Ocean Islands and mantle plumes: Outstanding geochemical and petrological questions

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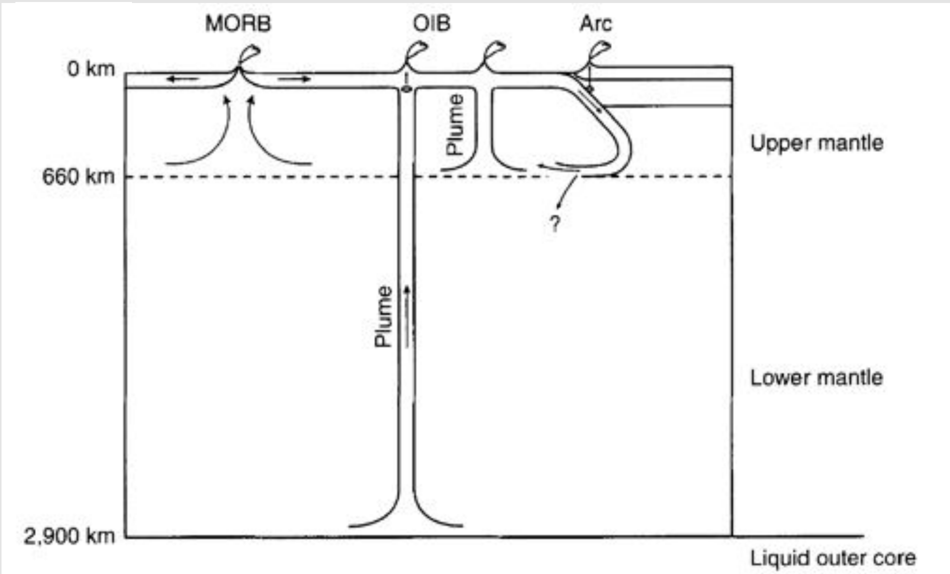
A virtually inaccessible interior

In God's kitchen

- 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

Ocean island lavas provide a "window" to the mantle's composition



Global Hotspot distribution

"Unmelt" lavas to infer mantle composition

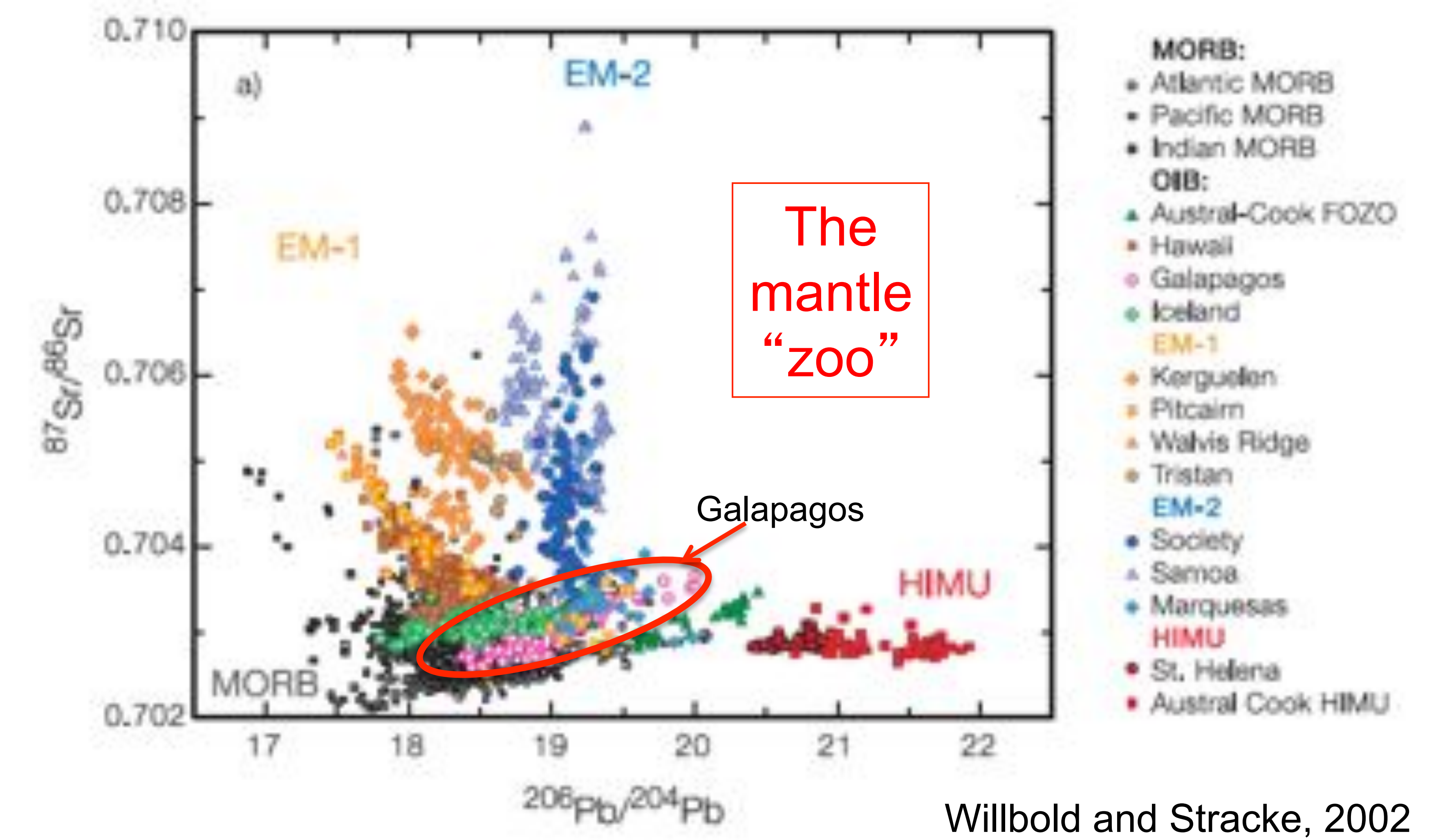
Lavas as probes of the mantle's composition:

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

$^{87}Sr/^{86}Sr$ solid mantle **=** **$^{87}Sr/^{86}Sr$ melt**

(Peridotite) **(Basalt)**

Hotspot lavas reveal a heterogeneous mantle



Willbold and Stracke, 2002

Lavas erupted at hotspots are isotopically heterogeneous.

Therefore: ***The solid mantle sources of these lavas are heterogeneous.***

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:

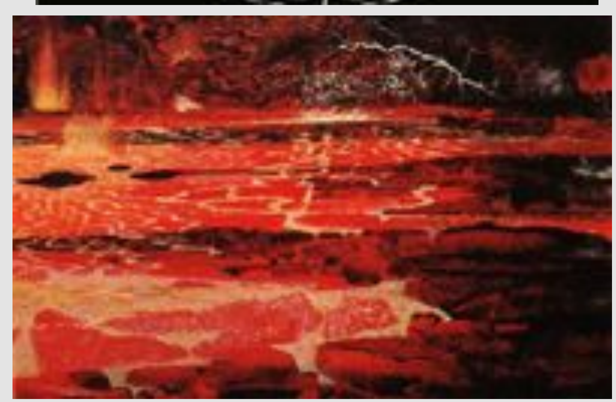
Part 1: How do ocean islands sample the heterogeneous mantle: plumes vs. cracks?

Part 2: How are mantle heterogeneities formed, and what are they made of?

Part 3: What was the starting point?

Part 4: How are the heterogeneities distributed, at what length-scales?

Brandenburg et al. (EPSL 2008)

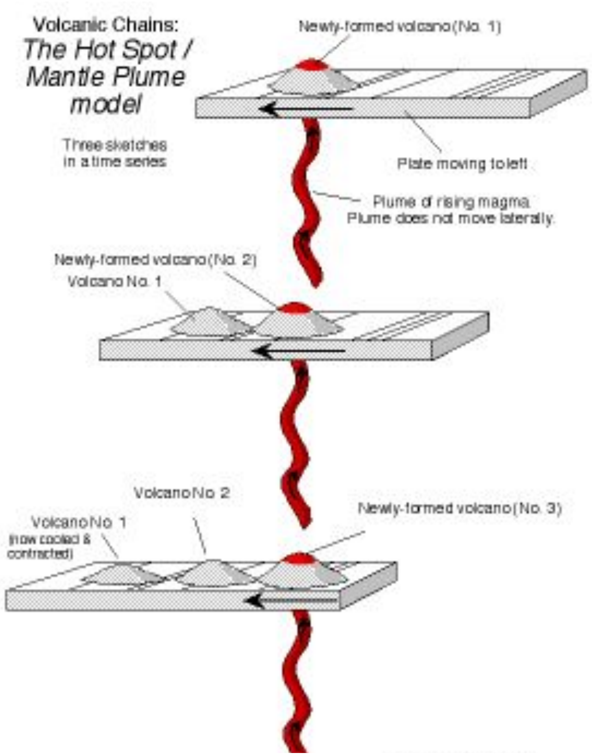


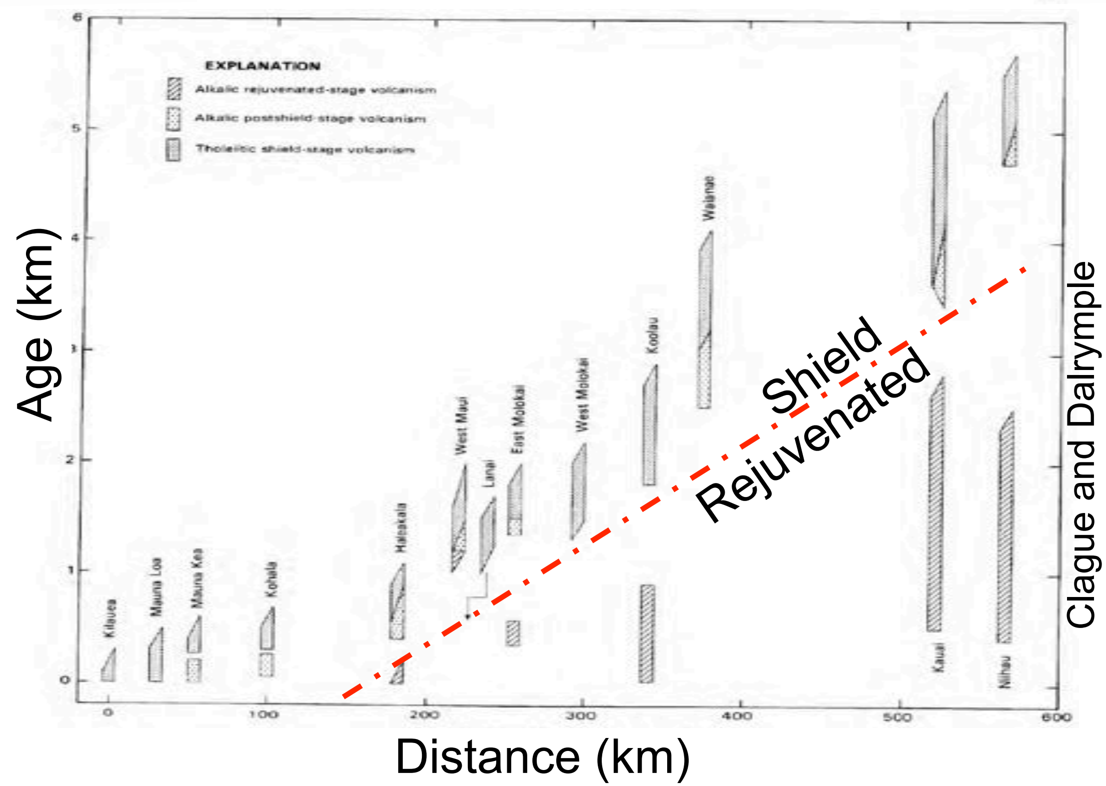
Part 1: How do ocean islands sample the mantle: Plumes vs. Cracks?

40th anniversary of an important hypothesis: Hotspots are formed by upwelling mantle plumes (Morgan, 1971).

I now propose that these hotspots are manifestations of convection in the lower mantle which provides the motive force for continental drift. In my model there are about twenty

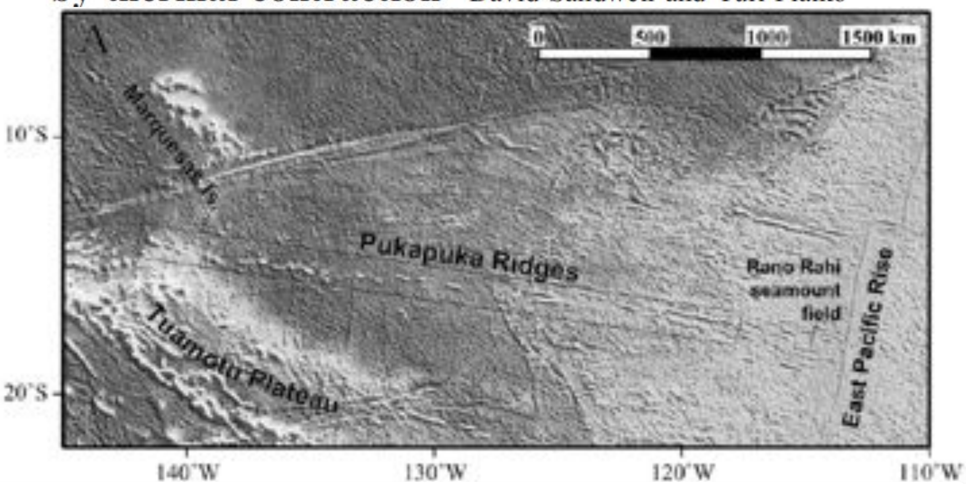
deep mantle plumes bringing heat and relatively primordial material up to the asthenosphere and horizontal currents in the asthenosphere flow radially away from each of these plumes

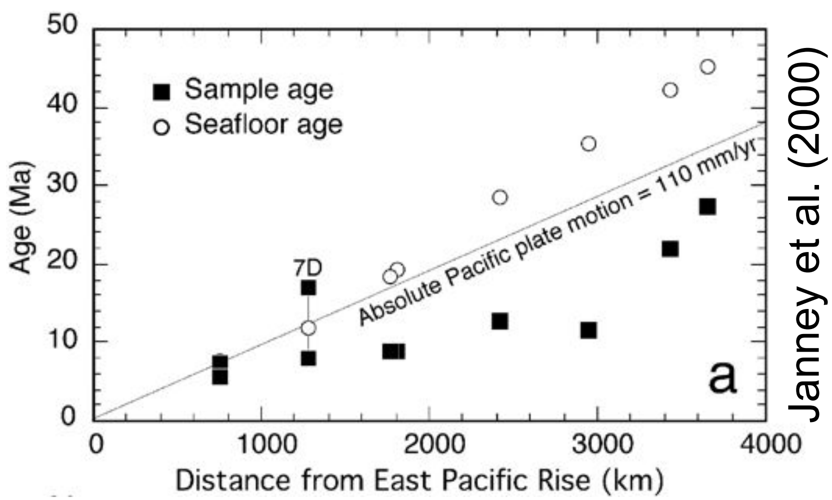




Revision: Not all hotspots are formed by plumes.

Warping and cracking of the Pacific plate by thermal contraction David Sandwell and Yuri Fialko



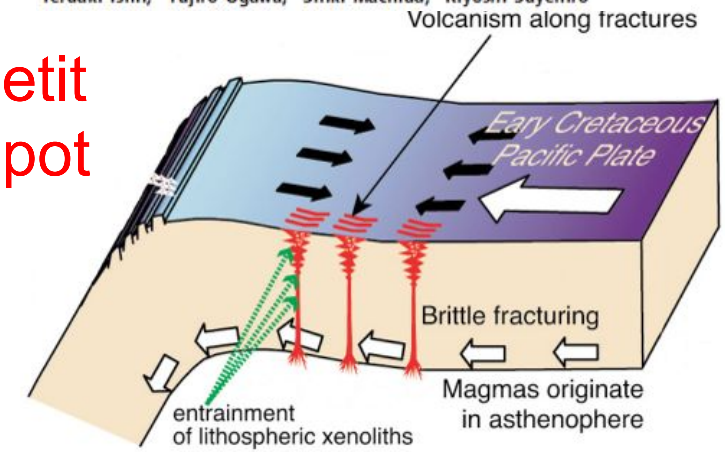


Janney et al. (2000)

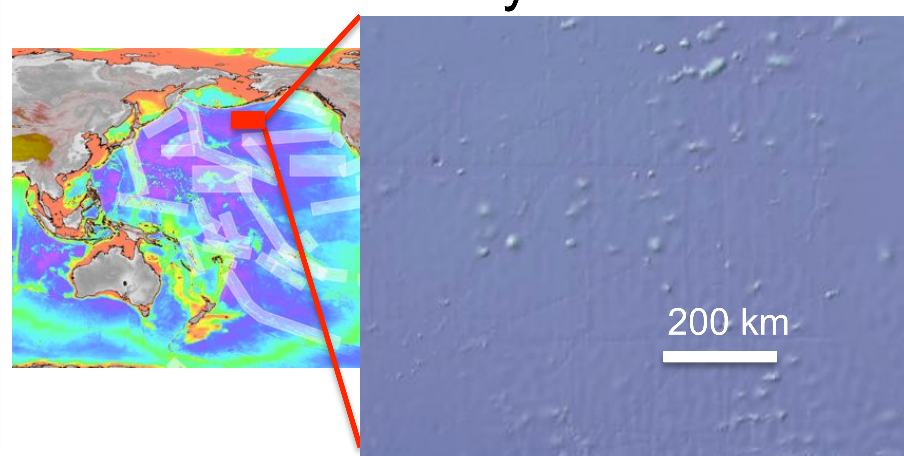
Volcanism in Response to Plate Flexure

Naoto Hirano,[1,2*] Eiichi Takahashi,[1,3] Junji Yamamoto,[1,4] Natsue Abe,[3] Stephanie P. Ingle,[1,5] Ichiro Kaneoka,[6] Takafumi Hirata,[1] Jun-Ichi Kimura,[7] Teruaki Ishii,[8] Yujiro Ogawa,[9] Shiki Machida,[8] Kiyoshi Suyehiro[3]

Petit Spot

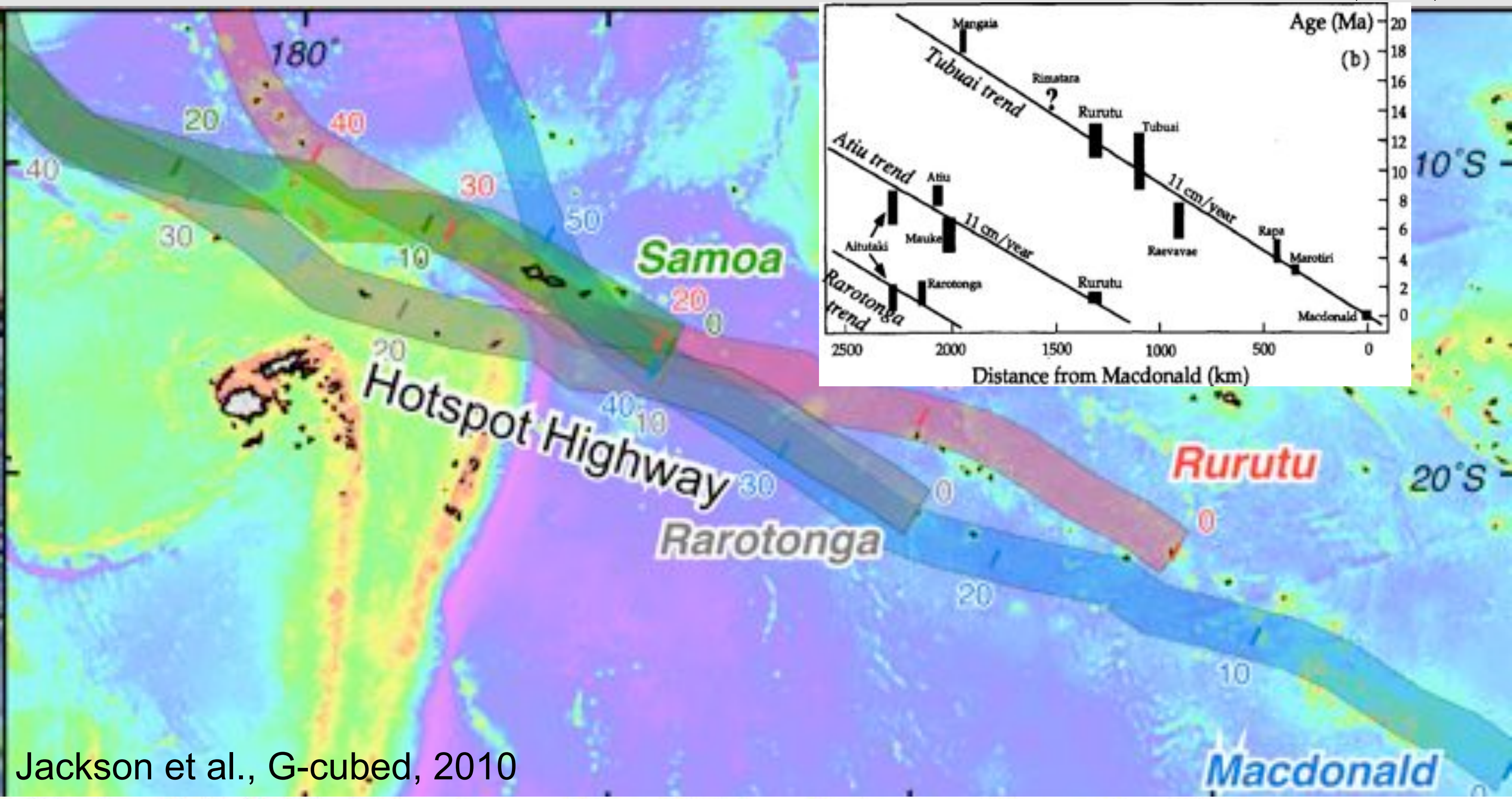


$>10^4$ solitary seamounts

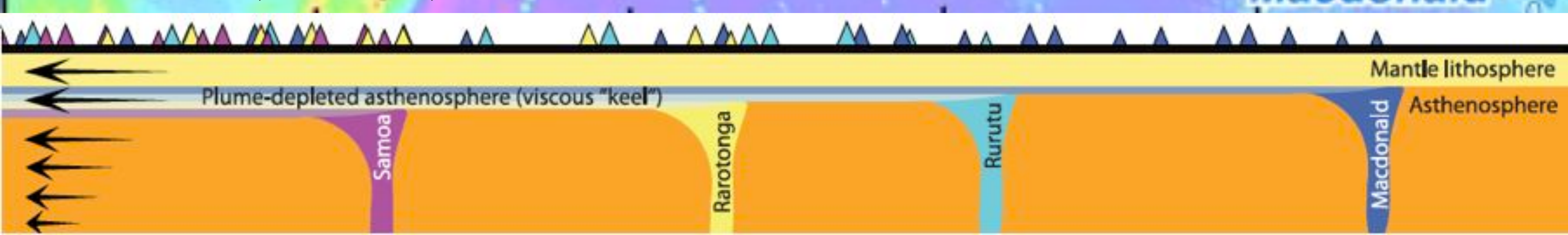


Hotspot "highway"

Chauvel et al., EPSL, 1997



Jackson et al., G-cubed, 2010

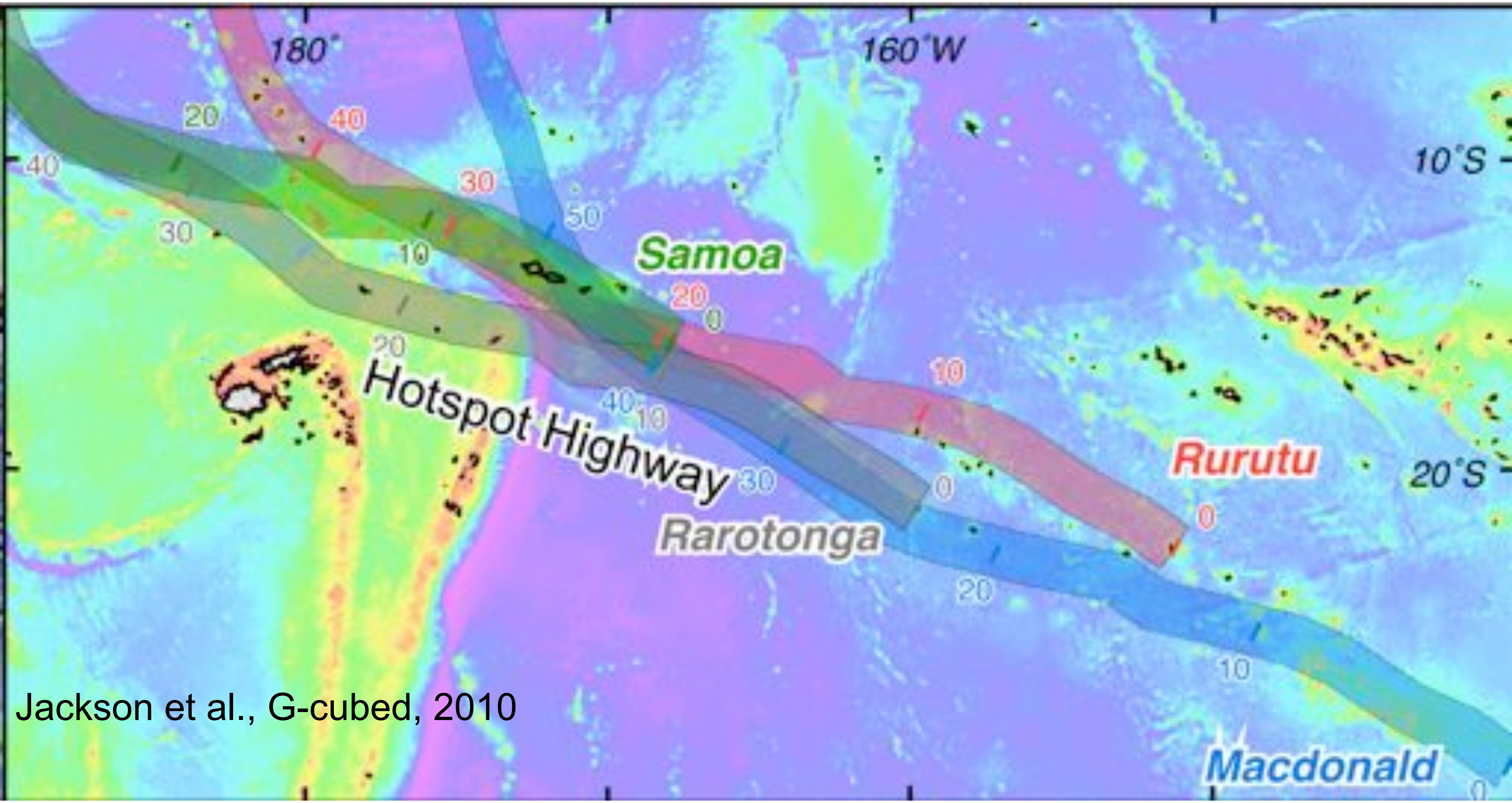


Iguana “highway”

The tortoise “highway”

The Cerro Negro **mud** “highway”

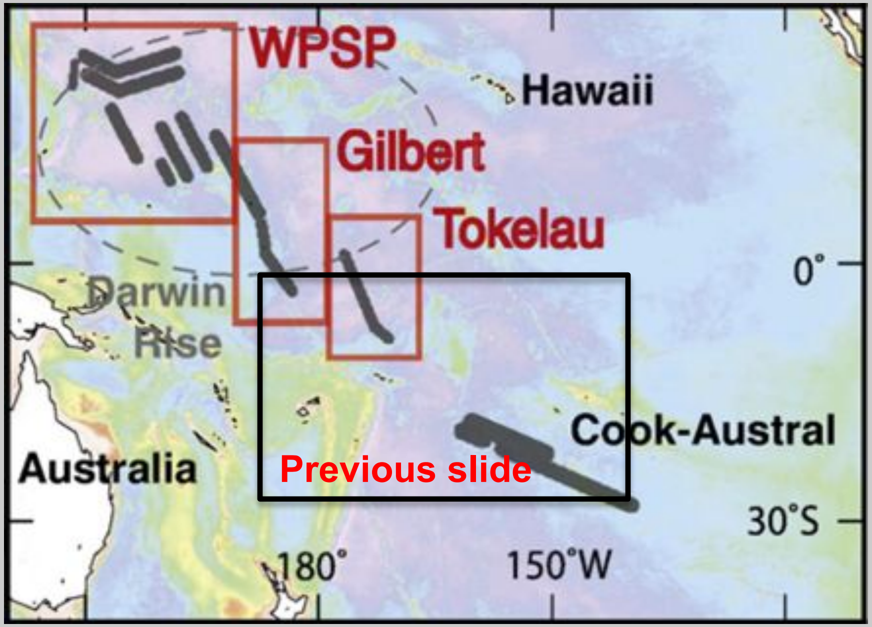
Hotspot “highway”

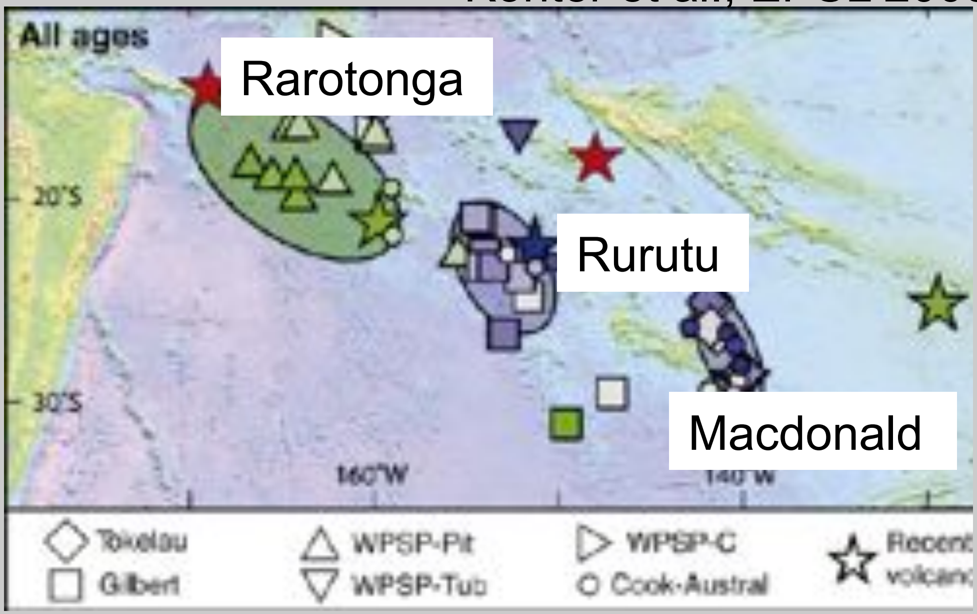


Jackson et al., G-cubed, 2010

Long-lived, overlapping hotspot tracks that preserve distinct isotopic pedigrees

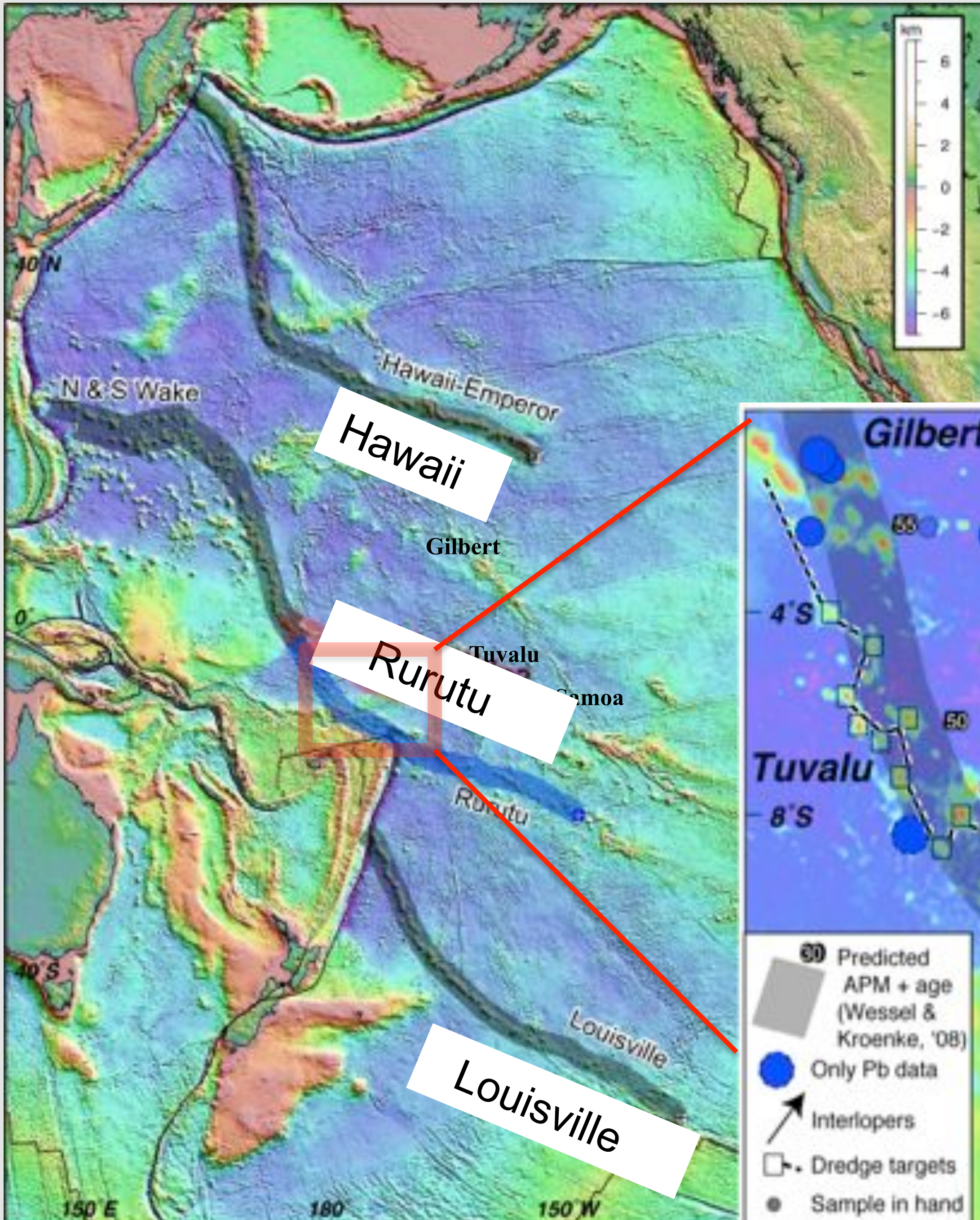
Konter et al., EPSL 2008

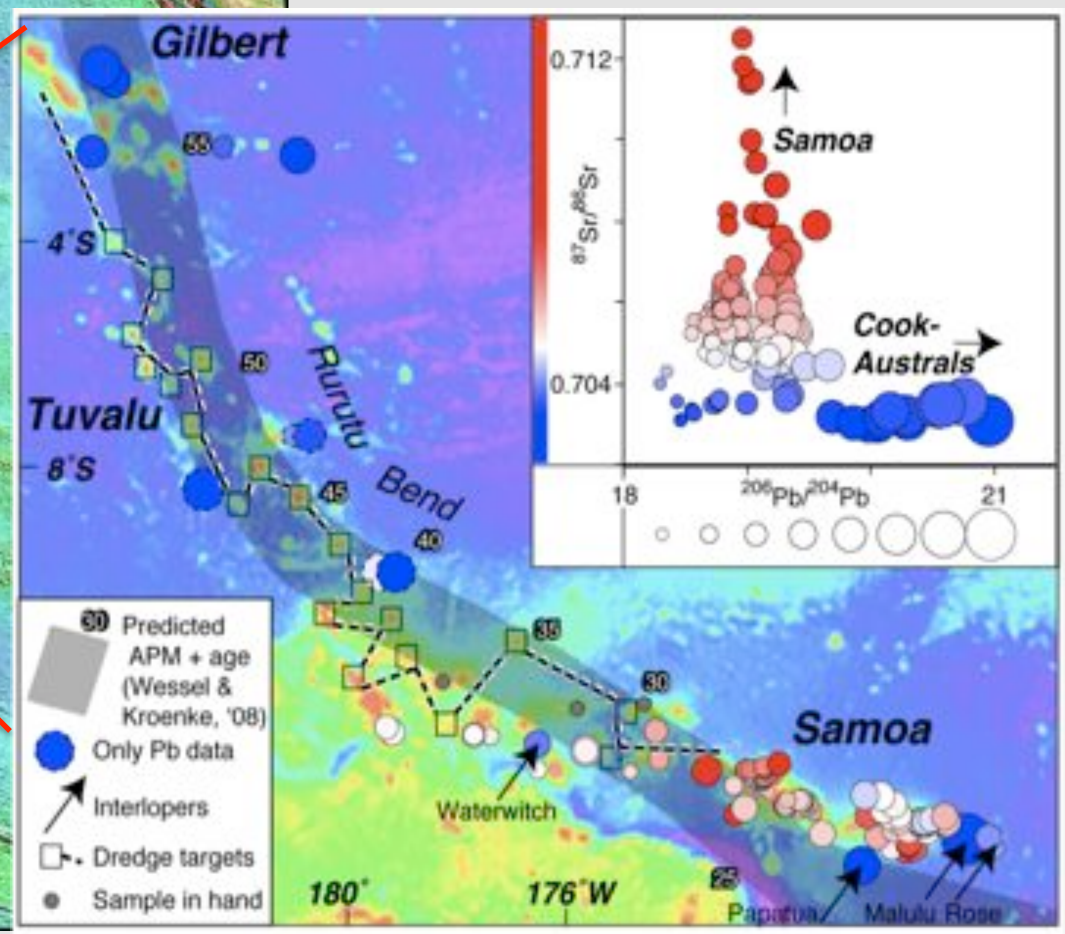


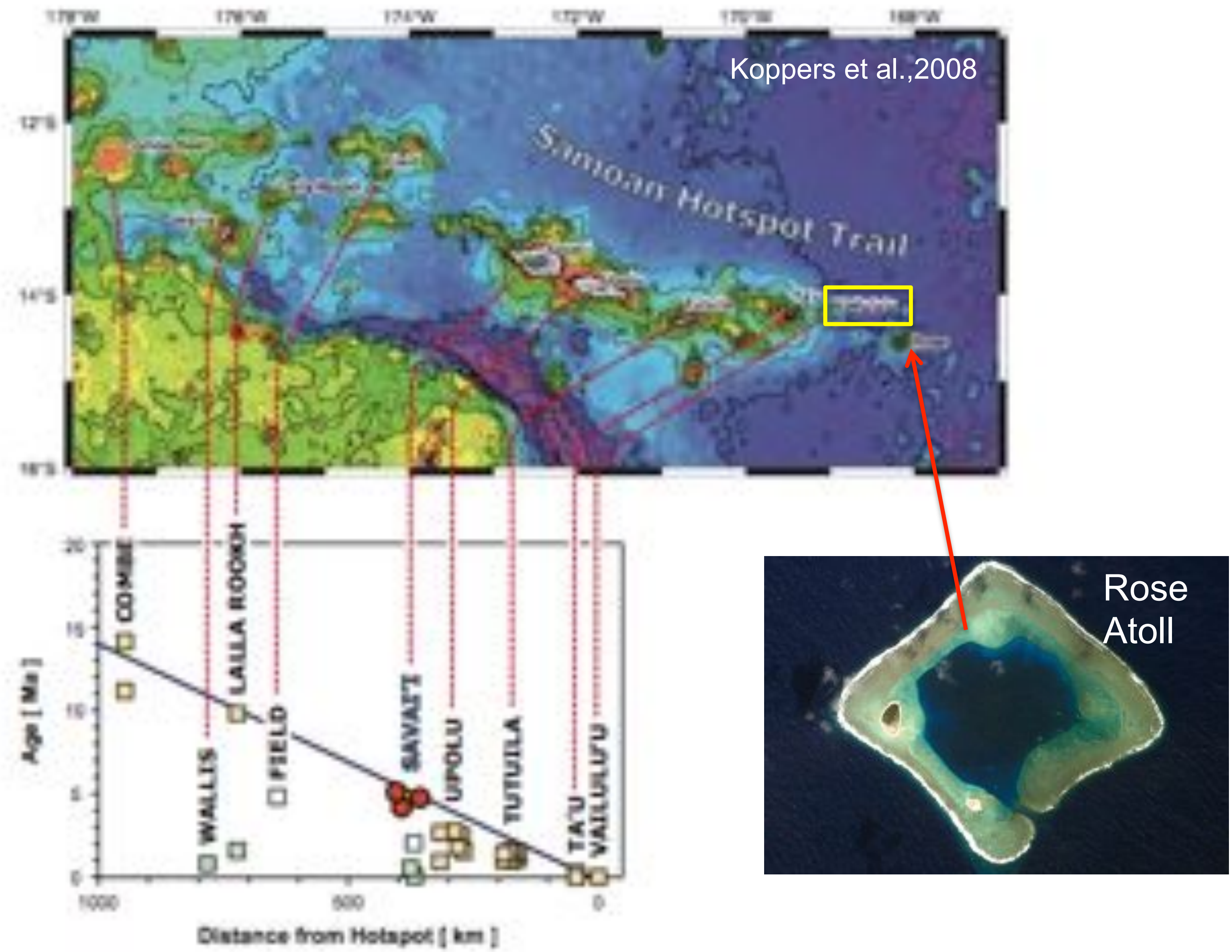


- 60-100 million-year-old seamounts in the west Pacific “backtrack” (using Wessel and Kroenke, 2008) to the current locations of 3 different active hotspots.
- The “backtracked” seamounts have the same geochemistry as the hotspot of origin.
- Age-progressive, geochemicaly distinct, long-lived.

