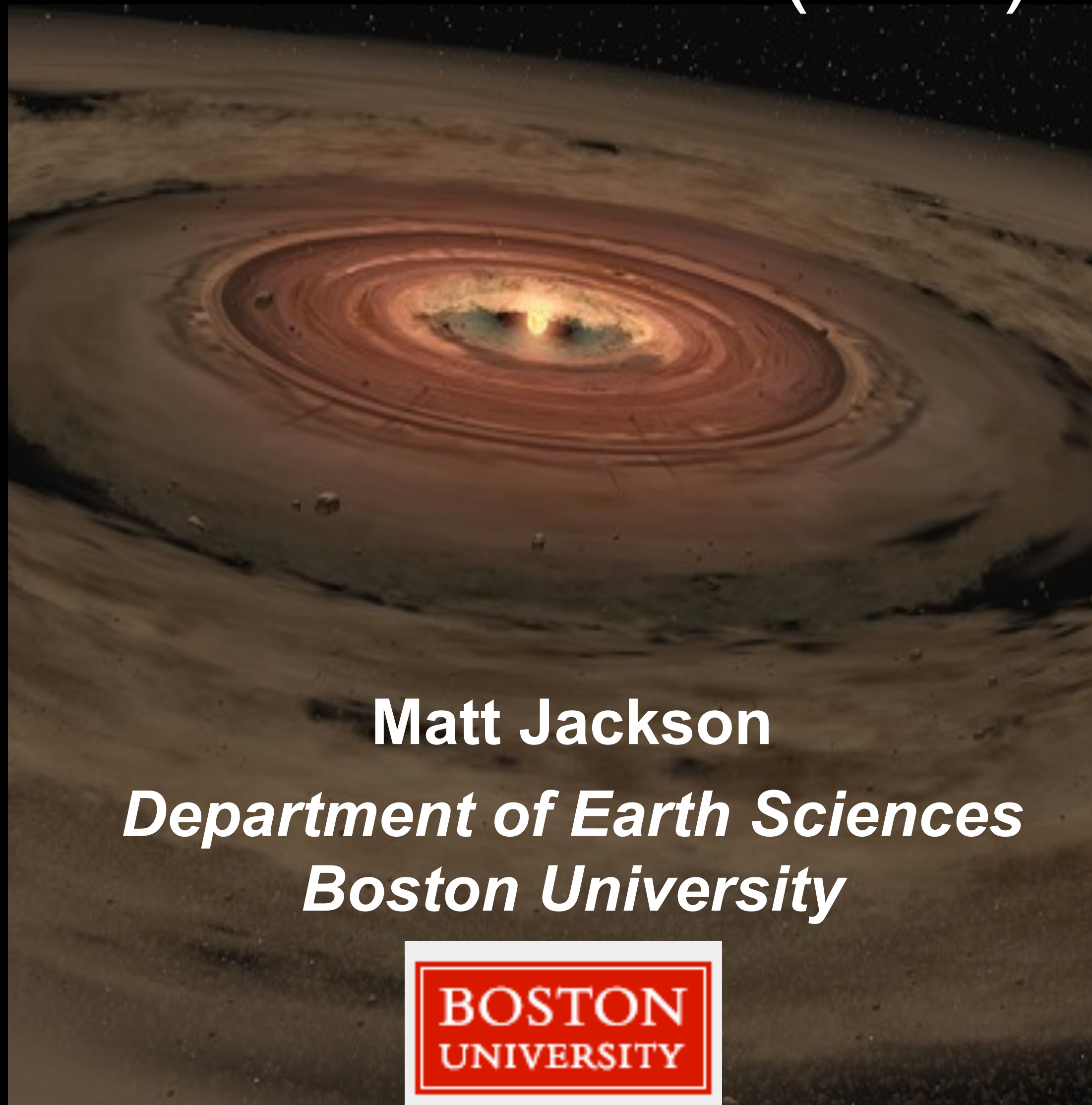
What is the Composition of the Bulk Silicate Earth (BSE)?



Courtesy of NASA/JPL-Caltech

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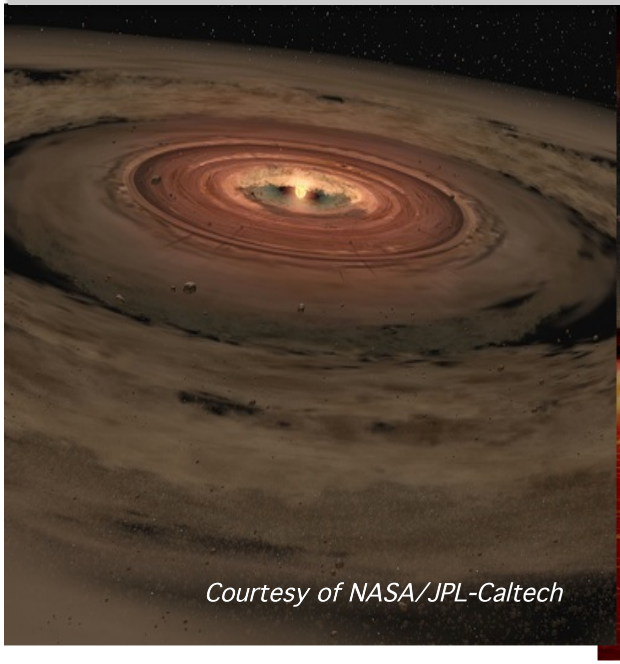
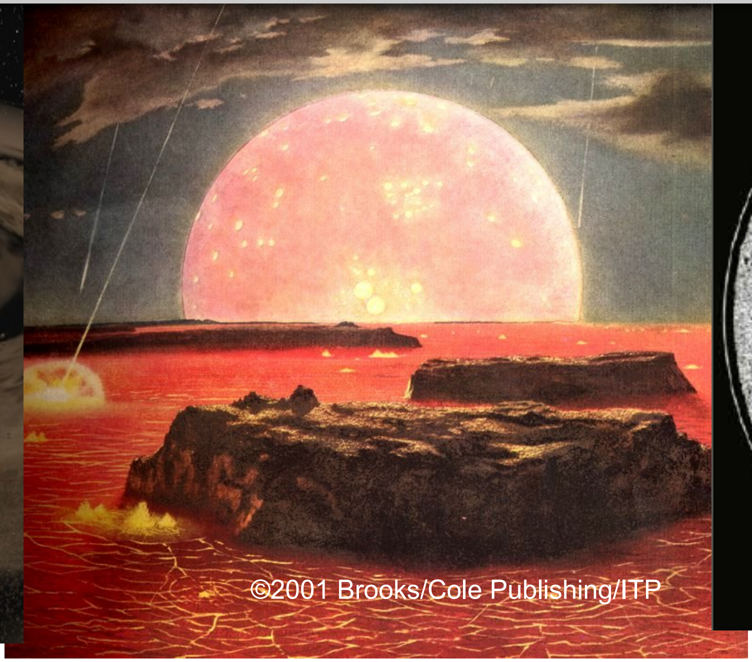
Part I: Where is "home"?

