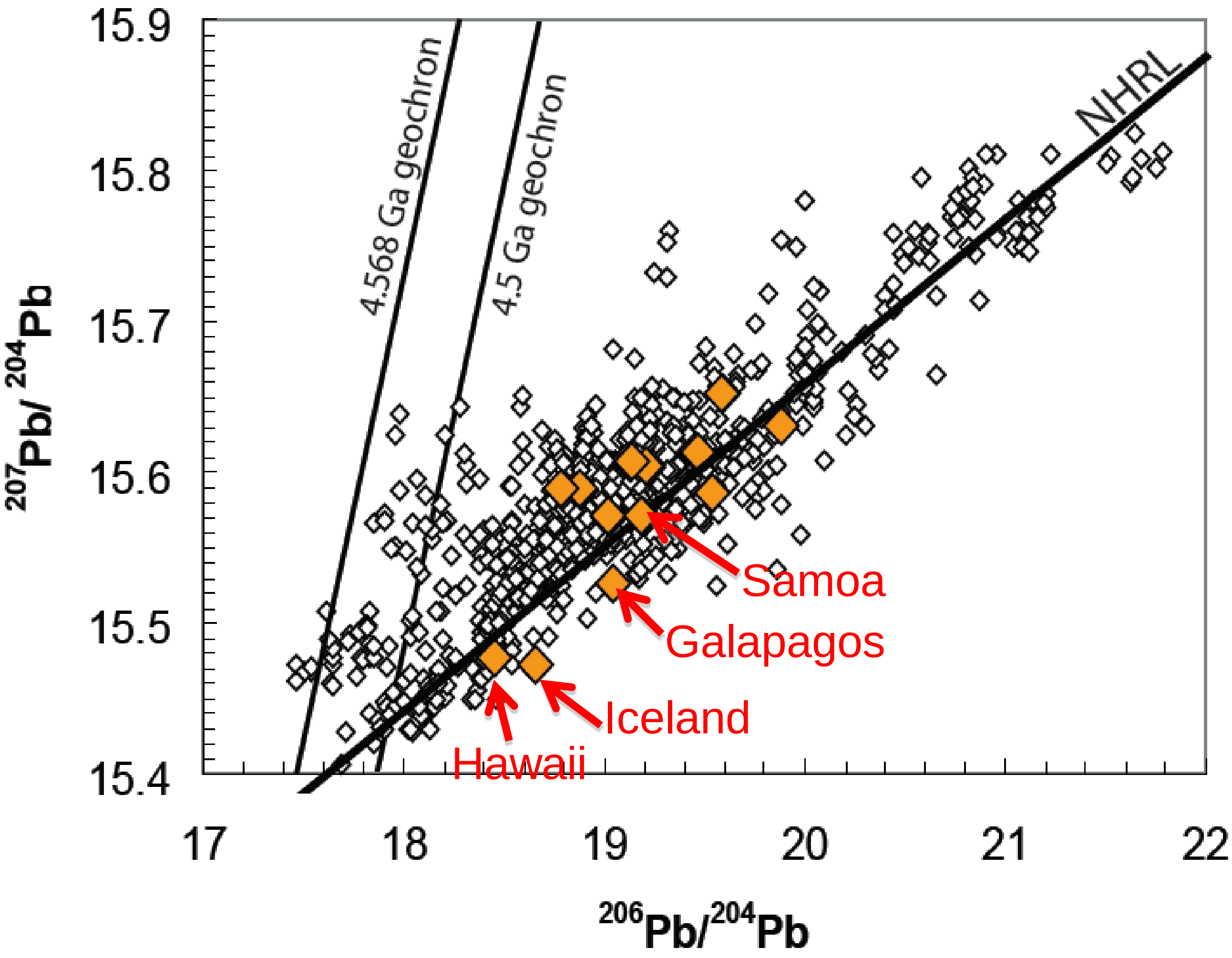
Baffin Island and West Greenland picrites



Starkey et al., 2009

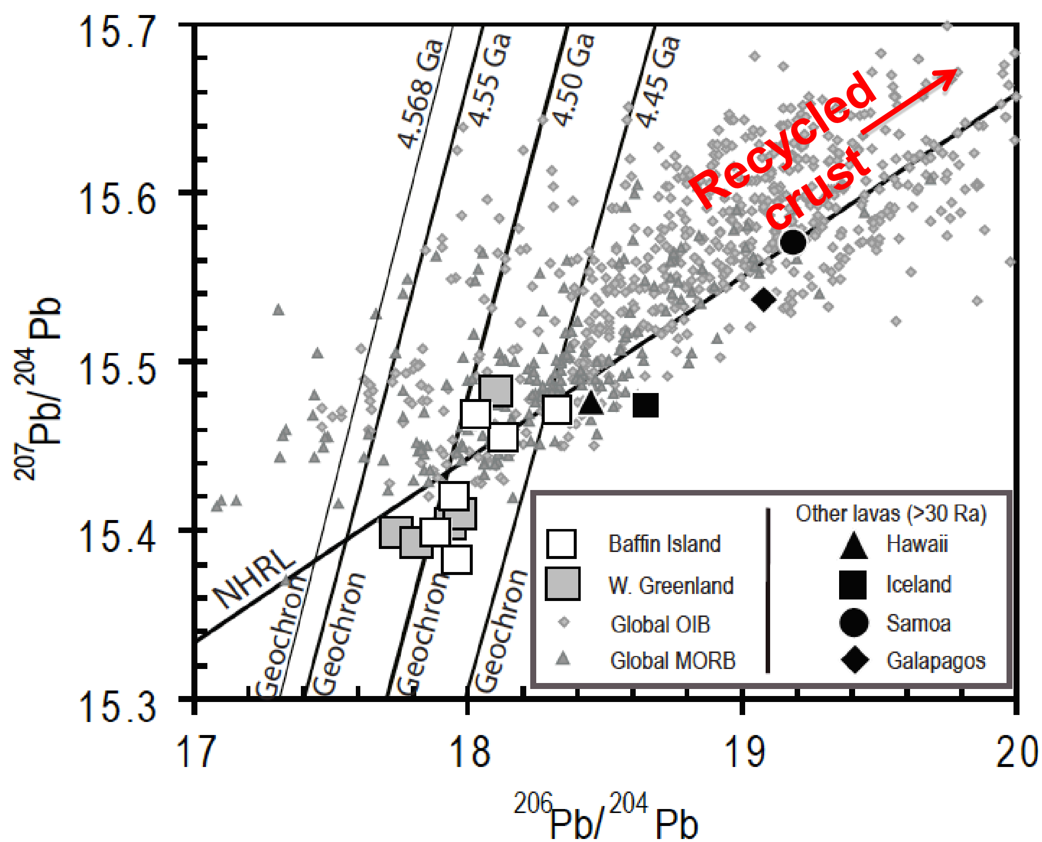
- Samples are from Padloping Island, east coast of Baffin Island.
- Lavas erupted ~62Ma as part of the proto-Iceland plume.