Rurutu hotspot: The longest lived hotspot?

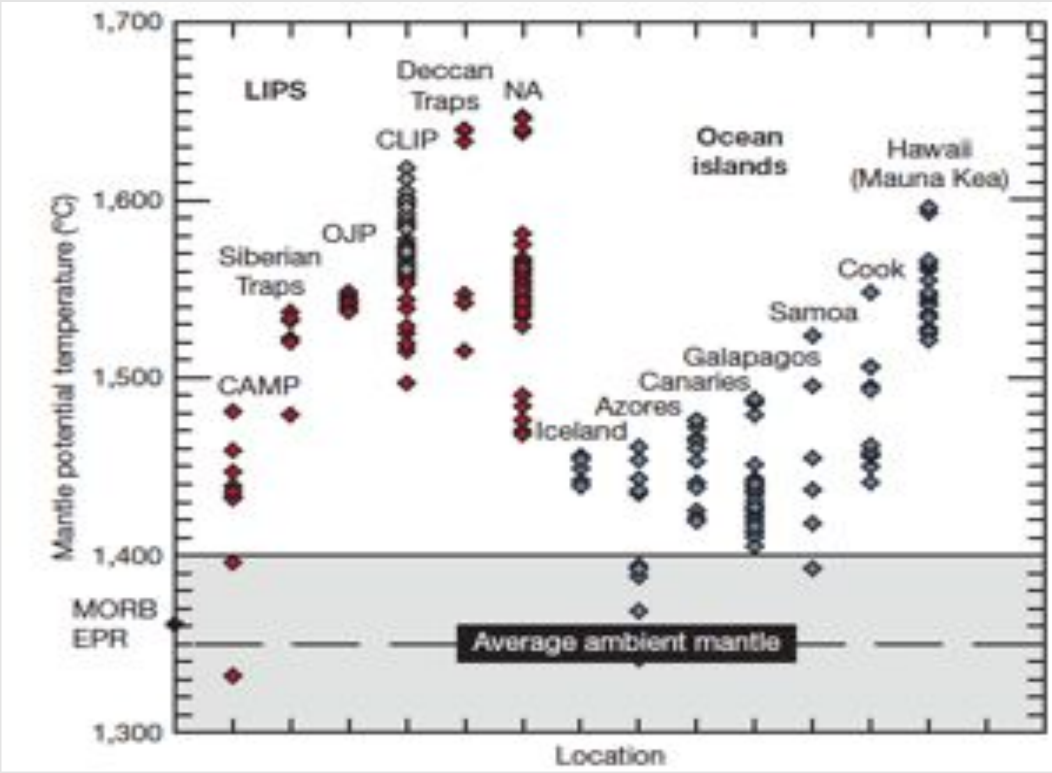





Koppers et al.,2008
Samoan Hotspot Trail
COMBE
WALLIS
LALLA ROOKH
FIELD
SAVAI'I
UPOLU
TUTUILA
TA'U
VAILULU'U
Age [Ma]
20
15
10
5
0
1000
500
0
Distance from Hotspot [km]
Rose
Atoll

Prediction of mantle plume hypothesis: Plumes must be hotter than the adjacent mantle

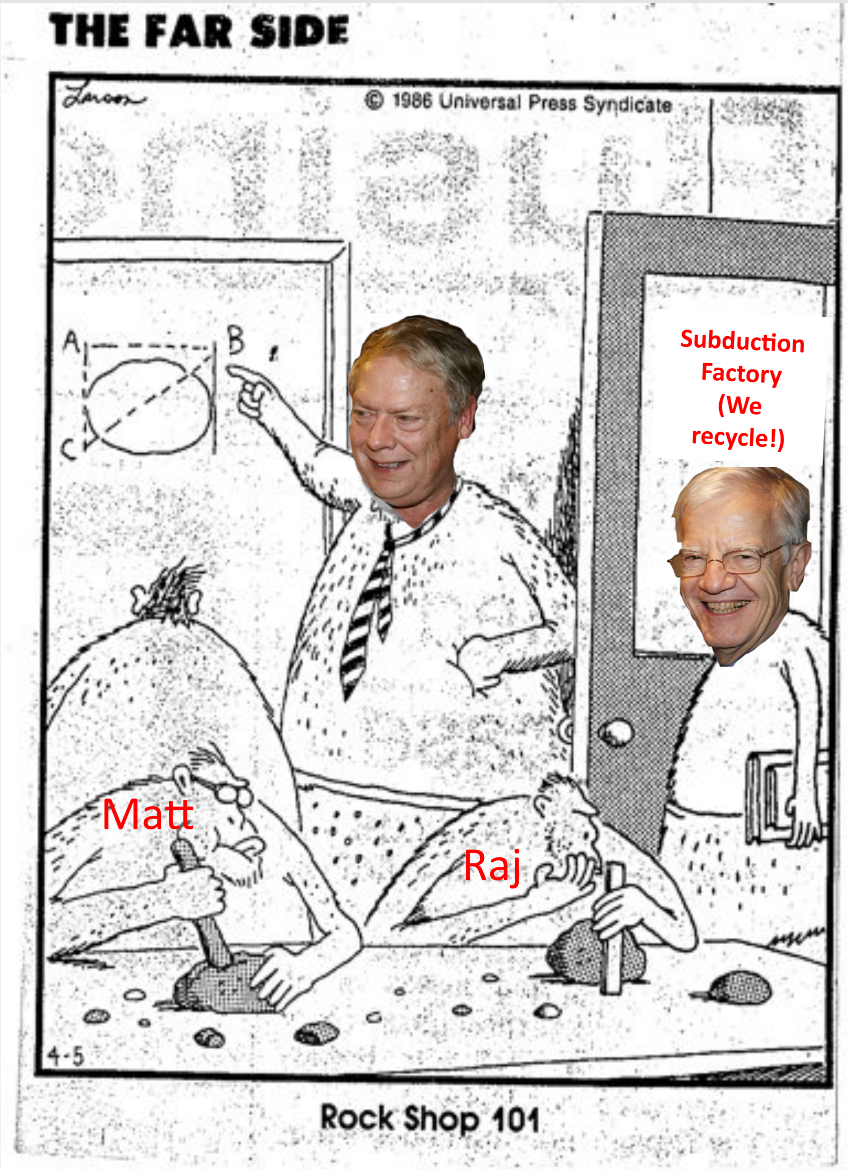
Use melt compositions to infer mantle melting temperatures.



Herzberg & Gazel, Nature, 2009

Controversial. Use olivine-melt compositions and extrapolate to mantle melting temperatures. Falloon et al. (2007) observed no difference between average ambient mantle (i.e., MORB) and plumes. Putirka et al. (2007) got a 200 degrees C difference.

Part 2: How did the mantle become heterogeneous?



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 *

Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington, DC 20015 (U.S.A.)

Nature Vol. 296 29 April 1982

Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution

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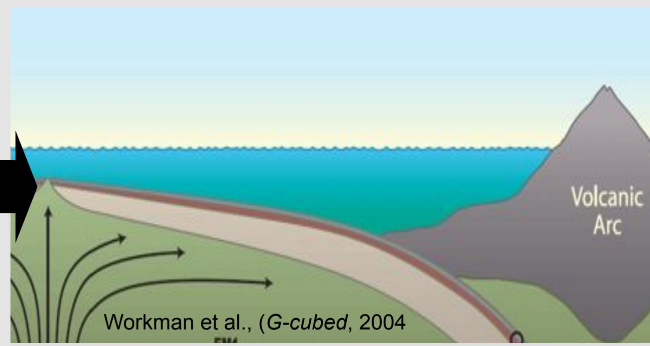
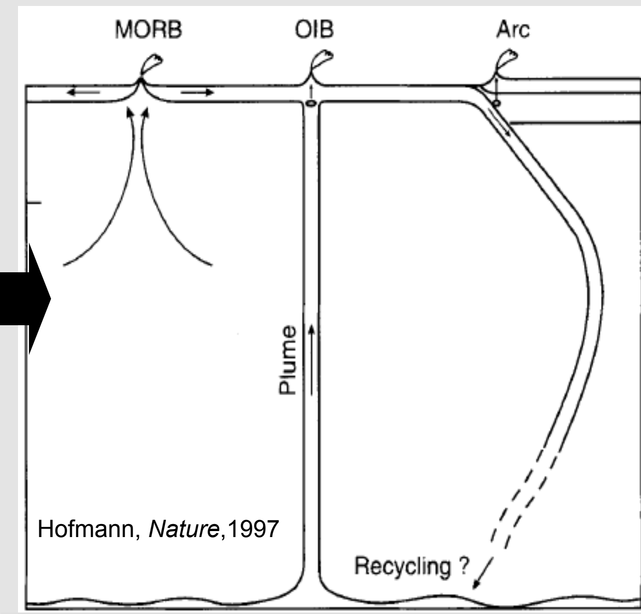
Recycling hypothesis

Oceanic plates and sediment are injected into the mantle at subduction zones, returned to the surface in mantle upwellings (plumes?), and melted beneath hotspots.

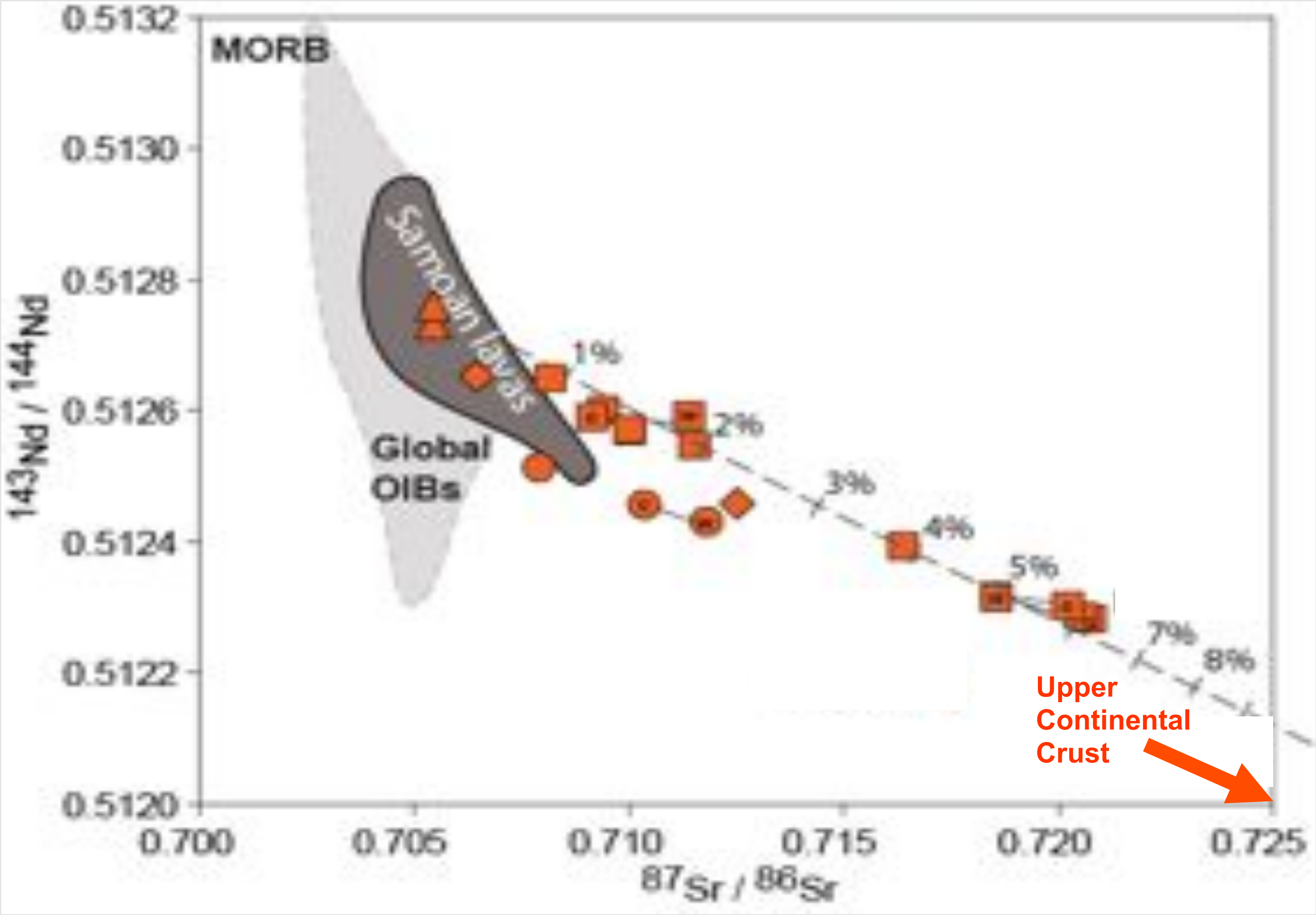
Rivers contribute > 85% of ocean floor sediment





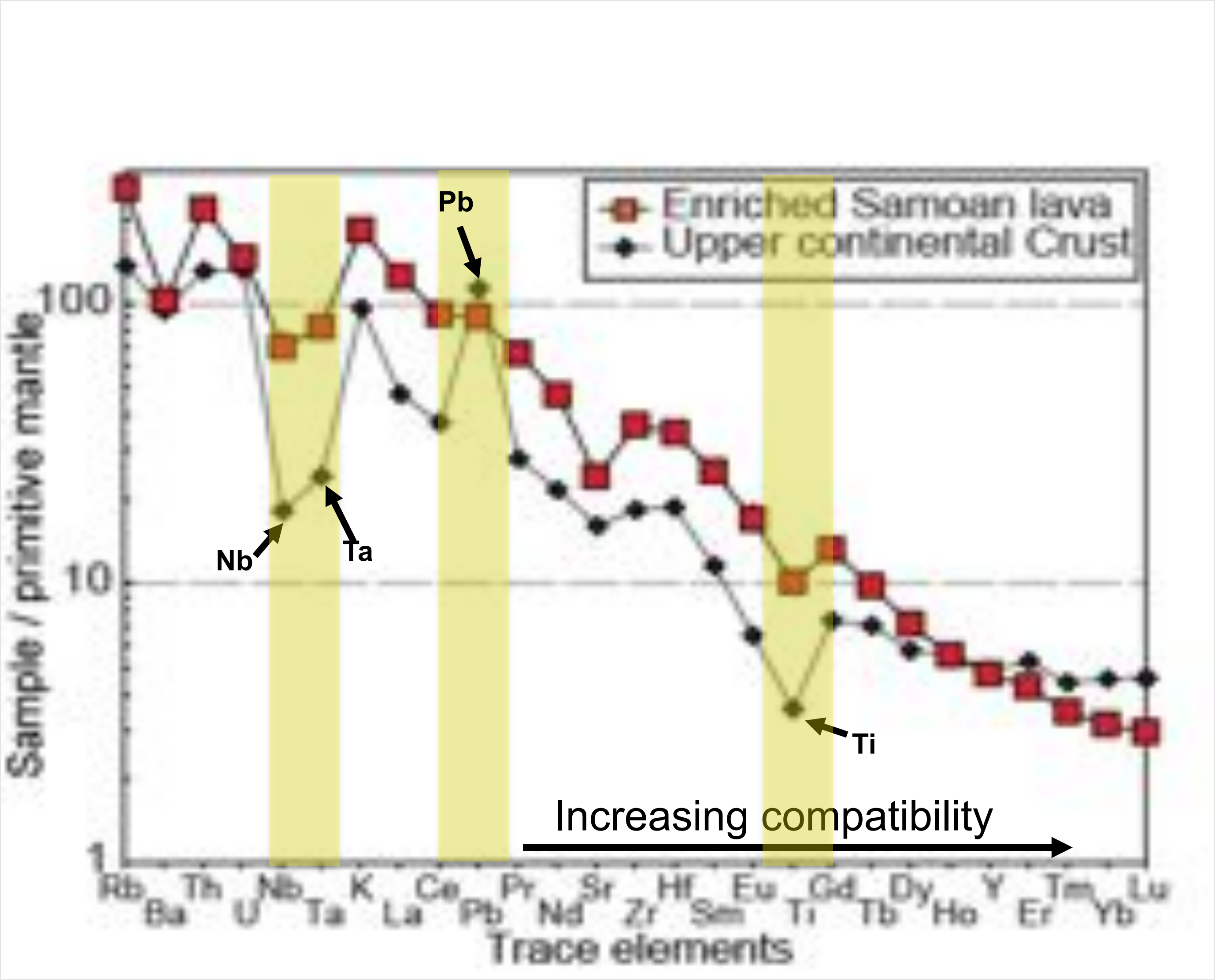
"The geochemical signature of OIB originated in the upper mantle and crust through melting."
-Bill White, 2008

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

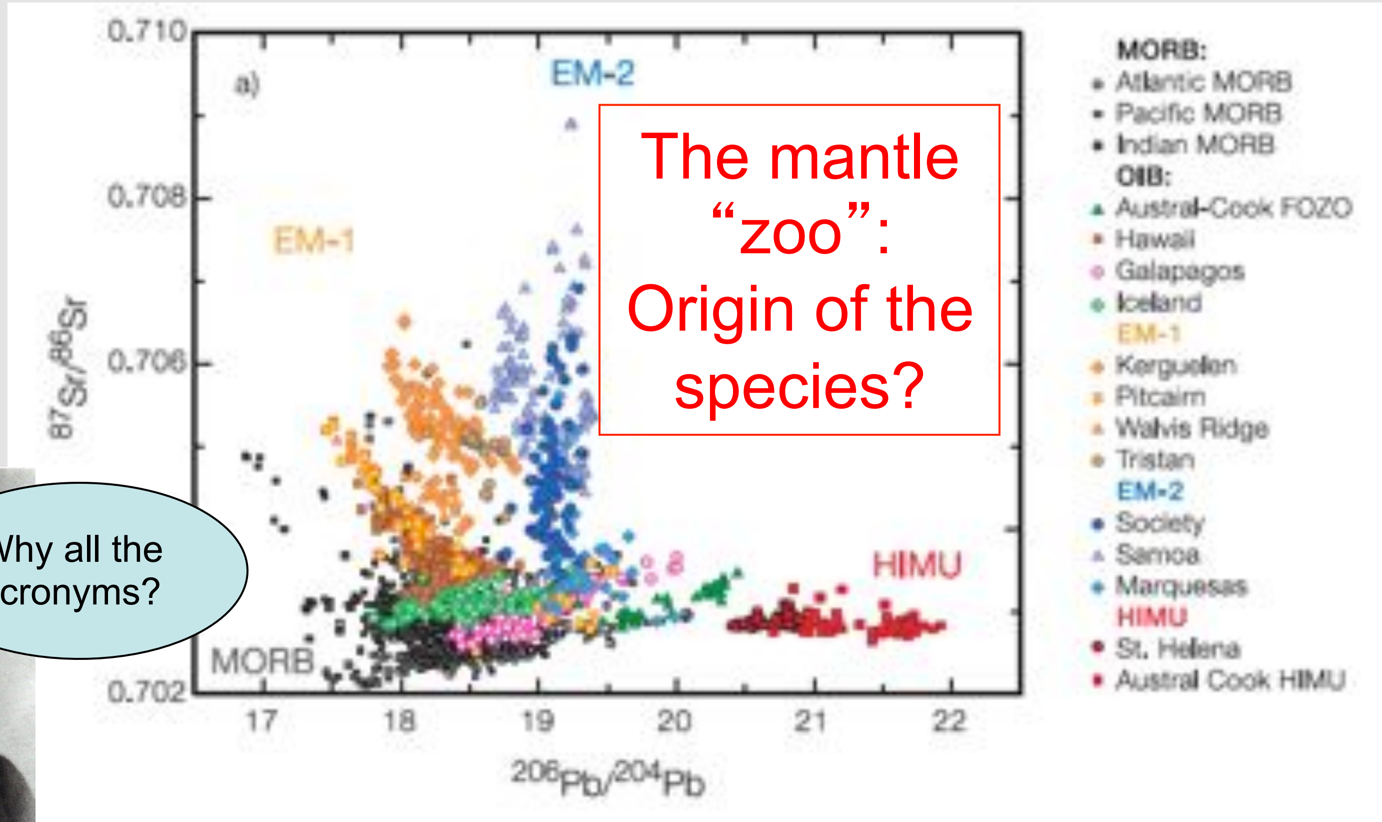


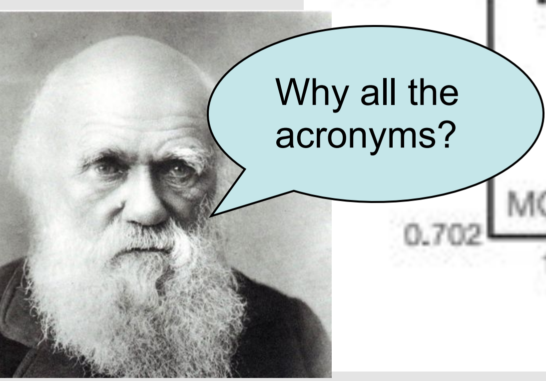
Jackson et al. (*Nature*, 2007)

Continental crust has unique trace element "fingerprints"



But what about the other components?

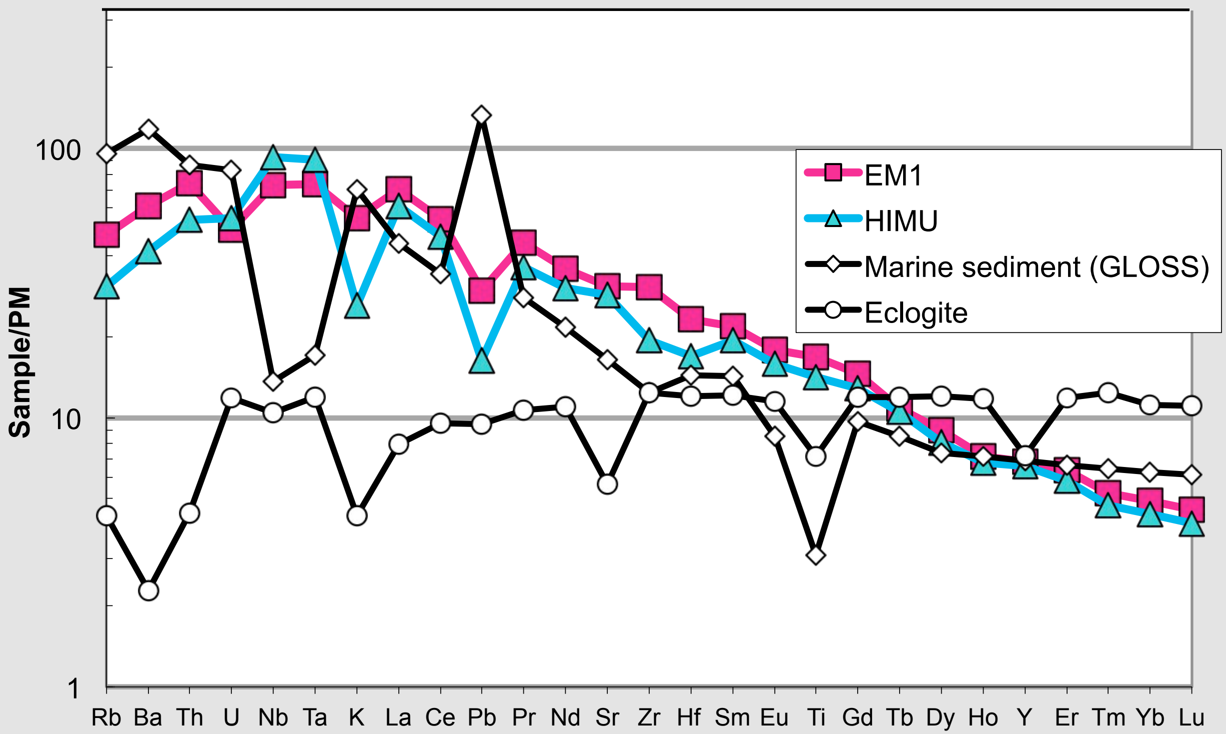




Willbold and Stracke, G-cubed, 2002

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

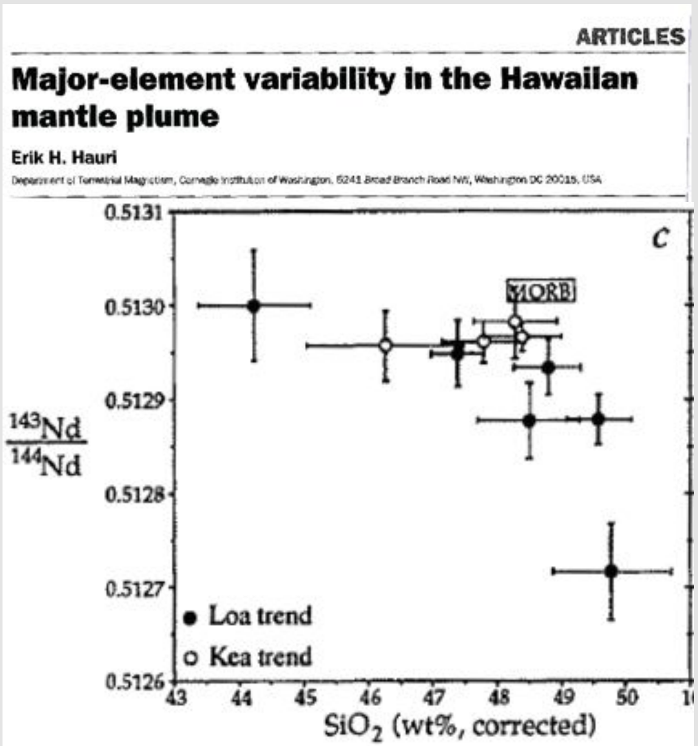
Paradox: How can radically different subducted lithologies generate such similar trace element patterns in OIBs?

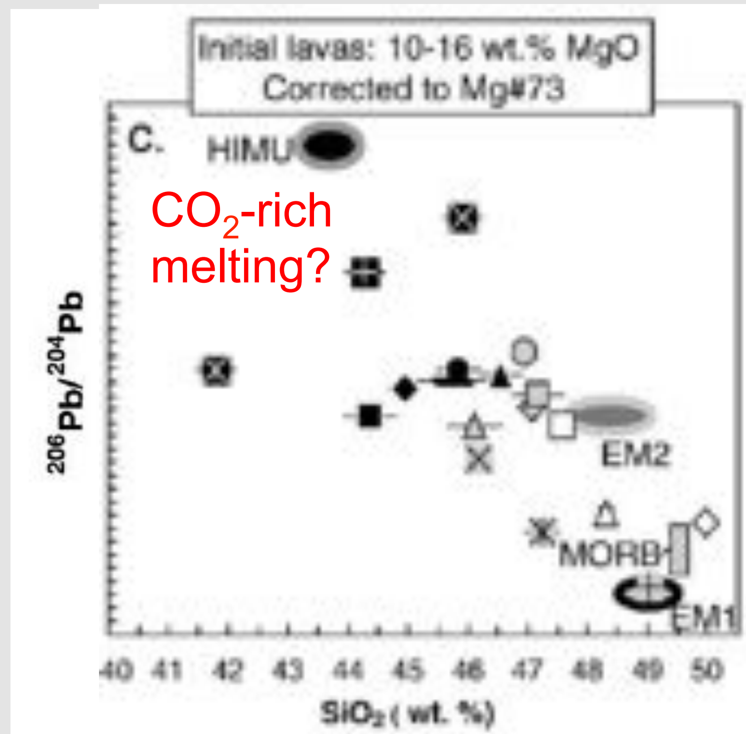


1. Exotic modern sediment?
2. Exotic metasomatic components?
3. Ancient sediments? Archaean, Neo-proterozoic? Poor constraints.

The "holy grail"

Major element (lithological?) heterogeneity accumulates in the mantle





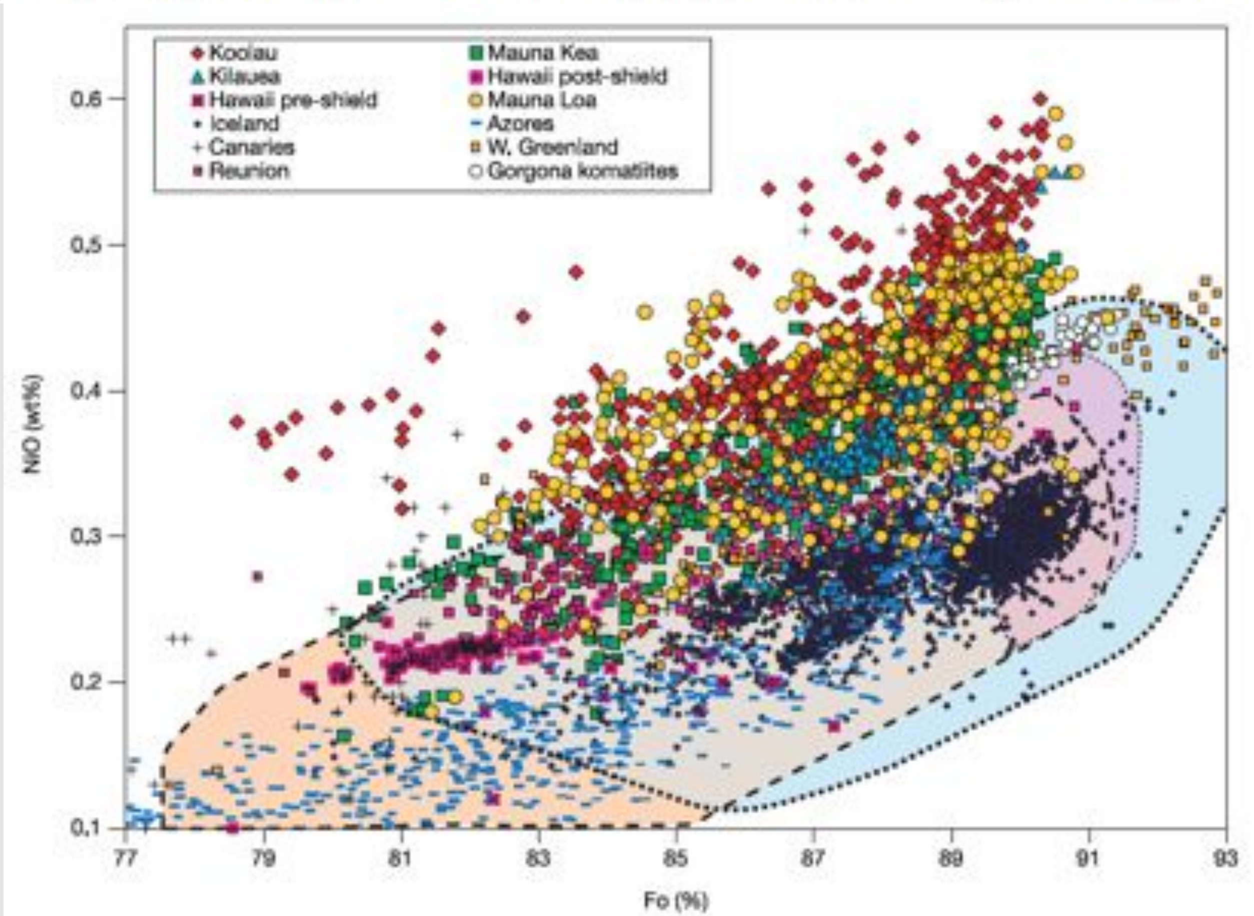
Jackson and Dasgupta, EPSL, 2008

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

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]



Part 3: Where is “home”?

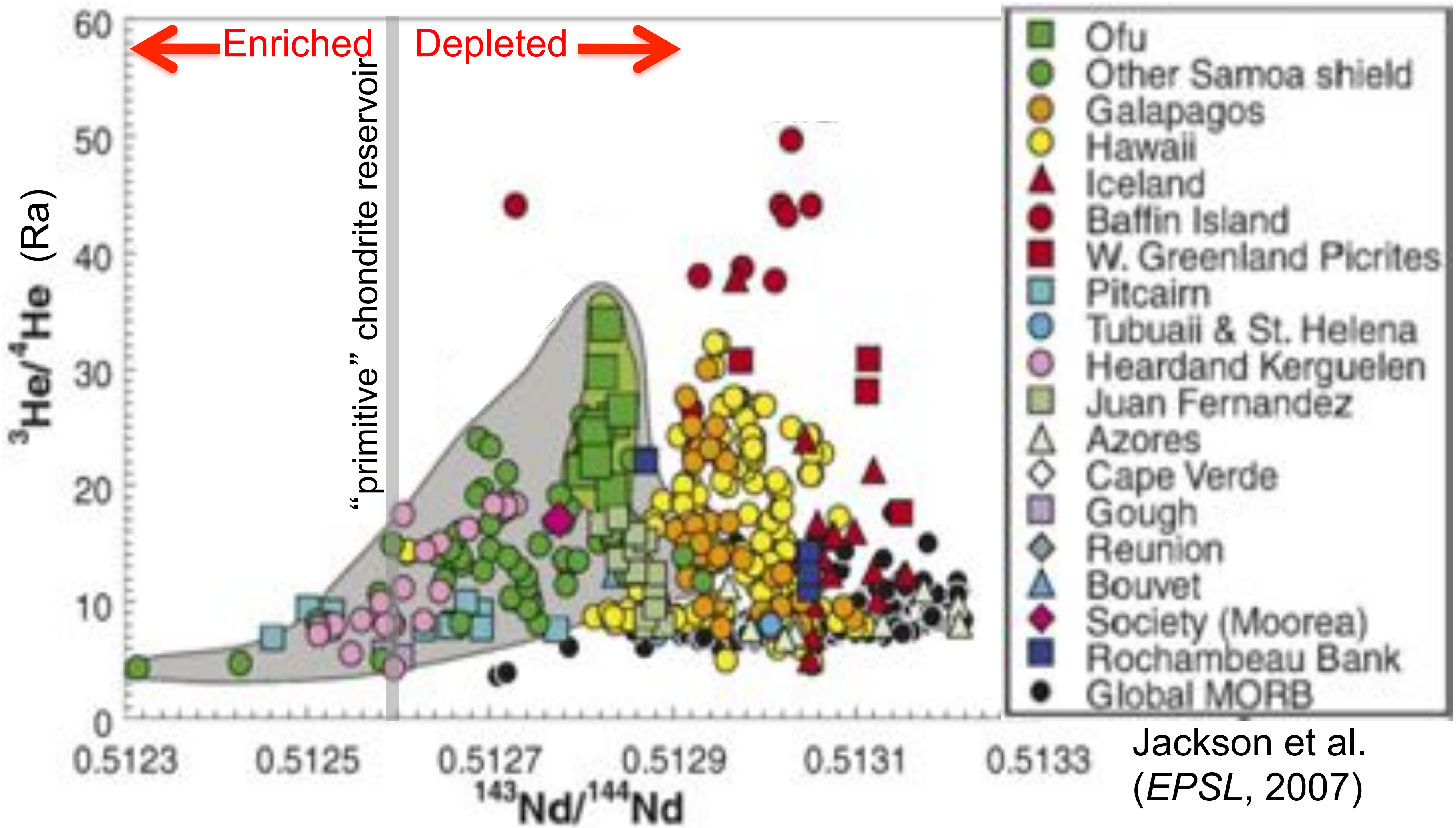
- Following accretion, a deep terrestrial magma ocean…
- Siderophile elements (Fe-Ni) to the core, leaving behind the early (primitive) silicate mantle.
- From the primitive silicate earth, the crust (continental and oceanic) was extracted from the early **primitive mantle**.
- Crust subducted back into the mantle & mixed/stirred.
- **Did portions of the earliest primitive mantle survive to the present day?**

"Prospecting" for primitive mantle: If any of the early-Earth survived, what would it look like today?

1. Noble gas isotopes and abundances (high $^{3}He/^{4}He$)
2. A primitive, mantle reservoir should have predictable abundances (chondritic?) of the refractory, lithophile elements (e.g., Sm and 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? No!**

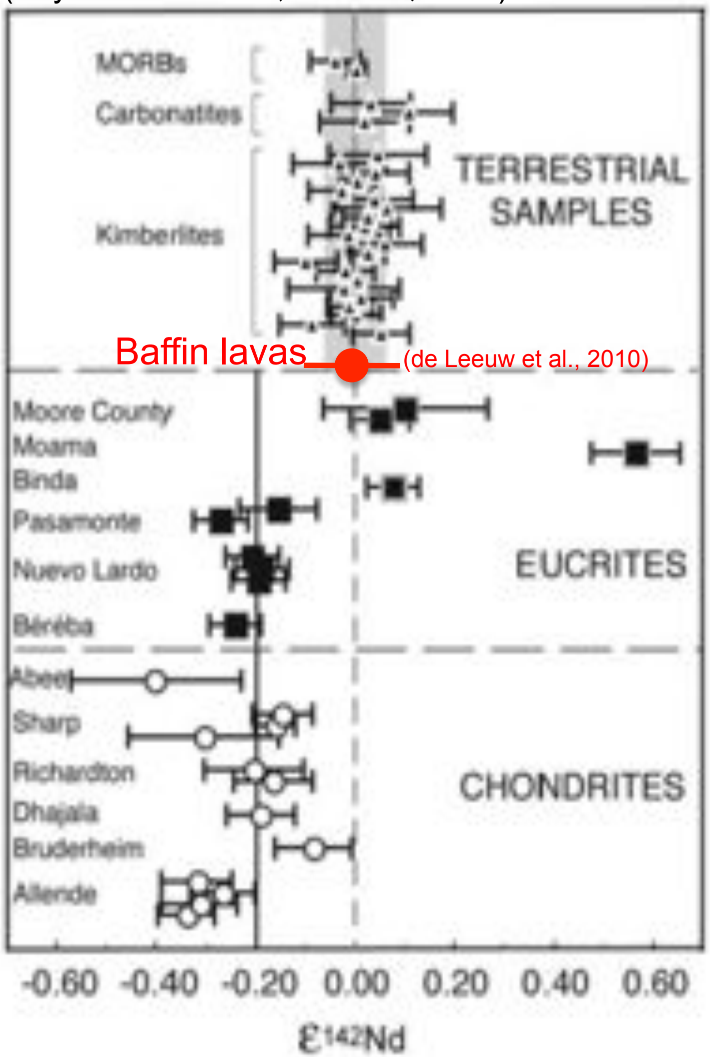
Lavas with primordial $^3He/^4He$ don't have primitive chondritic $^{143}Nd/^{144}Nd$



Jackson et al. (*EPSL*, 2007)

Implications for Neodymium-142

(Boyet and Carlson, Science, 2005)



- **Background:** Nd-isotopes, two "clocks":
  ^{147}Sm decays to ^{143}Nd ($t_{1/2}$=106 Ga)
  ^{146}Sm decays to ^{142}Nd ($t_{1/2}$=103 Ma)

- **Discovery:** Boyet and Carlson (2005) found that $^{142}Nd/^{144}Nd$ ratios in accessible modern terrestrial lavas are 18±5 ppm higher than O and C chondrites.

- **Implications:** All modern terrestrial samples evolved from a mantle reservoir with a Sm/Nd ratio 5% higher than chondrites, and super-chondritic $^{143}Nd/^{144}Nd$!