- Following accretion, a deep terrestrial magma ocean…
- Siderophile elements (Fe-Ni) to the core, leaving behind the early (primitive) silicate mantle/ BSE (bulk silicate Earth).
- From the primitive silicate earth, the crust (continental and oceanic) was extracted from the early **primitive mantle.**
- **But what material accreted to make the Earth in the first place…and what is the bulk composition of the Earth?**


Courtesy of NASA/JPL-Caltech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Brandenburg et al., EPSL 2008

To paraphrase a useful quotation…

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

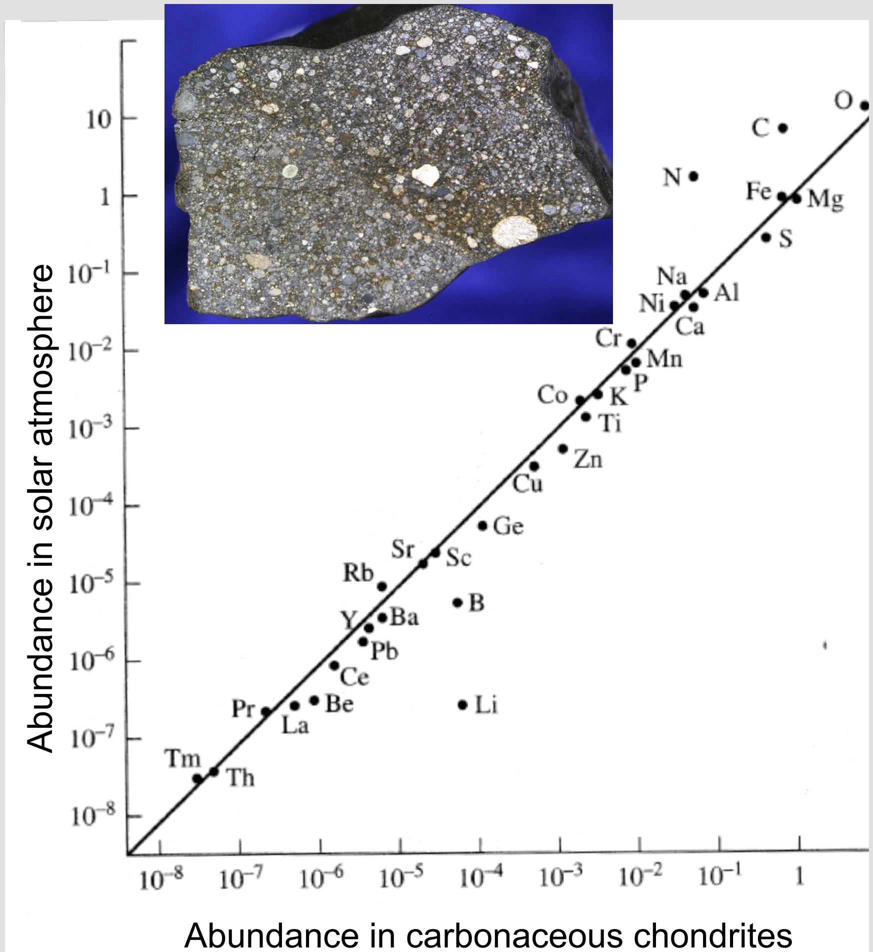
-RP Kirshner

Home? Primordial helium in Earth's mantle?

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

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

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 $\approx$ 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.

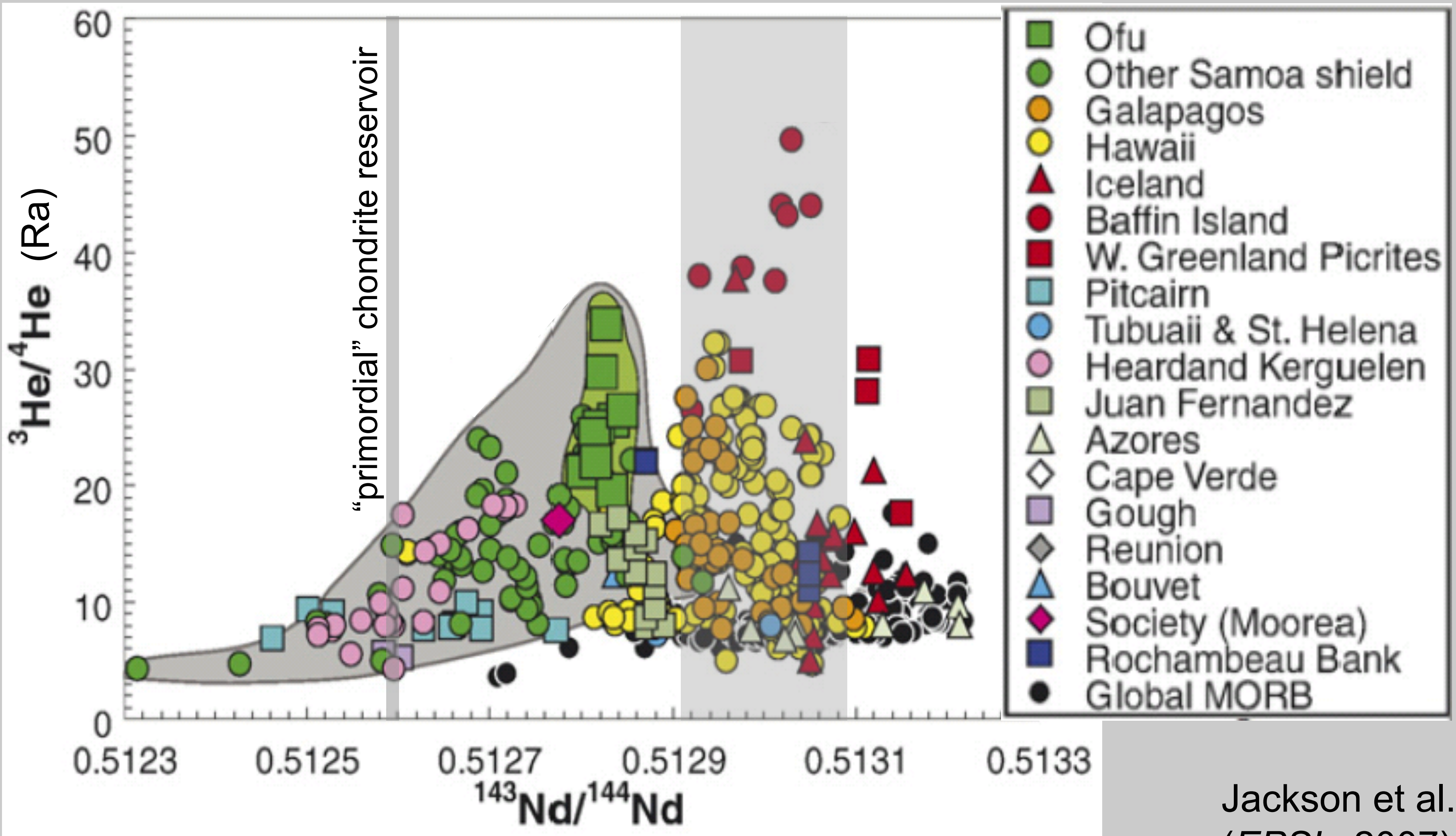
3.) Therefore, C-chondrites $\approx$ Earth (for the non-volatile, lithophile elements like Sm/Nd)

4.) ^{147}Sm → ^{143}Nd + ^{4}He ($t_{1/2}$=106 **Gyr**)
^{146}Sm → ^{142}Nd + ^{4}He ($t_{1/2}$=68 **Myr**)

5.) If the Earth is a C-chondrite, then Earth and chondrites have the same Sm/Nd & ^{143}Nd/^{144}Nd & ^{142}Nd/^{144}Nd.