Problem: Terrestrial lavas with high $^3He/^4He$ don't plot on the Geochron!



After Jackson et al. (*EPSL*, 2007)

Why do high $^3He/^4He$ lavas from other localities plot off of the Geochron (and have somewhat lower $^3He/^4He$)?



Jackson et al. (*Nature,* 2010)

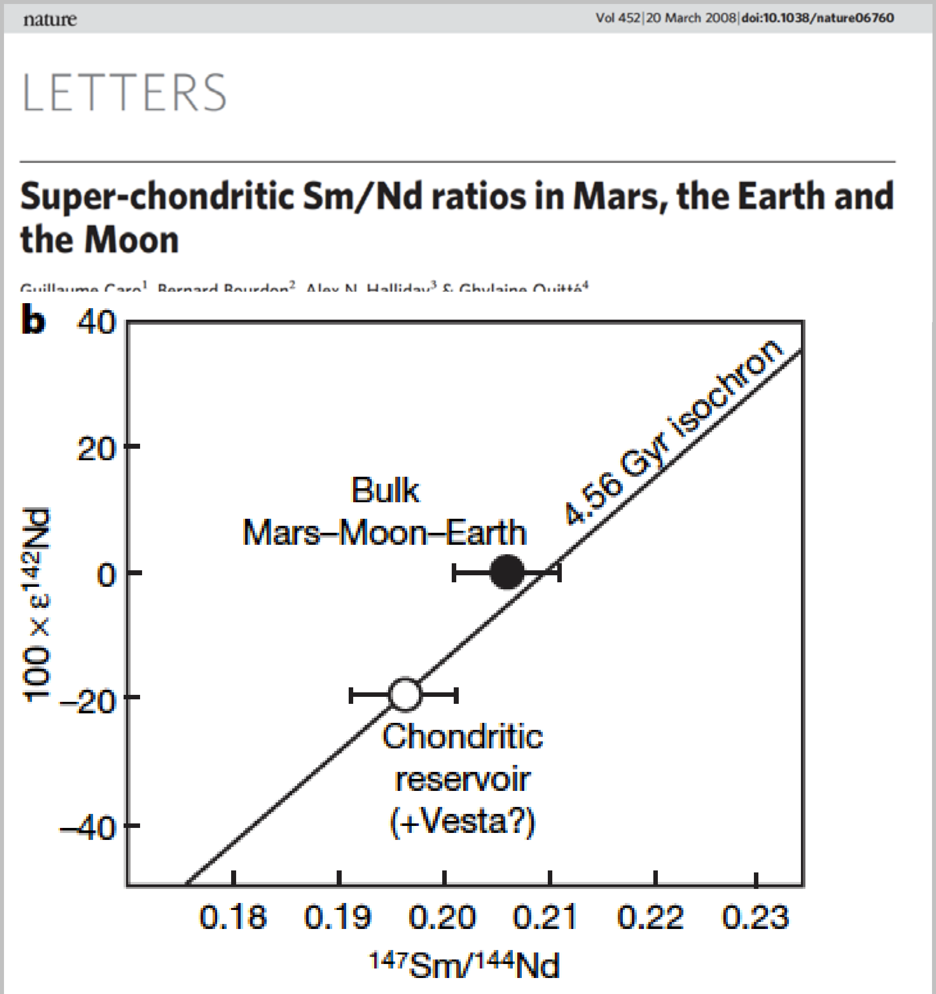
- Recycled crust is rich in Pb, U and Th.
- If recycled crust mixes with ambient mantle, or surviving pieces of primitive mantle, the mixture will be shifted away from the geochron.
- U and Th in recycled crust will generate ^4He and will reduce the $^3He/^4He$ of the mixture.

A growing clamor….

Bottom line: Terrestrial oxygen isotopes not like C and O-chondrites (Clayton)!

<u>Implications:</u>

1. DMM is >45-90% of the mantle (to >1600 km depth). If primitive mantle $^{143}Nd/^{144}Nd$ is 0.5130 (instead of 0.51263) then much more than 25% of the mantle needs to be depleted to make DMM!
2. What was once considered depleted may actually be enriched!
3. How to preserve for 4.5 Ga?
4. A whole new family of models are needed!