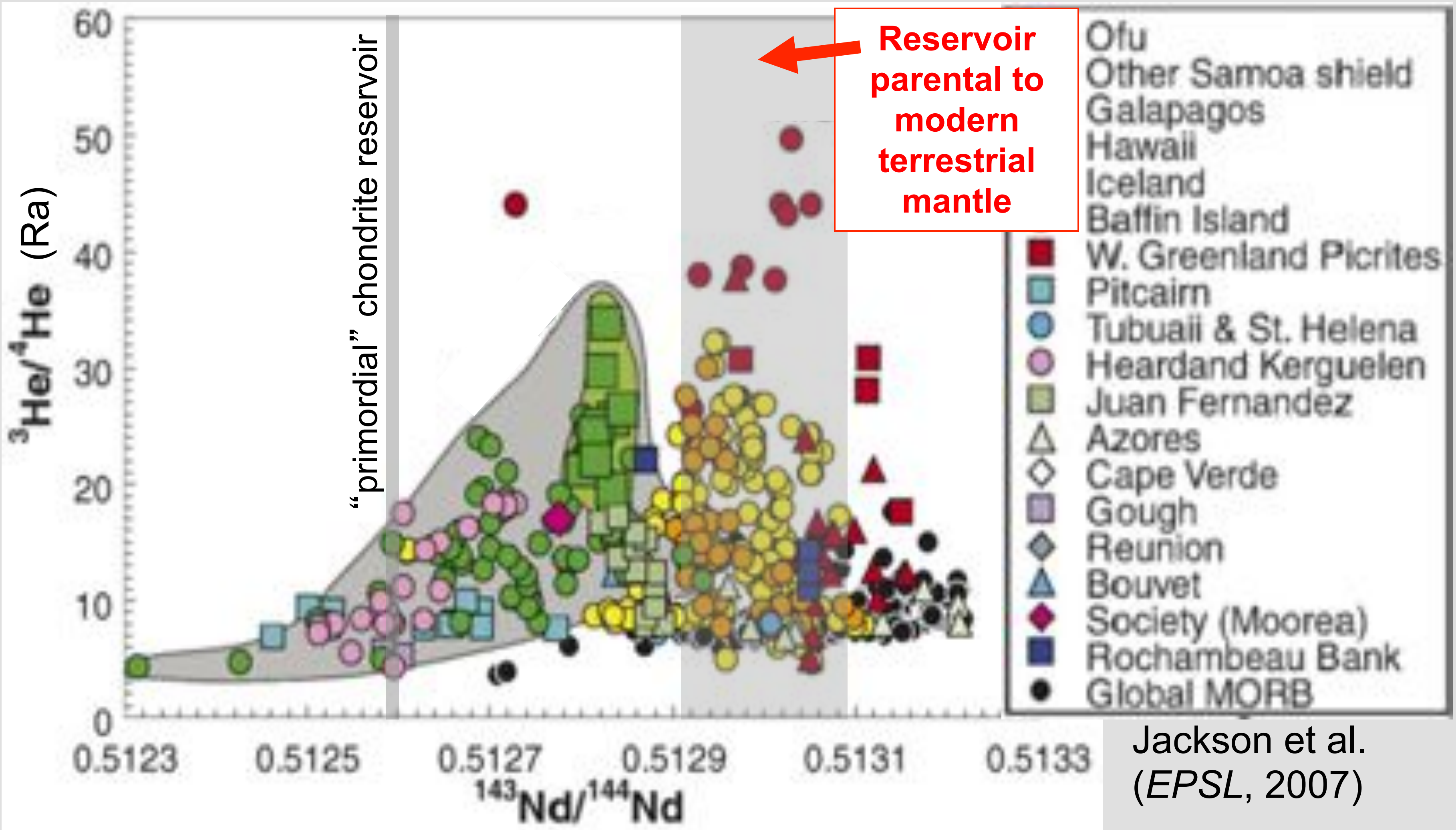
There are two models for this:

A. **Primitive mantle isn't chondritic**: $^{143}Nd/^{144}Nd$=0.5130

B. **Primitive mantle is chondritic** ($^{143}Nd/^{144}Nd$=0.51263) but differentiated into 2 complementary reservoirs that sum to chondrite:

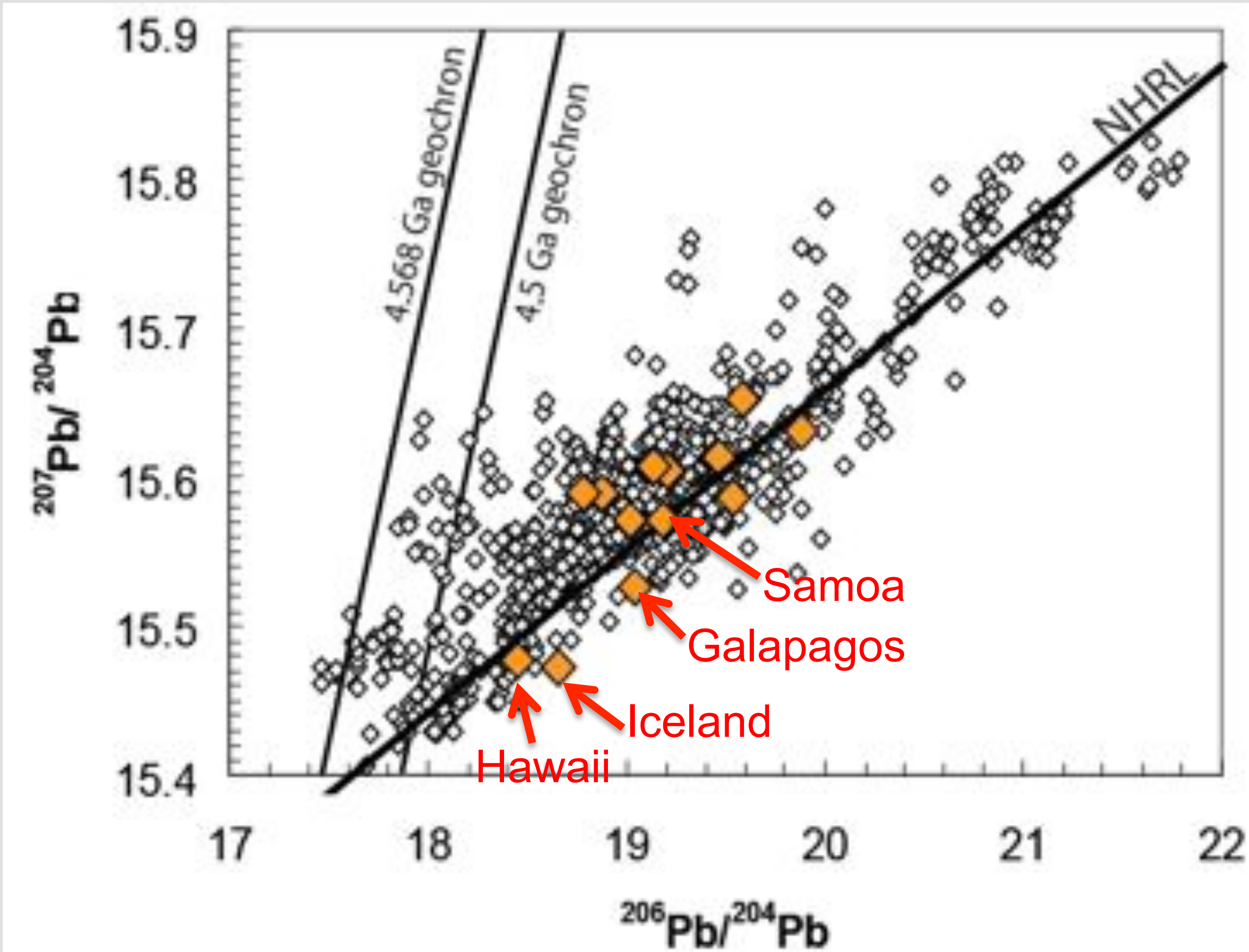
1. Early depleted reservoir, progenitor of all modern terrestrial lavas ($^{143}Nd/^{144}Nd$=0.5130)
2. Hidden enriched reservoir ($^{143}Nd/^{144}Nd$ << 0.51263).

Predicted parental mantle reservoir overlaps with high $^3He/^4He$ reservoir



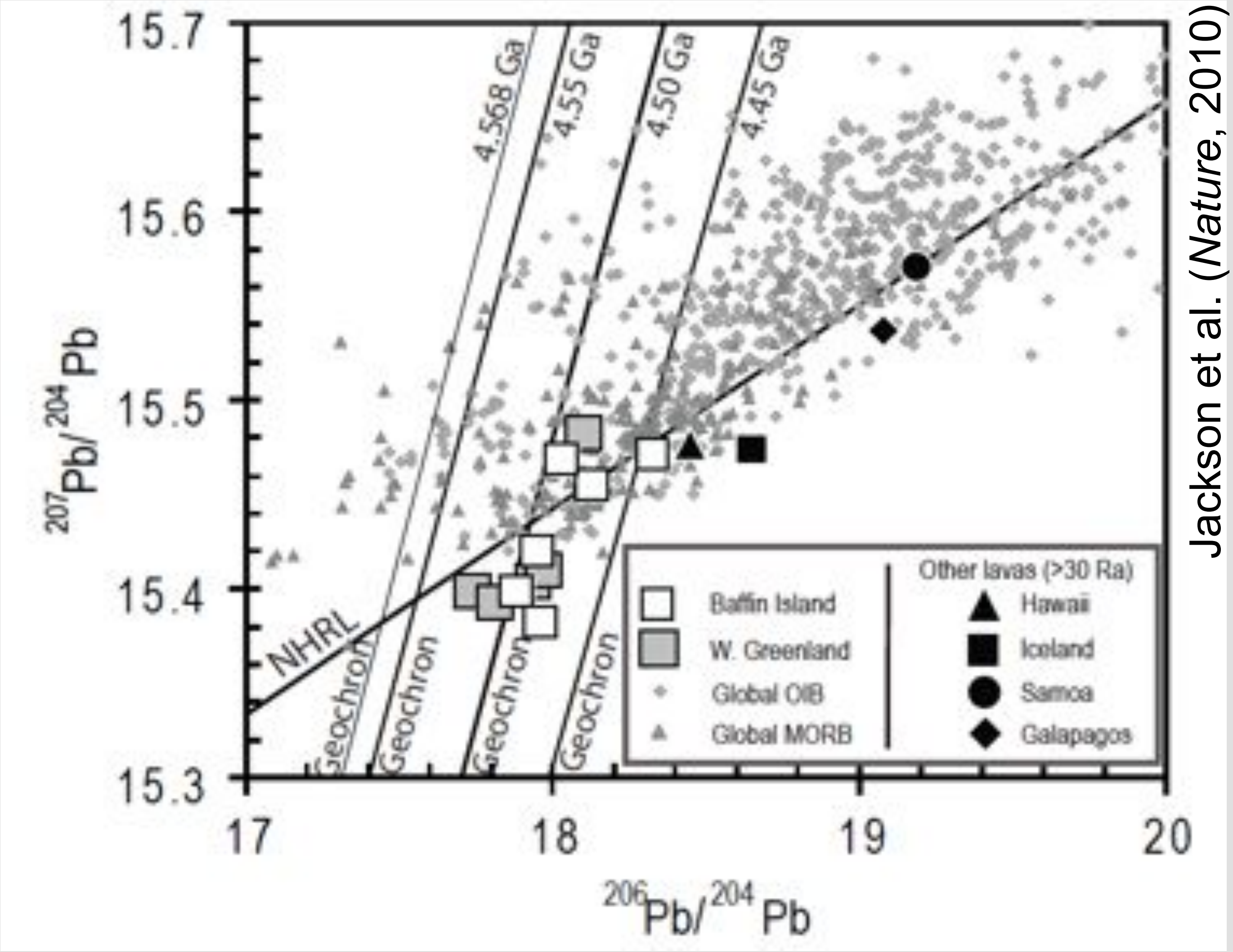
Jackson et al. (*EPSL*, 2007)

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



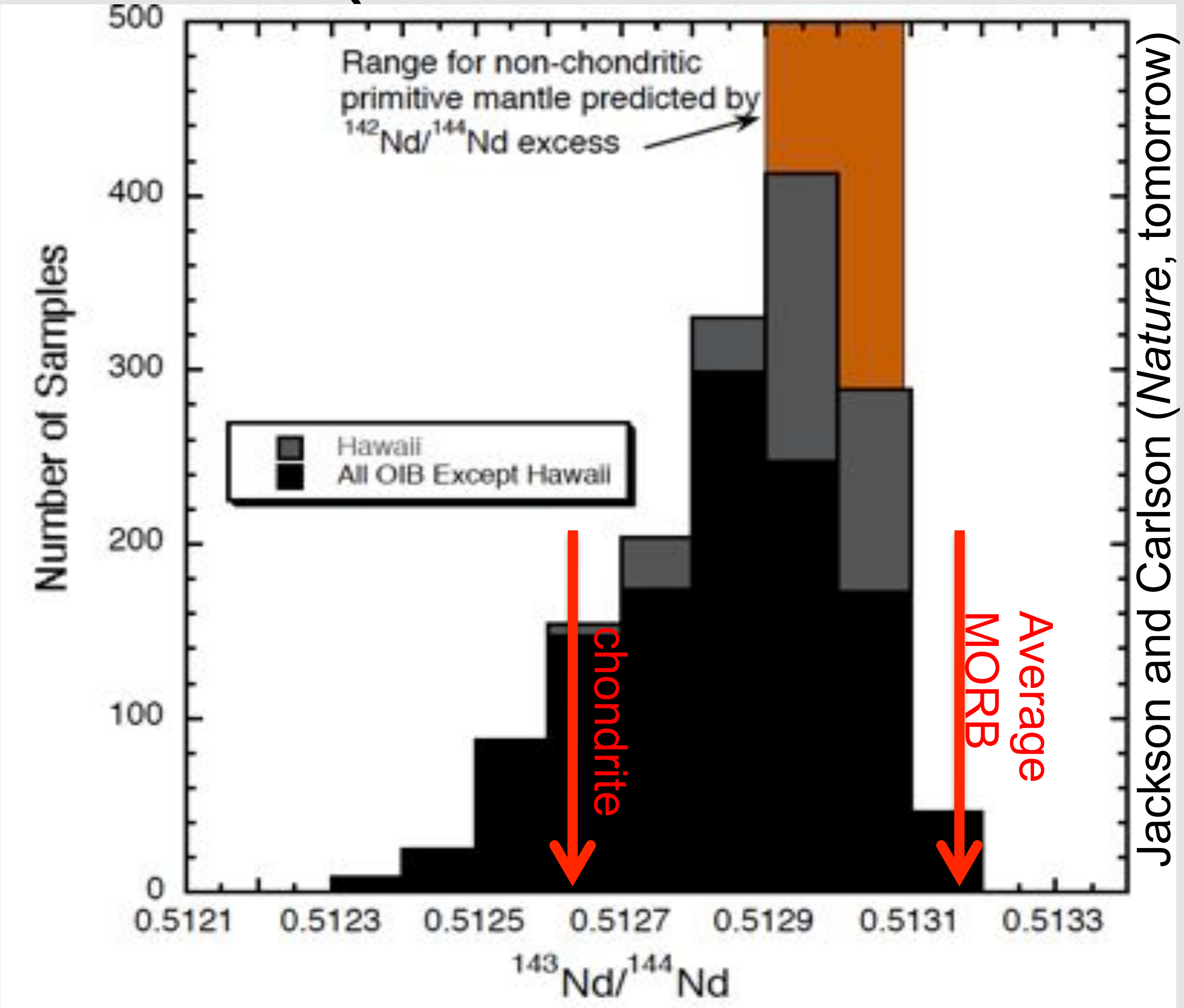
After Jackson et al. (*EPSL*, 2007)

Baffin and West Greenland picrites plot near the Geochron



Jackson et al. (*Nature*, 2010)

PREMA (Prevalent Mantle)



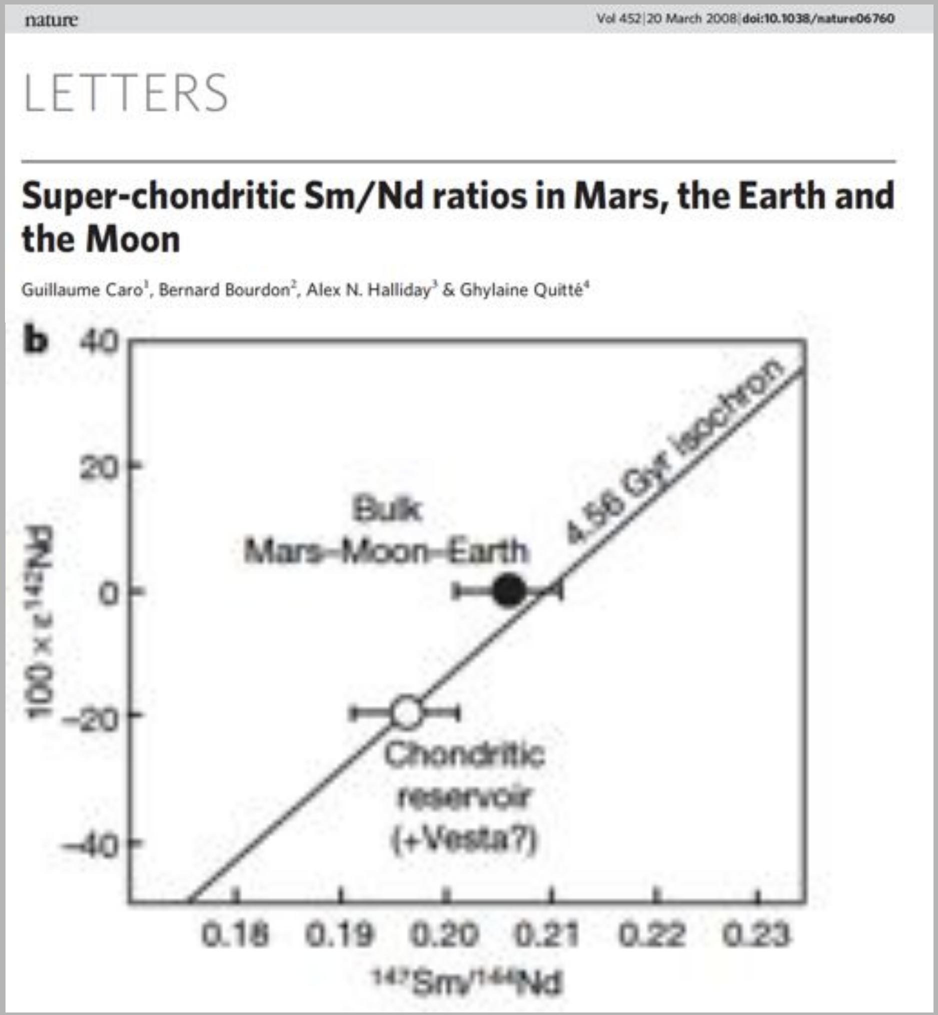
If the large proportion of OIB lavas with present-day $^{143}Nd/^{144}Nd$ near 0.5130 reflects a high proportion of non-chondritic primitive material in the mantle, then primitive material must comprise a substantial portion of the modern terrestrial mantle.

A growing clamor….

Bottom line: Terrestrial oxygen isotopes not like C and O-chondrites (Clayton)! Cr too (Qin & Carlson).

Implications:

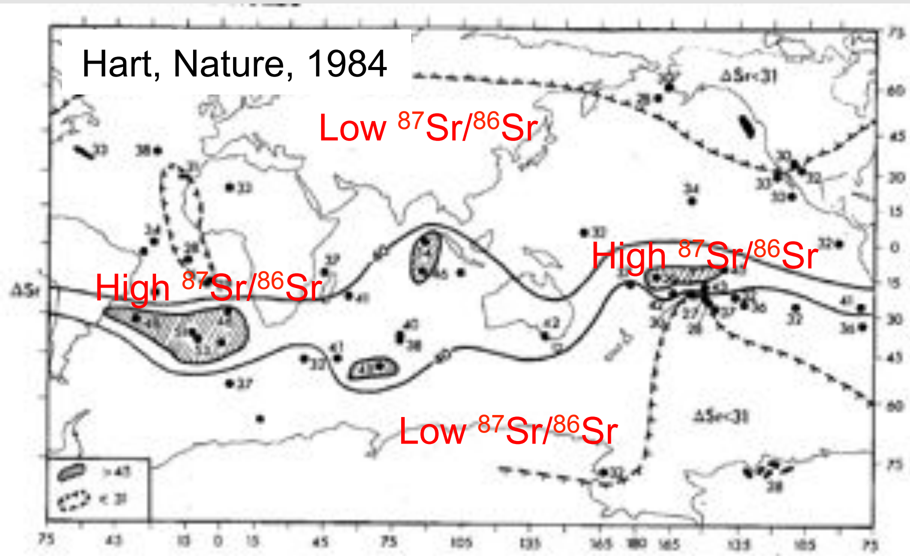
1. DMM is >45-90% of the mantle (to >1600 km depth). If primitive mantle $^{143}Nd/^{144}Nd$ is 0.5130 (instead of 0.51263) then much more than 25% of the mantle needs to be depleted to make DMM!
2. What was once considered depleted may actually be enriched!
3. How to preserve for 4.5 Ga?
4. A whole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



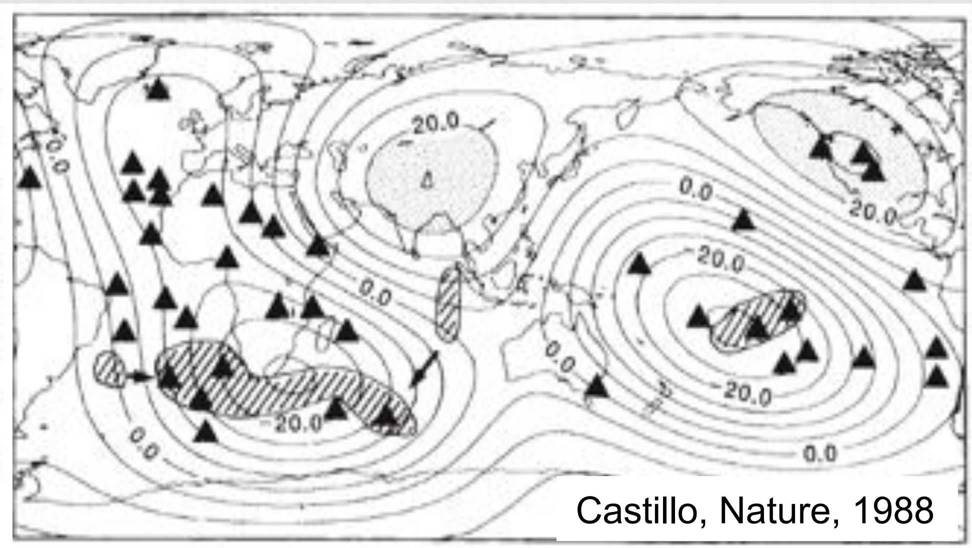
Far from being a "dying field", we are in the midst of a geochemical revolution!

Part 4: Distribution of mantle heterogeneities inferred from ocean islands

DUPAL anomaly



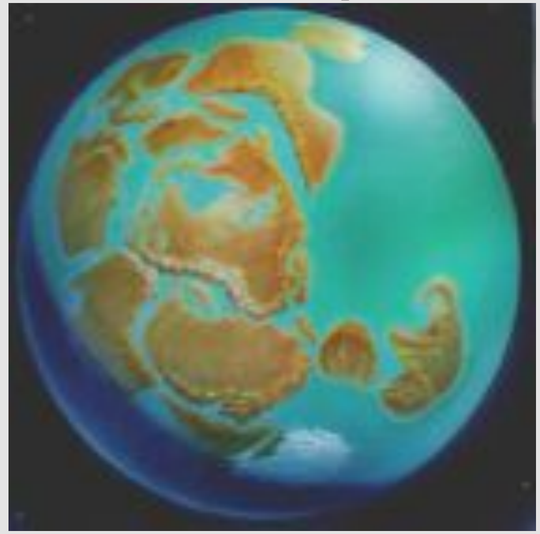
DUPAL vs. seismic low velocity anomaly



--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 anomalies at depth.

How to generate hemispheric heterogeneity in the first place?

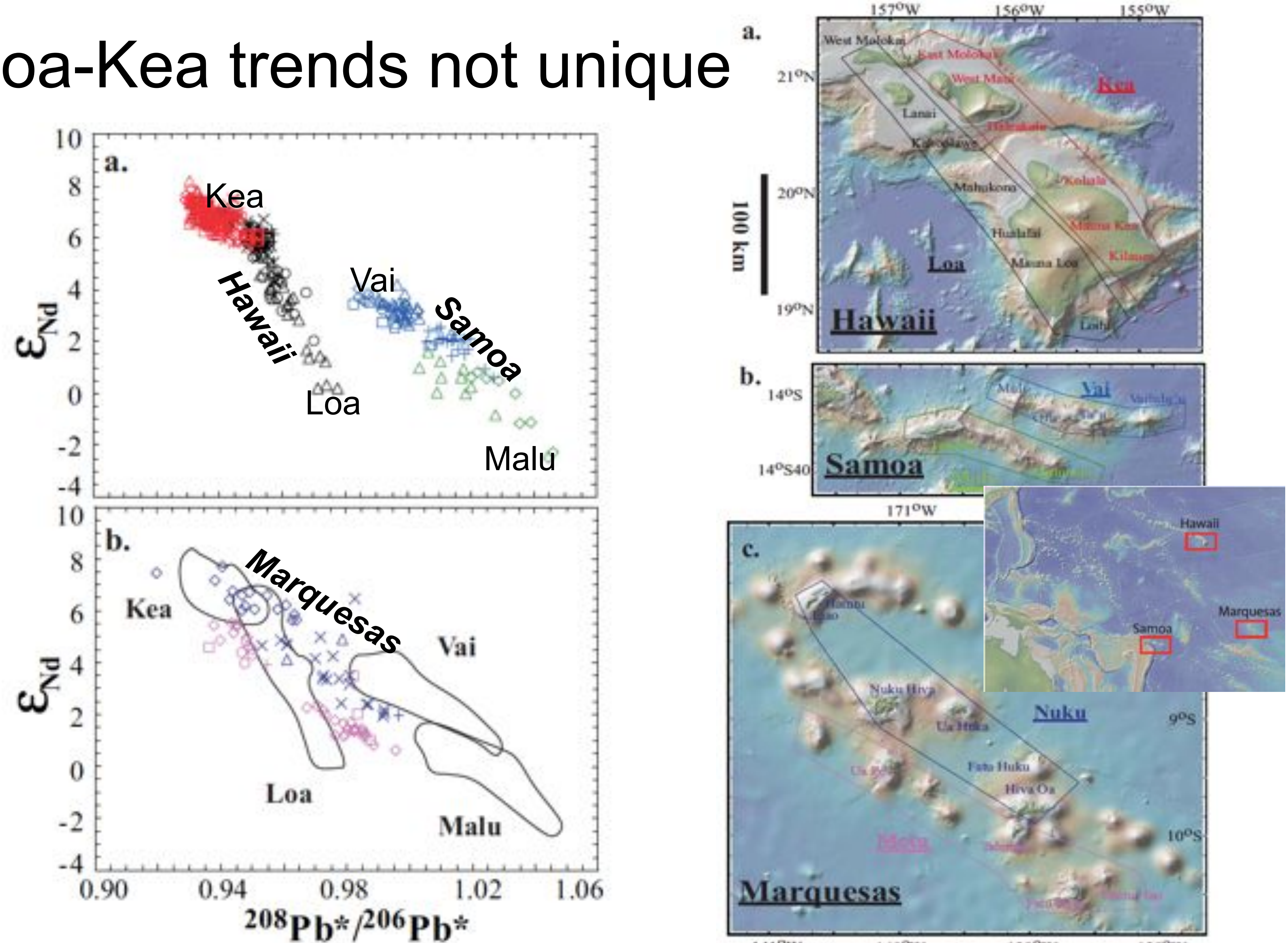


Focused subduction around
the perimeter of a supercontinent?

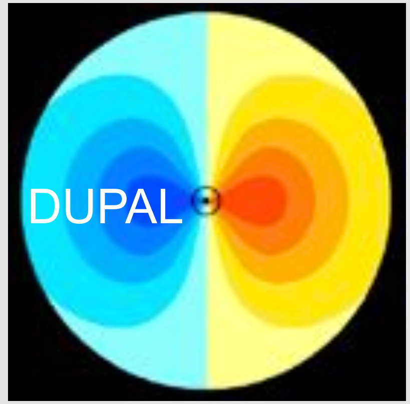
“Indeed, what *can* be proved in the Earth Sciences?”

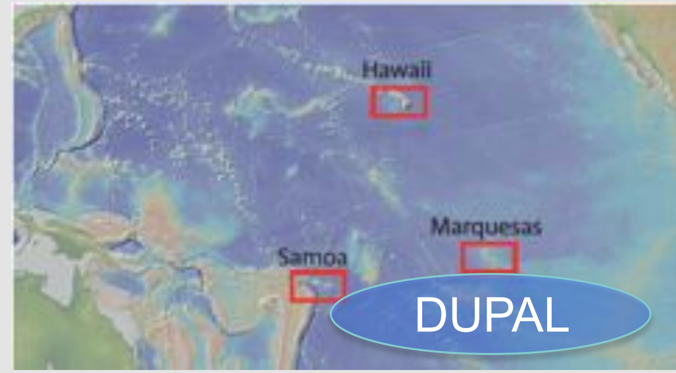
-C. Allègre
Phil. Trans. R. Soc. Lond. A
vol. 360, 2002

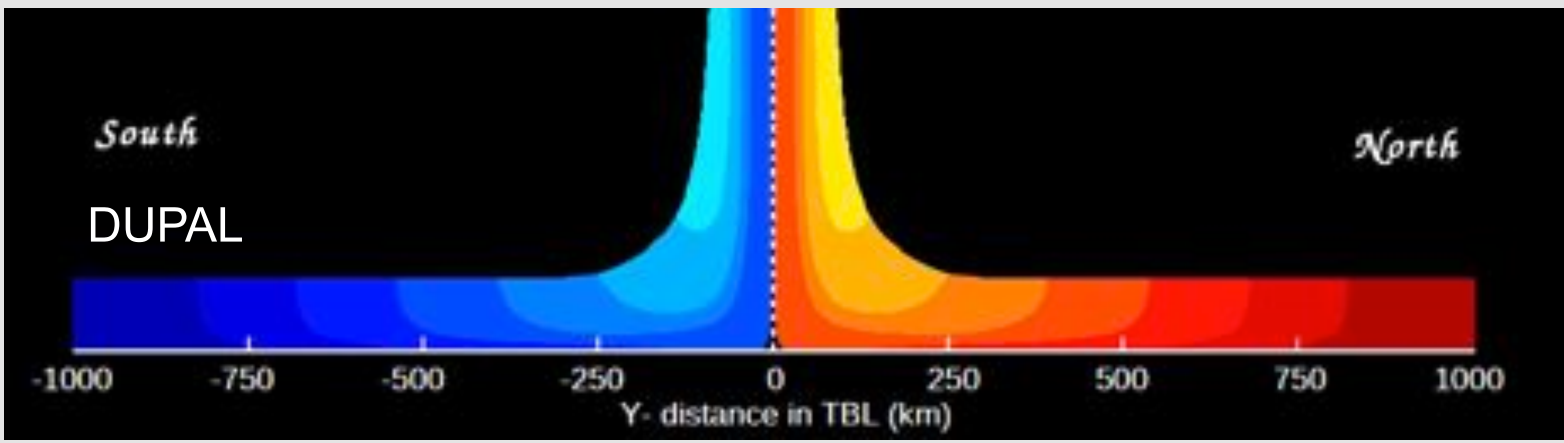
Loa-Kea trends not unique



Geochemical structure of CMB preserved in plume conduits

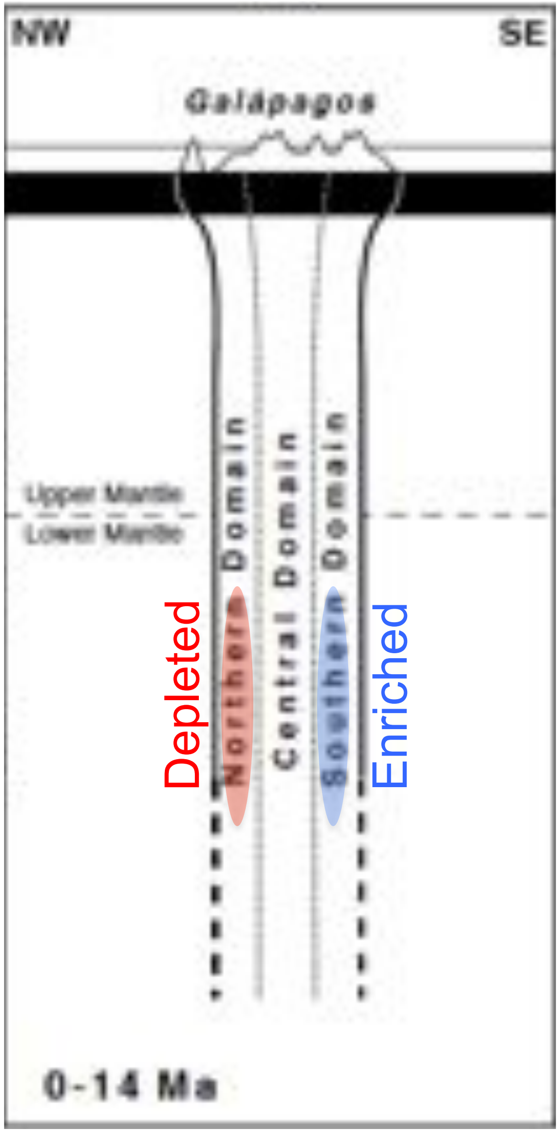






Farnetani

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

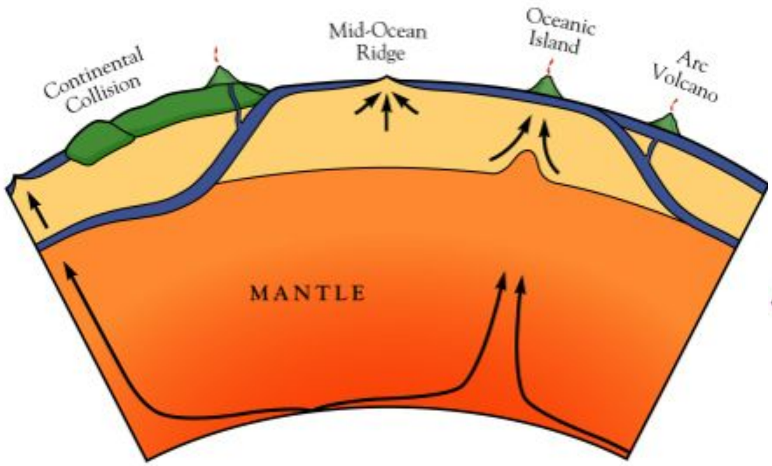


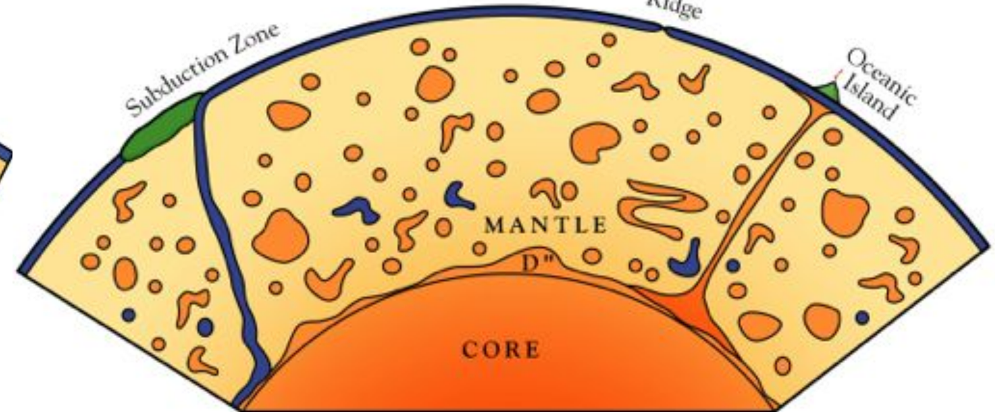
Hoernle et al., 2000

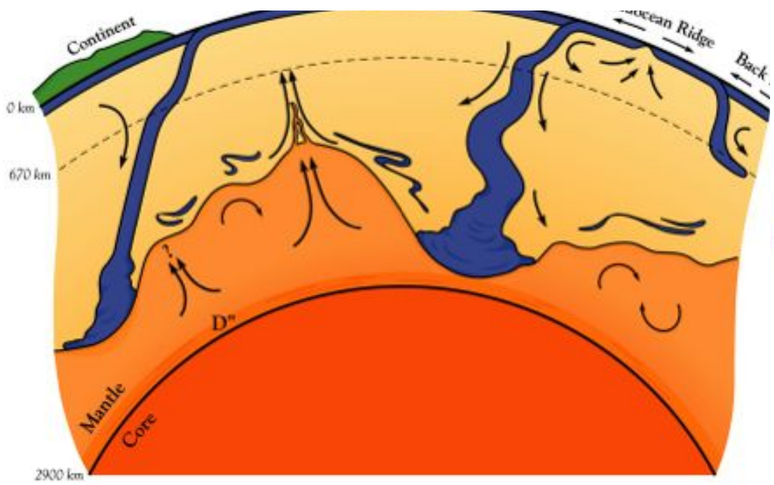
Looking ahead

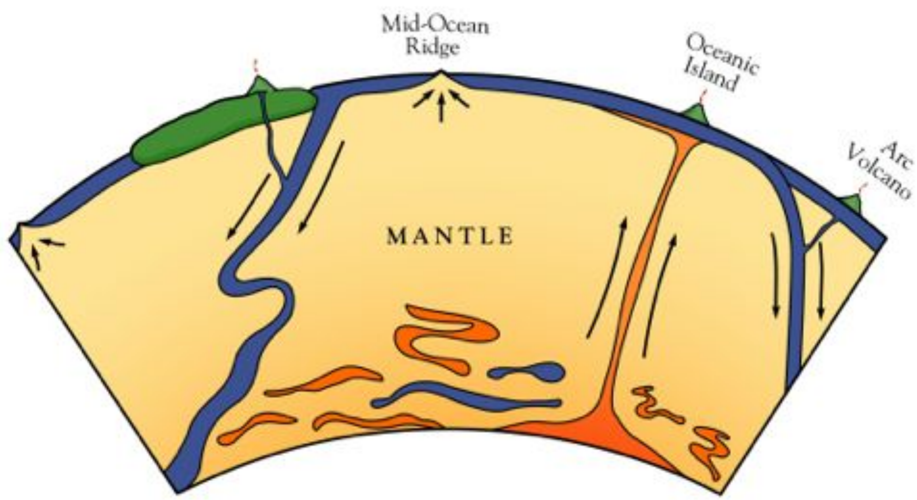
- Plumes, no plumes, or sometimes plumes? Are hotspots hotter?
- Does recycled crust and/or sediment explain hotspot geochemistry? Is the mantle lithologically heterogeneous?
- Is the Earth chondritic? Or does primitive mantle have $^{143}Nd/^{144}Nd=0.5130$?! **Without the chondrite model, the "road ahead" has no map!**
- What caused the DUPAL anomaly? Is the DUPAL anomaly responsible for the zoned nature of mantle plumes?