Caro et al, 2008 Nature “[chondrite] has
been considered to

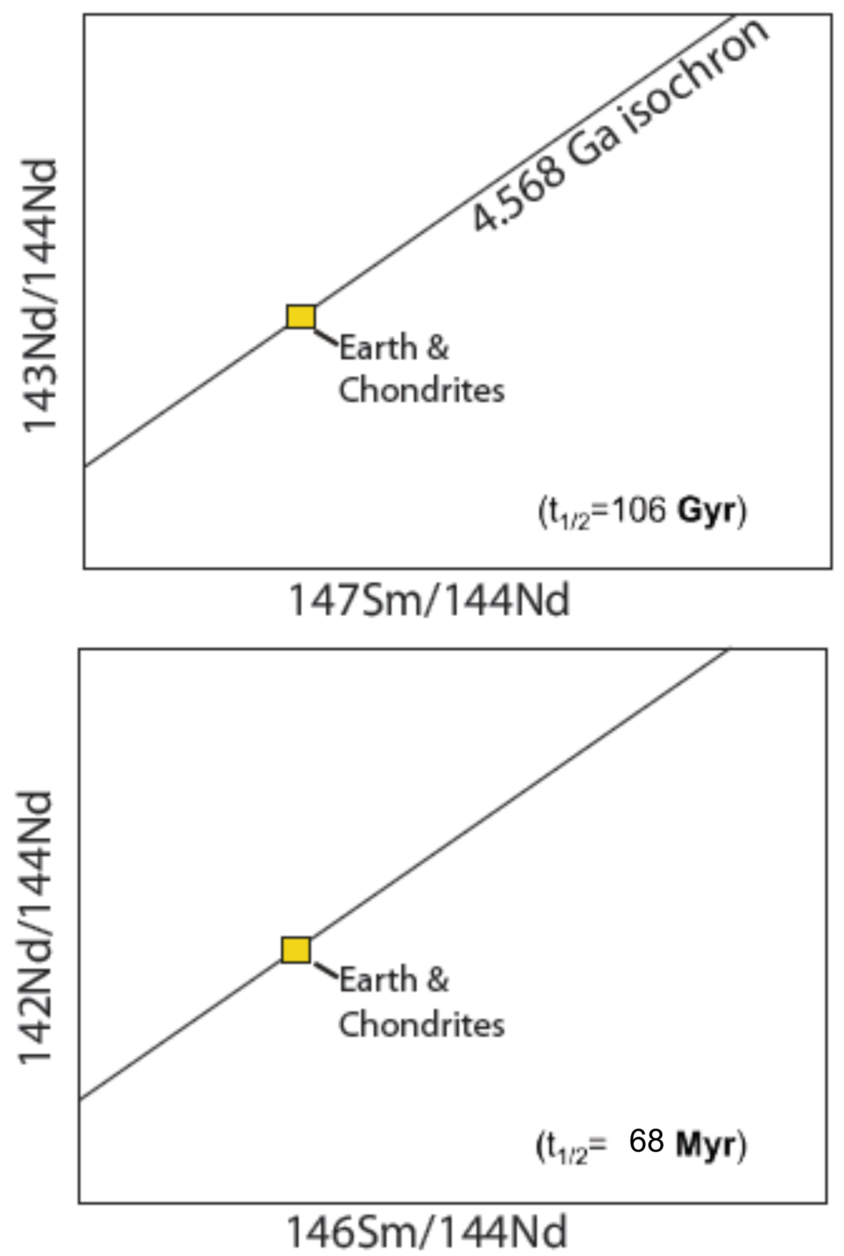
A paradox:
Primitive (high) $^3He/^4He$ lavas do not have primitive (chondritic) $^{143}Nd/^{144}Nd$



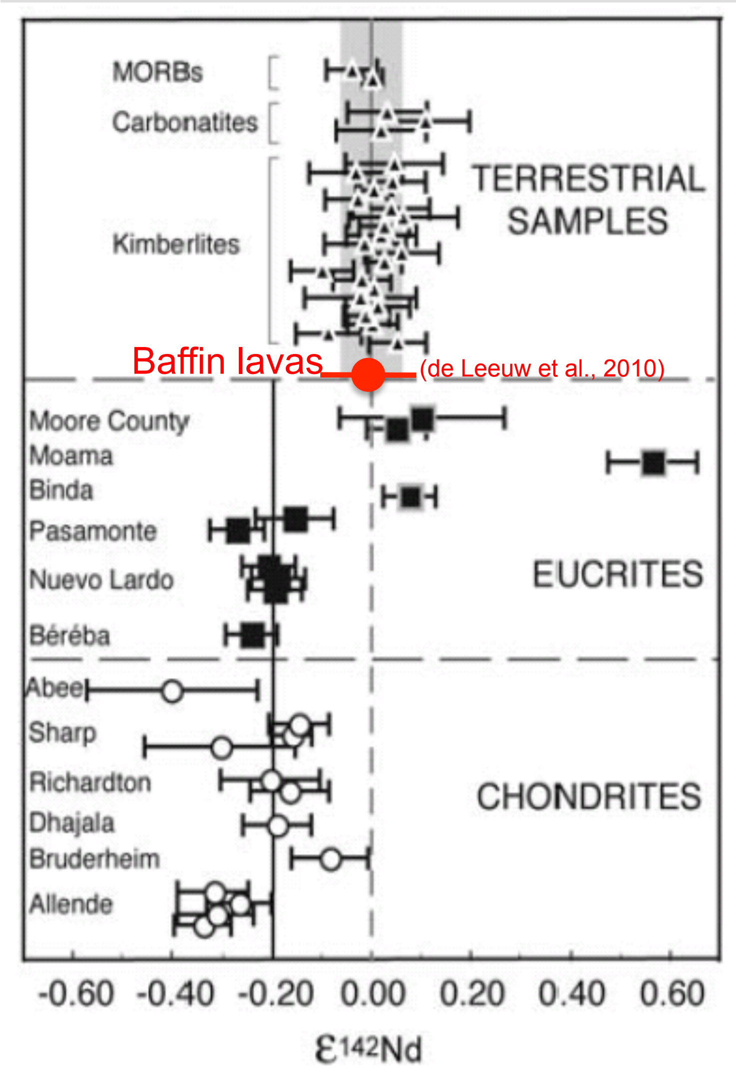
Jackson et al. (*EPSL*, 2007)

- **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 $^{142}Nd/^{144}Nd$.



Implications from Neodymium-142



(Boyet and Carlson, Science, 2005)

- **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.