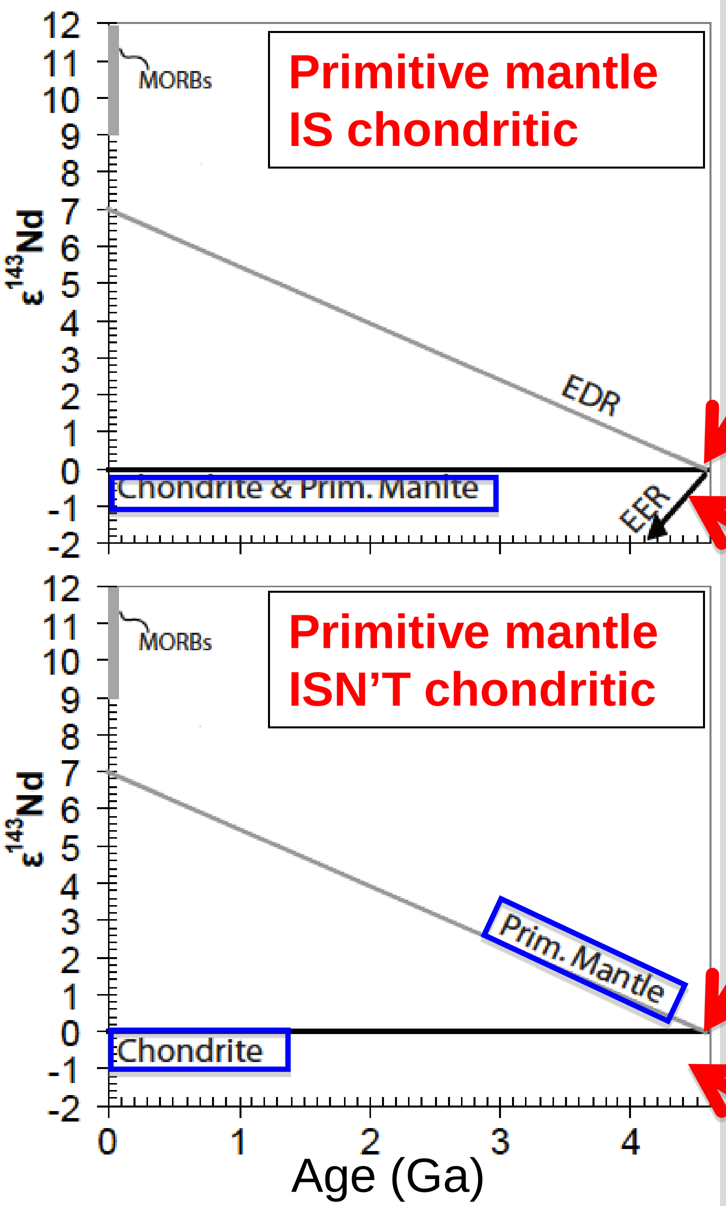
“ Who drank the ‘Cool-Aid’? ”

-S. Shirey, 2010

- Bill White
- Dave Graham
- Hubert Palme
- Hugh O’Neill
- Bernard Bourdon
- Guillaume Caro
- Nobu Shimizu

If the ^{142}Nd excess is from ^{146}Sm decay….two models

$^{142}Nd/^{144}Nd$ result requires that all modern terrestrial mantle reservoirs evolve from a reservoir of with $^{143}Nd/^{144}Nd = 0.5130$ ($\varepsilon^{143}Nd = +7$)