Models of mantle convection and distribution of heterogeneities

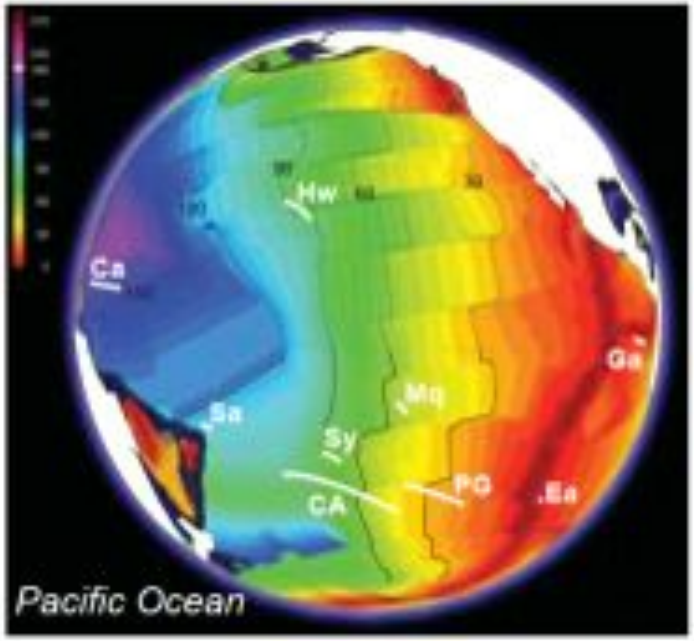






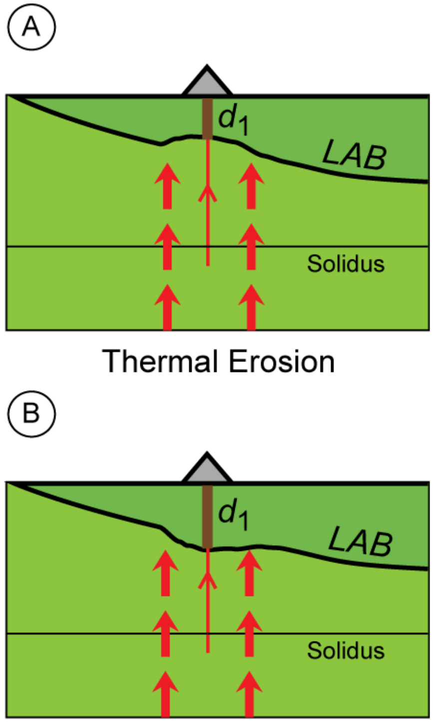


OIB Chemistry – *Conditions of Melting versus Source Heterogeneity*



Hw - Hawaii
Mq - Marquesas
Ga - Galapagos
Ea - Easter
PG - Pitcairn-Gambier
Sy - Society
Sa - Samoa
Ca - Caroline

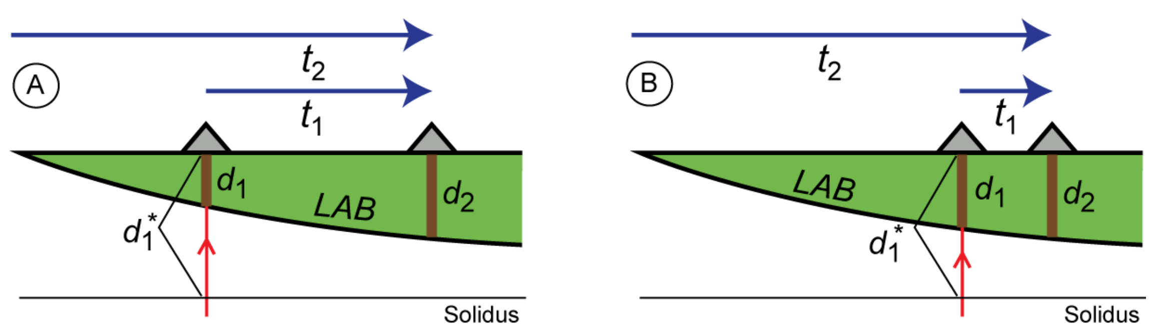
Dasgupta et al. (2010)



Thermal Erosion

Magmatic Underplating

$t_2 - t_1$ = plate age at the time of volcanism



t_2 - sea-floor age

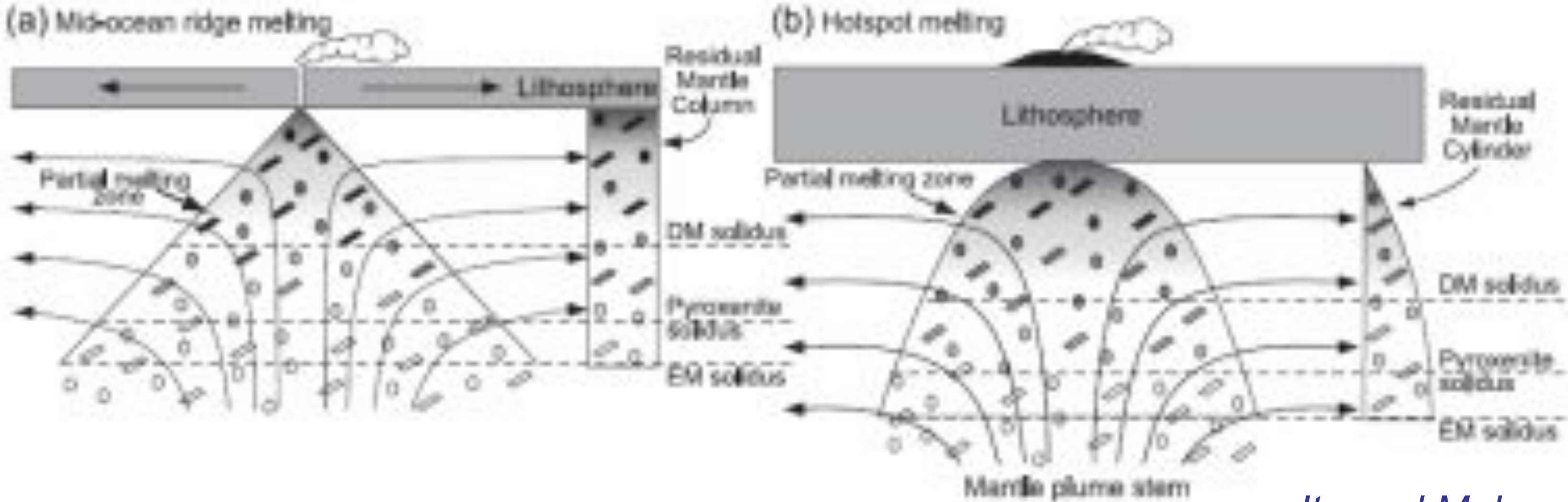
t_1 - eruption age

d_2 - LAB at the present-day

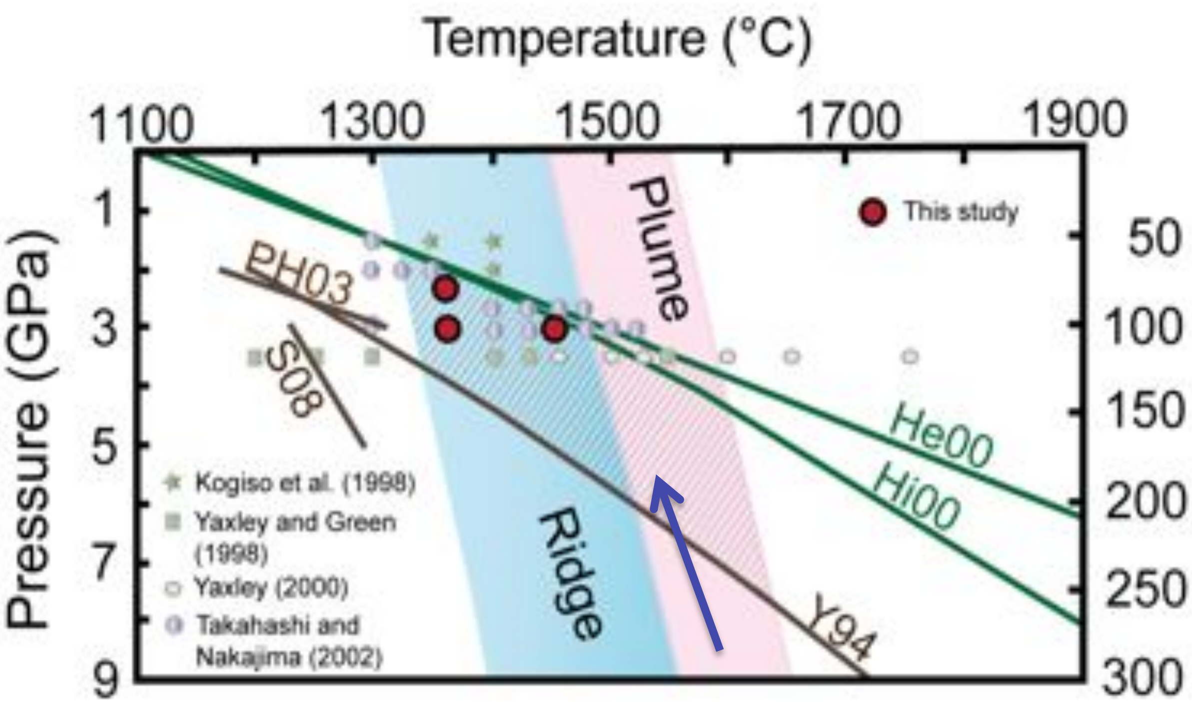
d_1 - LAB at the time of volcanism or the shallowest possible depth of decompression melting

d_1^* - solidus depth or deepest condition of decompression melting

OIB Chemistry – *Source Heterogeneity*



Ito and Mahoney (2005)

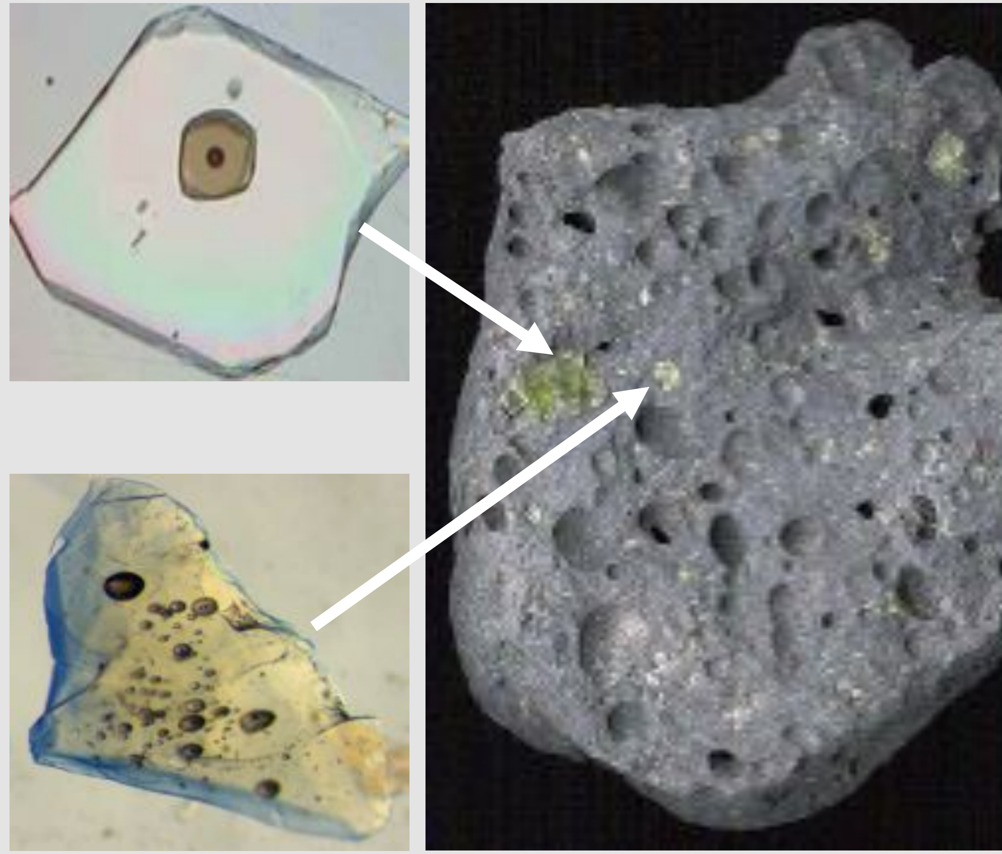


Mallik and Dasgupta (in prep)

Melt inclusions:

1. Small volumes of melt trapped in growing crystals at depth.

2. Melt inclusions record "snapshots" of intermediate mixing steps in magmas.

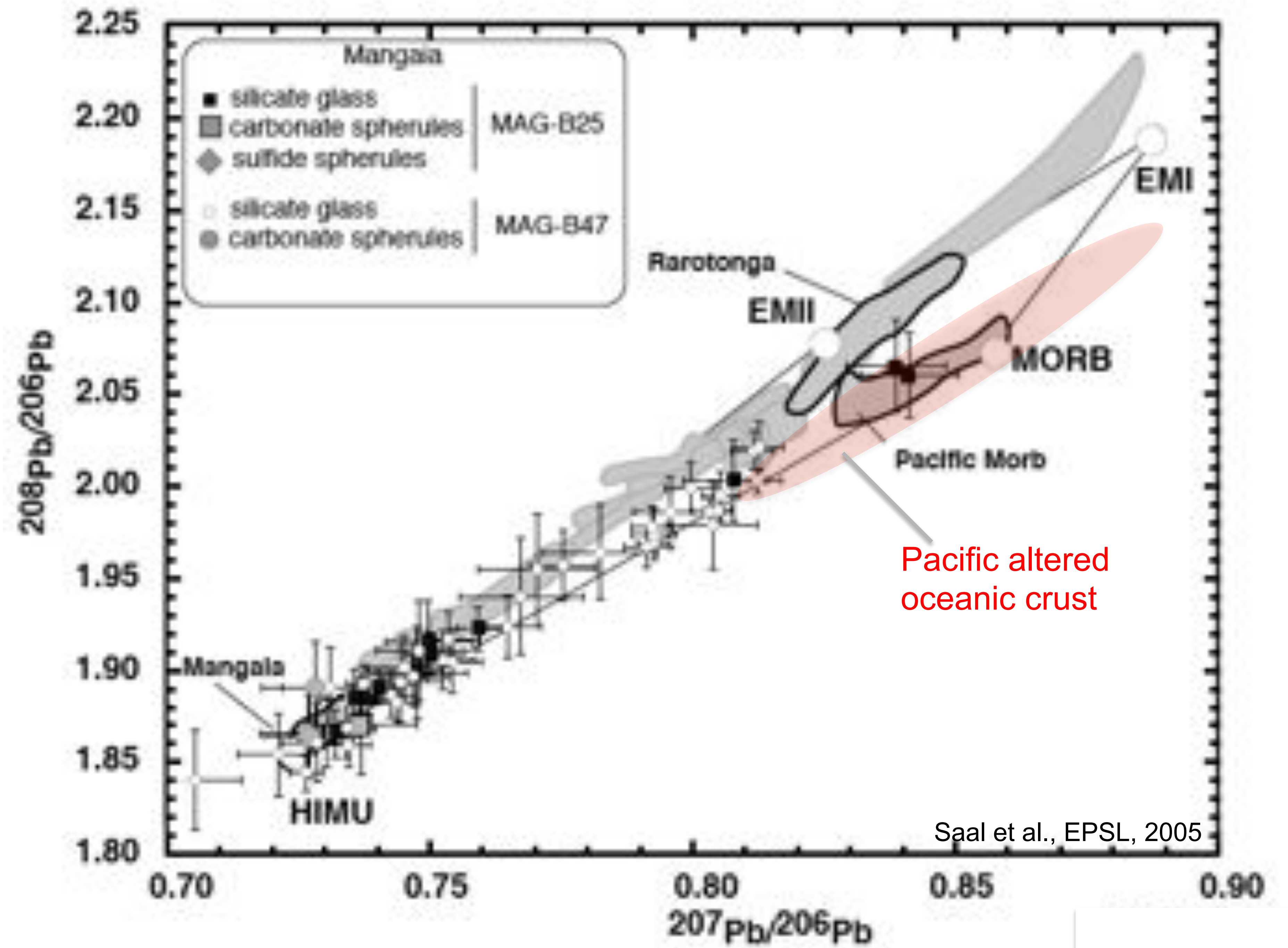


Melt inclusion compositions often do not reflect whole rock composition:

1.) The isotopic variability reflects the diversity of mantle sources that contribute to a single lava.

<u>OR</u>

2.) The isotopic heterogeneity results from processes operating at depth, including magmatic assimilation of crustal materials.



Mangaia
silicate glass
carbonate spherules
sulfide spherules
MAG-B25
silicate glass
carbonate spherules
MAG-B47
Rarotonga
EMII
EMI
MORB
Pacific Morb
Pacific altered oceanic crust
Mangaia
HIMU
Saal et al., EPSL, 2005
208Pb/206Pb
207Pb/206Pb
2.25
2.20
2.15
2.10
2.05
2.00
1.95
1.90
1.85
1.80
0.70
0.75
0.80
0.85
0.90

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

1. **Early (>4.53 Ga) differentiation event** of a chondritic primitive mantle, resulting in two complementary reservoirs:

A. *EDR (Early Depleted Reservoir)*:

-High Sm/Nd (~5% higher than chondrites)

-All modern mantle reservoirs derive from the EDR with $^{143}Nd/^{144}Nd \approx 0.5130$.

B. *EER (Early Enriched Reservoir):*

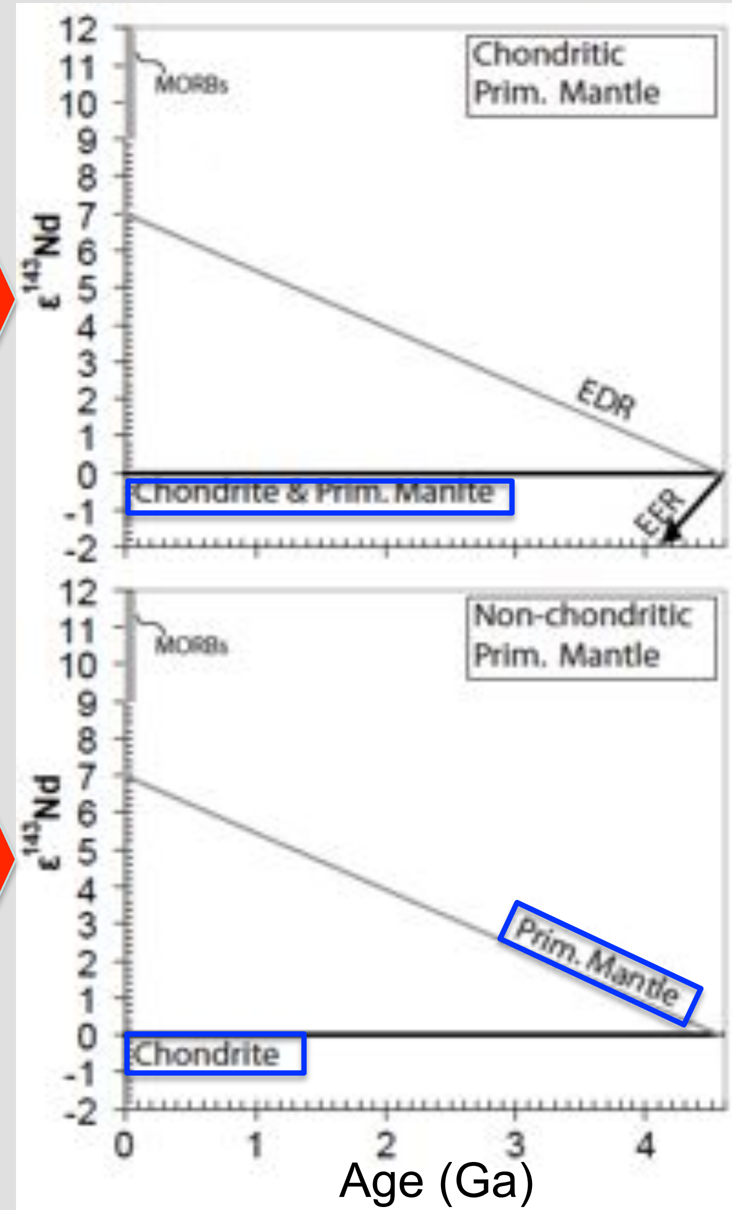
-"Hidden" reservoir with low Sm/Nd.

2. **Non-chondritic primitive mantle** that has Sm/Nd ~5% higher than chondrites.

-Earth accreted from material with super-chondritic Sm/Nd.

-All modern reservoirs derive from primitive mantle with $^{143}Nd/^{144}Nd \approx 0.5130$

**We don't know whether elevated $^{142}Nd/^{144}Nd$ in modern terrestrial rocks results from early depletion event or accretion from a non-chondritic material.



Moon-forming event, and the survival of a “hidden” early enriched reservoir?

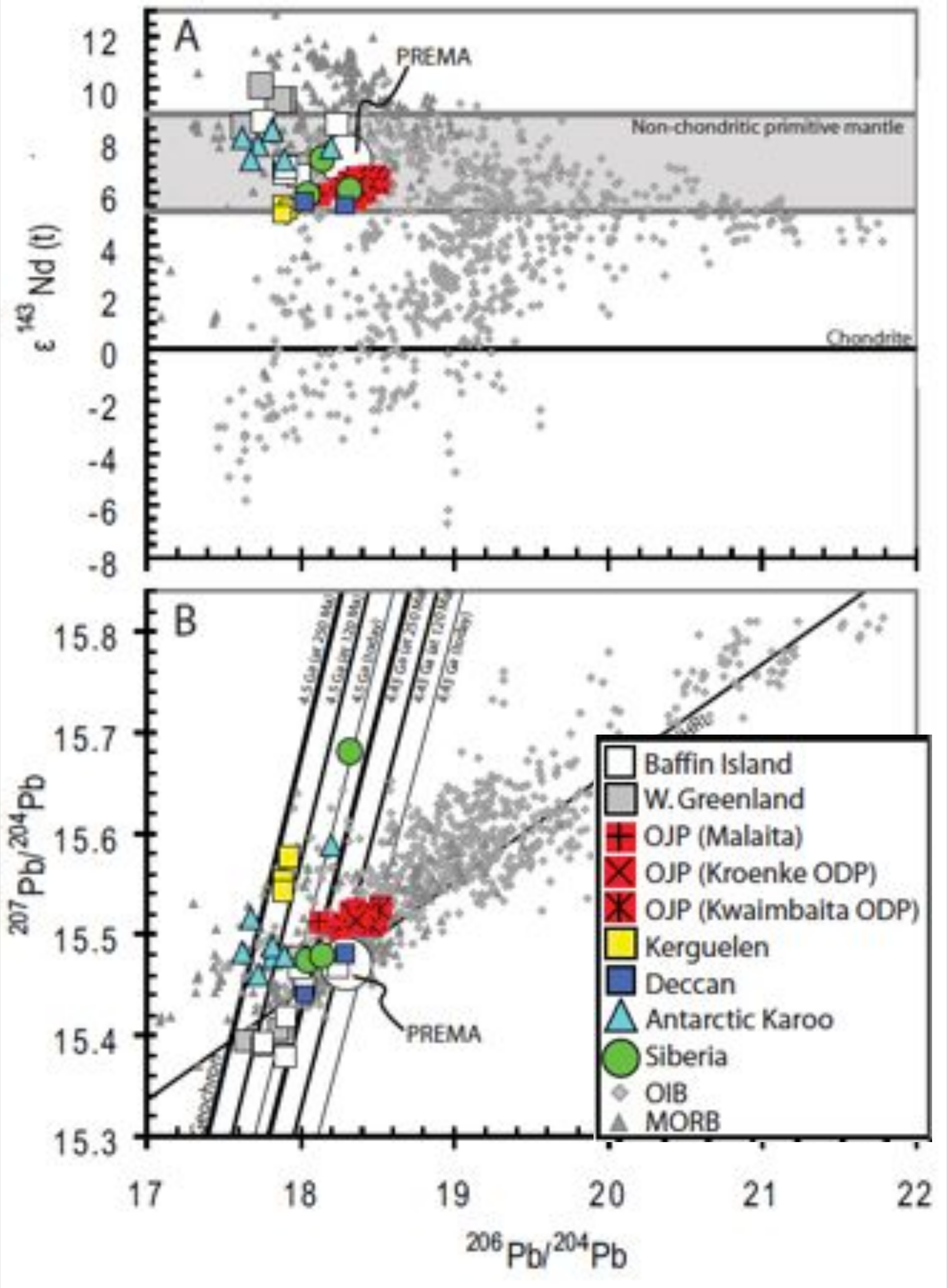
- An early differentiation event—if it even occurred—is constrained (^{146}Sm-^{142}Nd systematics) to have occurred within 30 million years (>4.53 Ga) of accretion.
- Moon formation must have followed any early differentiation event (^{182}W-^{182}Hf systematics).
- **How would a “hidden” reservoir remain hidden during a giant impact event?**
- **Also, a hidden enriched reservoir is ENRICHED (U,Th,K), and is therefore hot. Should be present in plumes.**

Half an Hour After the Giant Impact, based on computer modeling by A. Cameron, W. Benz, J. Melosh, and others. ***Copyright William K. Hartmann***

Global?

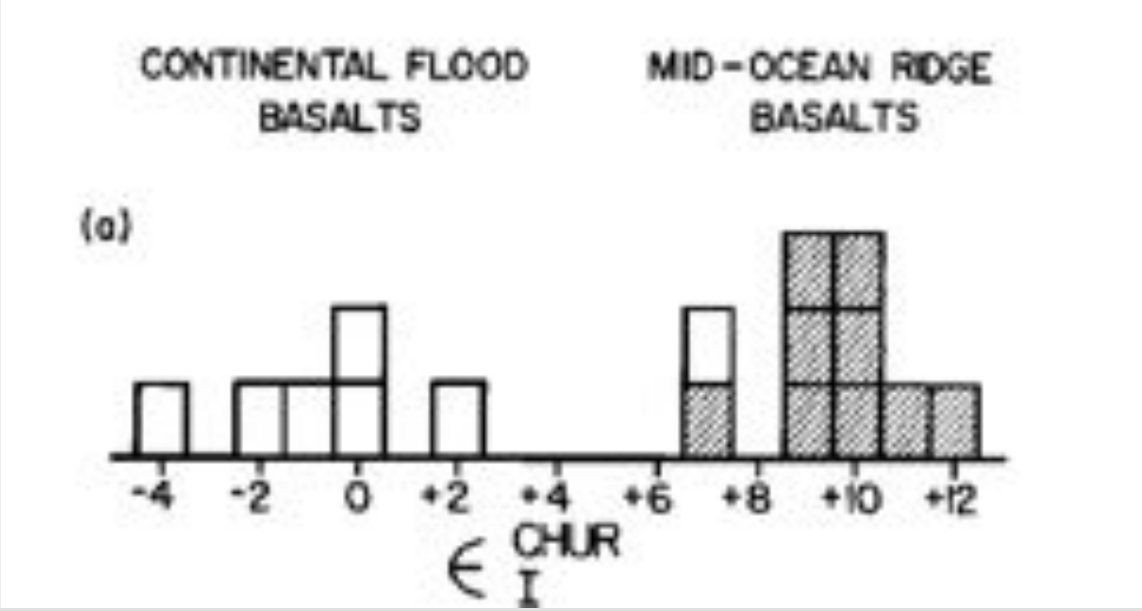
Baffin Island is a flood basalt.

Do other flood basalts have similar geochem signatures?



Jackson and Carlson (Nature, 2011, in press)

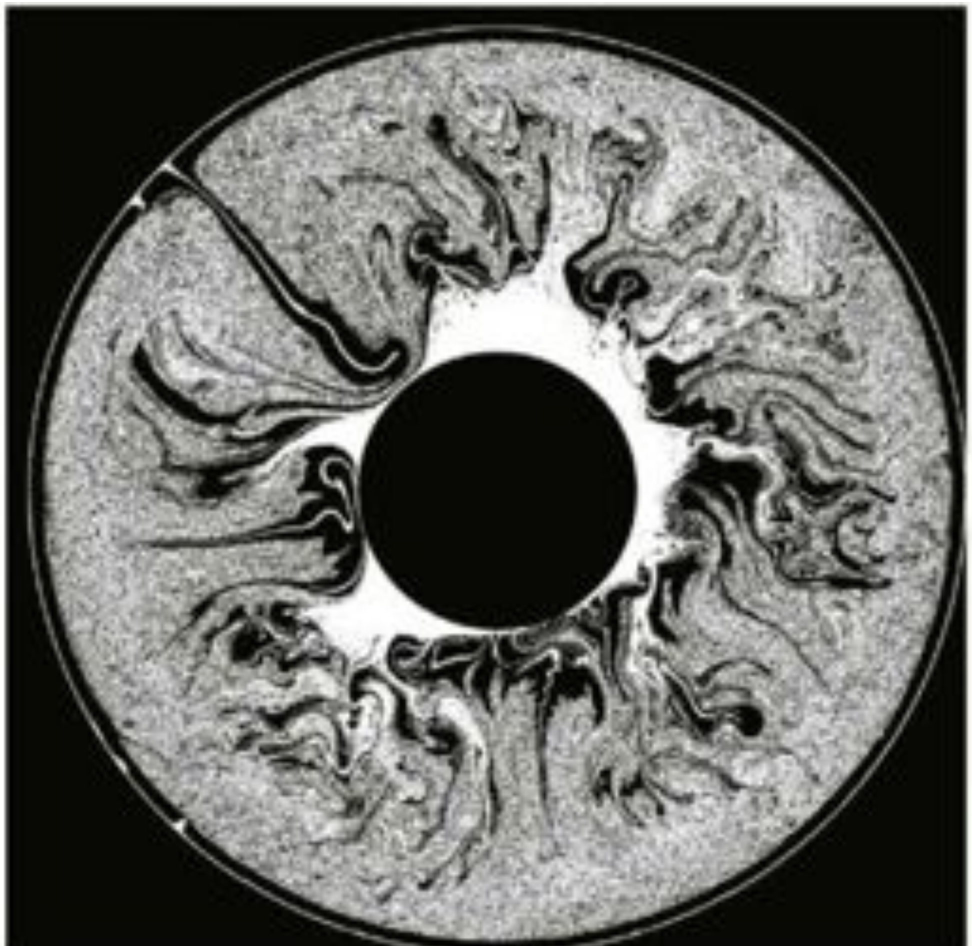
Old Reservoir, Old Idea (new possibilities)



"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

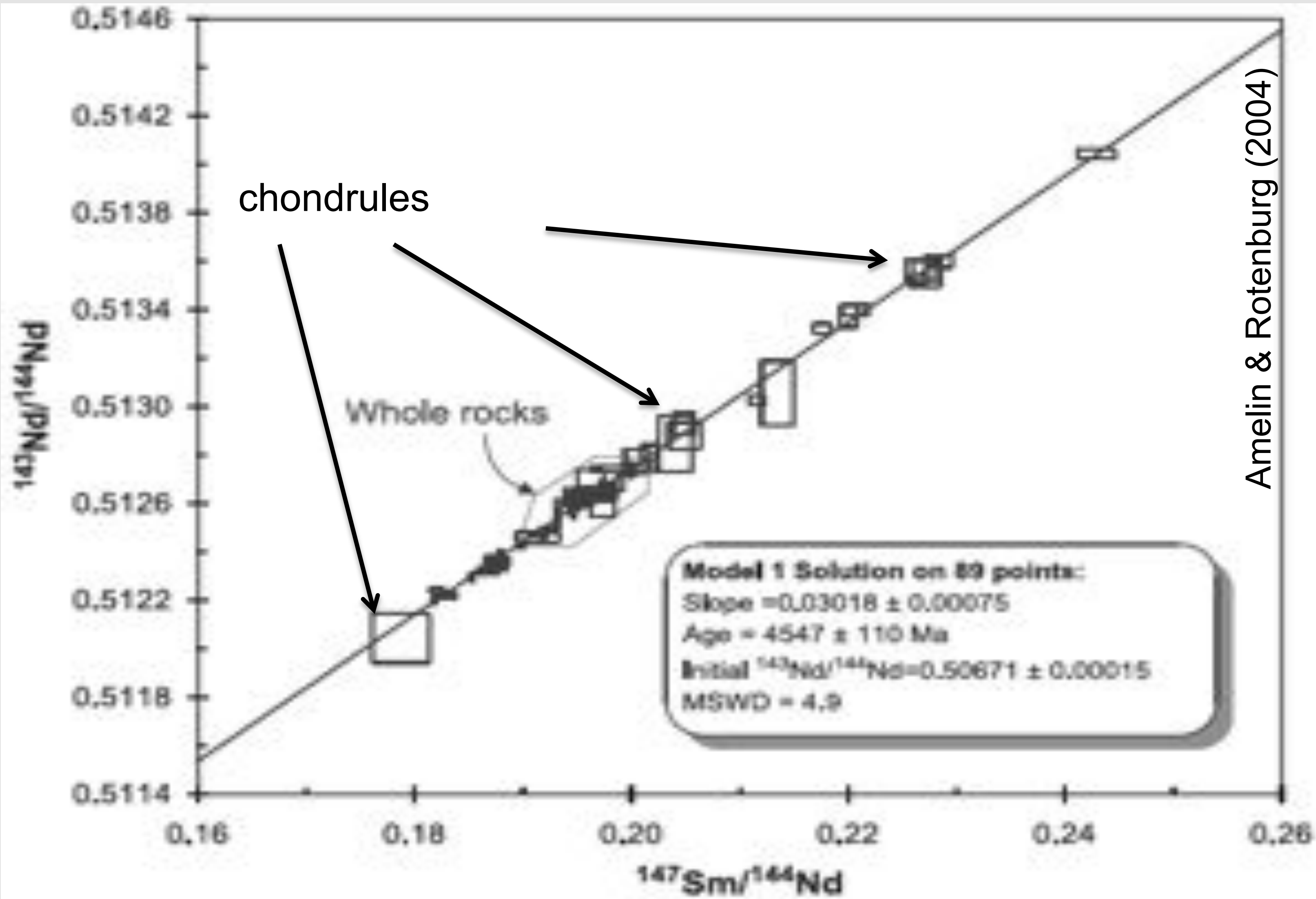
How does a portion of the mantle survive for ~4.5 Ga?



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"?).

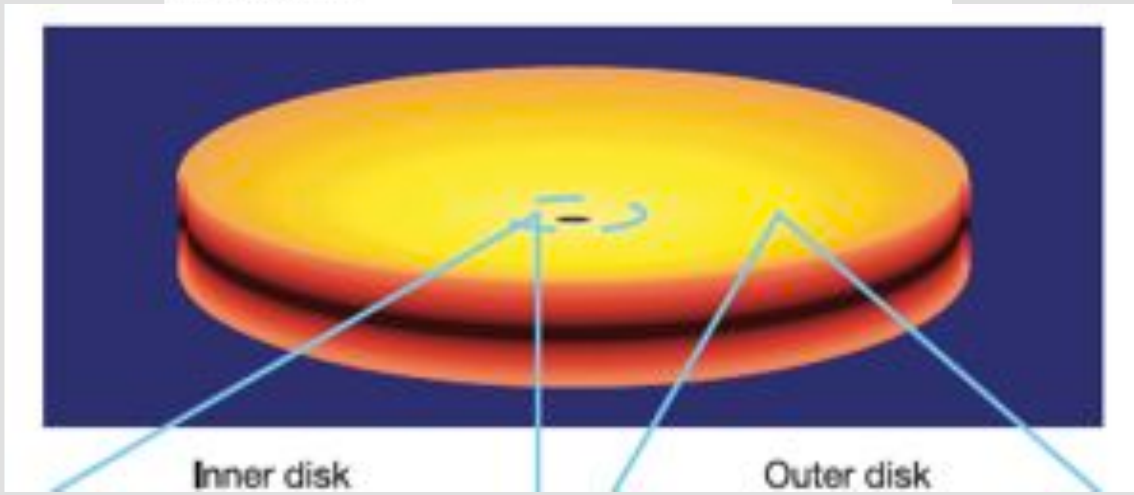
What do chondrites tell us?



In detail, chondrites aren't "chondritic"!

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]



(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}	$2.1^{+1.3}_{-0.7}$	$0.9^{+0.3}_{-0.1}$

van Boekel et al., The building blocks of planets within the 'terrestrial' region of protoplanetary disks, *Nature*, 2004.

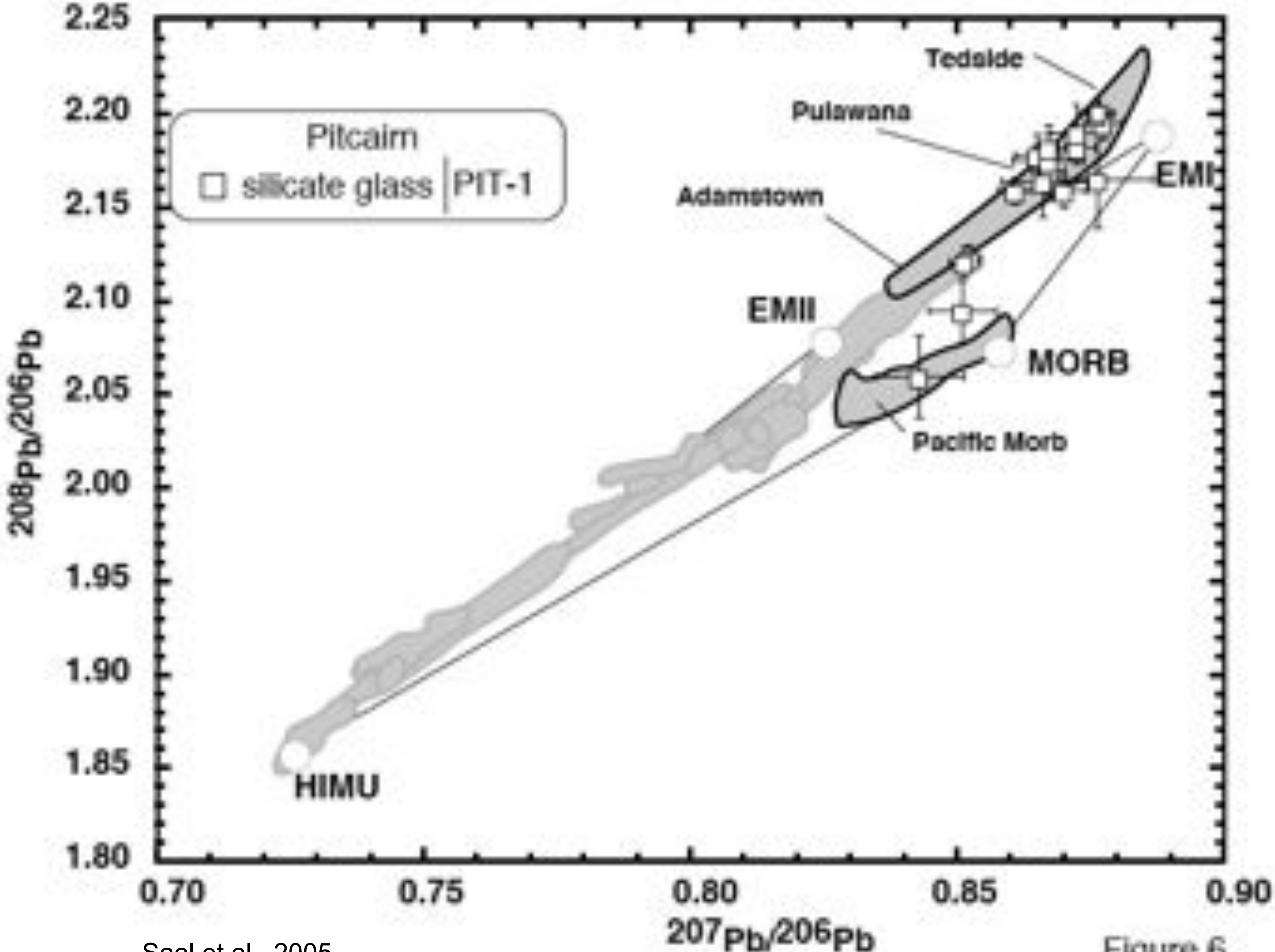


Figure 6

Saal et al., 2005

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

Australian-Indian plate

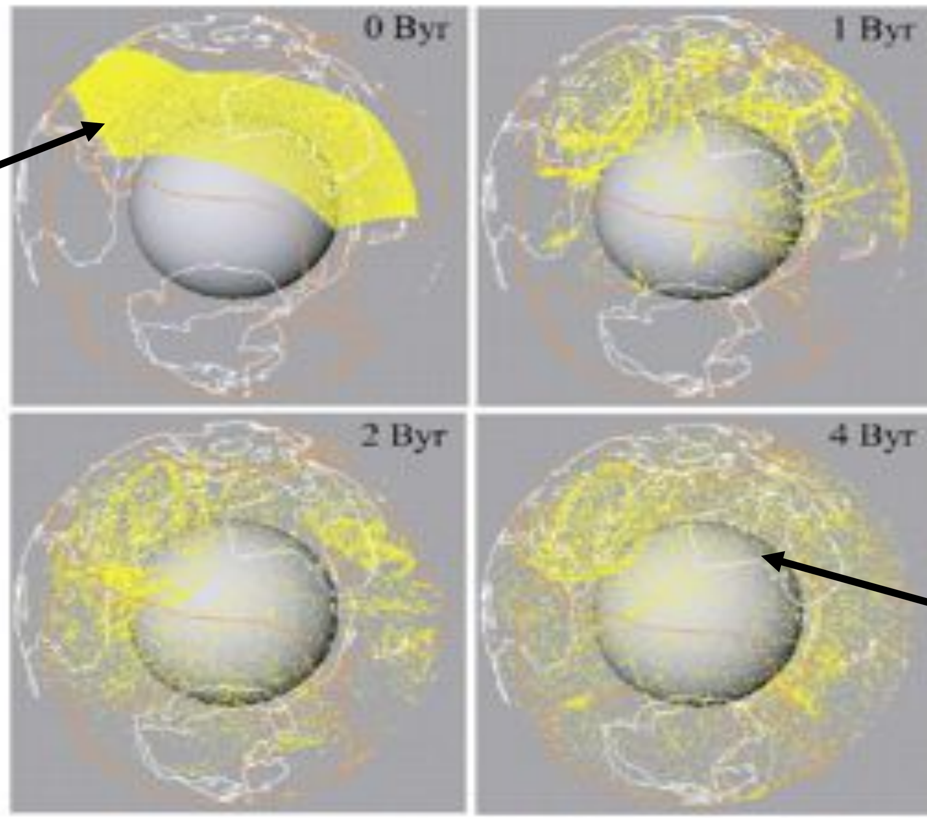
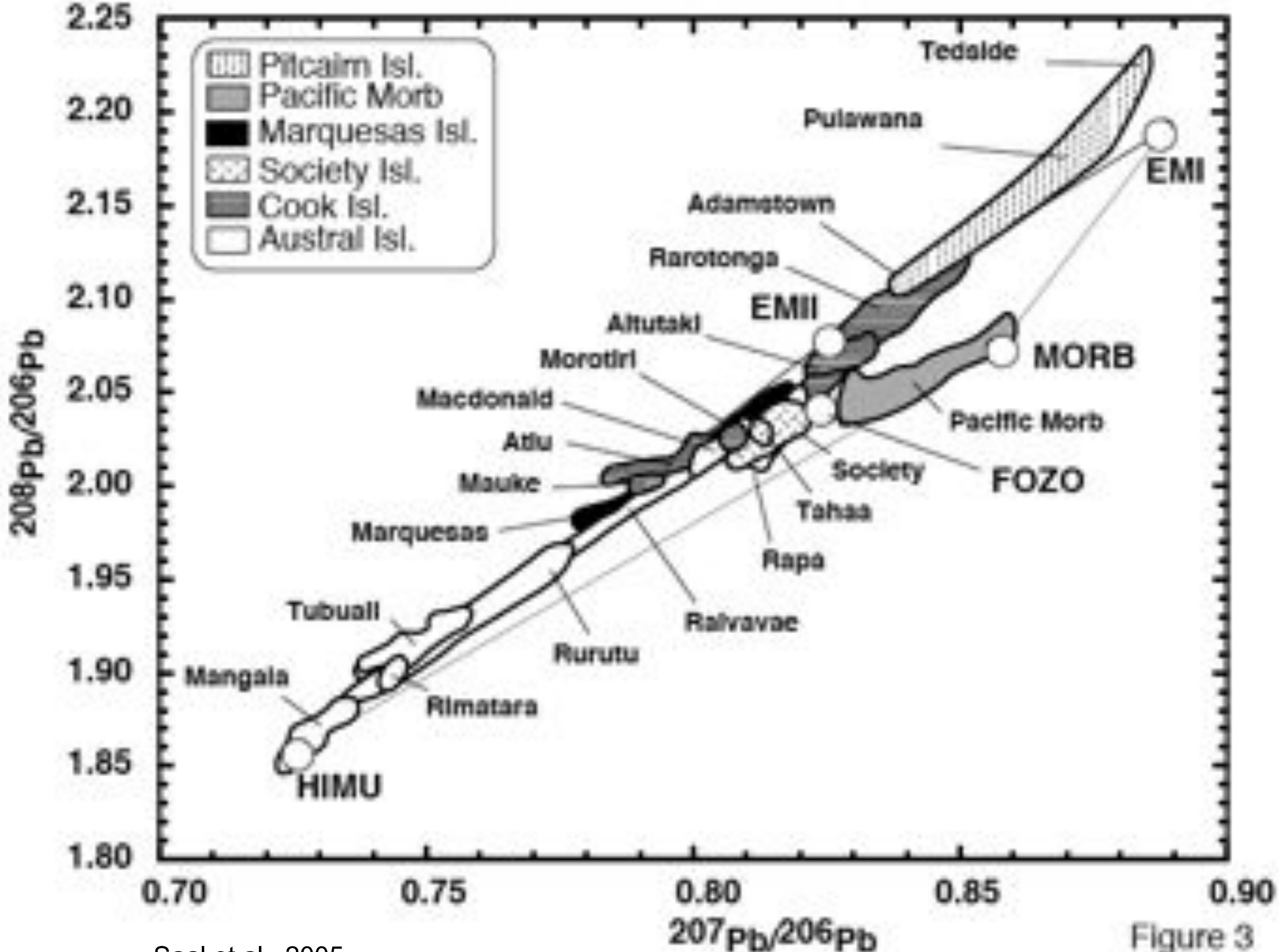


Figure 11 Evolution of the Australian-Indian plate in the steady state mixing model of Van Keken & Zhong (1999). Snapshots of the particles that composed the plate at time 0 are shown at 1, 2, and 4 Ga.