- **There are two interpretations of the new data:**

1. **^{142}Nd variation due to incomplete mixing of s-, r-, p-process nucleosynthetic products.** ^{142}Nd variation has nothing to due with ^{146}Sm decay. Earth has chondritic Sm/Nd.

OR….

2. **^{142}Nd variation due to ^{146}Sm decay.** All modern accessible terrestrial samples evolved from a mantle reservoir with a Sm/Nd ratio ~6% higher than chondrites.

How does this work?

1. $(^{143}Nd/^{144}Nd)_t = (^{143}Nd/^{144}Nd)_0 + (^{147}Sm/^{144}Nd)_t(e^{\lambda t}-1)$

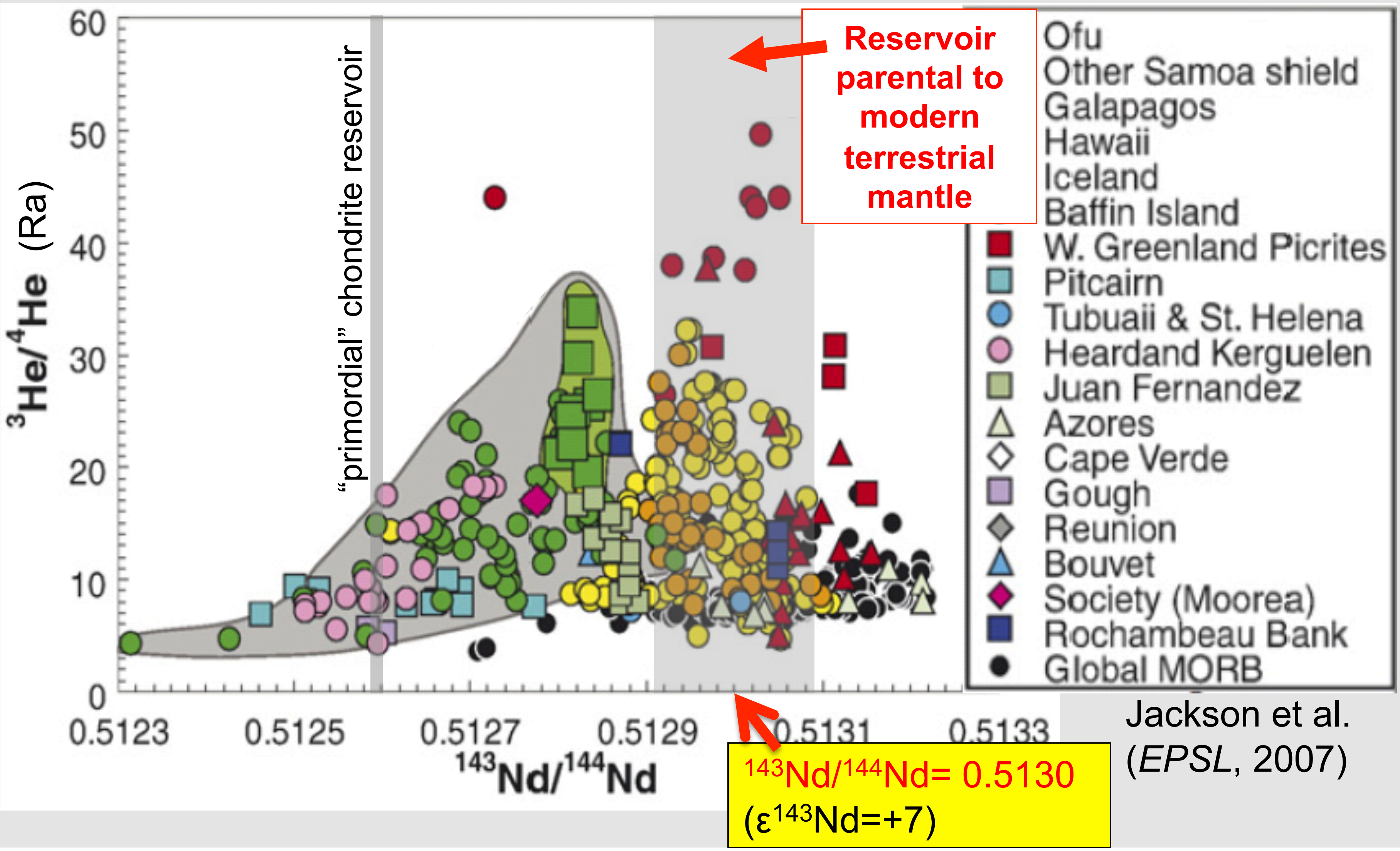
2. $(^{142}Nd/^{144}Nd)_t = (^{142}Nd/^{144}Nd)_0 + (^{146}Sm/^{144}Nd)_t(e^{\lambda t}-1)$

3. $^{146}Sm/^{147}Sm$ = Constant

4. Therefore, if $^{142}Nd/^{144}Nd$ is 18 ppm higher, then $^{143}Nd/^{144}Nd$ is a LOT higher….

Paradox resolved?

Lavas with high $^{3}He/^{4}He$ have "primitive" (but not chondritic) $^{143}Nd/^{144}Nd$



Jackson et al. (*EPSL*, 2007)