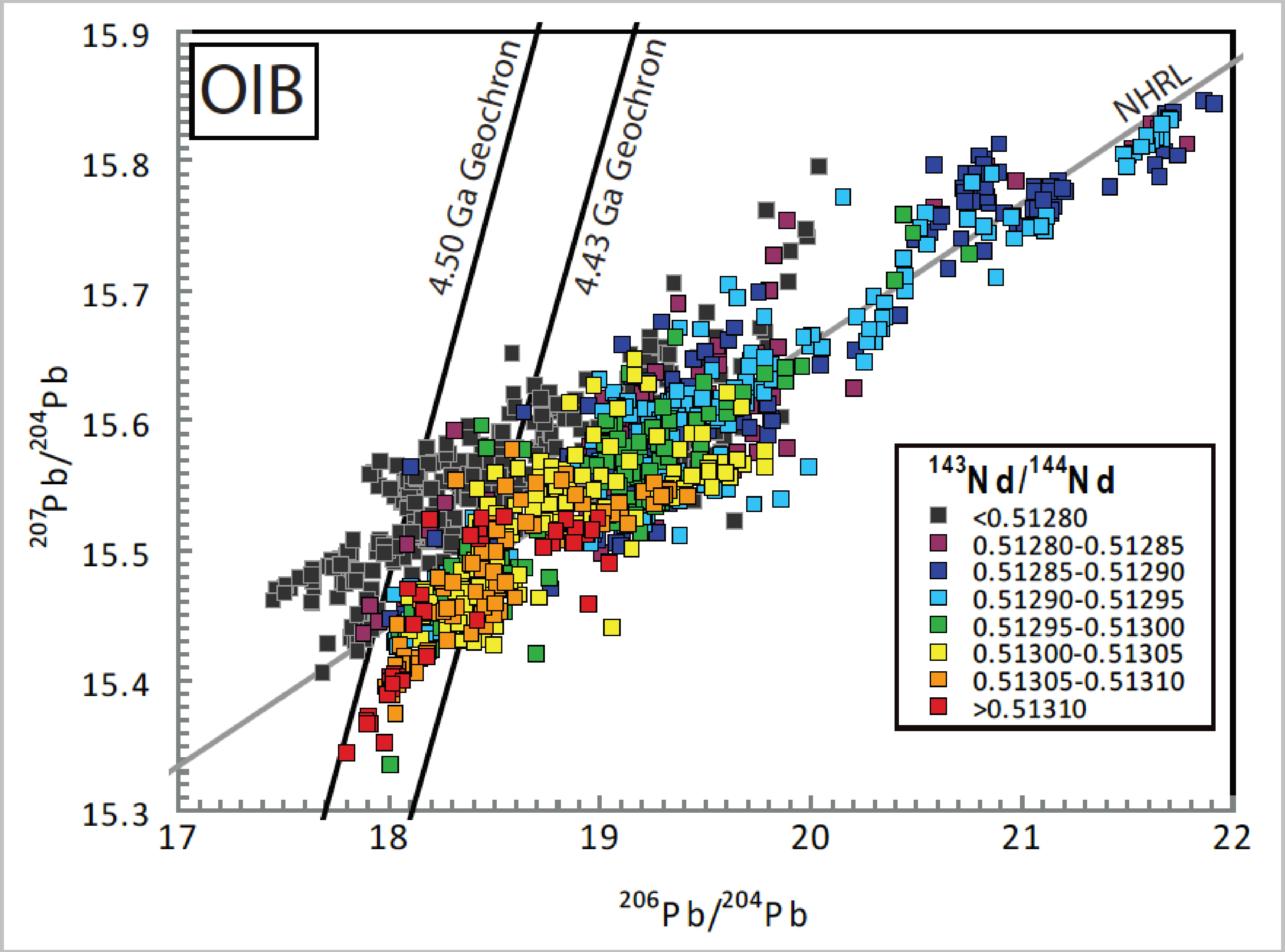


Early differentiation event

"Hidden" early enriched reservoir

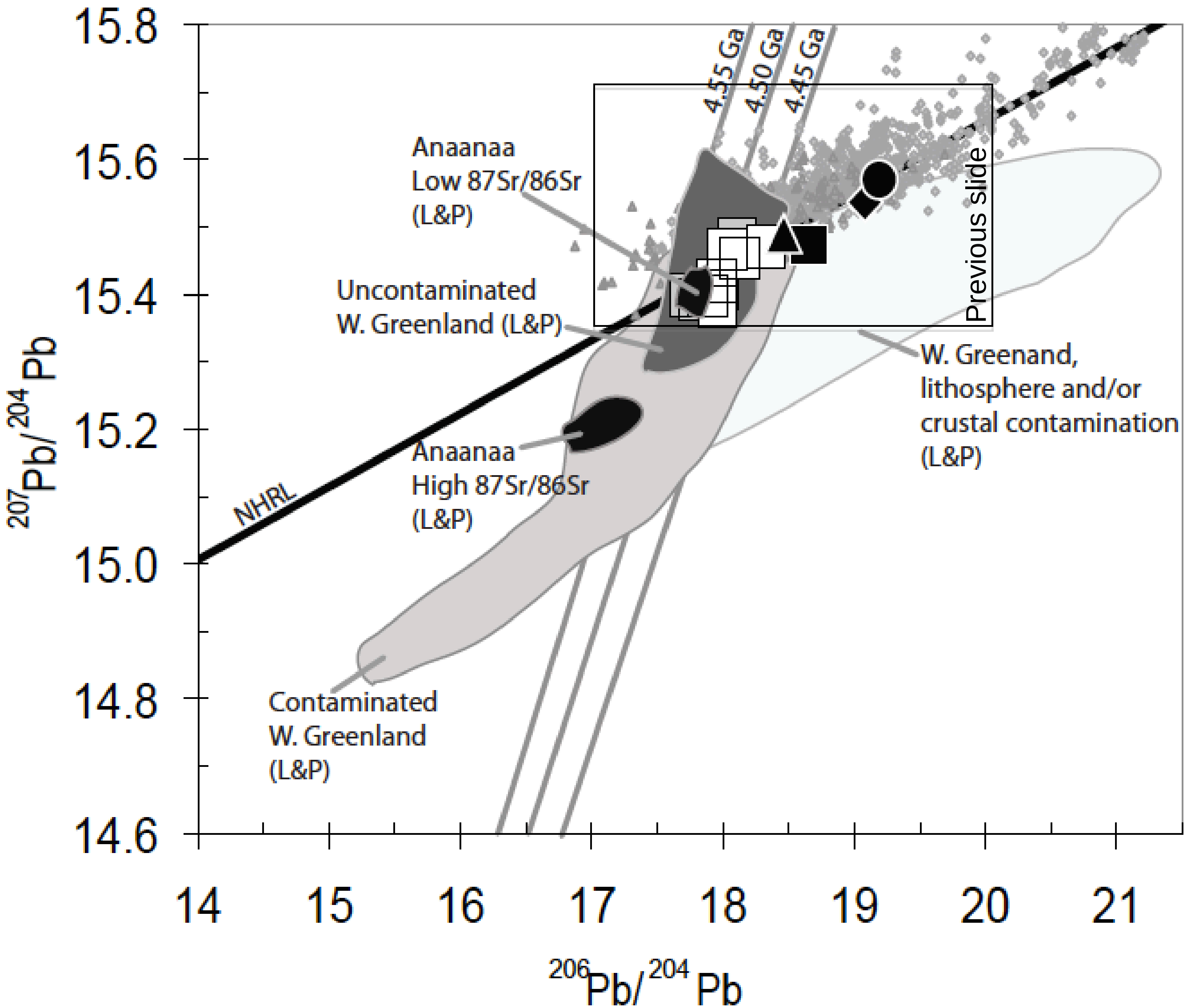
No Early differentiation event

No "Hidden" early enriched reservoir



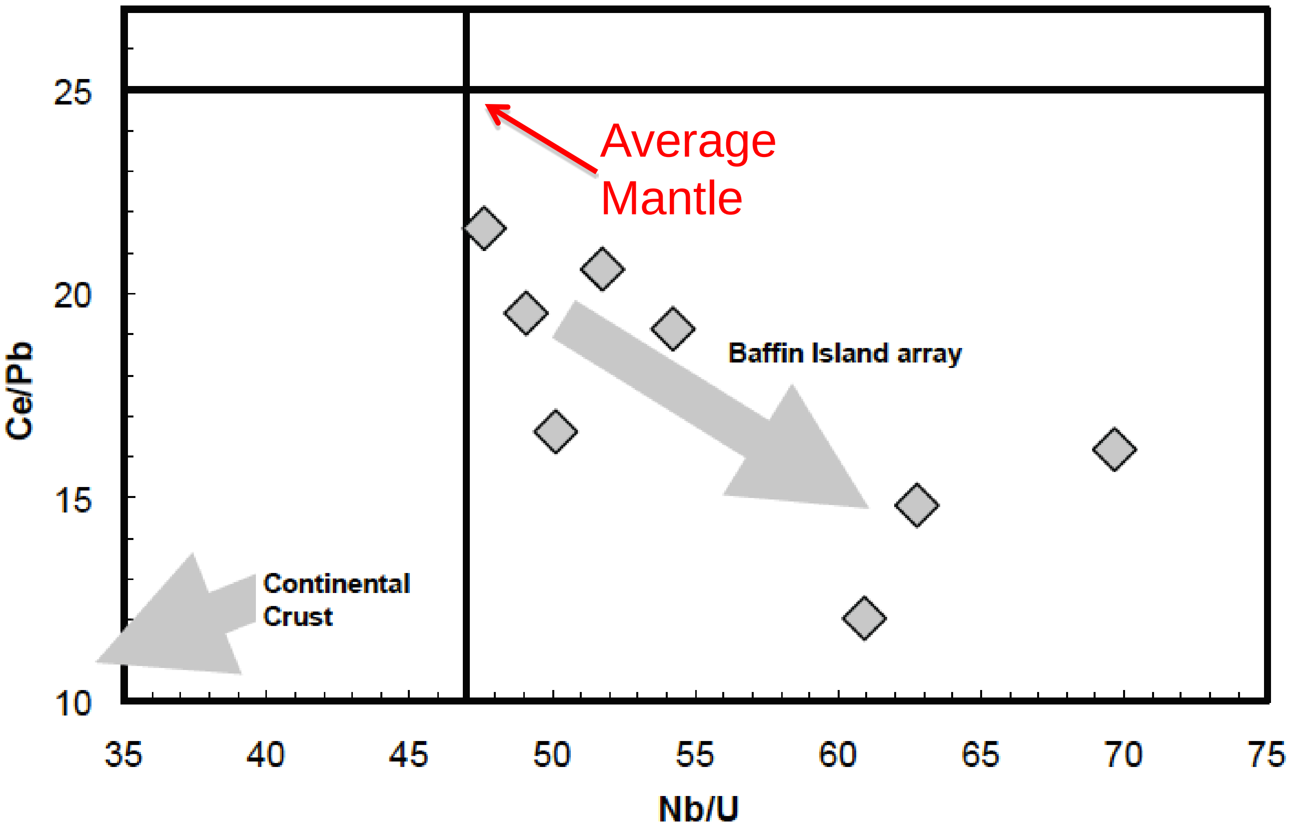