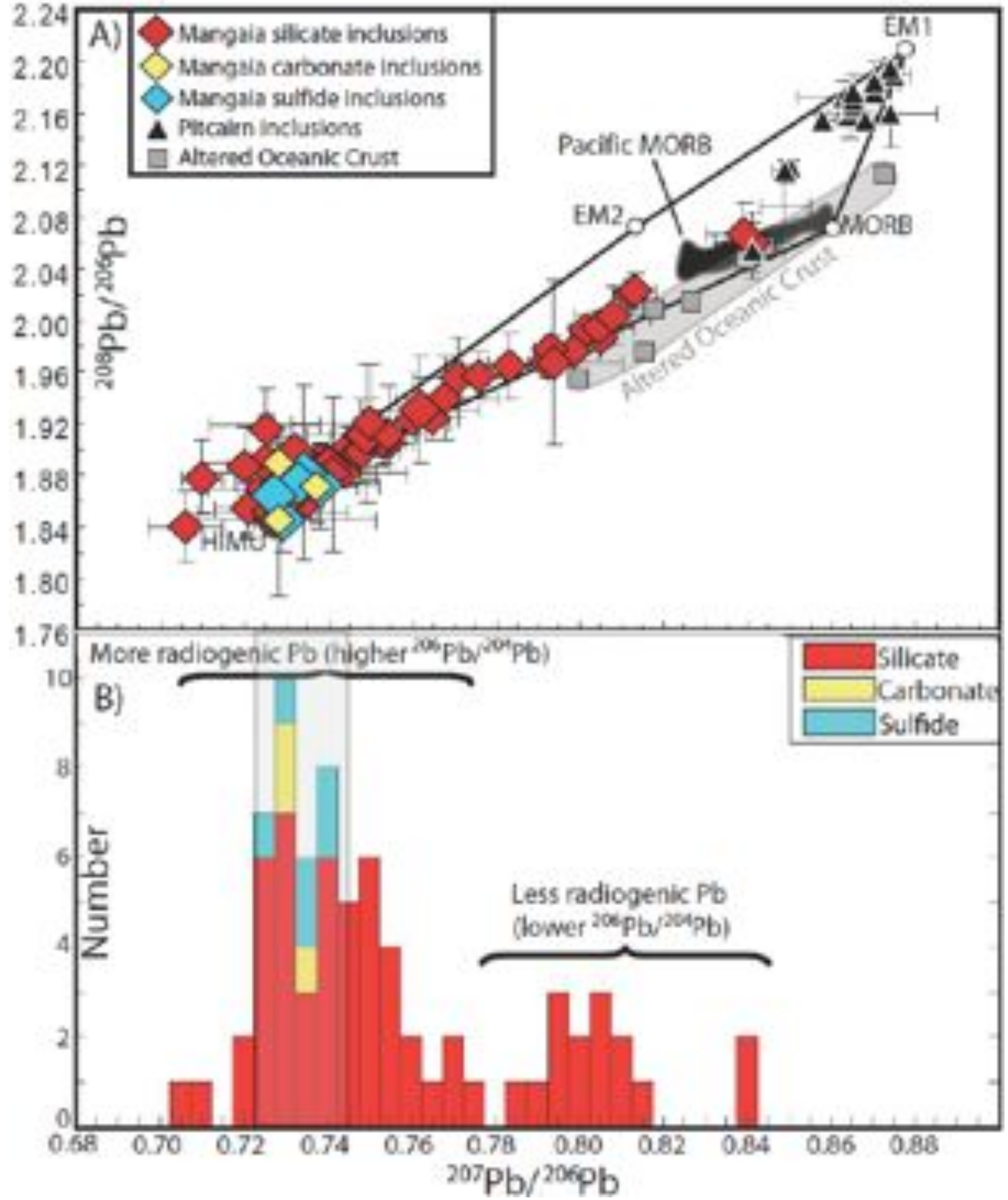
Van Keken et al. (*Ann. Rev. Earth Planet. Sci.*, 2002)

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.

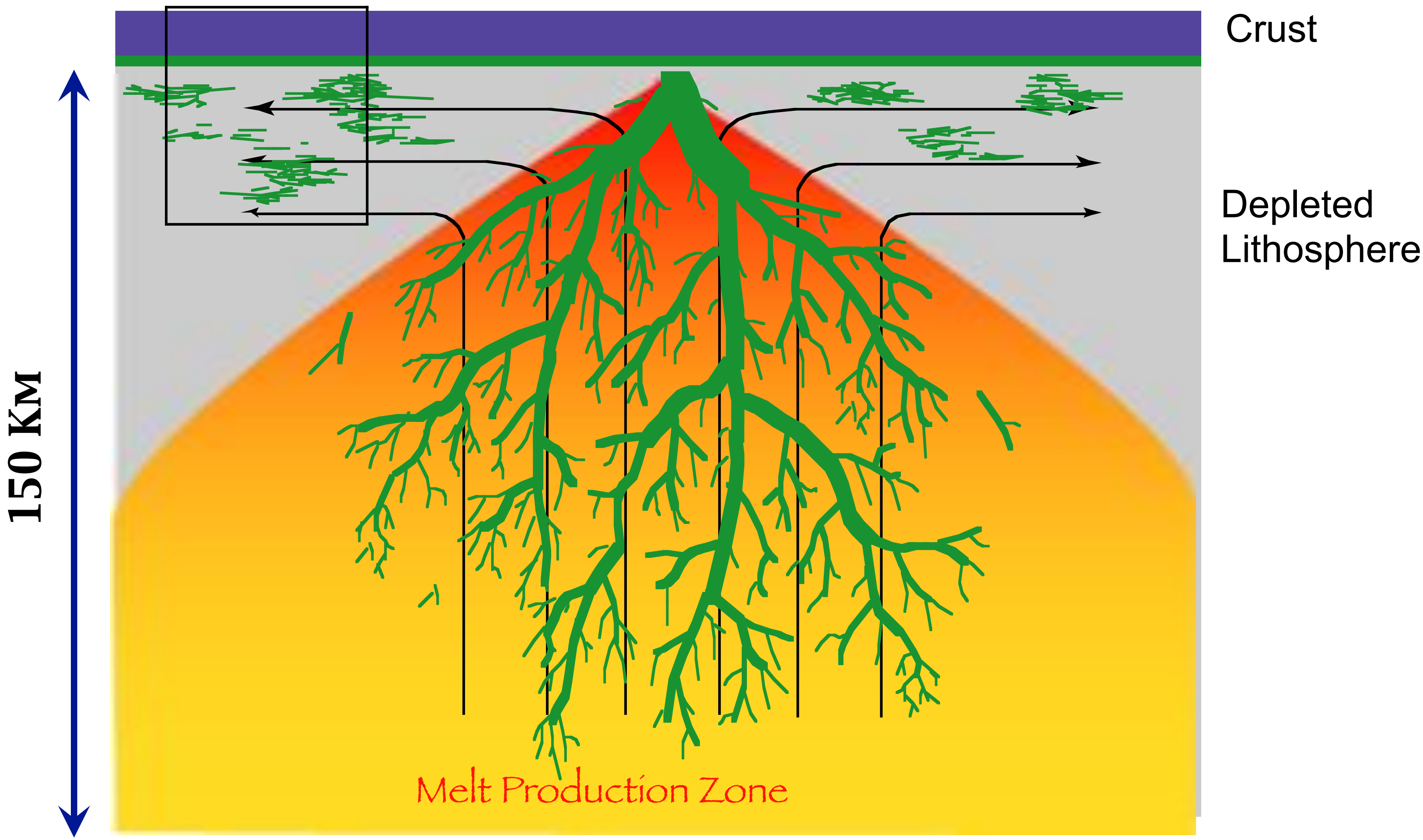


Saal et al., 2005

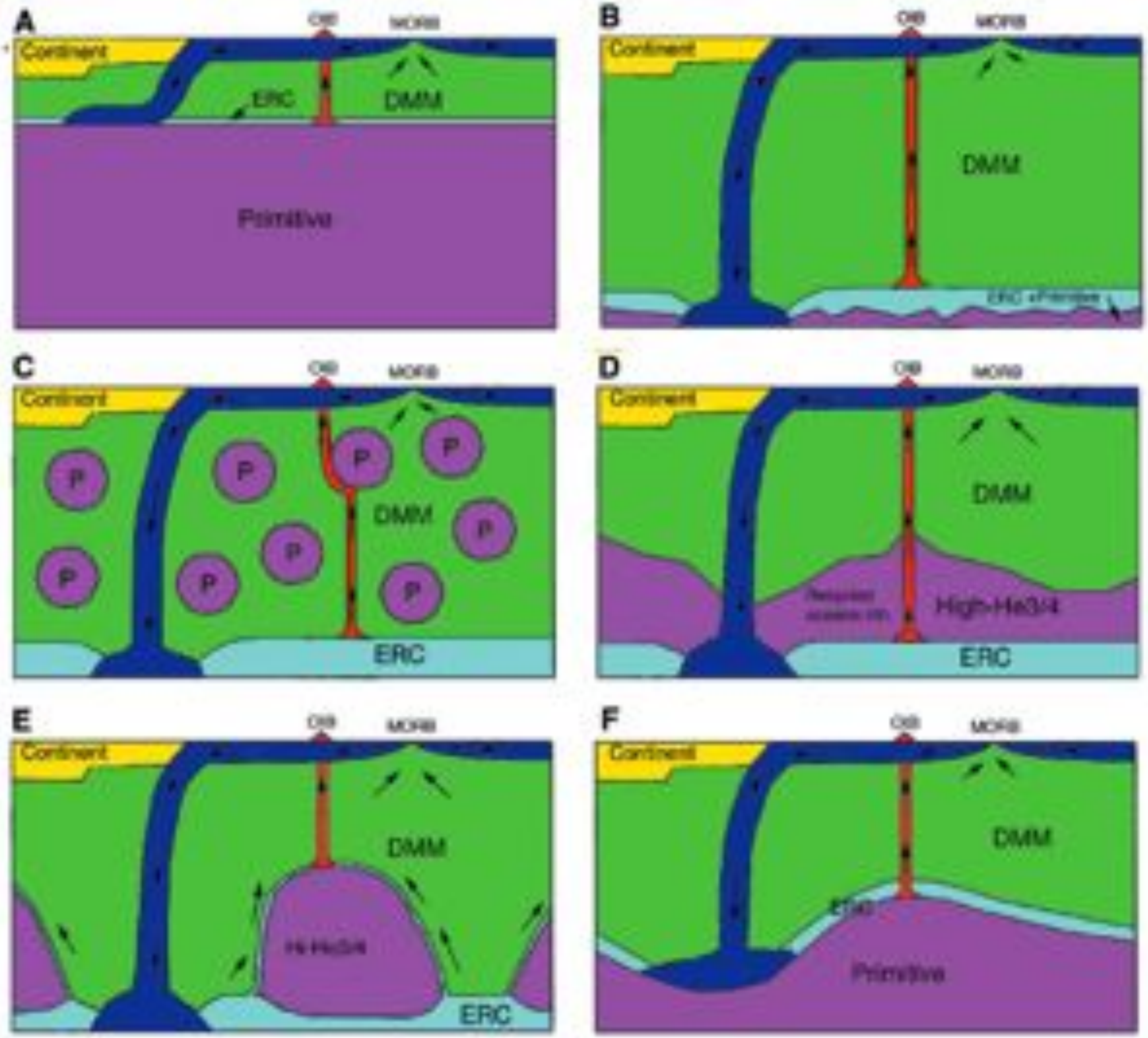


A)
Mangaia silicate inclusions
Mangaia carbonate inclusions
Mangaia sulfide inclusions
Pitcairn inclusions
Altered Oceanic Crust
EM1
EM2
Pacific MORB
MORB
HIMU
Altered Oceanic Crust
208Pb/206Pb
2.24
2.20
2.16
2.12
2.08
2.04
2.00
1.96
1.92
1.88
1.84
1.80
1.76
B)
More radiogenic Pb (higher 206Pb/204Pb)
Less radiogenic Pb (lower 206Pb/204Pb)
Silicate
Carbonate
Sulfide
Number
10
8
6
4
2
0
0.68 0.70 0.72 0.74 0.76 0.78 0.80 0.82 0.84 0.86 0.88
207Pb/206Pb

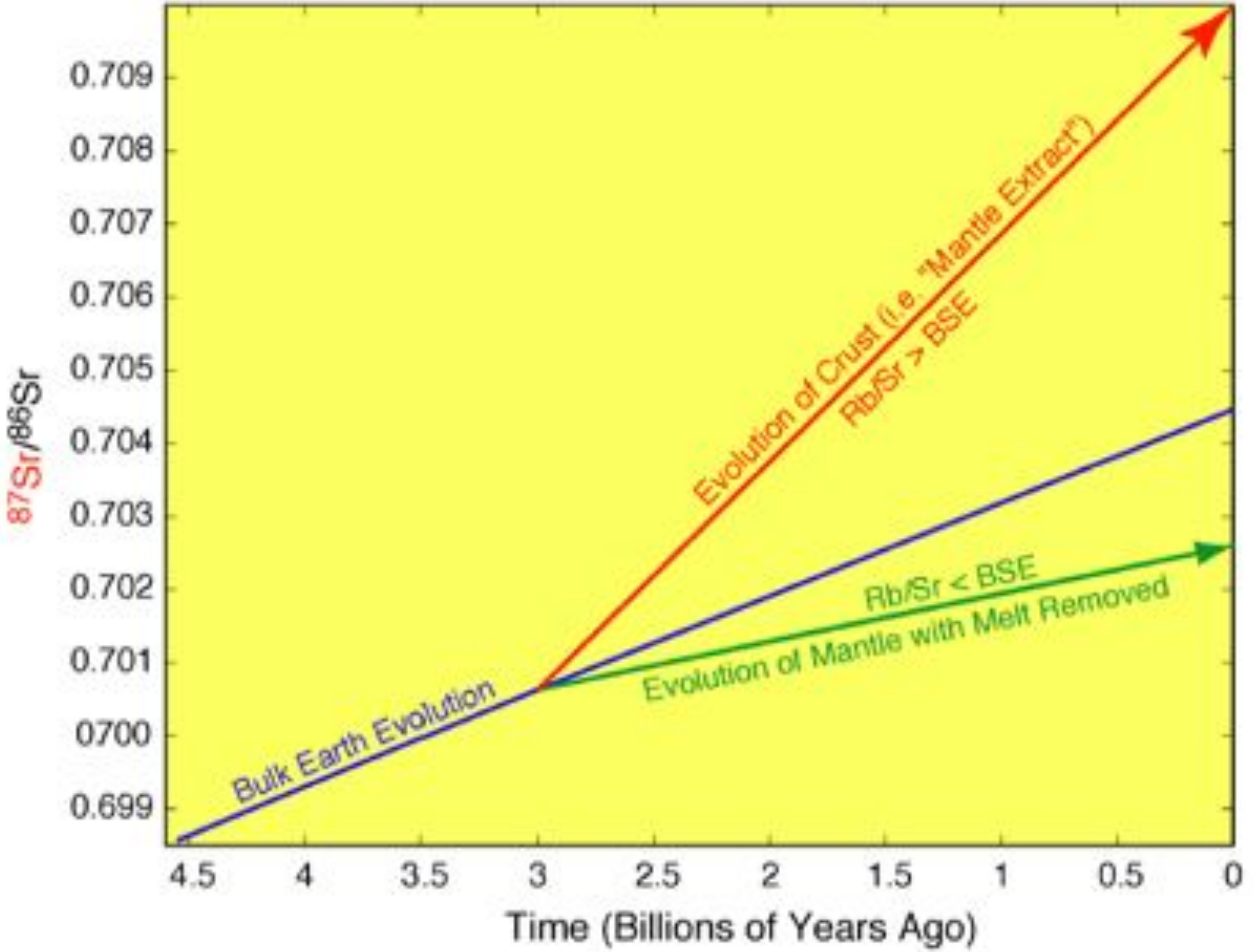
Melt Transport Through Focused Porous Flow



M. Braun via
Workman, 2004



Tackley, 2000



0.709
0.708
0.707
0.706
0.705
0.704
0.703
0.702
0.701
0.700
0.699
87Sr/86Sr
Evolution of Crust (i.e. "Mantle Extract")
Rb/Sr > BSE
Rb/Sr < BSE
Evolution of Mantle with Melt Removed
Bulk Earth Evolution
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Time (Billions of Years Ago)

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.

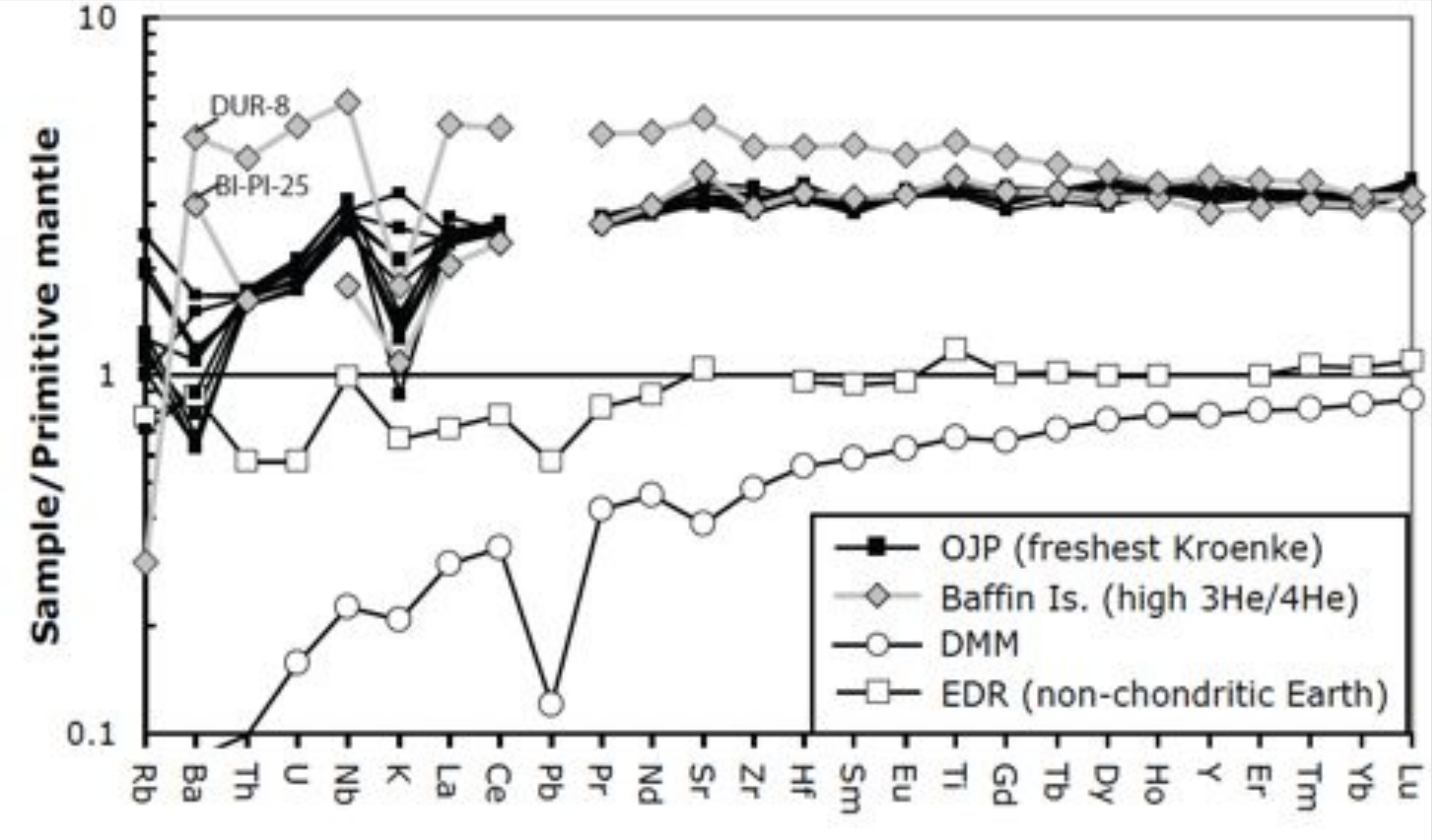
1. These anomalies not confirmed in either previous (Hidaka et al. 2003) or more recent studies (Andreasen & Sharma 2007; Carlson et al. 2007; Wombacher & Becker 2007).
2. Although excesses in 135Ba and 137Ba, which are related to variations in the ratio of r- to s-process components, have been observed 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

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



Jackson and Carlson (Nature, in review)

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?

Primitive Material in "superplumes"?

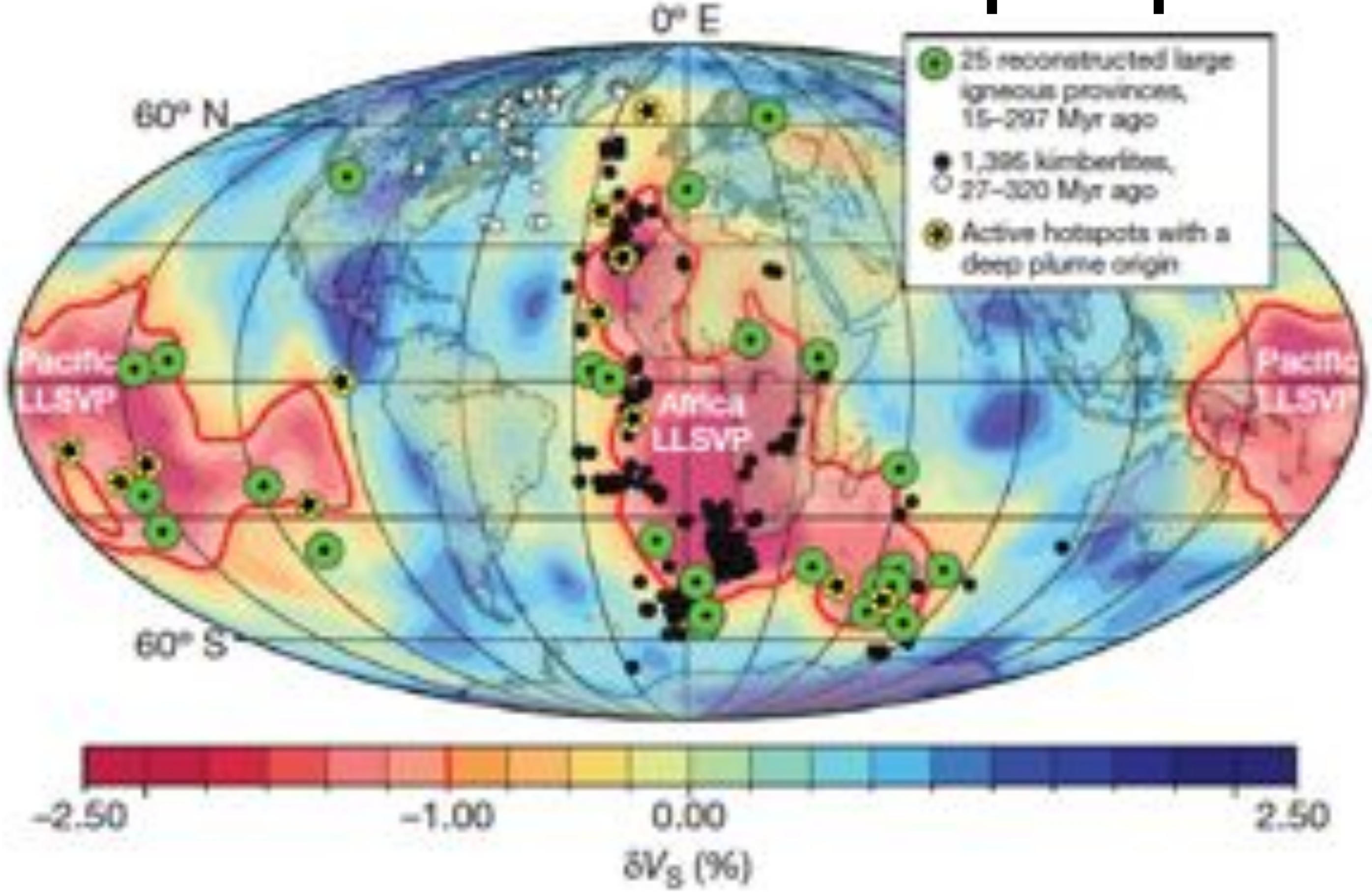
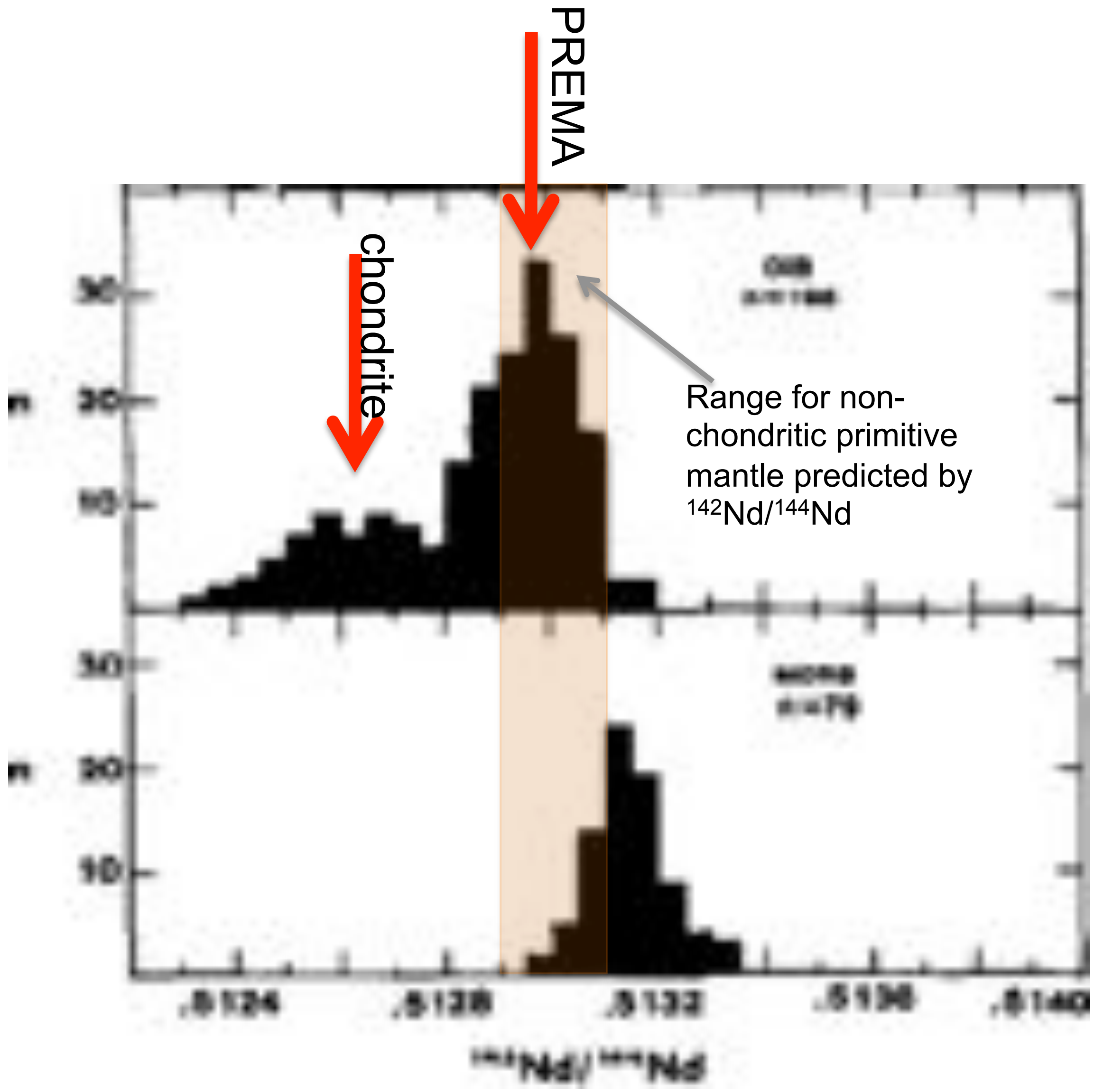


Figure 1 | Reconstructed large igneous provinces and kimberlites for the past 320 Myr with respect to shear-wave anomalies at the base of the mantle. The deep mantle (2,800 km on the SMEAN tomography model[20]) is dominated by two LLSVPs beneath Africa and the Pacific. The 1% slow contour (approximating to the PGZs) is shown as a thick red line. 80% of all reconstructed kimberlite locations (black dots) of the past 320 Myr erupted near or over the sub-African PGZ. The most 'anomalous' kimberlites (17%)

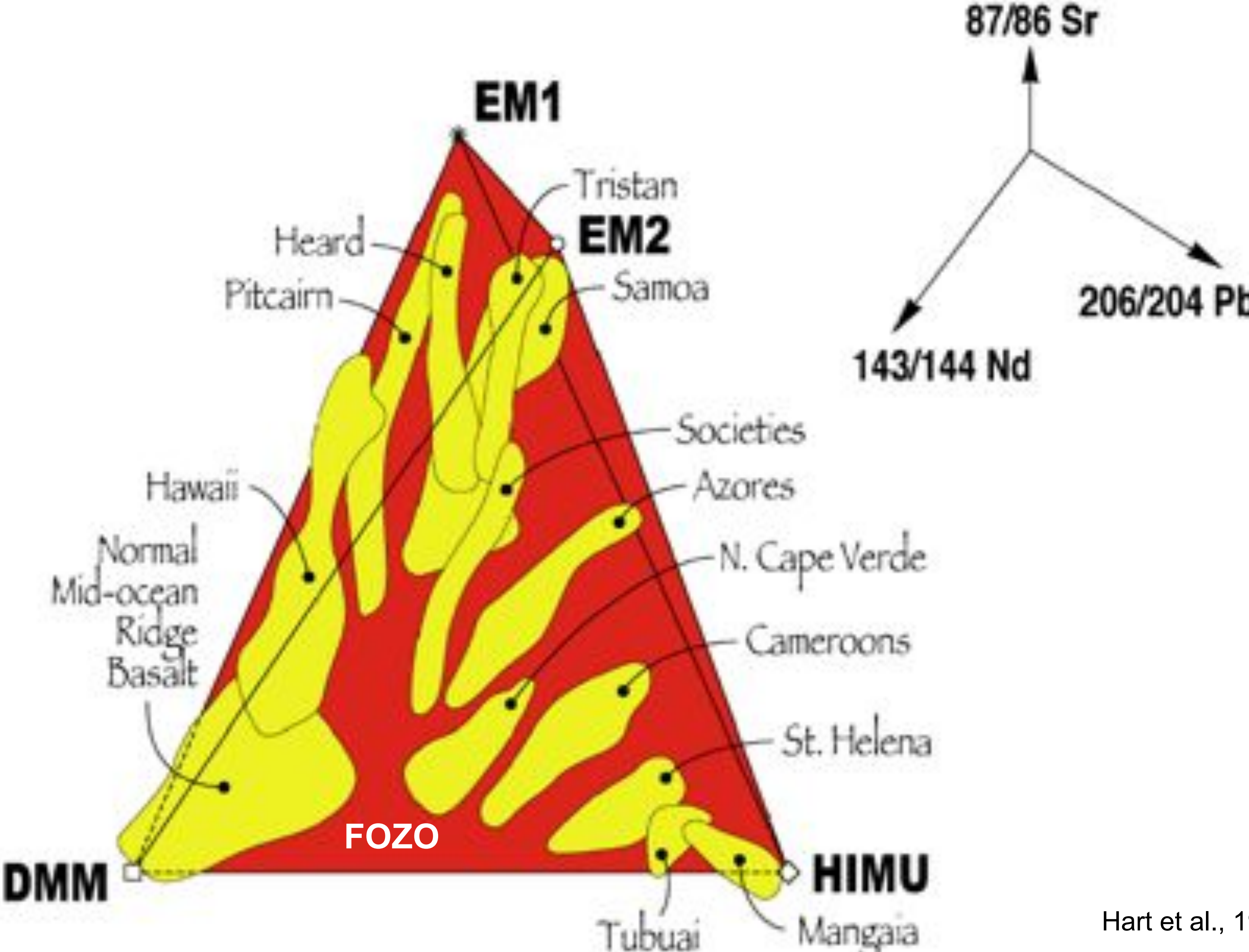
Torsvik et al. (Nature, 2010)

PREMA? (*Pre*valent *Ma*ntle)

- PREMA defined by the most frequently occuring $^{143}Nd/^{144}Nd$ in global OIB dataset. Zindler and Hart (1986)
- PREMA is isotopically similar to the highest $^{3}He/^{4}He$ lavas from Baffin Island.
- Is PREMA a surviving portion of a non-chondritic Primitive Mantle?

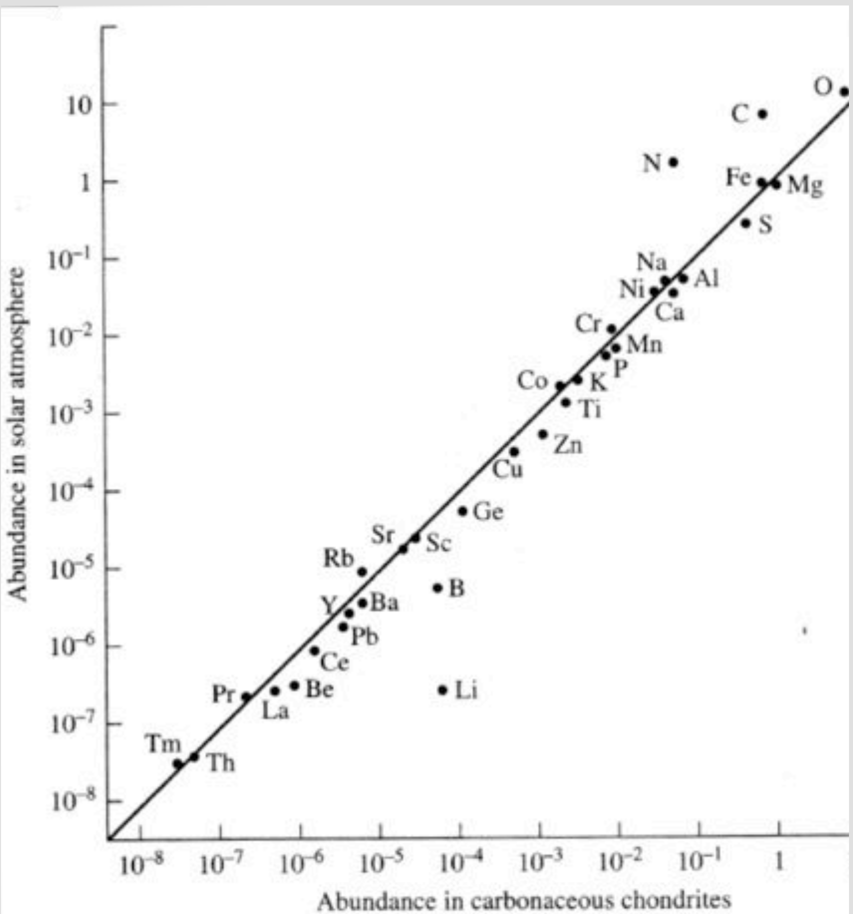


Zindler and Hart, 1986



Hart et al., 1992

Starting composition of the Earth—Chondritic?



Comparison of solar-system abundances (relative to silicon) determined by solar spectroscopy and by analysis of carbonaceous chondrites (after Ringwood, 1979)

1.) Carbonaceous (C) chondrites ≈ Sun

2.) C-chondrites and Earth came from the same (**homogeneous?**) solar nebula, and the sun represents over 99.9% of solar system's mass.

The next step requires a **huge** assumption:

3.) Therefore, C-chondrites ≈ Earth (non-volatile, lithophile elements like Sm and Nd)

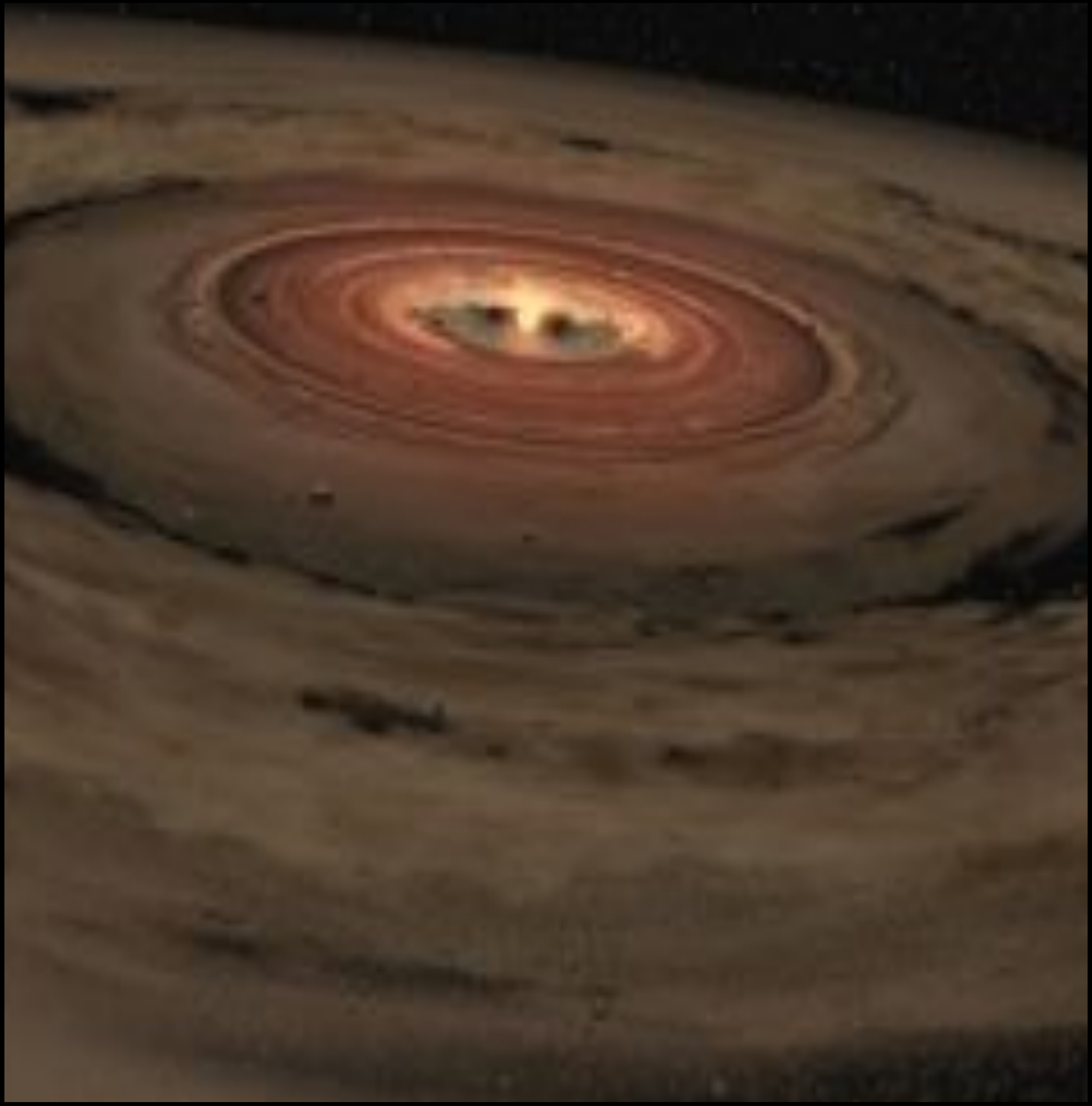
4.) If the Earth is a C-chondrite, then Earth and chondrites have the same $^{143}Nd/^{144}Nd$. ($^{147}Sm \rightarrow {}^{143}Nd + {}^{4}He$)

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}).

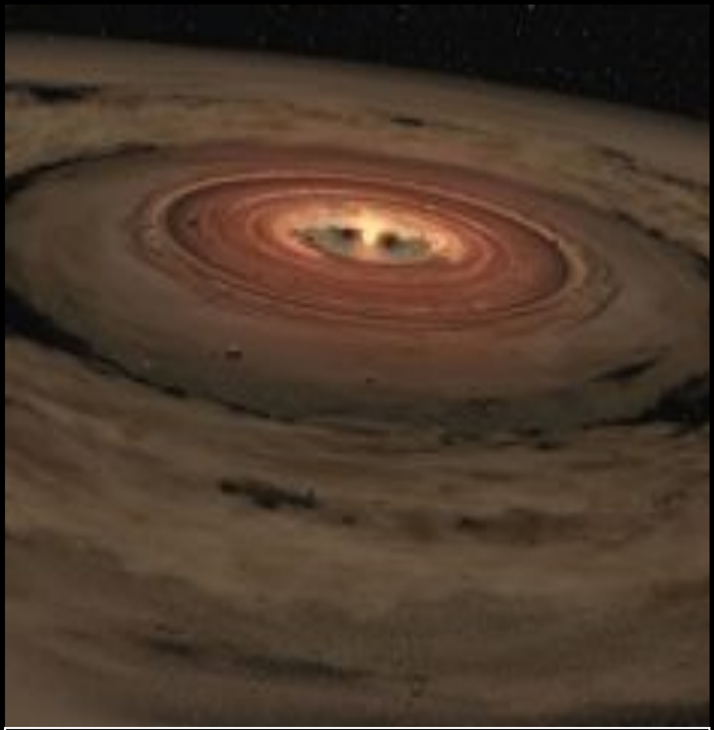
- The sun (solar wind) and the atmosphere of Jupiter have high $^3He/^4He$. High $^3He/^4He$ is thought to be primordial.