Preserving the Chondrite model

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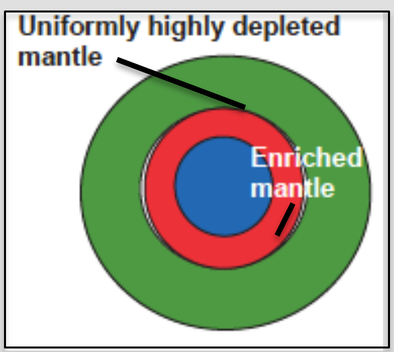
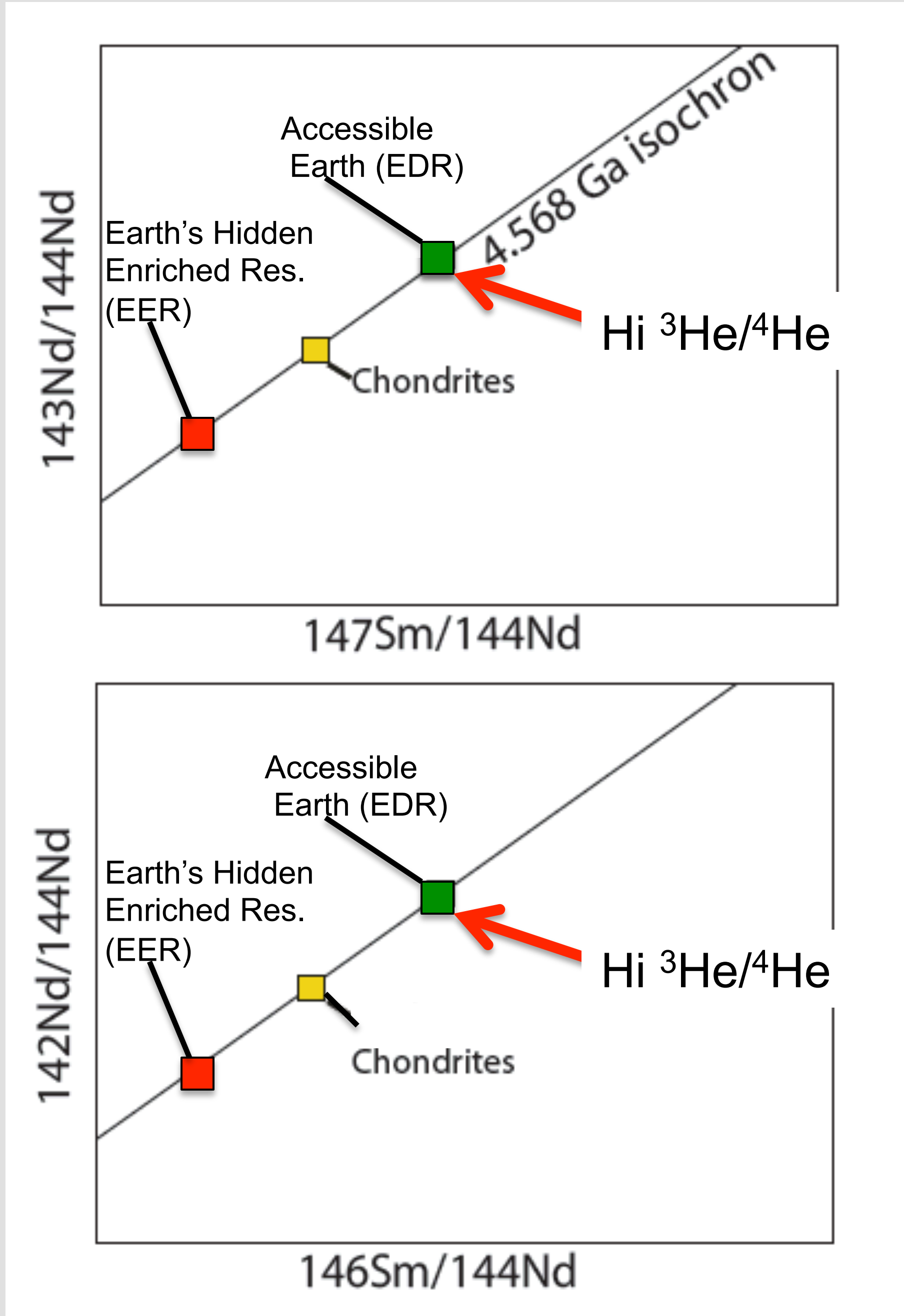




Survival of a “hidden” early enriched reservoir?

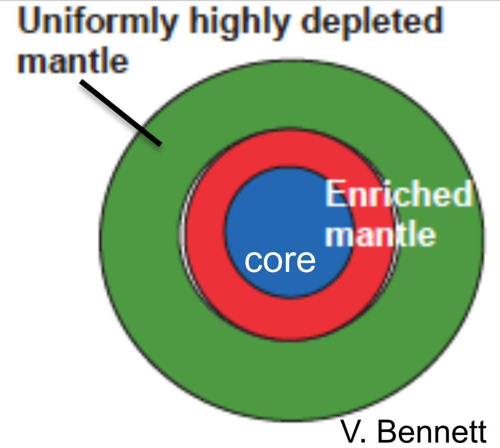
Two problems with “hidden” reservoir hypothesis:

1. ^{146}Sm-^{142}Nd and ^{182}W-^{182}Hf systematics:

<u>How would a “hidden” reservoir remain *completely* hidden at the bottom of the mantle during a giant impact event?</u>

2. How to keep a hidden <u>ENRICHED (U, Th, K)</u> reservoir hidden?

<u>No evidence for “hidden” reservoir in plume-fed hotspots.</u>



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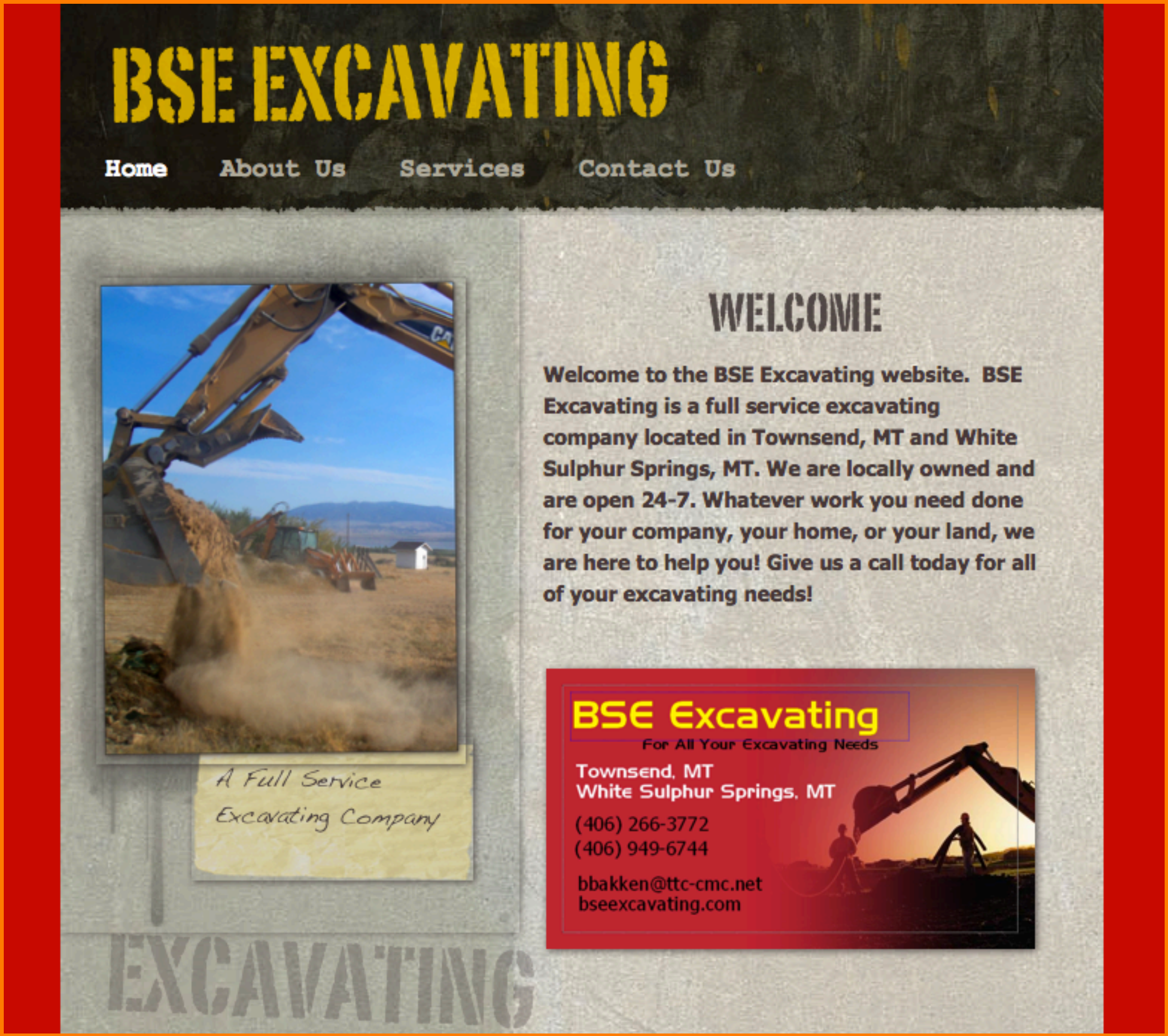
Bulk Silicate Earth (BSE)?