Jackson and Carlson (Nature, TODAY)

Caveat: Crustal contamination



Jackson et al. (*Nature*, 2010)

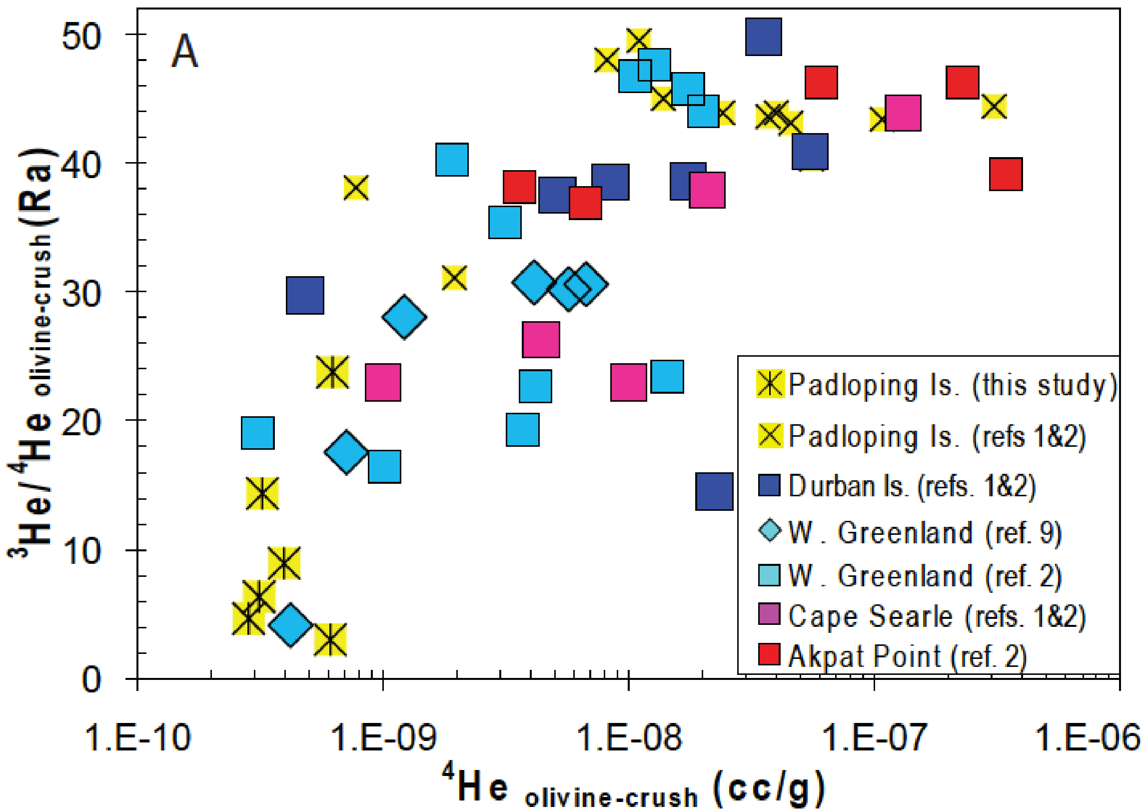
Trace elements indicate no role for continental contamination in our sample suite



Jackson et al. (*Nature*, 2010)