Homogeneous?



Courtesy of NASA/JPL-Caltech

In the beginning….



Courtesy of NASA/JPL-Caltech

4.568 Ga (Bouvier & Wadhwa, 2010)

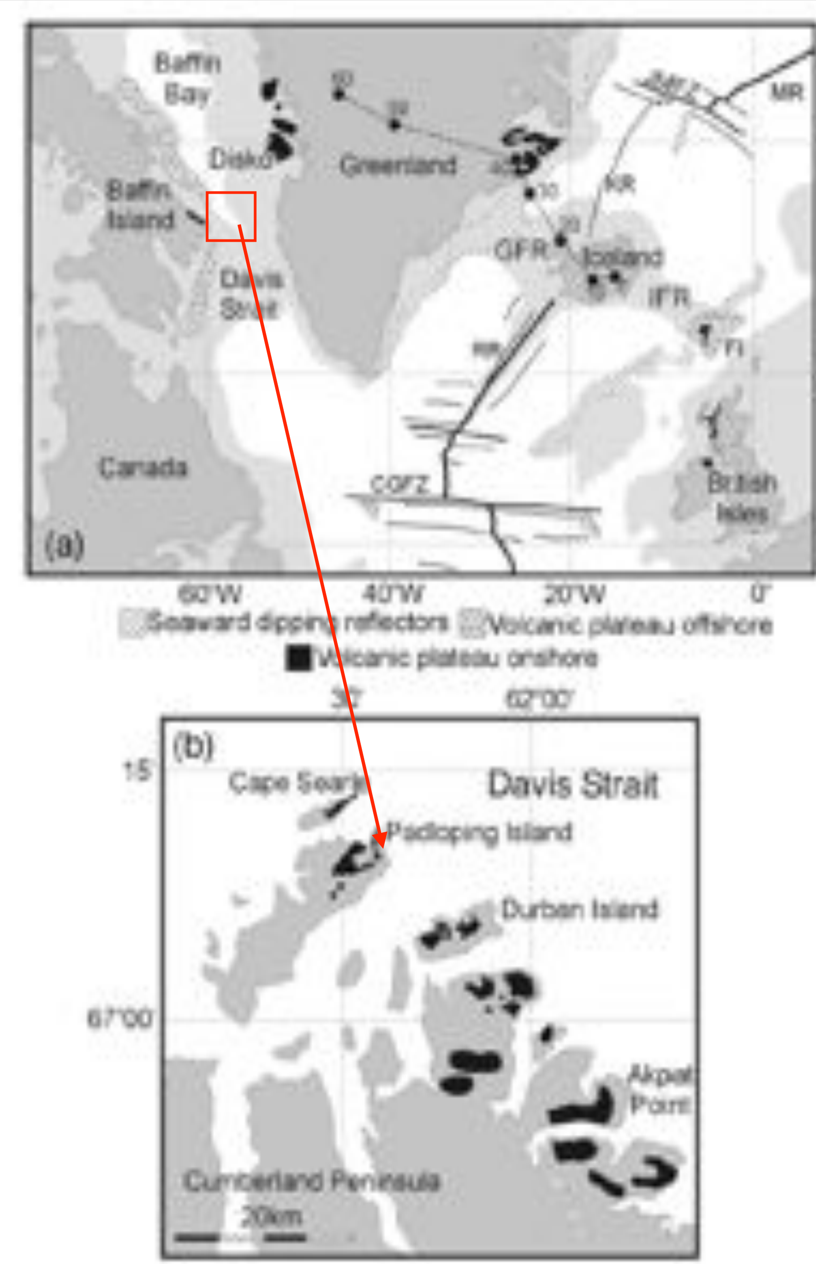
Solar Nebula Theory:

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

Part 2: Did portions of the earliest, primitive mantle survive to the present day?

--The "Holy Grail" of mantle geochemistry
--The "initial condition" for the silicate Earth required for modeling evolution.
--The discovery would constrain the Earth's early chemical evolution: How did the Earth arrived at its present geochemical state?

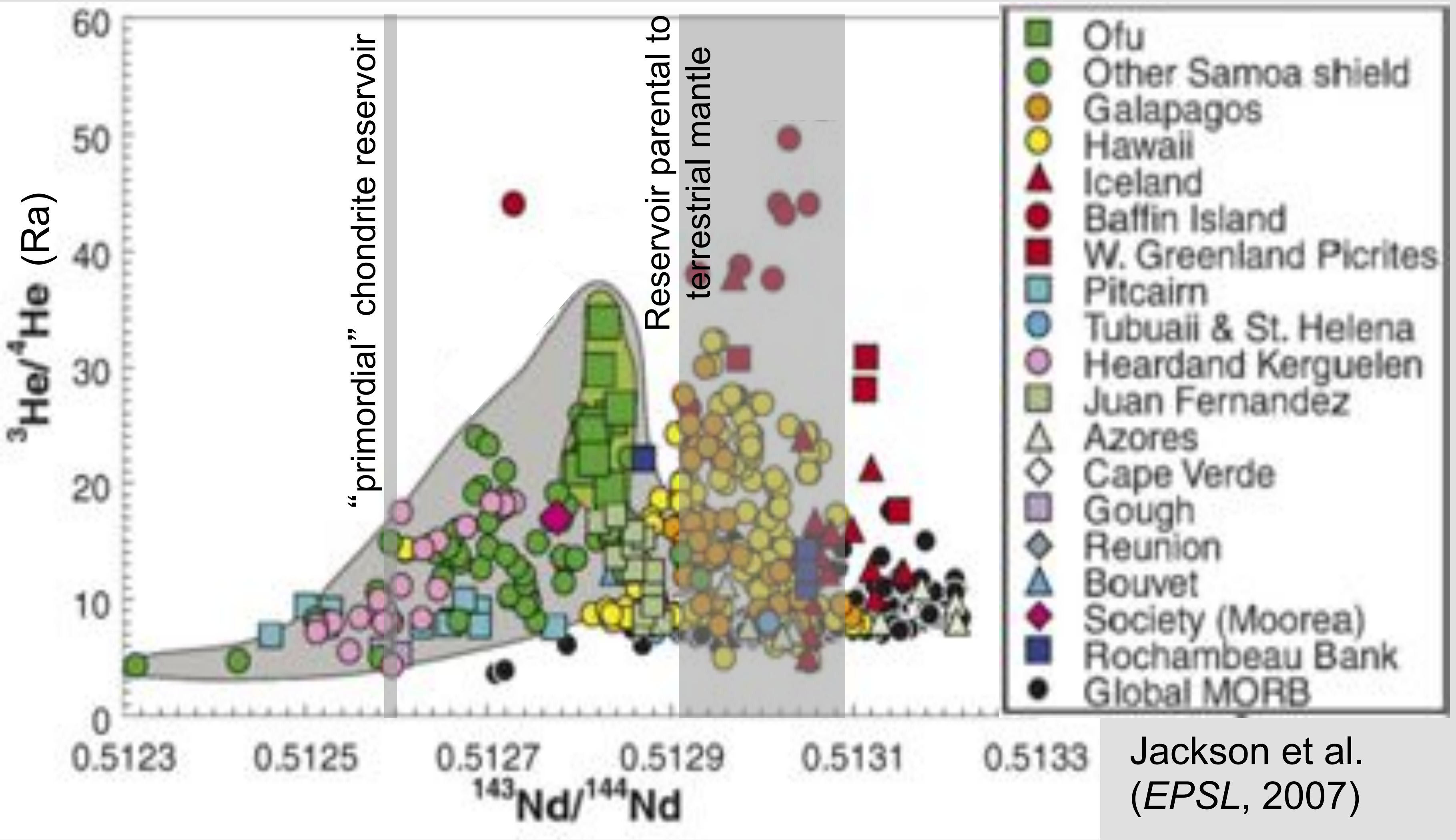
Baffin Island and West Greenland picrites



Starkey et al., 2009

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

Baffin Island lavas have highest terrestrial mantle $^3He/^4He$



Jackson et al. (*EPSL*, 2007)

What about *initial* ^{3}He/^{4}He on OJP? (and the other *old* flood basalts?)

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]

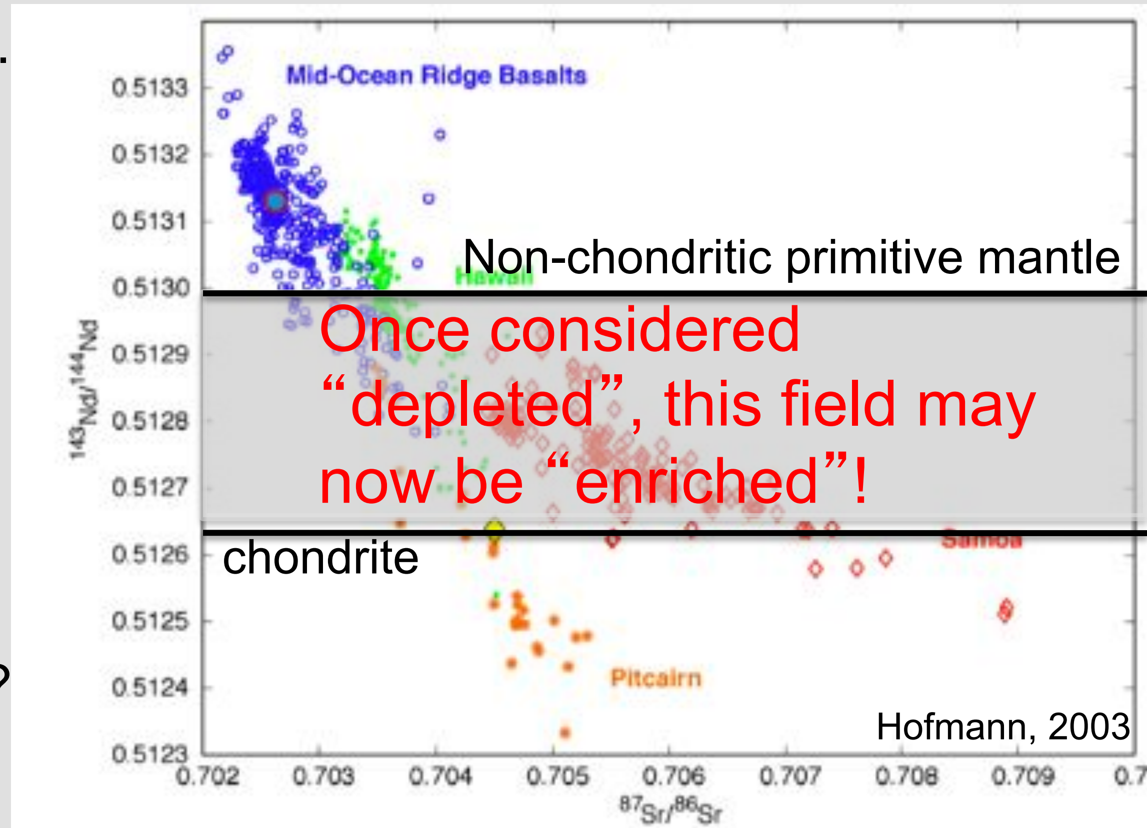
"….olivine phenocrysts in basalt are embedded in basaltic groundmass that has much higher [U] and [Th] than the olivine. Consequently, ^{4}He from alpha-decay of groundmass U is implanted into the rims of the olivine grains."

A non-chondritic Earth?

The community has known for several decades that the Earth doesn’t have oxygen isotopes like C and O-chondrites!

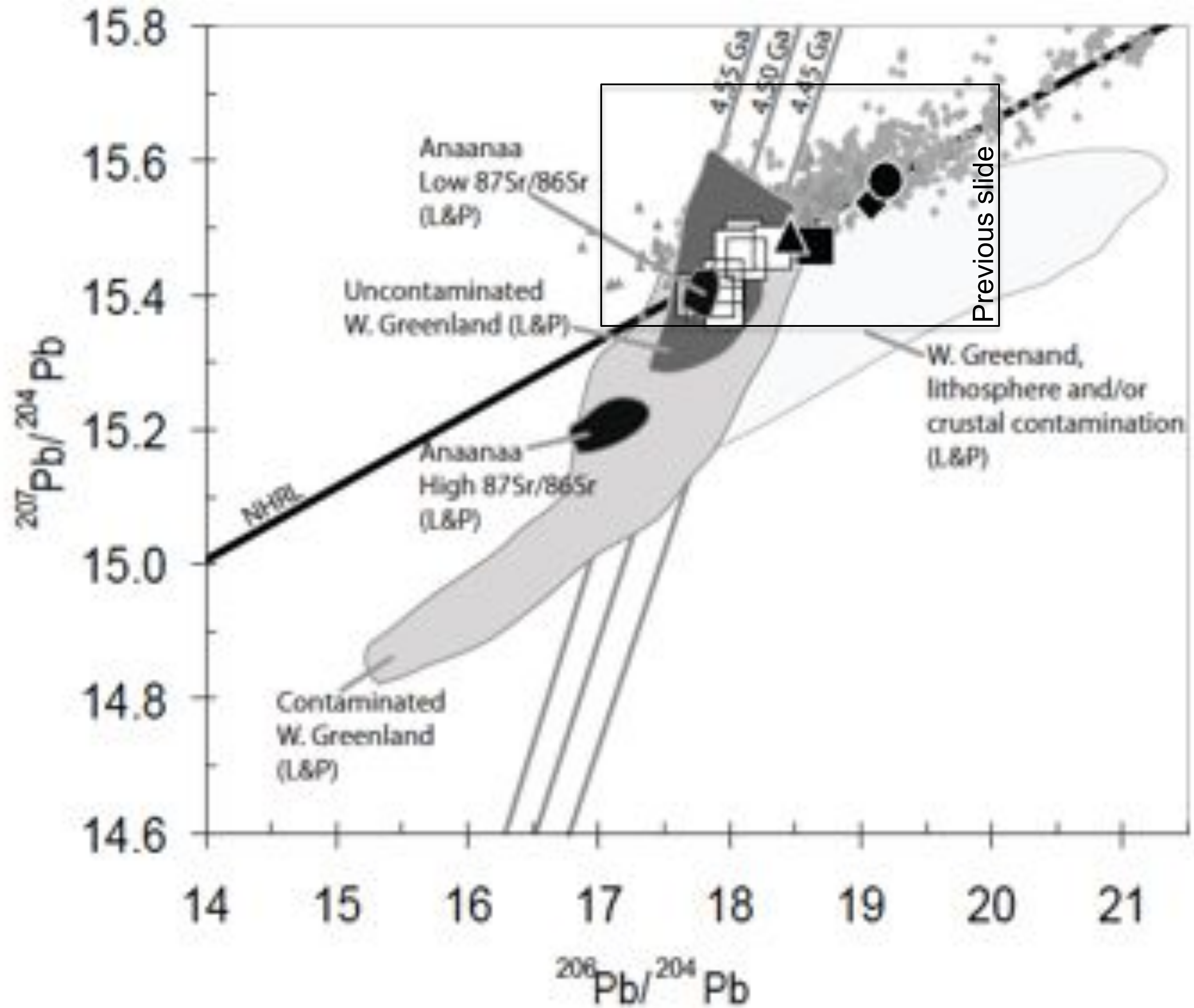
Implications:

1. DMM is >45-90% of the mantle (to >1600 km depth). If primitive mantle $^{143}Nd/^{144}Nd$ is 0.5130, instead of 0.51264, 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!



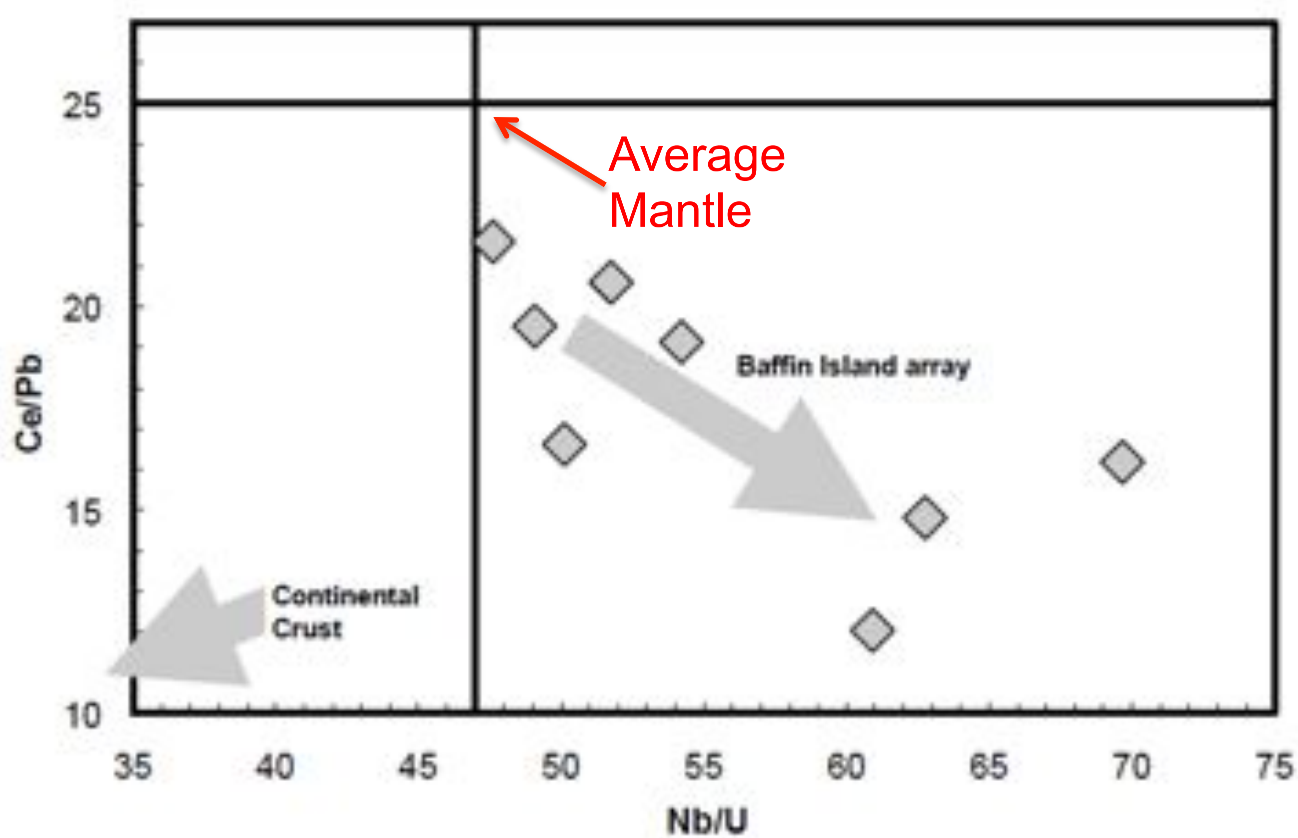
Far from being a “dying field”, we are in the midst of a geochemical revolu

Caveat: Crustal contamination



Jackson et al. (*Nature*, 2010)

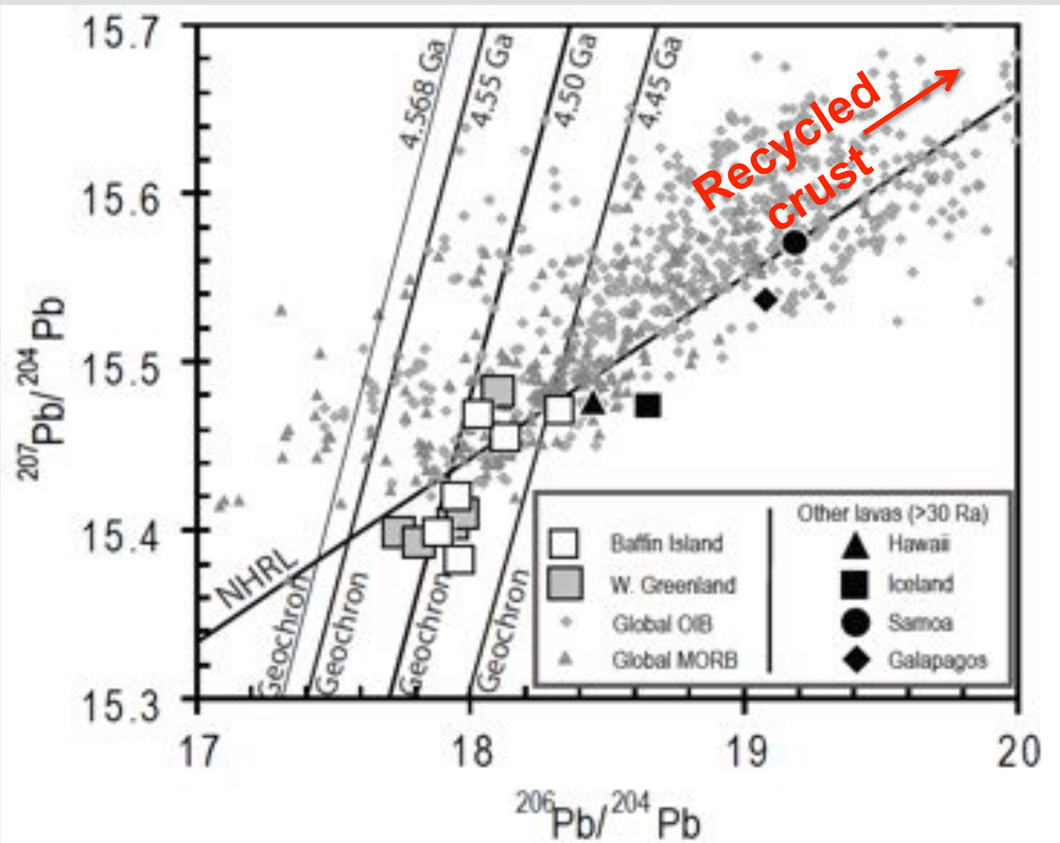
Trace elements indicate no role for continental contamination in our sample suite



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.

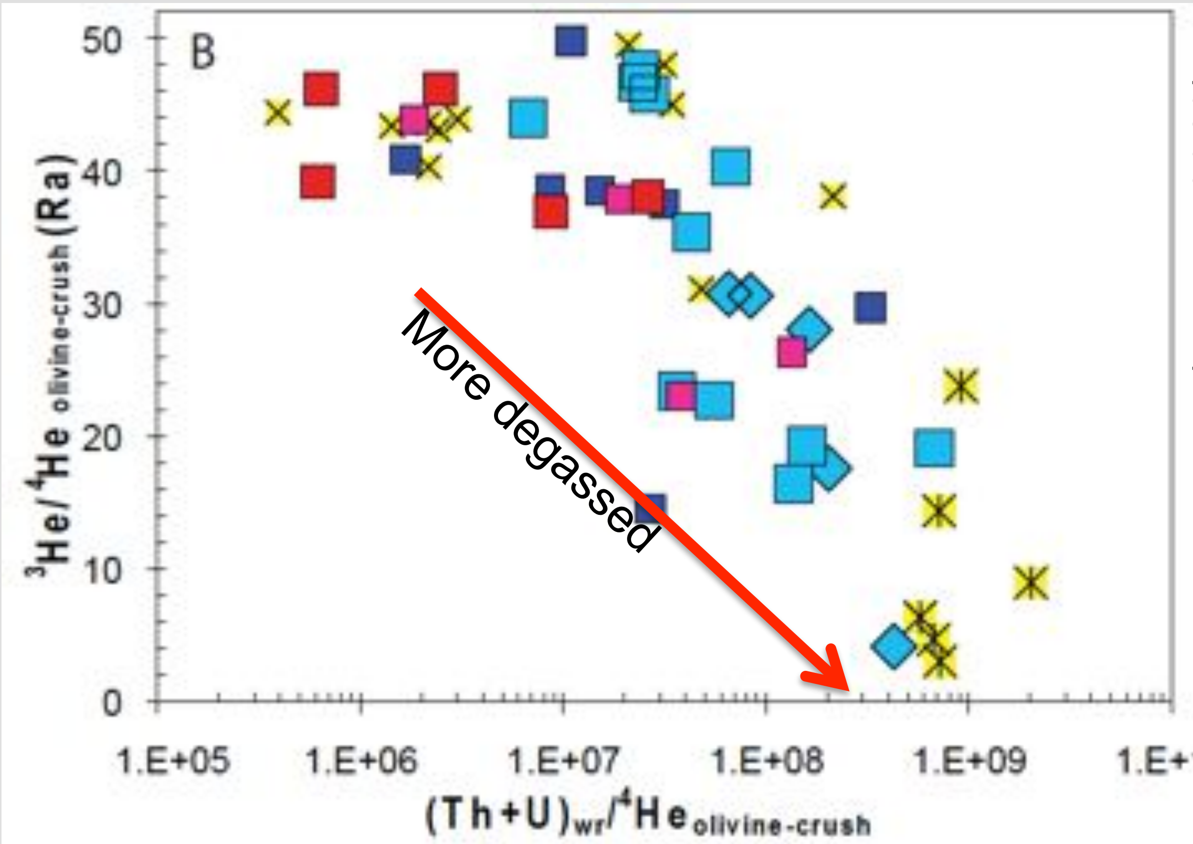
Why do high $^3He/^4He$ lavas from other localities plot off of the Geochron (and have somewhat lower $^3He/^4He$)?



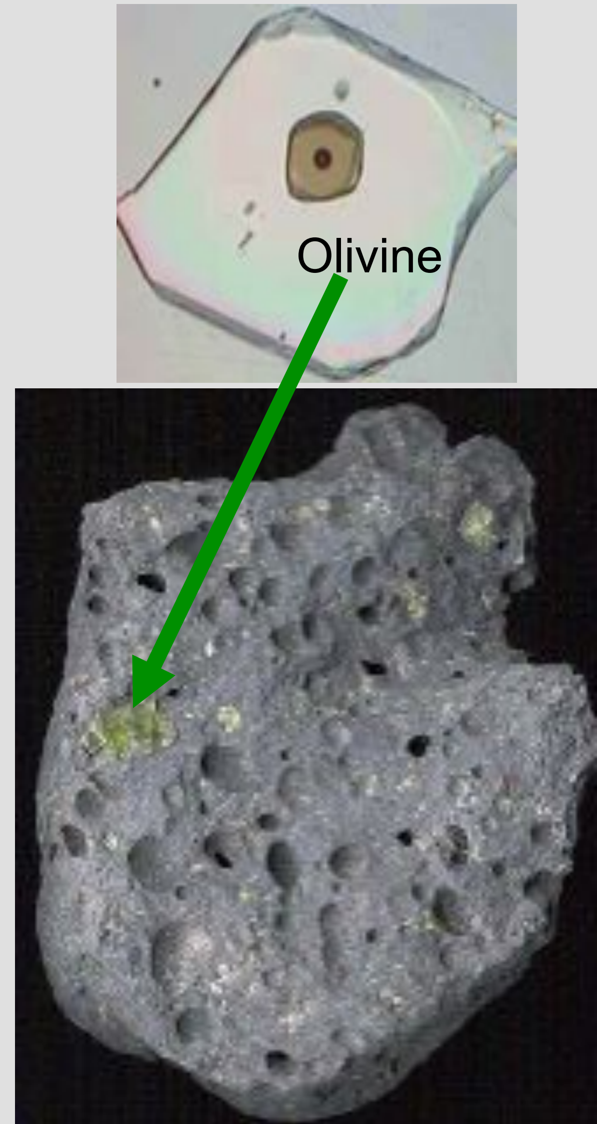
Jackson et al. (*Nature,* 2010)

- 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.

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

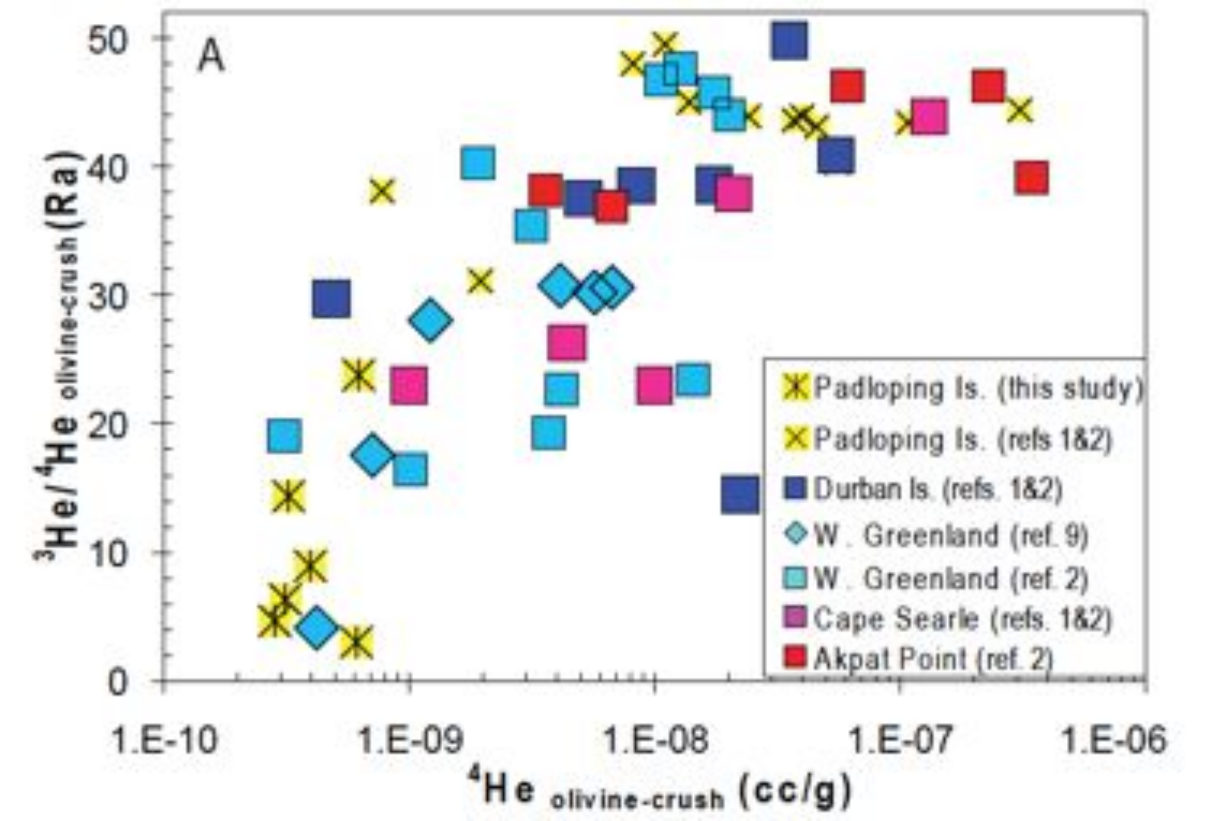


Jackson et al. (*Nature*, 2010)



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. ^{4}He generated by U and Th decay diminishes $^3He/^4He$ ratio.
4. **<u>Lesson:</u> Avoid measuring $^3He/^4He$ on old lavas (62 Ma)!**

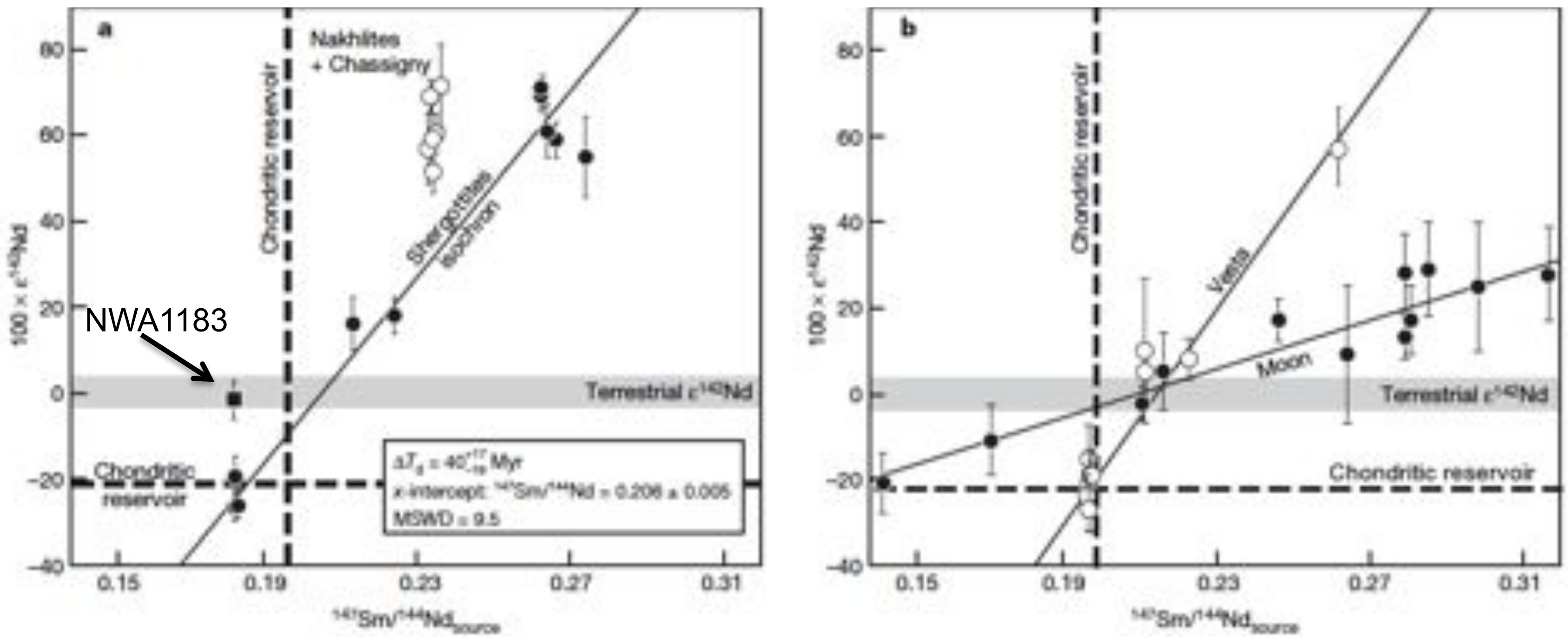
Another Caveat: Radiogenic ^4He



Jackson et al. (*Nature*, 2010)

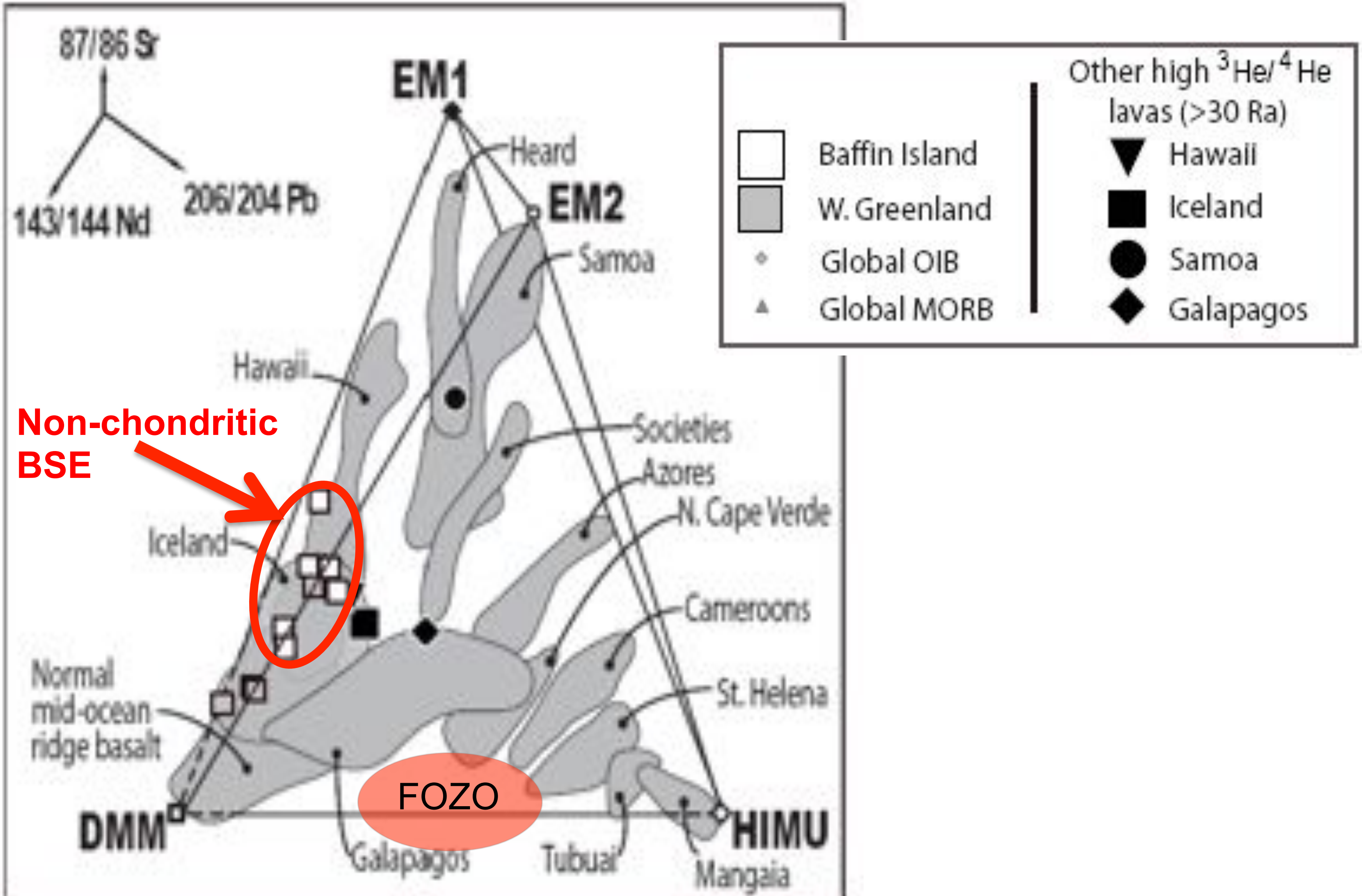
Super-chondritic Sm/Nd ratios in Mars, the Earth and the Moon

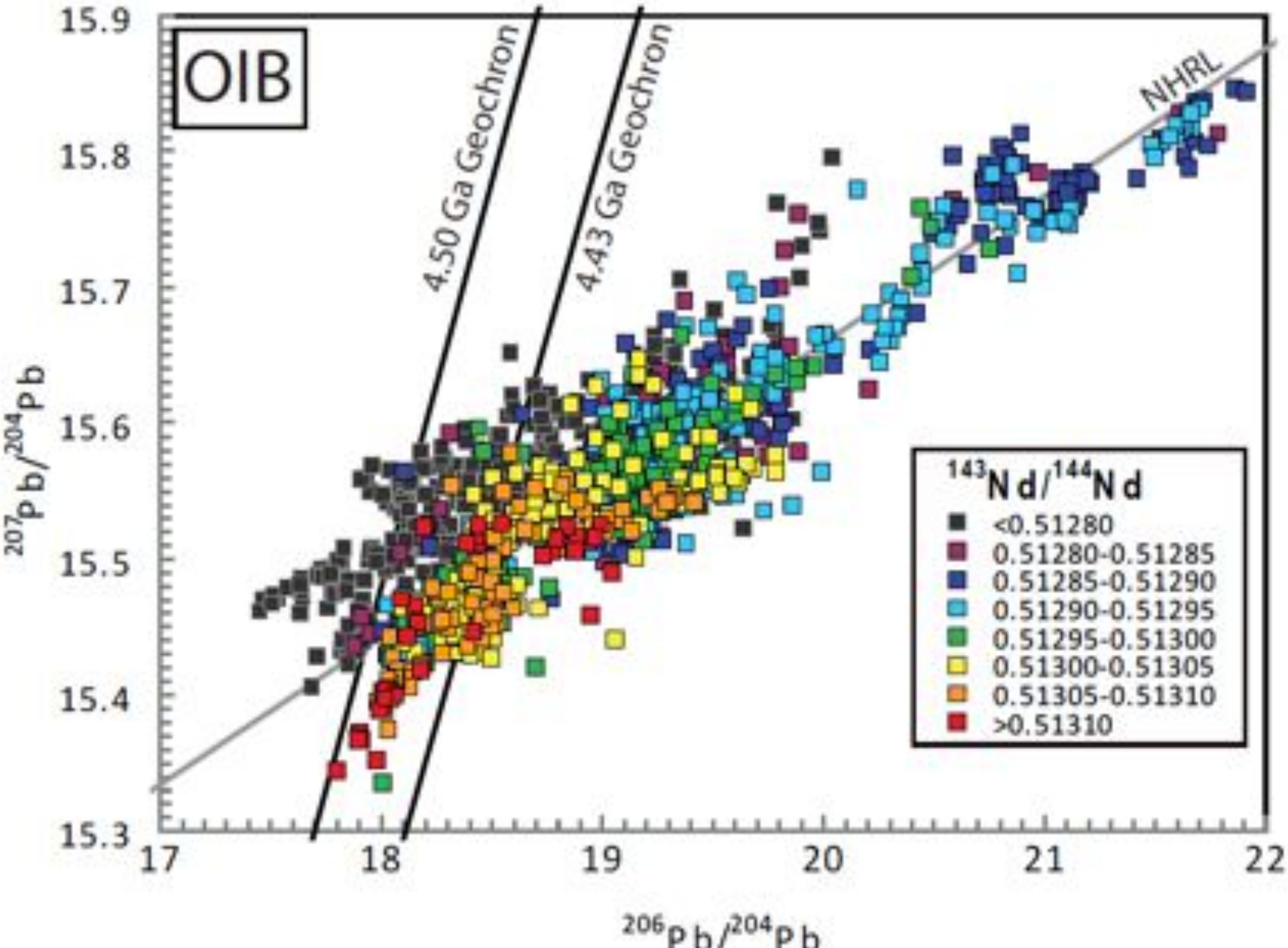
Guillaume Caro[1], Bernard Bourdon[2], Alex N. Halliday[3] & Ghylaine Quitté[4]



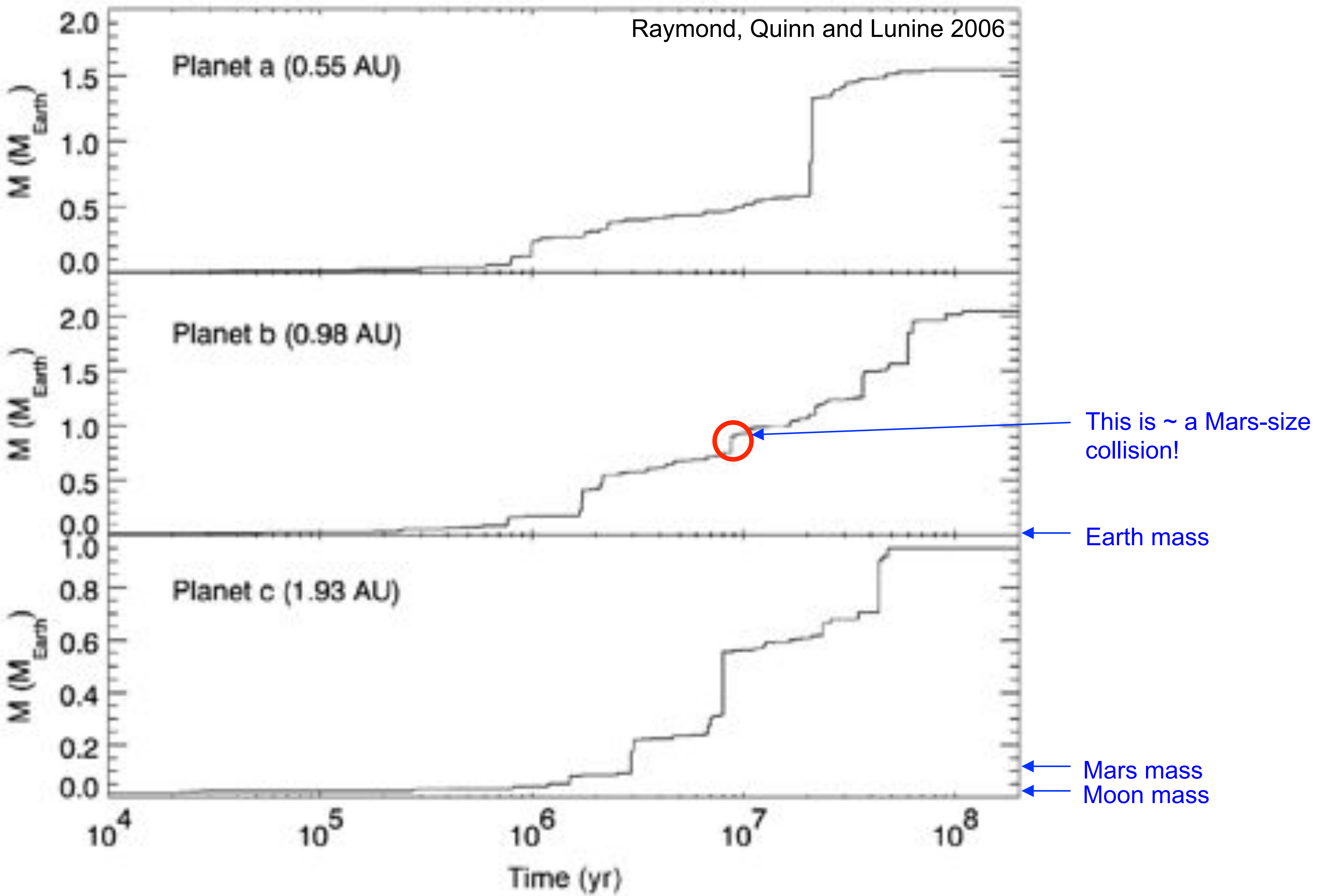
- Combined lunar datasets define an isochron which intersects the shergottite isochron at a value of Sm/Nd ~5% higher than chondritic, and $^{142}Nd/^{144}Nd$ like Earth.
- Planetary differentiation? If so, we need hidden enriched reservoirs on Earth, Moon and Mars which would have shifted the composition of the depleted reservoirs by the same amount.
- Given differences in size and age, this seems unlikely.
- The fact that the lunar and martian isochrons intersect at a $^{142}Nd/^{144}Nd$ ratio identical to the terrestrial value can hardly be coincidental….instead, all 3 bodies accreted form material with Sm/Nd ratio ~5% higher than chondrites.