No hidden reservoir. So Bulk Earth isn't chondritic? A growing clamor……

doi:10.1038/nature10901

29 MARCH 2012 | VOL 483 | NATURE | 553

Evidence against a chondritic Earth

Ian H. Campbell[1] & Hugh St C. O'Neill[1]

nature Vol 452 | 20 March 2008 | doi:10.1038/nature06760

LETTERS

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]

Nature Vol. 258 December 11 1975

Earth isn't chondritic?

Naming the Loch Ness monster

Recent publicity concerning new claims for the existence of the Loch Ness monster has focused on the evidence offered by Sir Peter Scott and Robert Rines. Here, in an article planned to coincide with the now-cancelled symposium in Edinburgh at which the whole issue was due to be discussed, they point out that recent British legislation makes provision for protection to be given to endangered species; to be granted protection, however, an animal should first be given a proper scientific name.

Better, they argue, to be safe than sorry; a name for a species whose existence is still a matter of controversy among many scientists is preferable to none if its protection is to be assured. The name suggested is Nessiteras rhombopteryx.

doi:10.1038/nature10901

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Evide ... arth

Ian H. Campbell[1]

nature ... 08|doi:10.1038/nature06760

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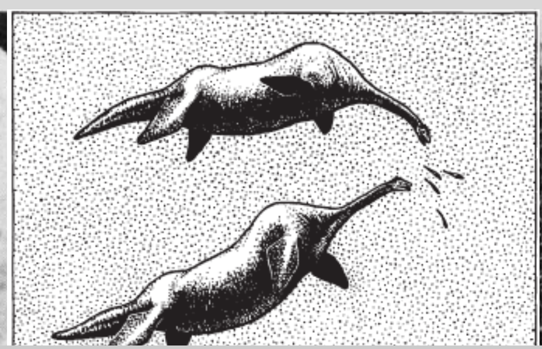
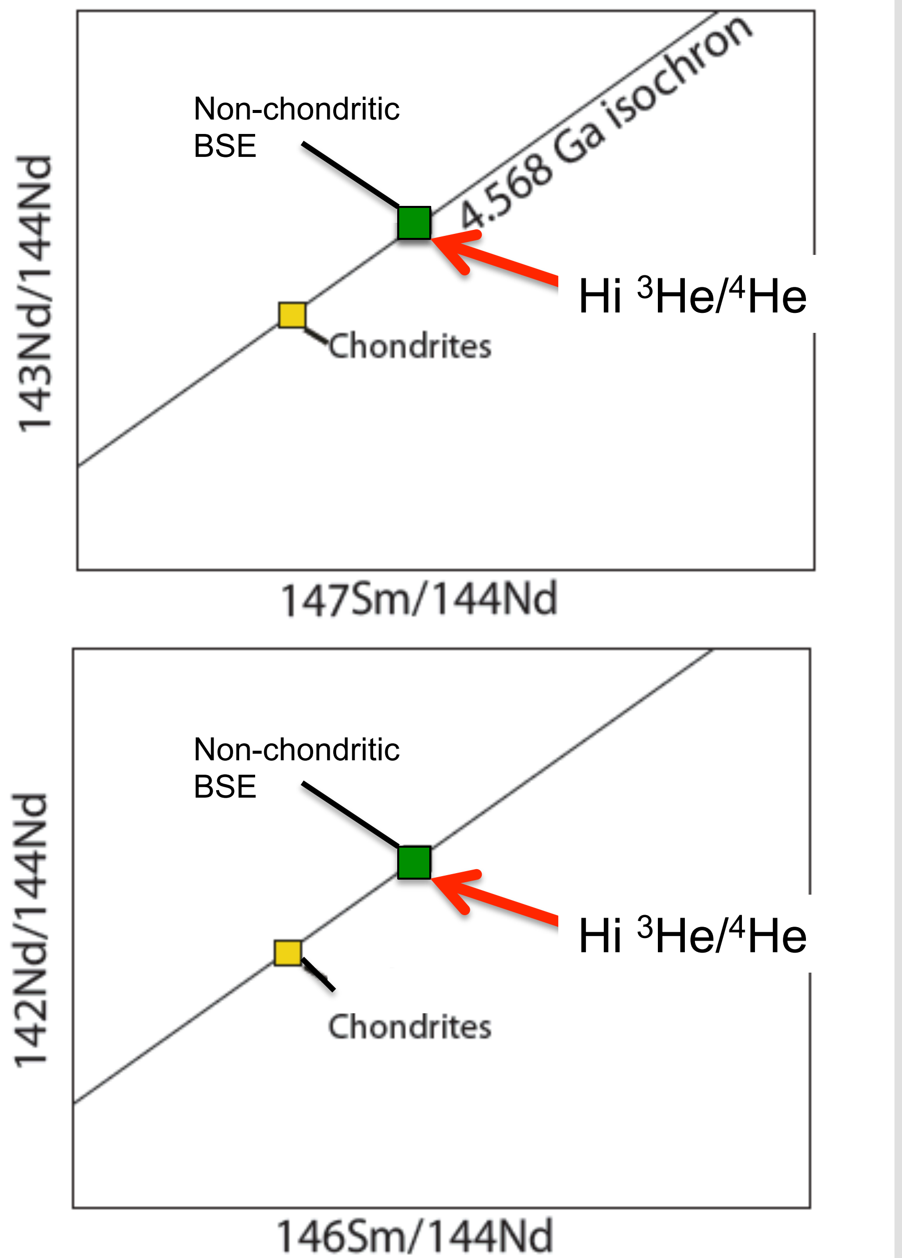
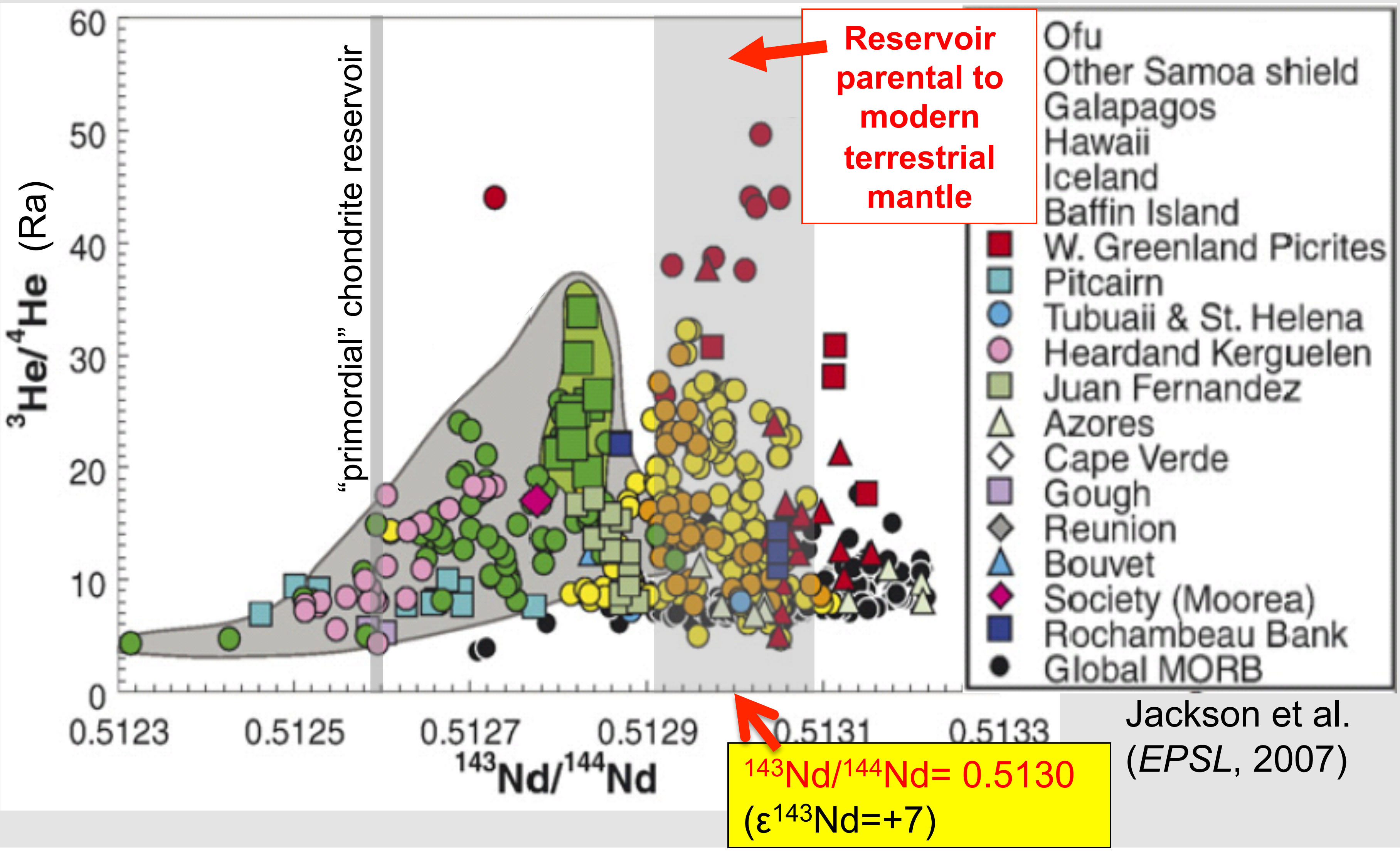