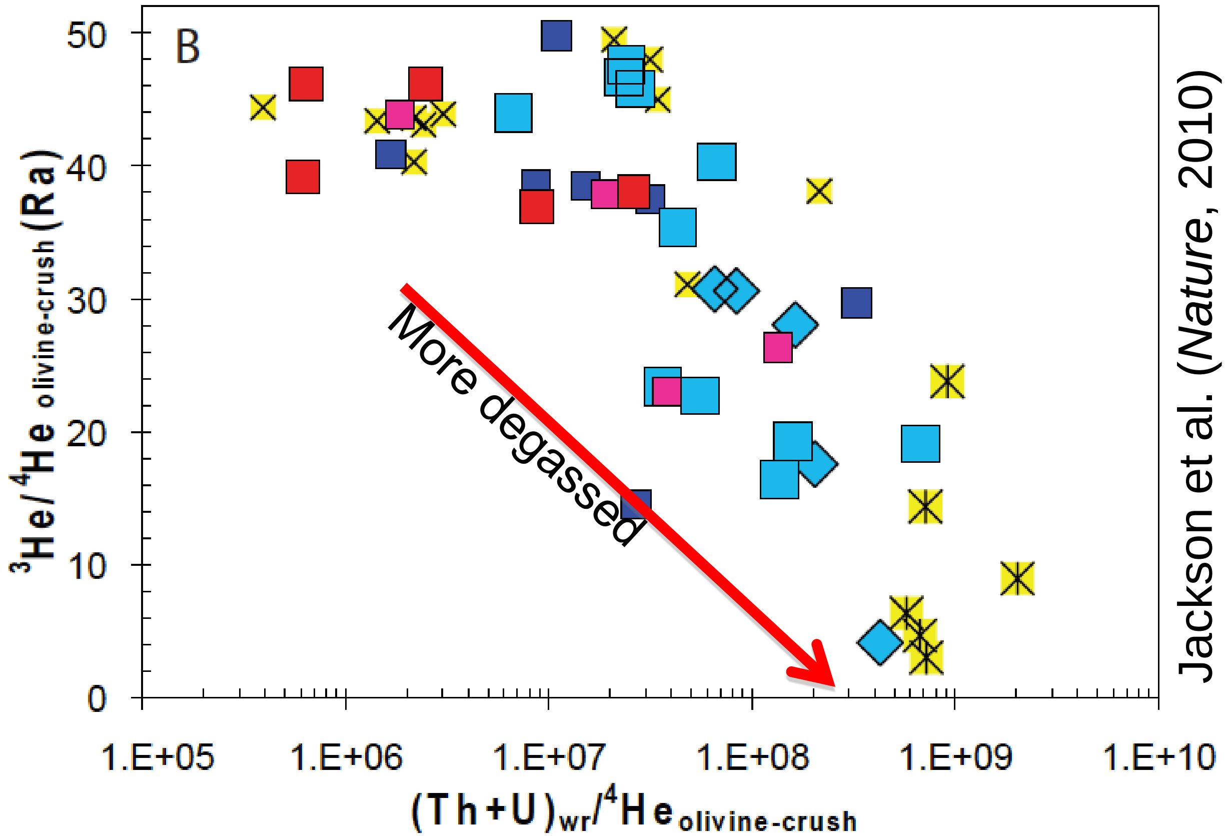
Kent et al. (2004) obtained a trace element dataset on Baffin Island glasses (pillow rims). The glasses are extremely fresh, give pristine Pb and U.

Another Caveat: Radiogenic ^{4}He

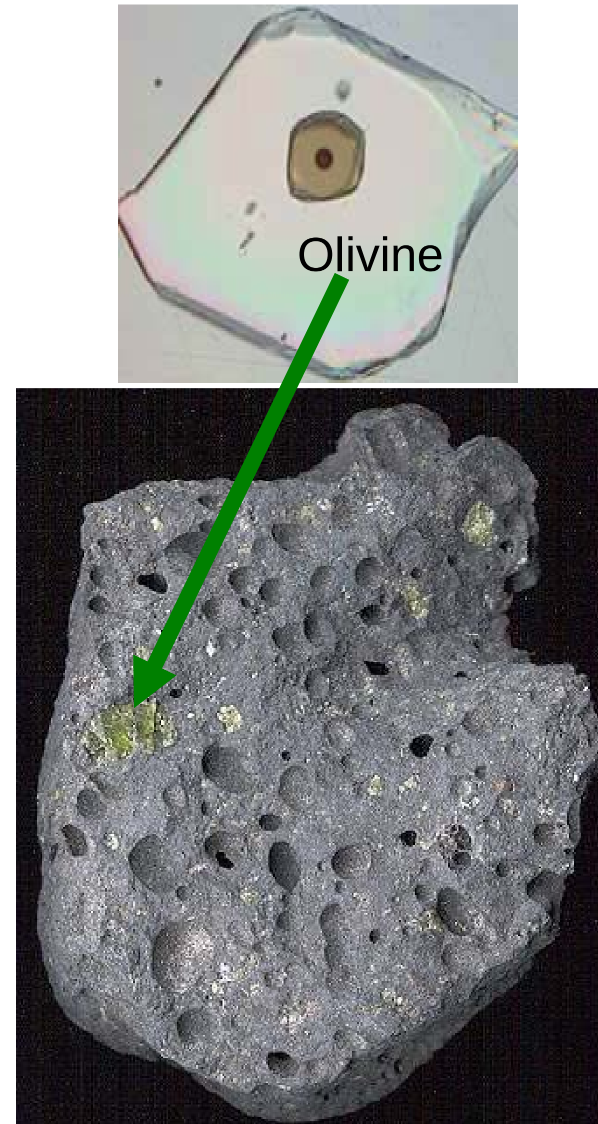


Jackson et al. (*Nature*, 2010)

Magmatic He is hosted in the olivine, U and Th in the basalt matrix



Jackson et al. (*Nature*, 2010)