The mantle tetrahedron



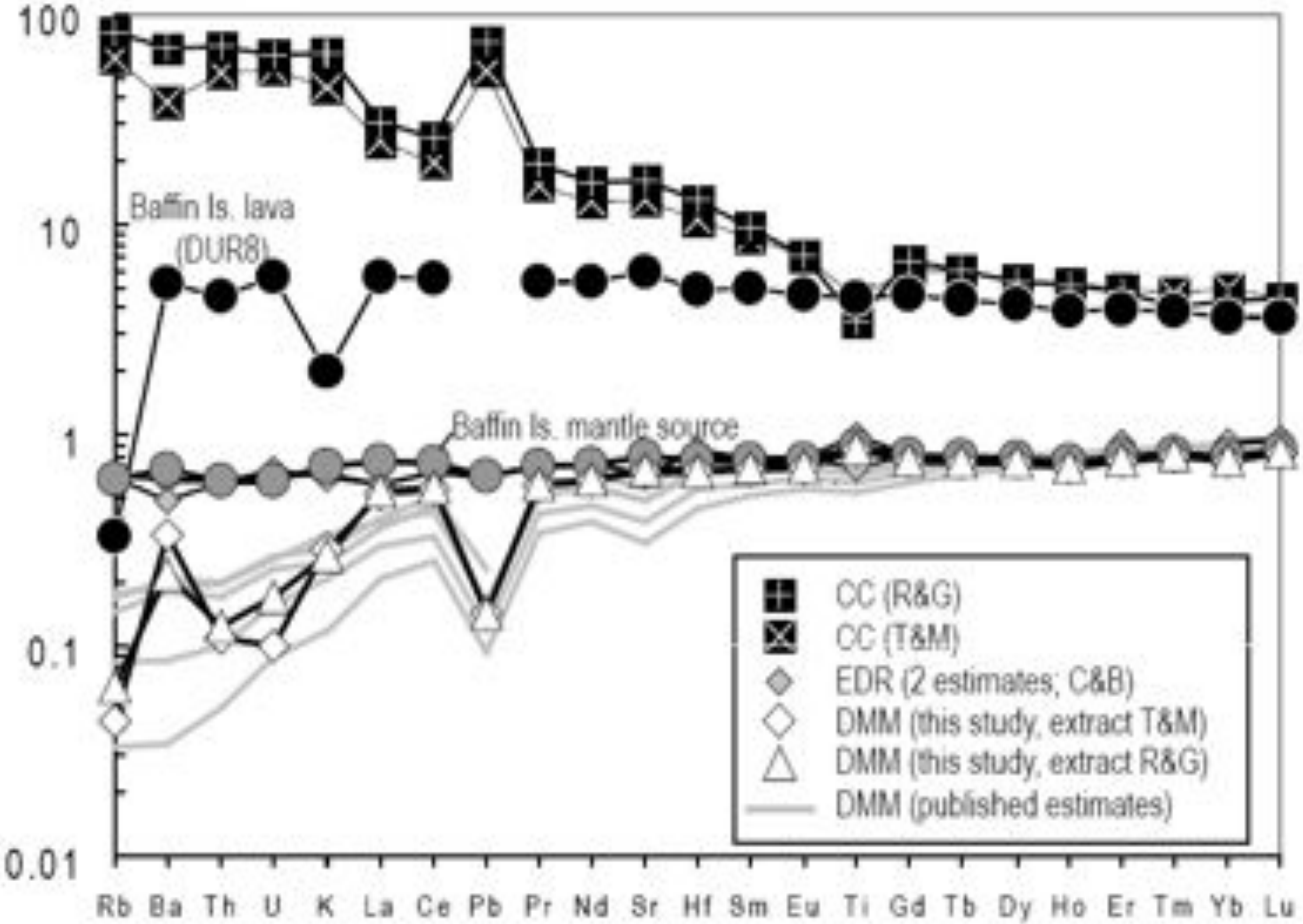


Jackson and Carlson (Nature, in review)

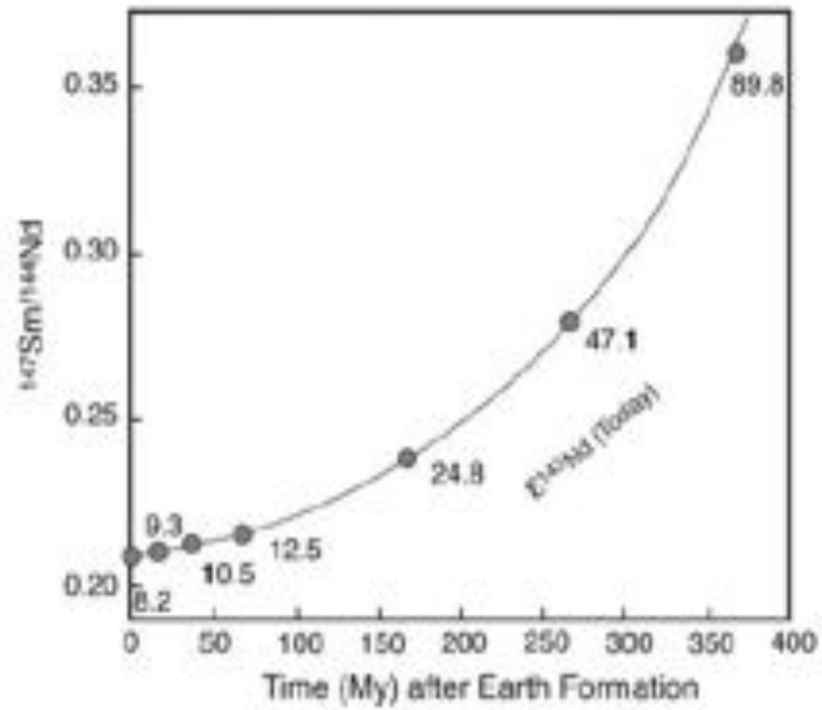


Showing the time-wise accretion of the largest three final planets

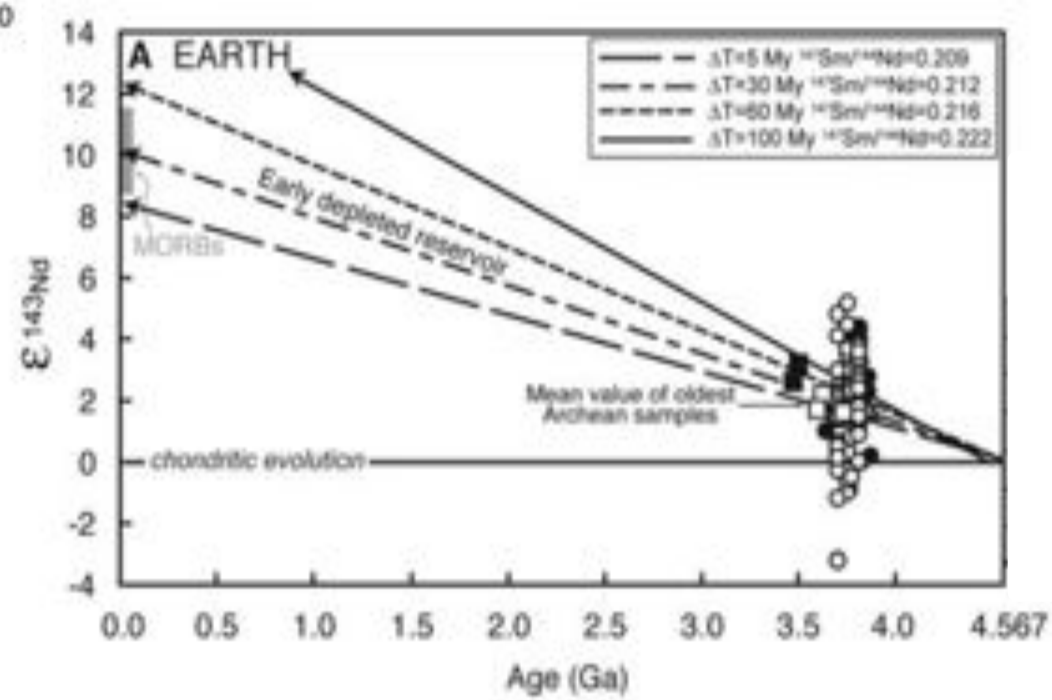
The three final planets were built from 175-500 initial embryos during 47-98 separate collisions



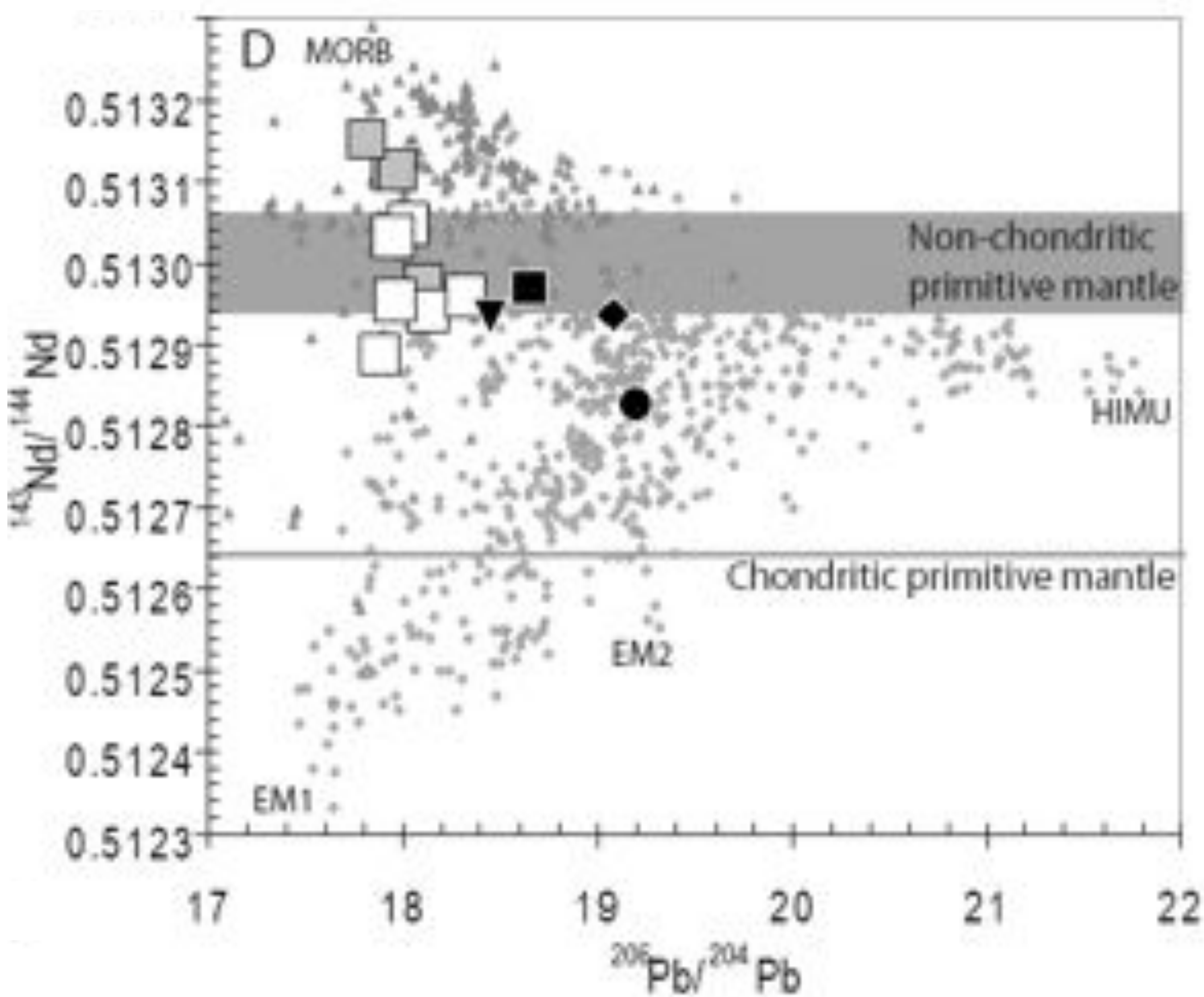
Jackson and Carlson (*Nature*, 2010)



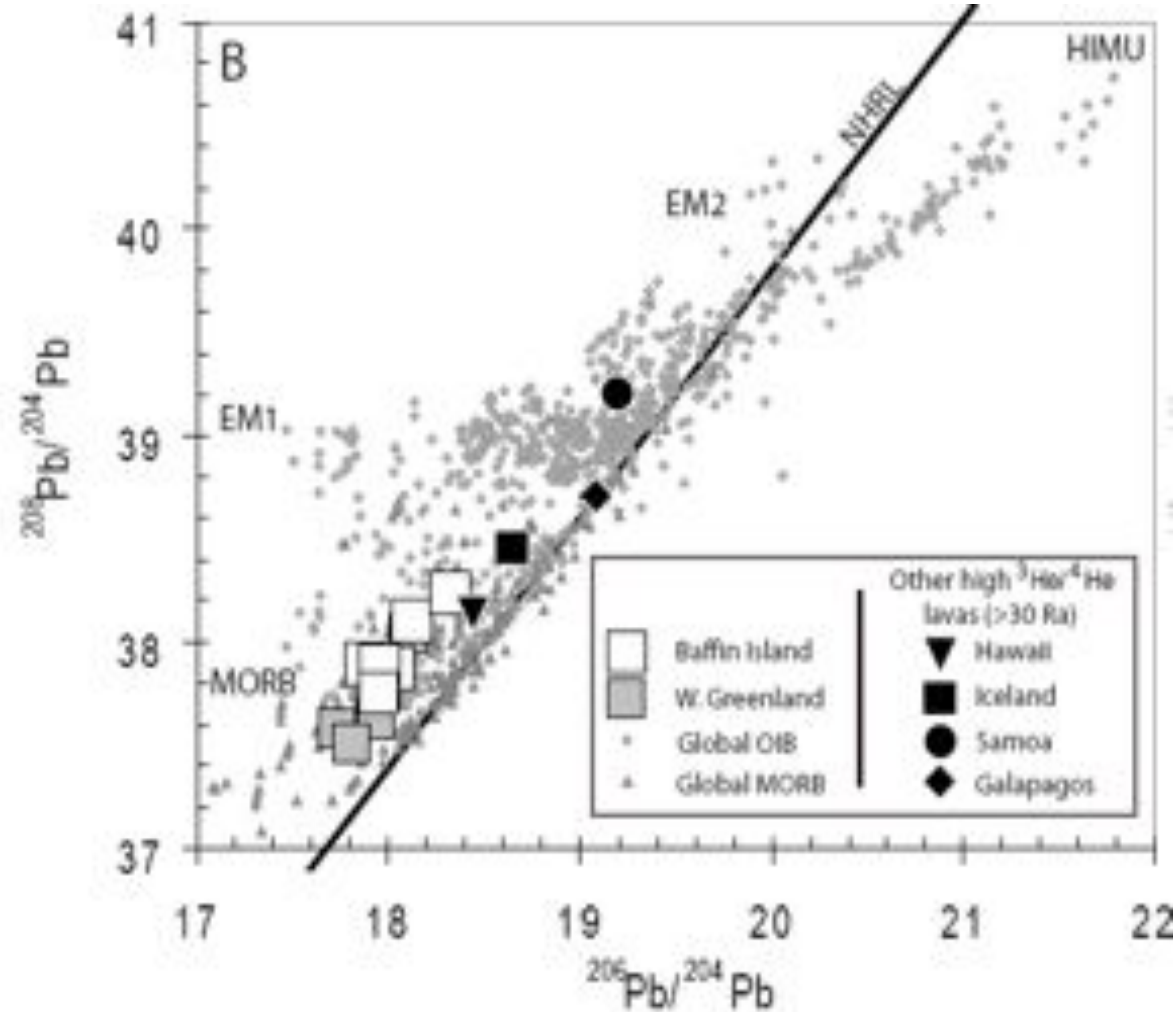
0.35
0.30
0.25
0.20
89.8
47.1
24.8
12.5
10.5
9.3
8.2
0
50
100
150
200
250
300
350
400
Time (My) after Earth Formation



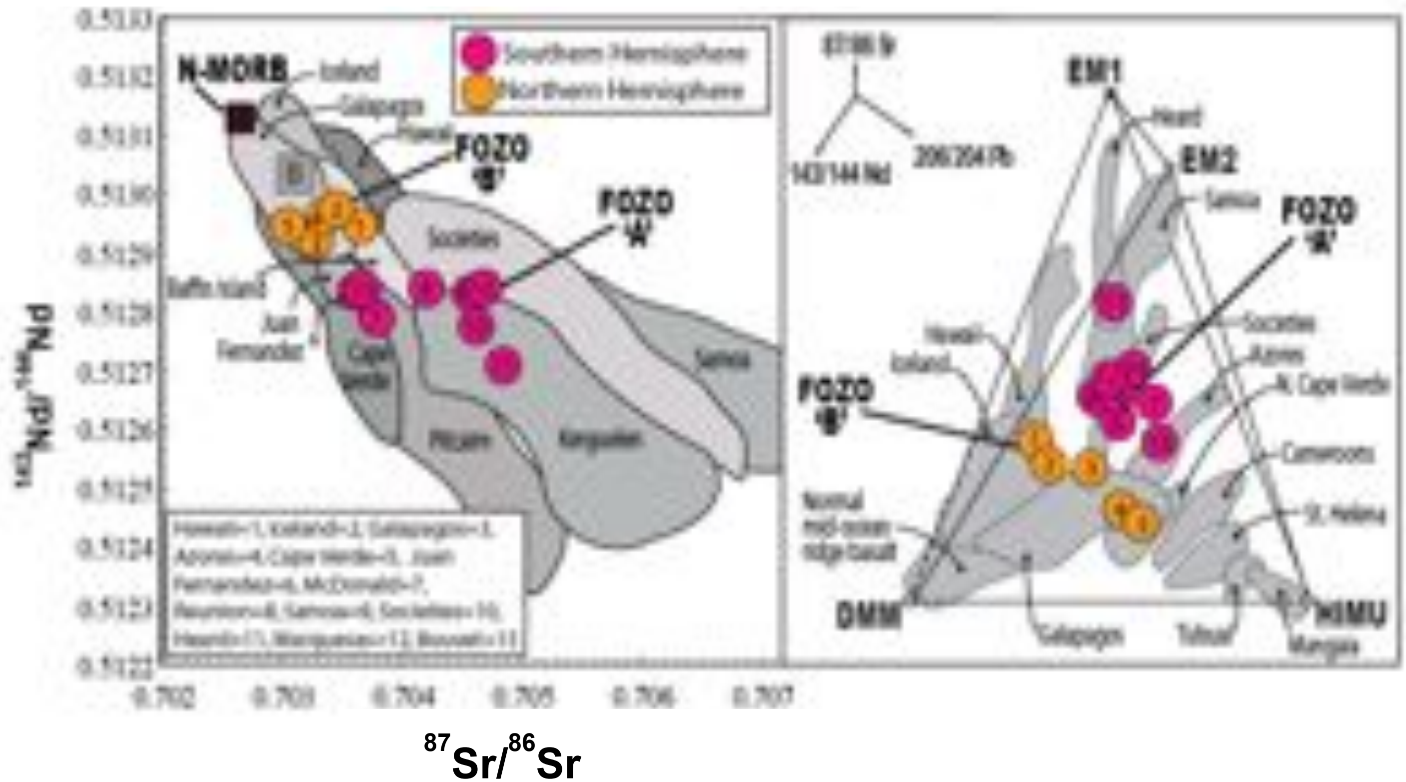
A EARTH
Early depleted reservoir
MORBs
chondritic evolution
Mean value of oldest Archean samples
14
12
10
8
6
4
2
0
-2
-4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.567
Age (Ga)

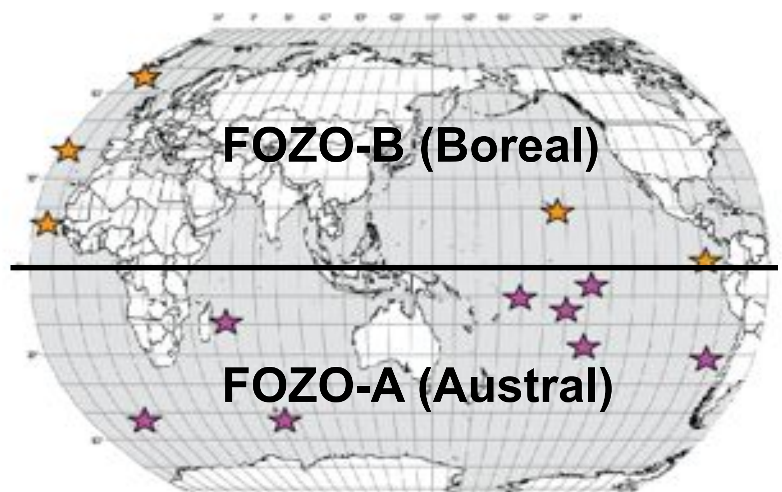


D
MORB
Non-chondritic
primitive mantle
HIMU
Chondritic primitive mantle
EM2
EM1
0.5132
0.5131
0.5130
0.5129
0.5128
0.5127
0.5126
0.5125
0.5124
0.5123
17
18
19
20
21
22
$^{143}Nd/^{144}Nd$
$^{206}Pb/^{204}Pb$

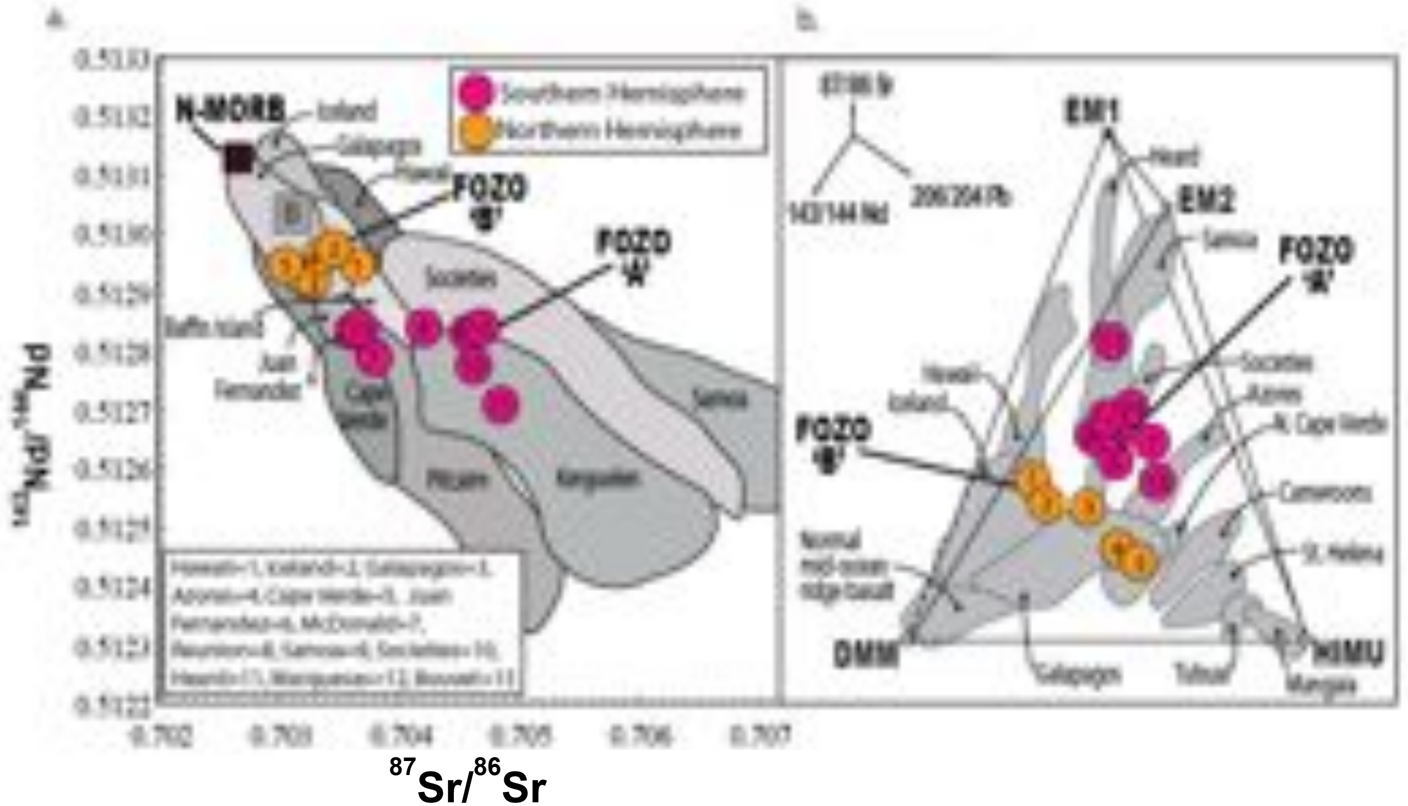

B
41
40
39
38
37
17
18
19
20
21
22
$^{208}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$
HIMU
NHRL
EM2
EM1
MORB
Baffin Island
W. Greenland
Global OIB
Global MORB
Other high $^3He/^4He$ lavas (>30 Ra)
Hawaii
Iceland
Samoa
Galapagos

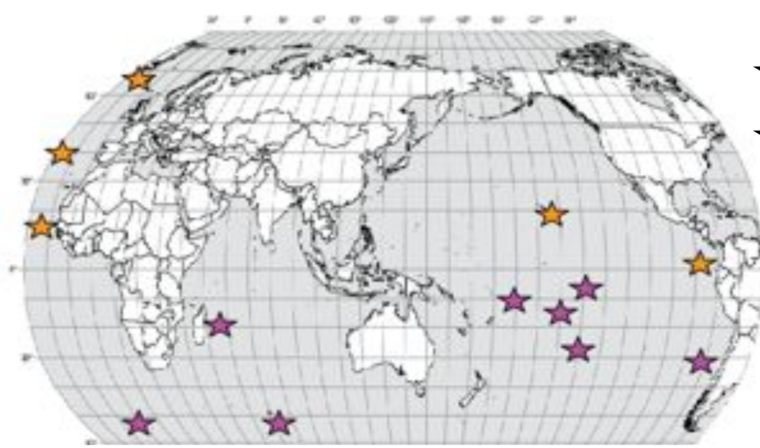
Hemispherically heterogeneous high $^{3}He/^{4}He$ mantle.





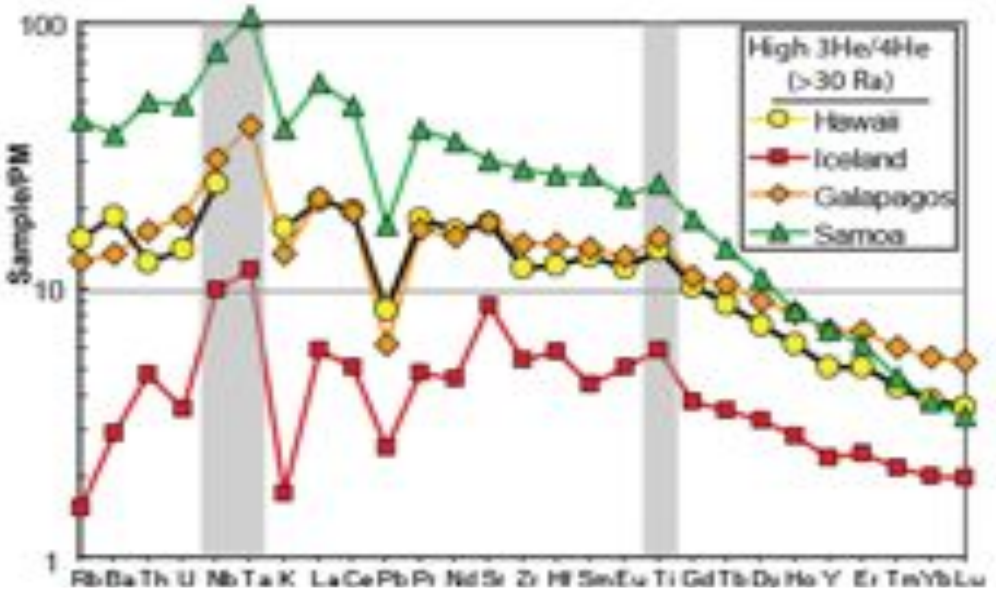
High $^{3}He/^{4}He$ mantle is heterogeneous.



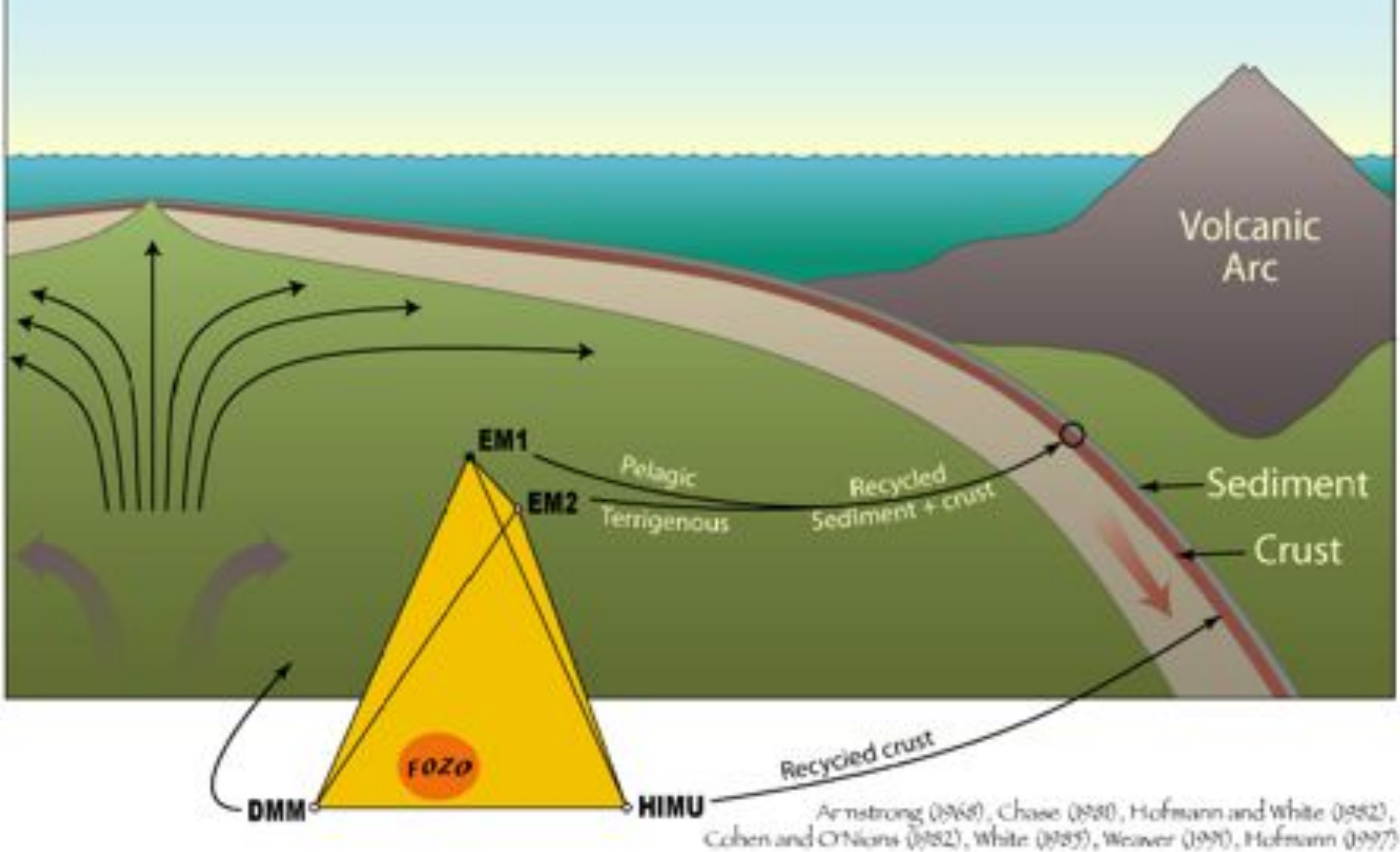


N. Hemisphere (boreal)
S. Hemisphere (austral)

Earth's "missing" titanium, tantalum and niobium (TITAN)