Non-chondritic Earth model

NO HIDDEN RESERVOIR

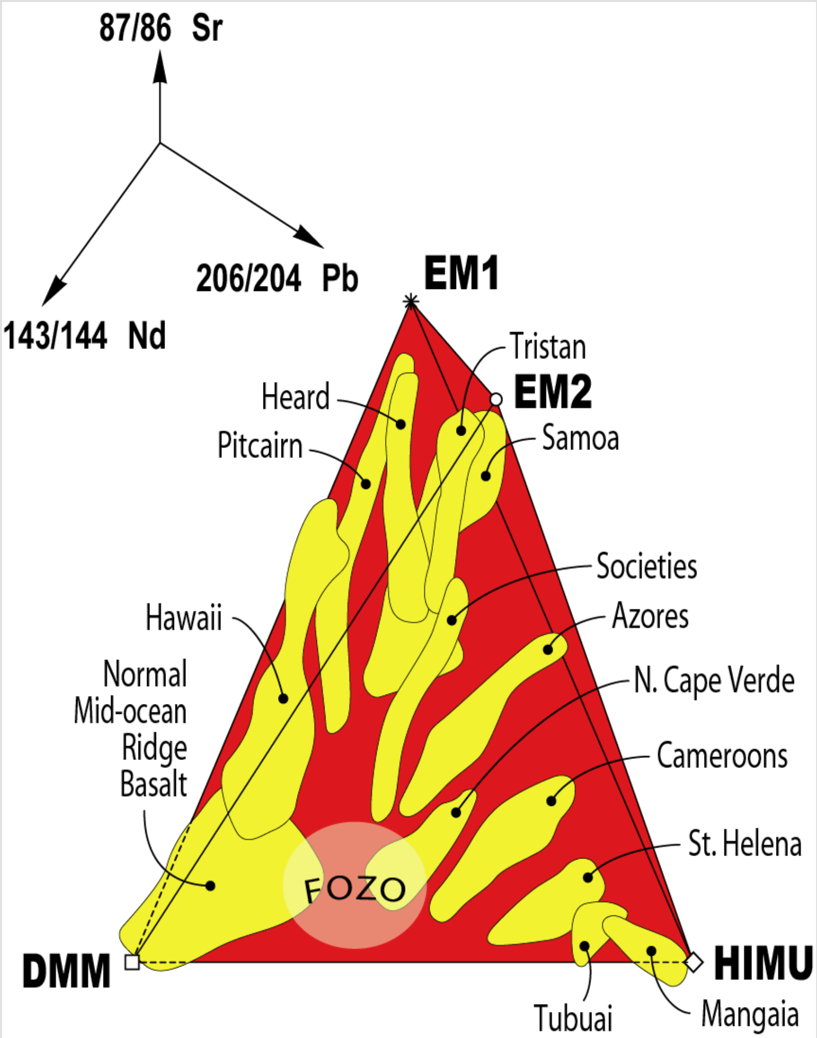


Predicted non-chondritic mantle reservoir (or "early depleted" reservoir) overlaps with high $^3He/^4He$ reservoir



Jackson et al. (*EPSL*, 2007)

Bulk Silicate Earth is FOZO?