1. Helium is massively degassed before and during eruption.
2. Following degassing of He, parent-daughter ratios (U/He & Th/He) are increased by many orders of magnitude.
3. ^4He generated by U and Th decay diminishes $^3He/^4He$ ratio.
4. **<u>Lesson:</u> Avoid measuring $^3He/^4He$ on old lavas (62 Ma)!**

Post-eruptive radiogenic ^{4}He ingrowth from U & Th decay

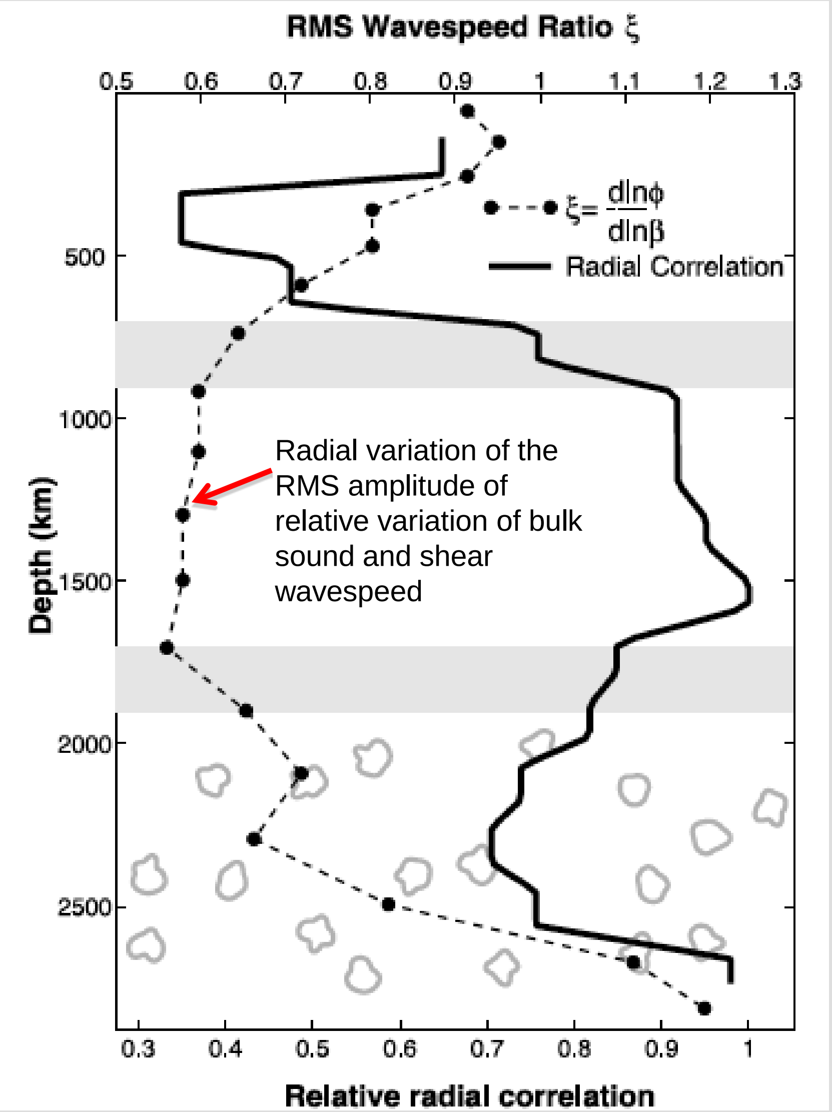
Combining [^{3}He] cosmogenic dating with U–Th/He eruption ages using olivine in basalt

Sarah M. Aciego [a,b,*], Donald J. DePaolo [a,b], B.M. Kennedy [a], Michael P. Lamb [b], Kenneth W.W. Sims [c], William E. Dietrich [b]

"….olivine phenocrysts in basalt are embedded in basaltic groundmass that has much higher [U] and [Th] than the olivine. Consequently, ^{4}He from alpha-decay of groundmass U is implanted into the rims of the olivine grains."

Extracting continental crust from a non-chondritic primitive mantle

- Depleted MORB mantle and continental crust are geochemically complementary.
- If primitive mantle $^{143}Nd/^{144}Nd$ is 0.5130, instead of 0.51264, then much more than 25% of the mantle needs to be depleted to make DMM!
- DMM is >45-90% of the mantle!
- DMM extends down to 1600 km?



van der Hilst et al., Science 1999

Nucleosynthetic anomalies?

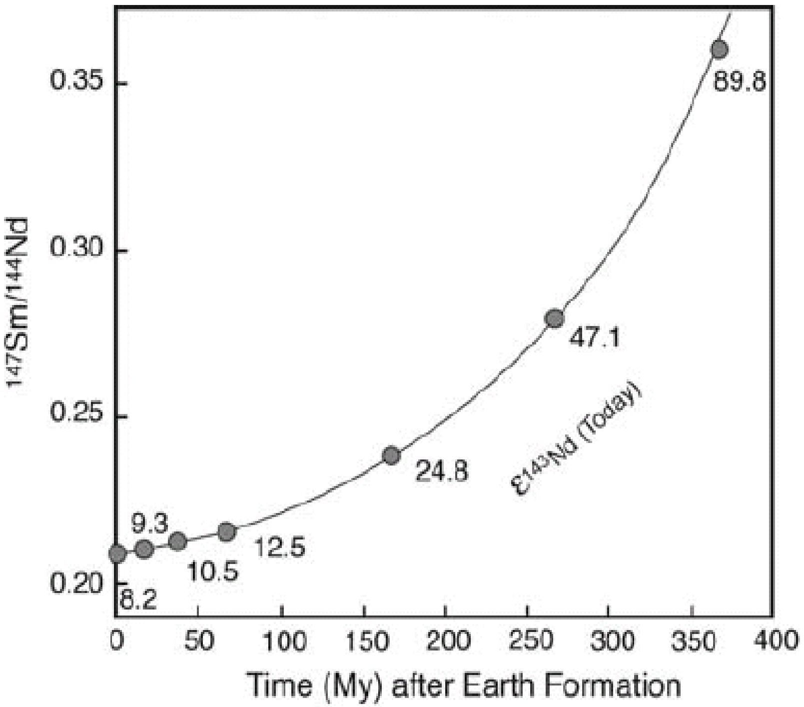
Ranen & Jacobsen (2006): Measured anomalies in the abundance of 137Ba and 138Ba in a variety of chondrites, and concluded that the difference in 142Nd/144Nd between chondrites and terrestrial rocks reflects nucleosynthetic heterogeneity in the solar nebula. They argued that imperfect mixing of the nucleosynthetic contributions from various stars thus could result in variations in 142Nd/144Nd that are not related to 146Sm decay.