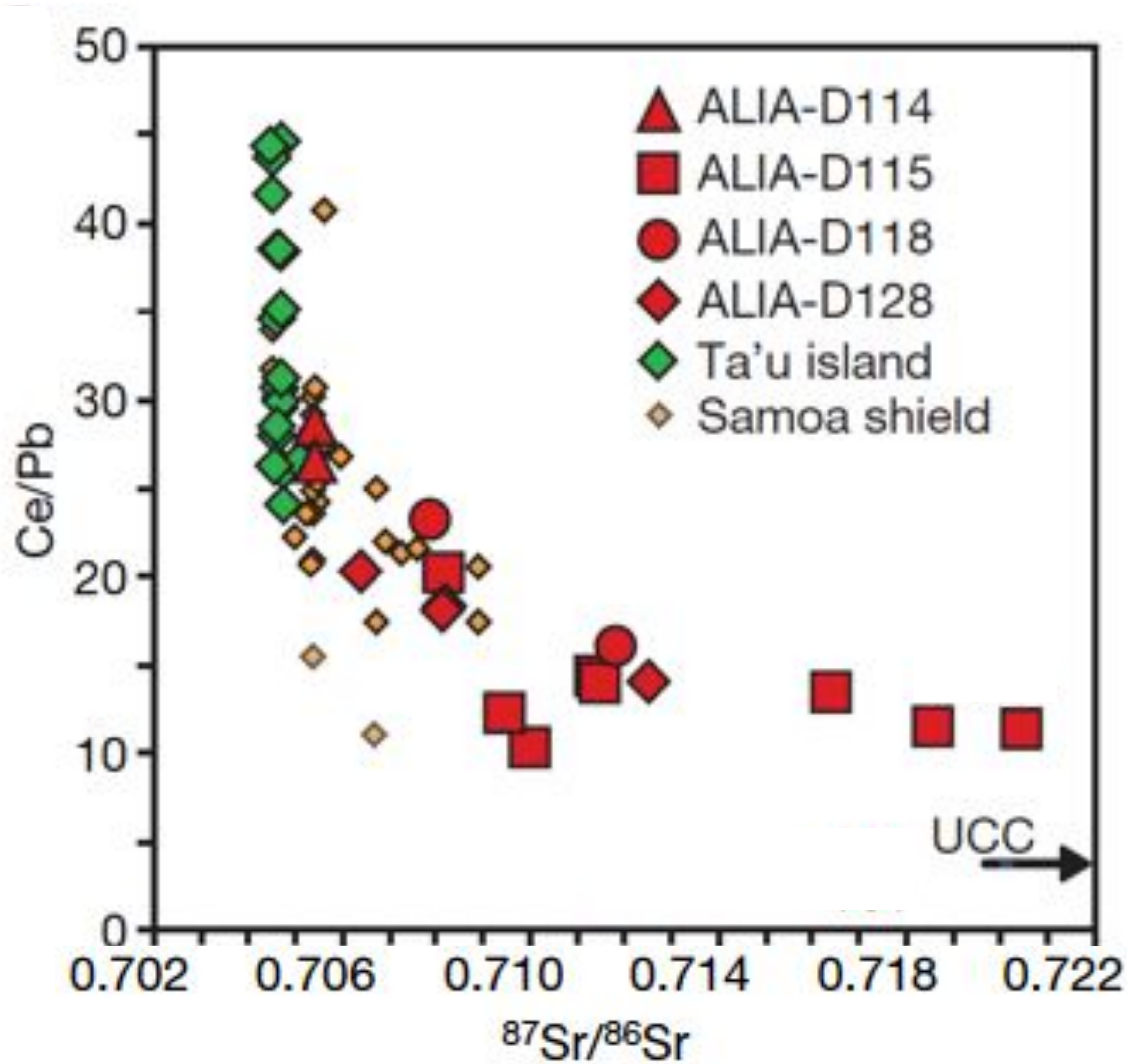


The Standard Model

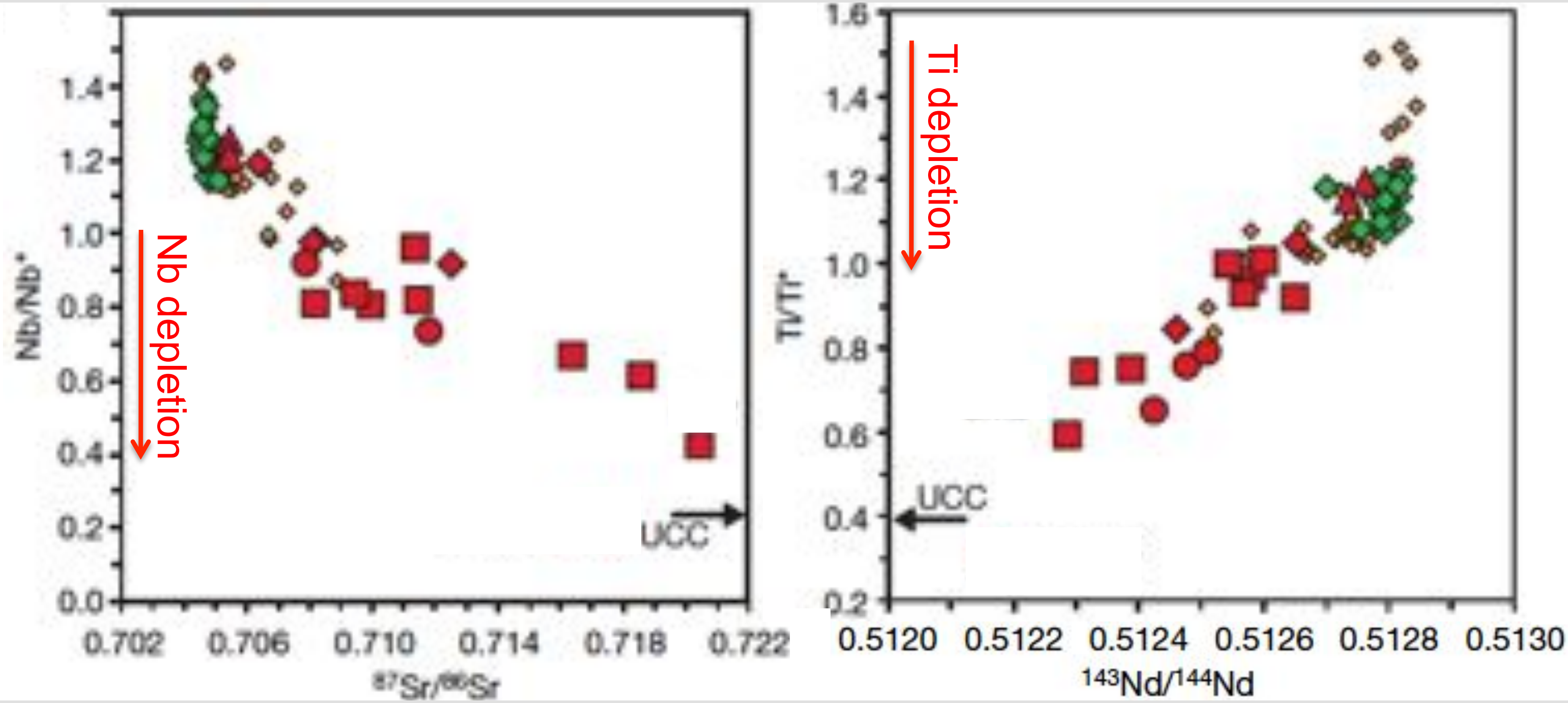


Workman et al., 2004

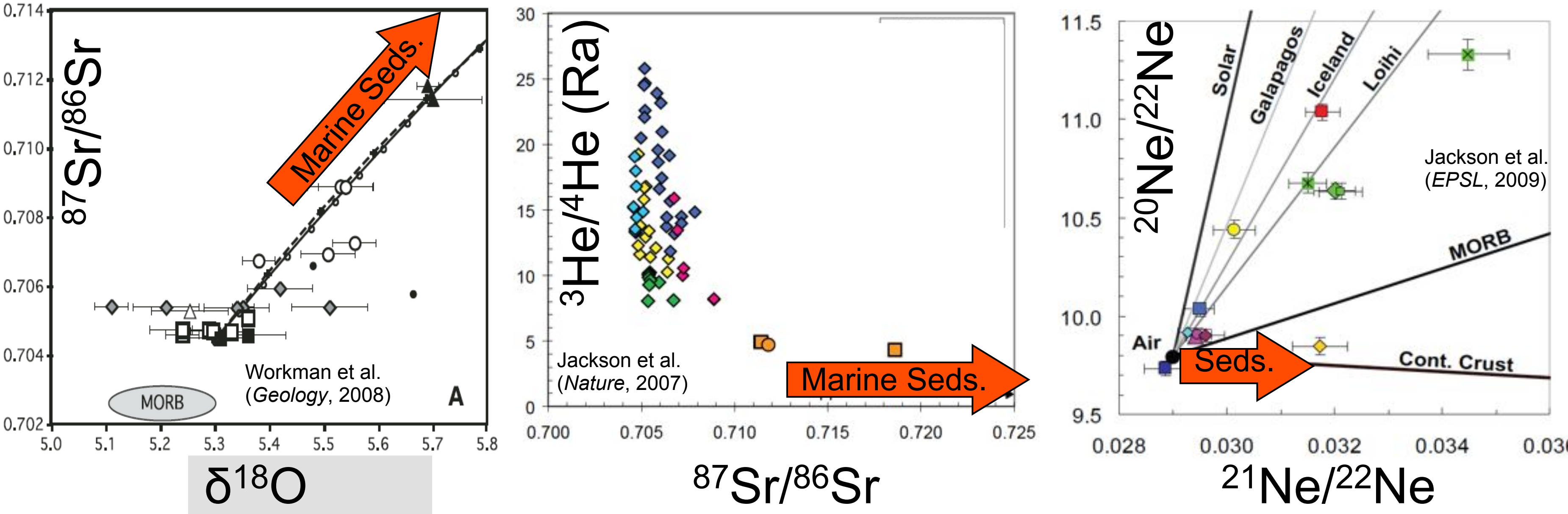
Remarkable agreement between trace elements and isotopes fingerprints



Ti and Nb depletions vs. isotopes



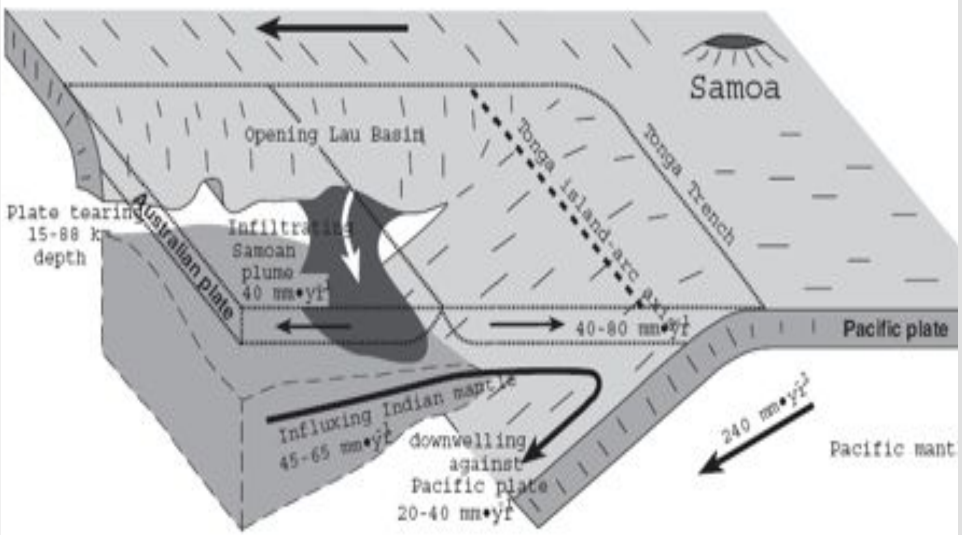
Multiple isotopic systems consistent with recycled sediment



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

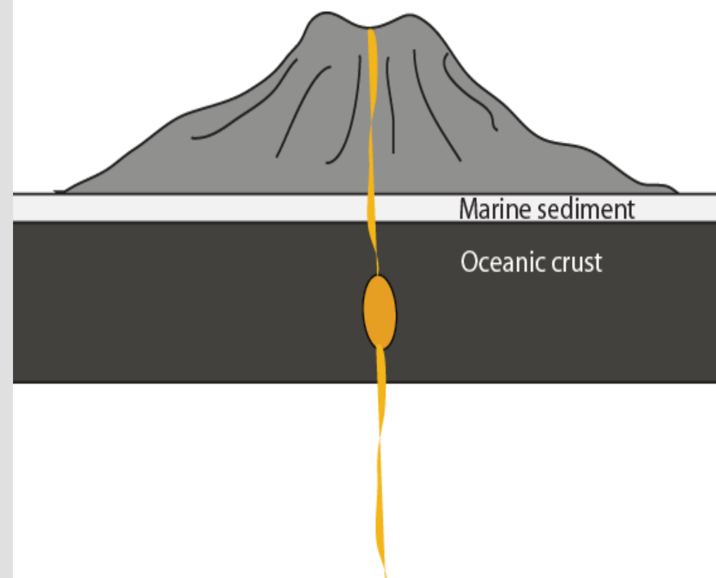
Recap: Strong geochemical evidence for a sediment signature in Samoan lavas, but….

Rapid-cycled sediment from the Tonga trench?

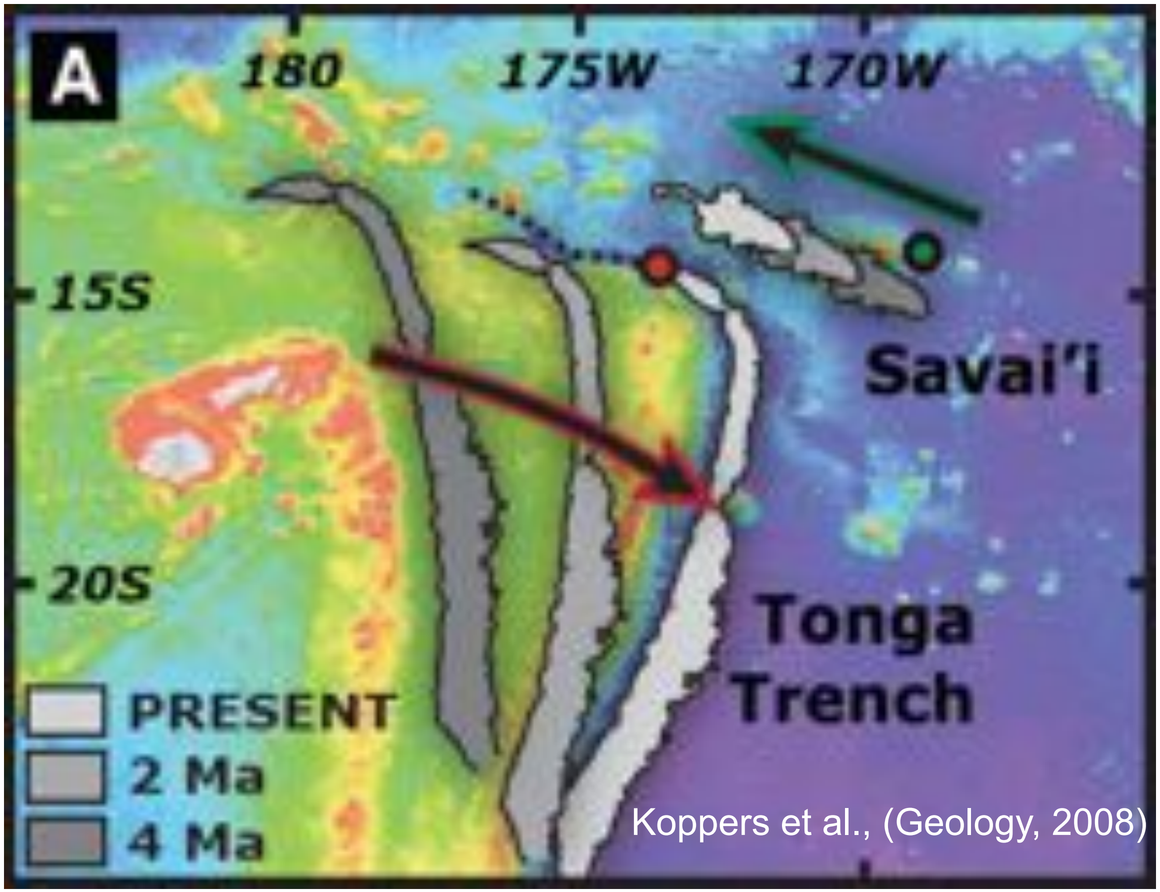


Turner and Hawkesworth, *Geology* 1998

Shallow-level assimilation of marine sediment?

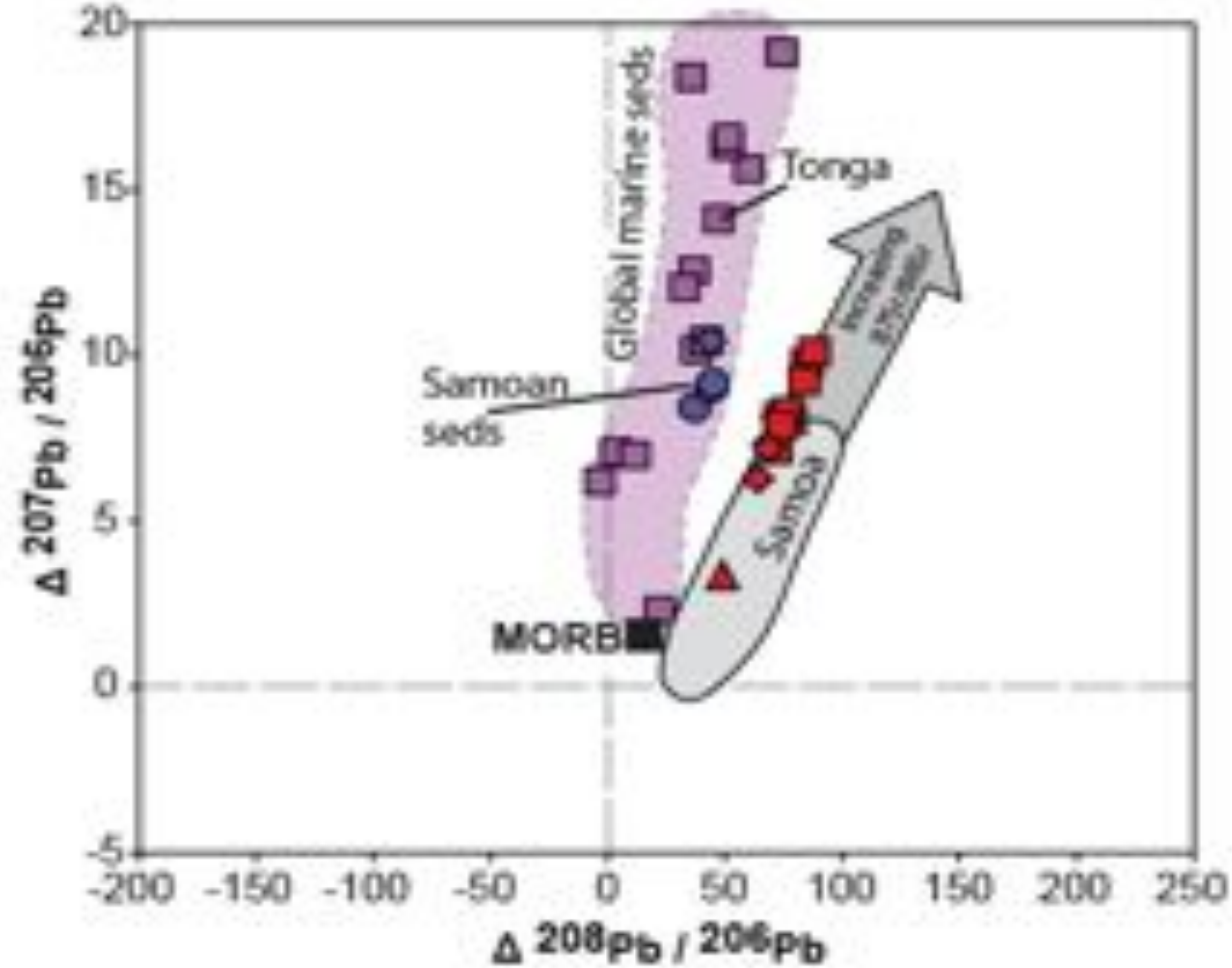


Rule out contamination by sediments from the Tonga trench

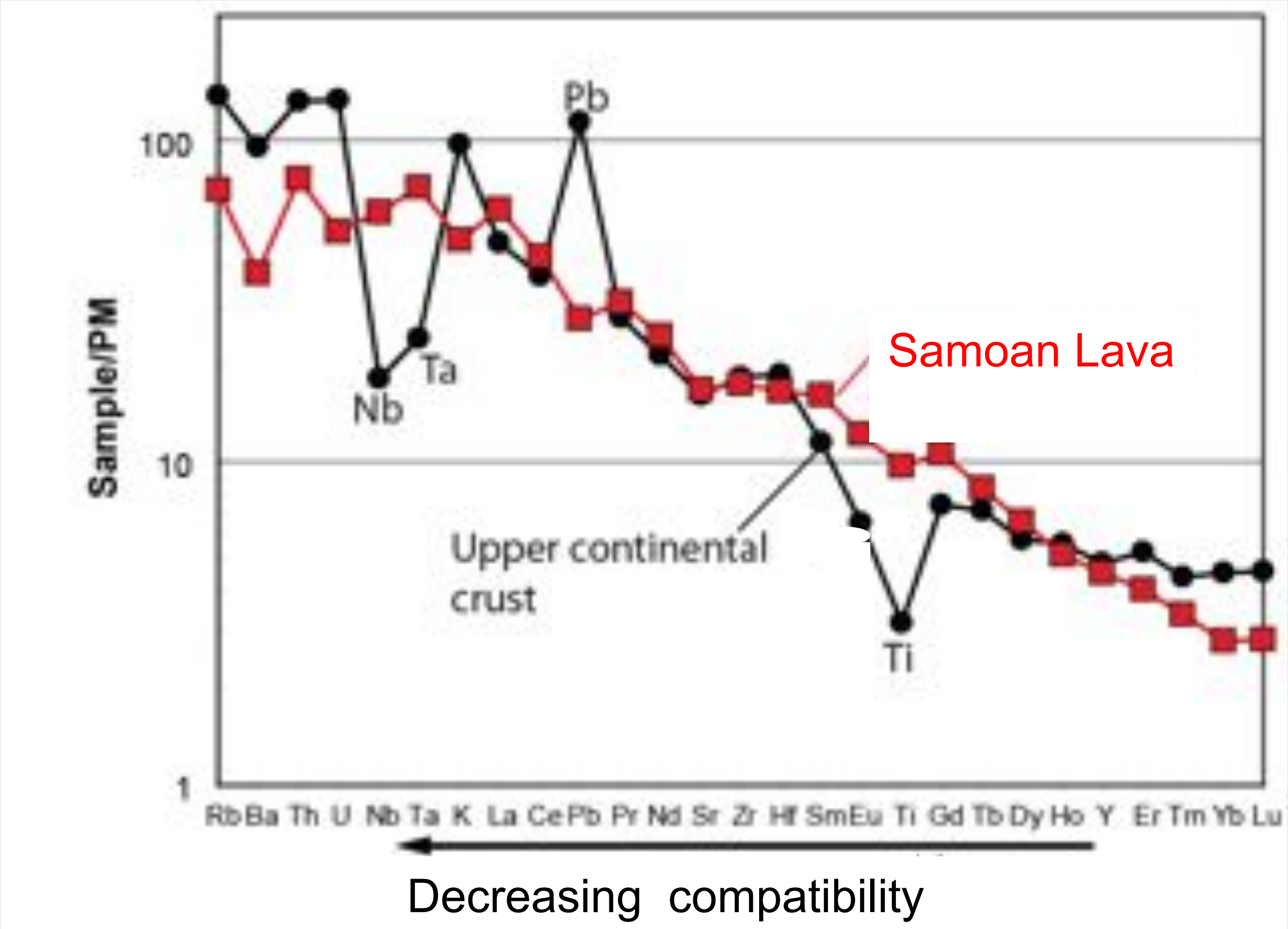


Tonga trench – Savai’i convergence rate = 24 cm/year !

Rule out contamination by shallow modern marine sediments



Trace elements didn’t indicate a sediment signature either….



“High tech” dredging in the 21st century

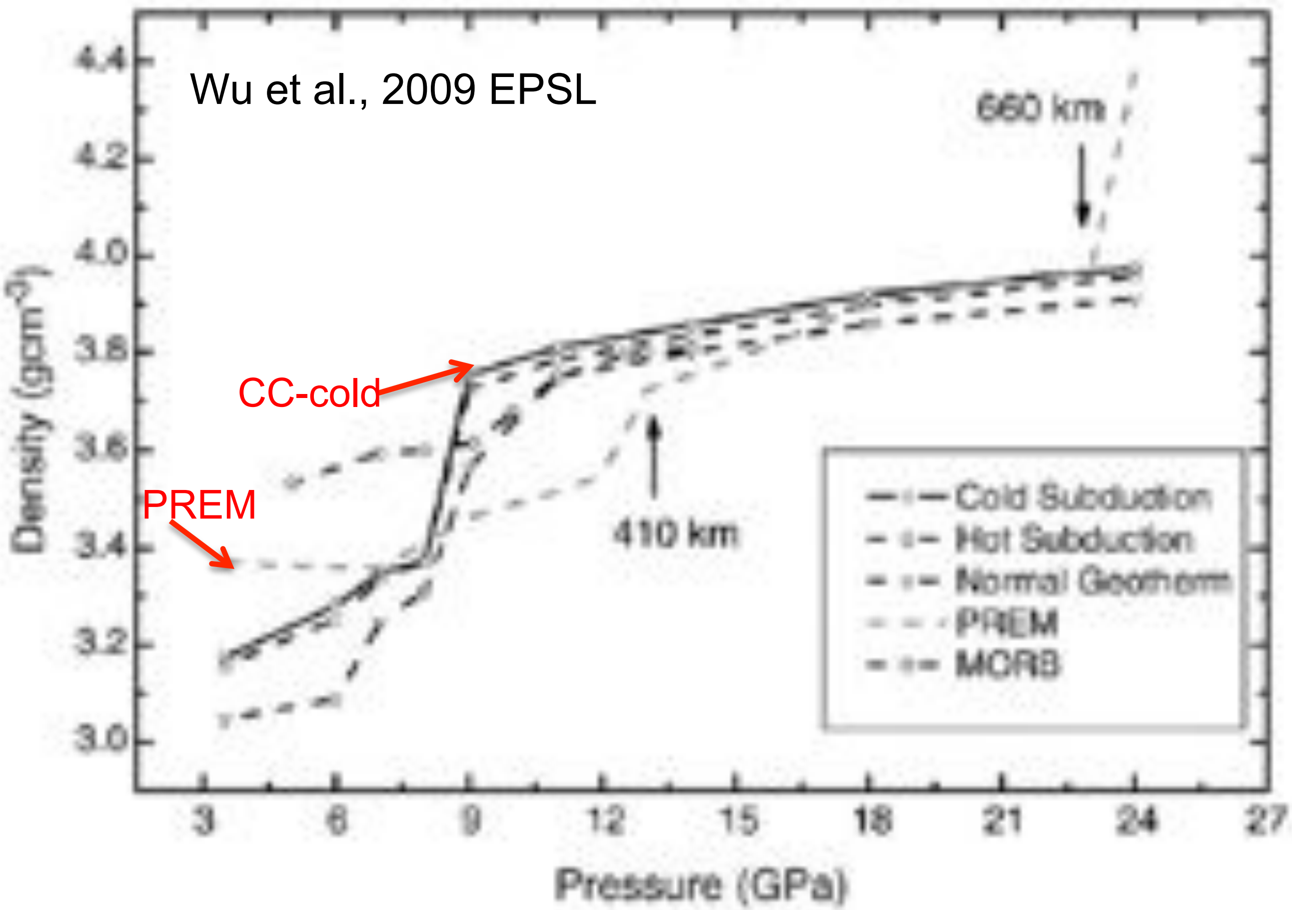
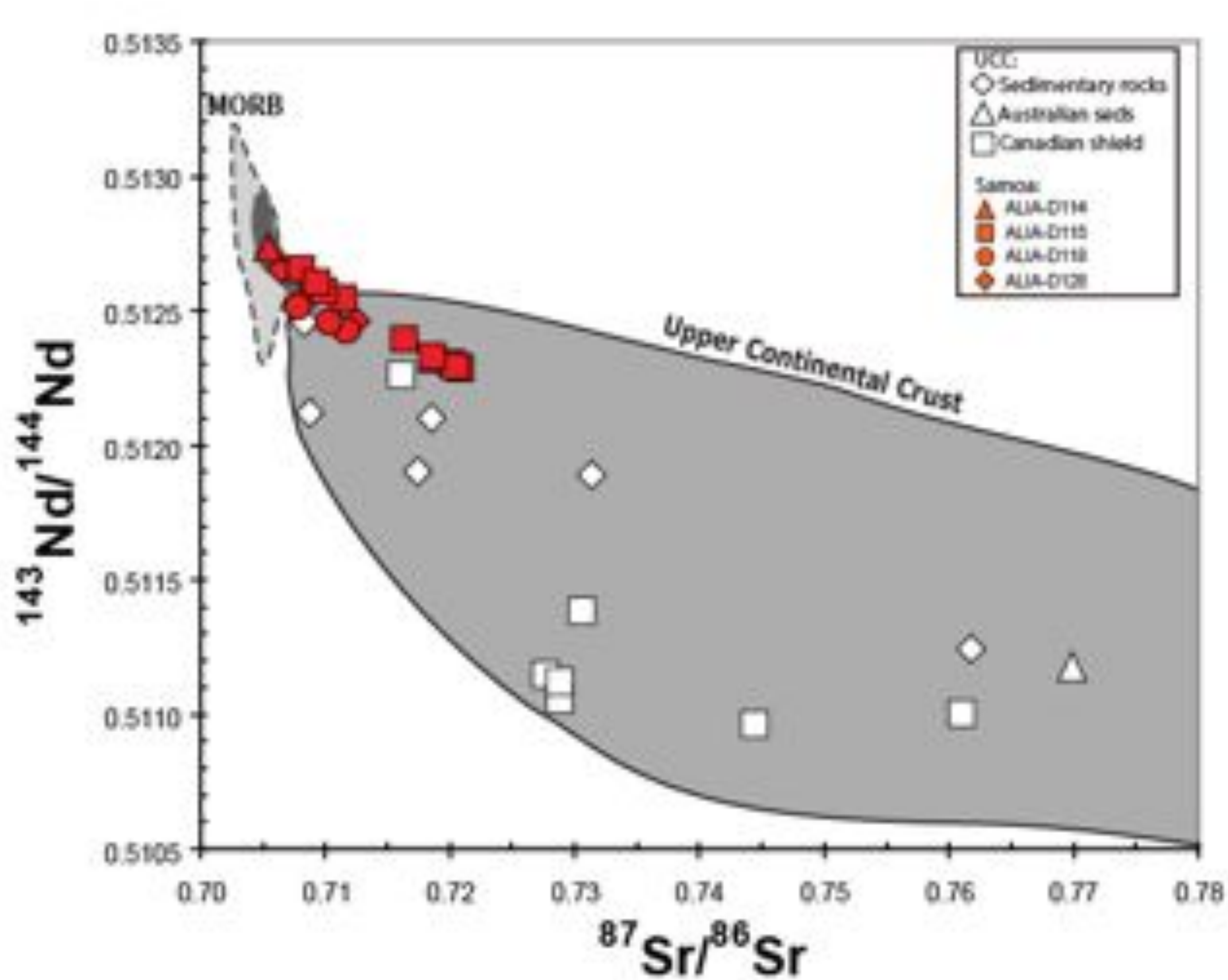


Fig. 5. Comparison of the calculated densities of the subducted continental crust and MORB (Aoki and Takahashi, 2004; Hirose et al., 1999) with respect to the density profile derived from PREM model (Dziewonski and Anderson, 1981). Density calculations were carried out along the three geotherms which are typical for cold and hot subduction and normal mantle (Akaogi and Navrotsky, 1989; Aoki and Takahashi, 2004). The third-order high-temperature Birch–Murnaghan equation of state was used in the density calculations.

Trending toward continental crust…



Lost Continents?

- 0.5-0.7 km^3 marine sediment (mostly derived from continents) is subducted annually.

- In 4 Ga, this is a LOT of sediment—or about 1/3 of the mass of modern continents.
  That's Africa + S. America !

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

Typical oceanic hotspot lavas: No clear sediment signature

Yellow = Continental Crust

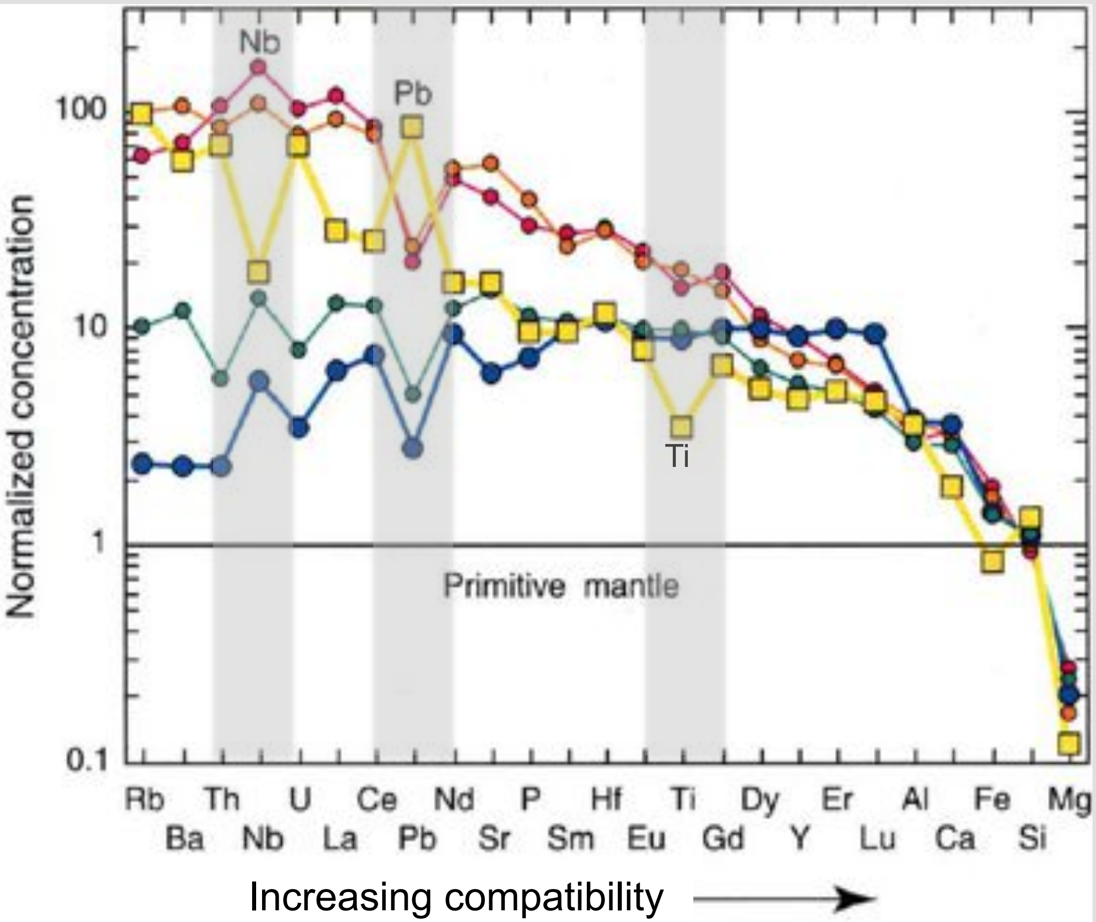
Blue = MORB

OIBs:

Green = Hawaii

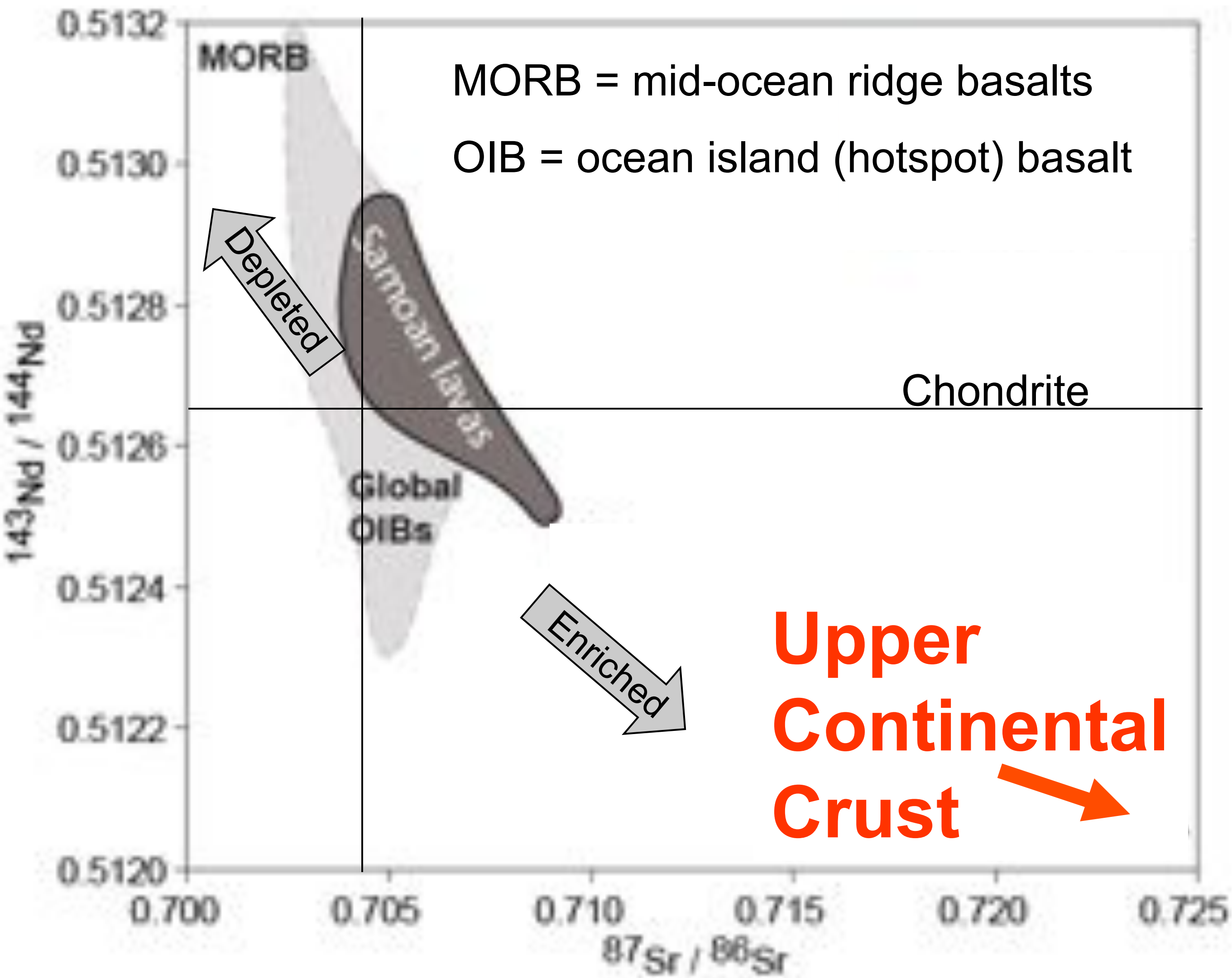
Red = Mangaia Is.

Orange = Tristan Is.



Hofmann (*Nature*, 1997)

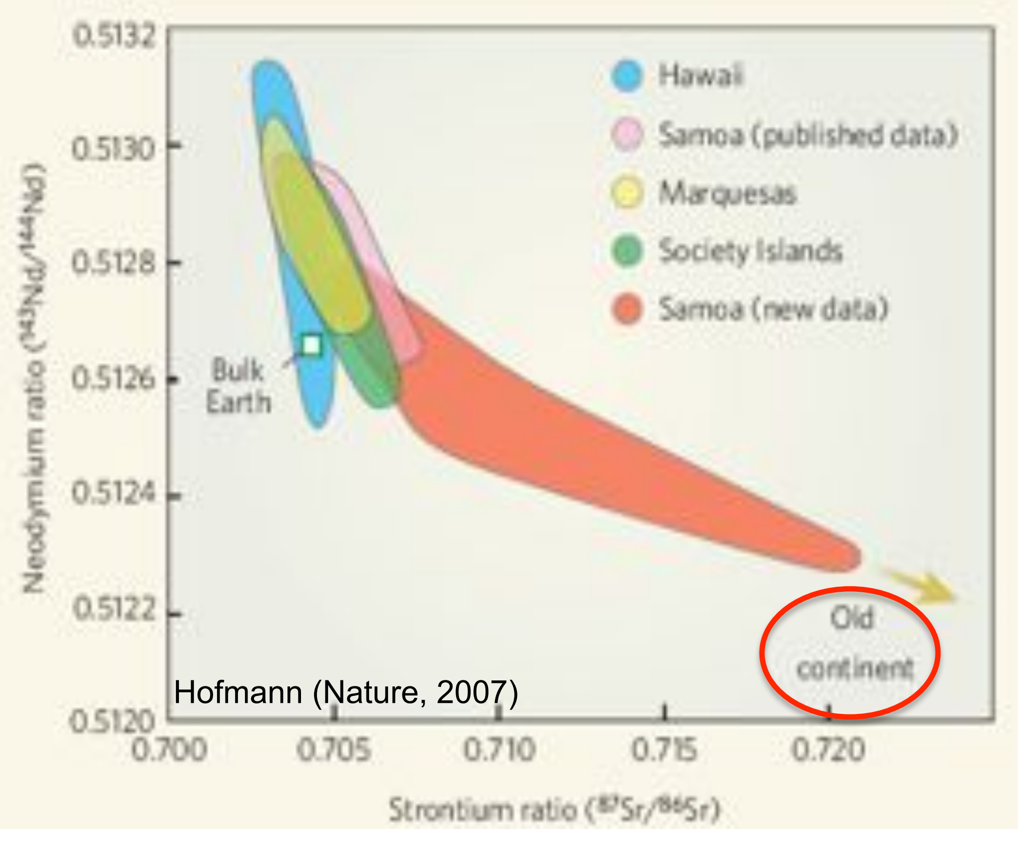
Samoa historically an example of a hotspot that samples a recycled sediment component, but….



Recycled sediment signatures in hotspot lavas are rare…

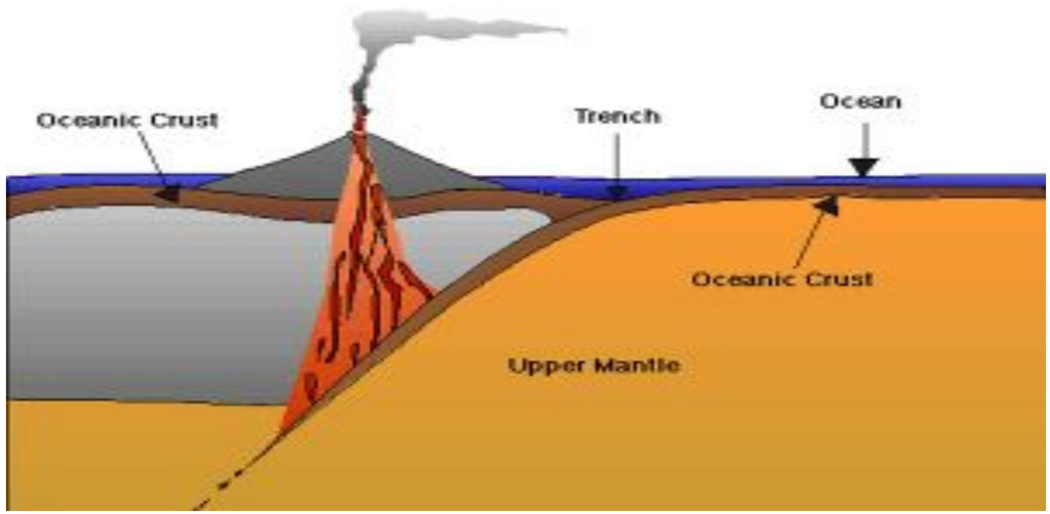
- Large quantities of sediment enter the mantle. Africa AND S. America in 4 Ga !

- **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?

Island-Arc Volcano



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."

An attempt to “frame” the debate

Two end-member positions:

Plumes are real

- Plumes exist as upwellings from the core-mantle boundary layer.
- Most of the active hotspots in the oceans are driven by plumes.
- Age-progressive hot spot tracks are a key signature of plumes.
- These plumes sample mantle that has been sequestered for ~ 2 Gy.
- These upwellings are ~ 150°C hotter than ambient mantle.
- Three of the species in the mantle zoo live in this boundary layer.

Don’t need ‘em

with apologies to the FHAN Club if I’ve misstated their position - (Foulger-Hamilton-Anderson-Natland)

- Plumes don’t exist as important dynamical features of the mantle.
- We rarely if ever see material from the lower mantle.
- hotspots are volcanism from the upper mantle, related to plate fracturing.
- age progression in hotspot chains is related to fracture propagation.
- the upper mantle is wildly heterogeneous, both chemically and lithologically.
- the > 10^4 volcanic seamounts in the ocean are ephemeral “crack-melts” from the uppermost mantle.

What is a Mantle Plume?

a narrow quasi-vertical upwelling of mantle, driven either by thermal or chemical buoyancy (or both).

- As a plume decompresses near the surface (<200 km), it may partially melt, leading to volcanism. This surface expression is usually called a “hot spot”.
- The term “hotspot” should not be taken as always implying a “plume”.
- Plumes may or may not be “fixed” in position (typically migrate at < cm/year).
- Plumes may or may not “live” for a long time (typically < 100 Ma).
- Plumes may or may not have ever been “seen”.
- Plumes are of unknown diameter, but usually “considered” to be circa 100 - 500 km.
- Plume upwelling velocities are unknown, but usually “considered” to be circa meters/year.