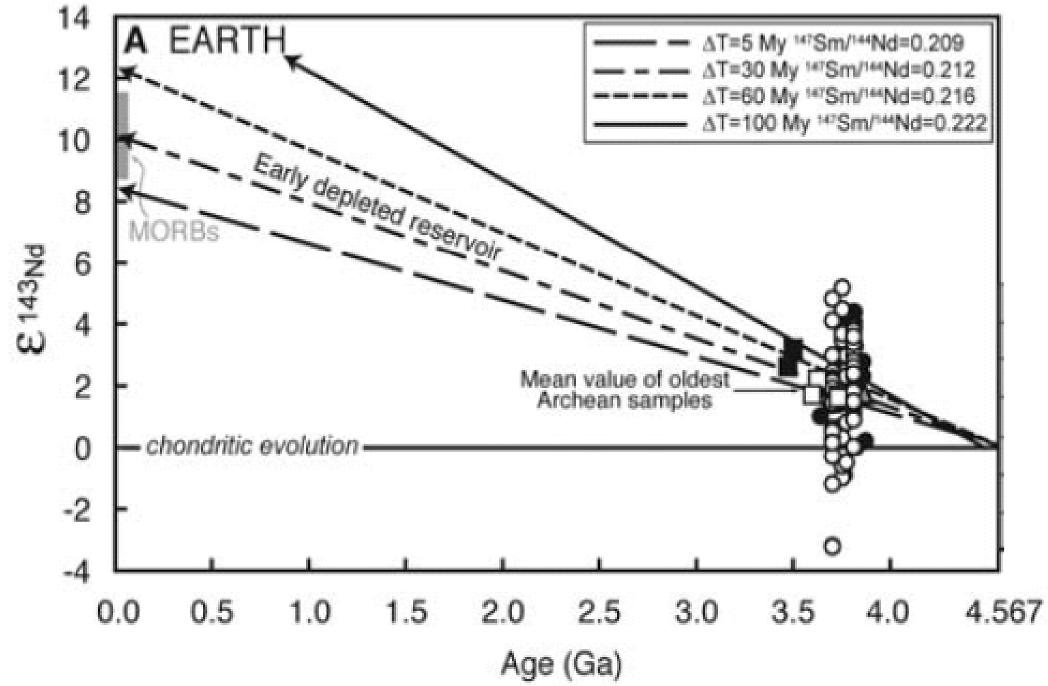
1. These anomalies not confirmed in either previous (Hidaka et al. 2003) or more recent studies (Andreasen & Sharma 2007; Carlson et al. 2007; Wombacher & Becker 2007).
2. Although excesses in 135Ba and 137Ba, which are related to variations in the ratio of r- to s-process components, have been observed in carbonaceous chondrites, they have not been observed in ordinary chondrites or eucrites (Hidaka et al. 2003; Andreasen & Sharma 2007; Carlson et al. 2007).
3. When Ba isotopic anomalies are measured in carbonaceous chondrites, they show little or no correlation with the magnitude of 142Nd deficit measured in the same sample (Carlson et al. 2007). Ba isotopic anomalies in carbonaceous chondrites appear to have little or no significance for the interpretation of the 142Nd/144Nd difference between chondrites and terrestrial rocks.

Of greater concern is the discovery that carbonaceous chondrites contain approximately 100 ppm deficits in 144Sm (Andreasen & Sharma 2006; Carlson et al. 2007), which, like 146Sm, is produced by the p-process. This result indicates nucleosynthetic variability in C-chondrites.

1. It is possible to correct for this p-process deficit in C-chondrites. A 100 ppm deficit in 144Sm/152Sm would translate into an 11 ppm deficit in 142Nd/144Nd due to the reduced abundance of 146Sm (Andreasen & Sharma, 2006). Therefore, the correction brings the average C-chondrite 142Nd/144Nd value to ~21 ppm below terrestrial, a value that is similar to that obtained for other meteorite groups.
2. P-process heterogeneity does not appear to be significant for O- and E-chondrites, basaltic eucrites or lunar samples, as all these materials have the same 144Sm/152Sm as measured for terrestrial rocks

Conclusion: The observed difference between chondritic and terrestrial 142Nd/144Nd does not reflect nucleogenic heterogeneity in the solar nebula, but instead is best explained by the decay of 146Sm.


0.35
0.30
0.25
0.20
^{147}Sm/^{144}Nd
0
50
100
150
200
250
300
350
400
Time (My) after Earth Formation
89.8
47.1
24.8
12.5
10.5
9.3
8.2
ε^{143}Nd (Today)


A EARTH
ΔT=5 My ^{147}Sm/^{144}Nd=0.209
ΔT=30 My ^{147}Sm/^{144}Nd=0.212
ΔT=60 My ^{147}Sm/^{144}Nd=0.216
ΔT=100 My ^{147}Sm/^{144}Nd=0.222
Early depleted reservoir
MORBs
Mean value of oldest
Archean samples
chondritic evolution
ε ^{143}Nd
14
12
10
8
6
4
2
0
-2
-4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.567
Age (Ga)