After Hart et al., 1992

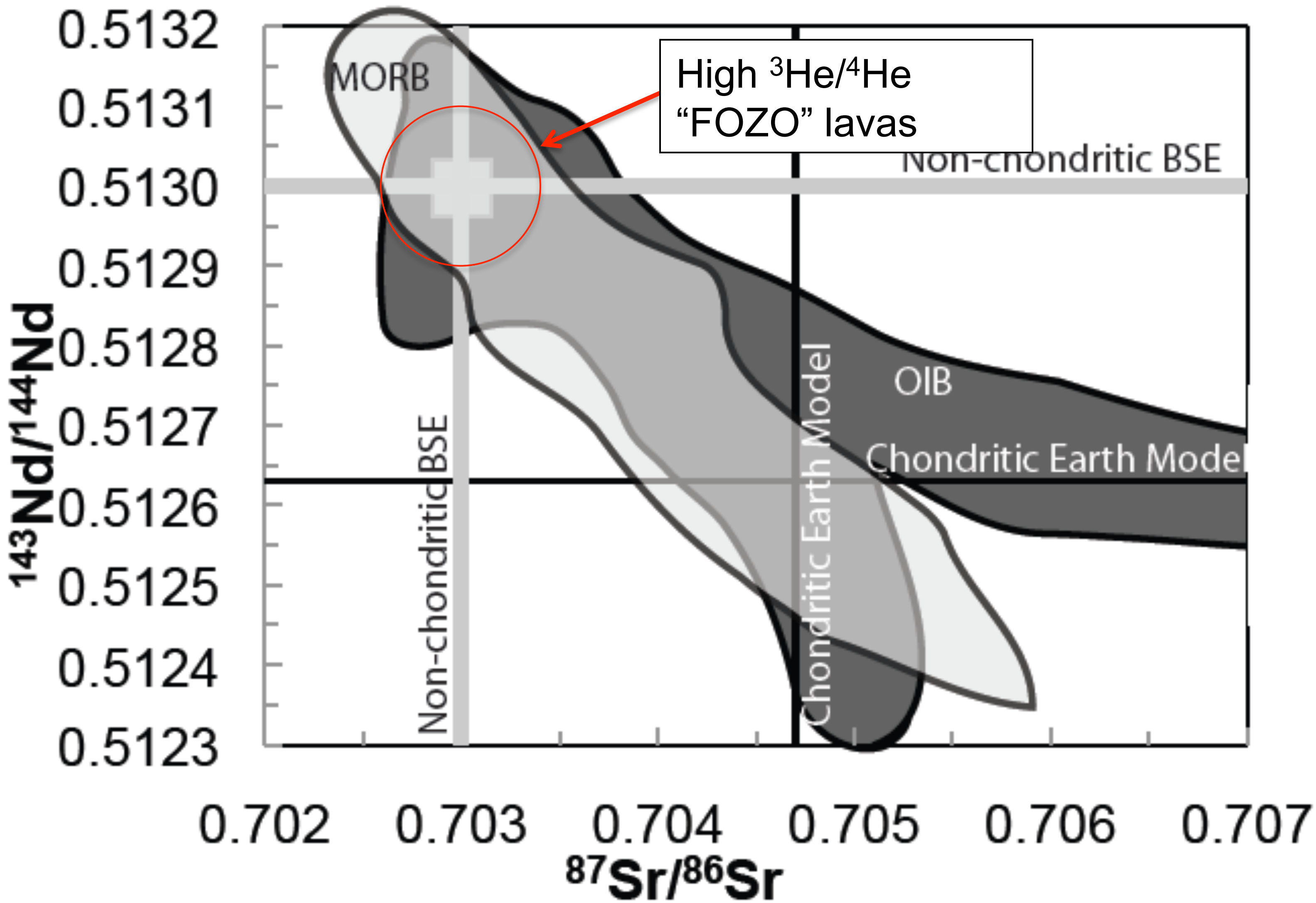
- FOZO has high $^3He/^4He$ and $^{143}Nd/^{144}Nd$ of ~0.5130
- FOZO is a "common component" in the mantle:
  FOZO=Focus Zone
- If Bulk Silicate Earth (BSE) isn't chondritic, FOZO is a good bet for Primitive Mantle composition.

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).**

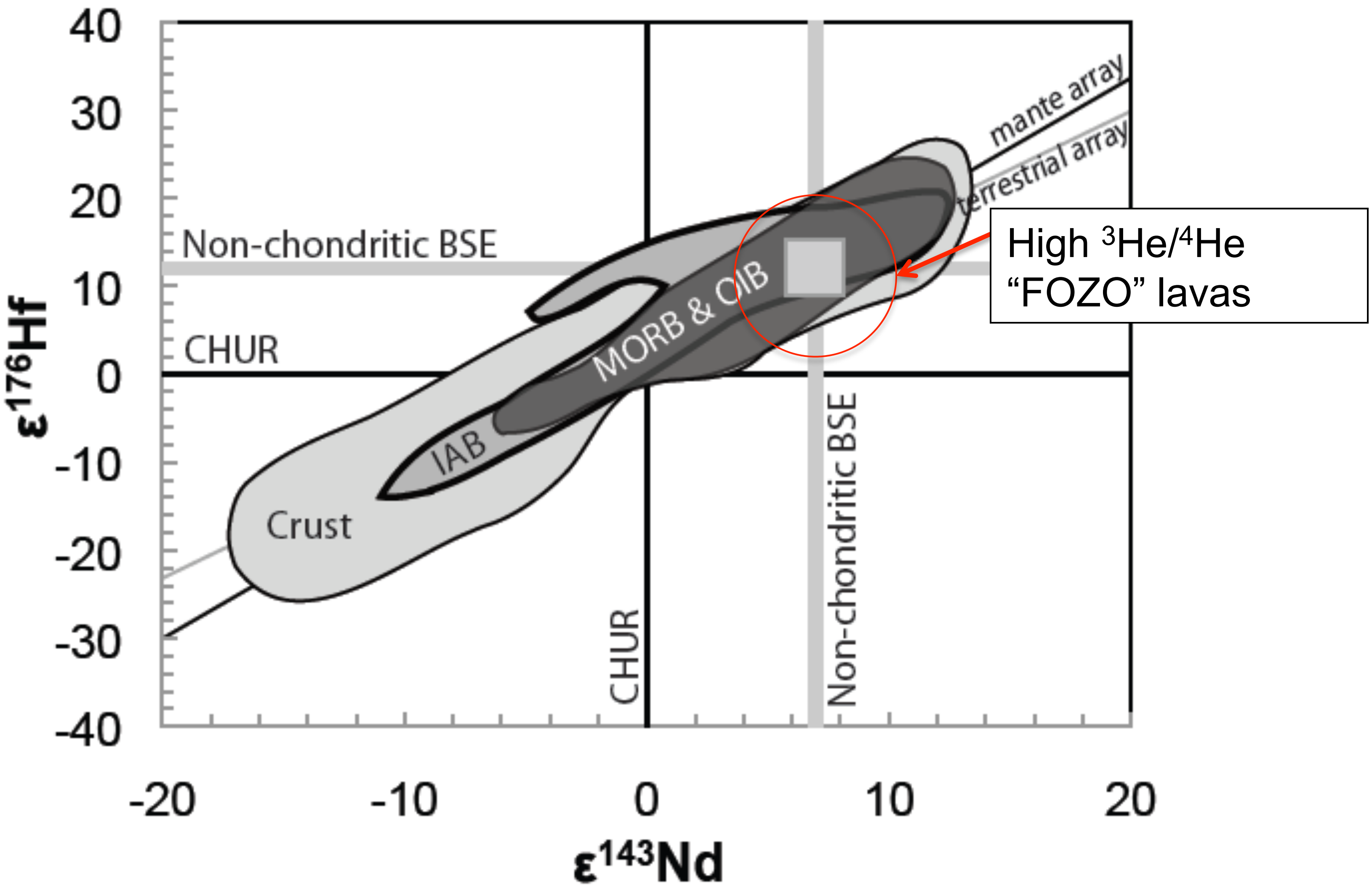
Use many of the assumptions used in the chondrite-based model

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



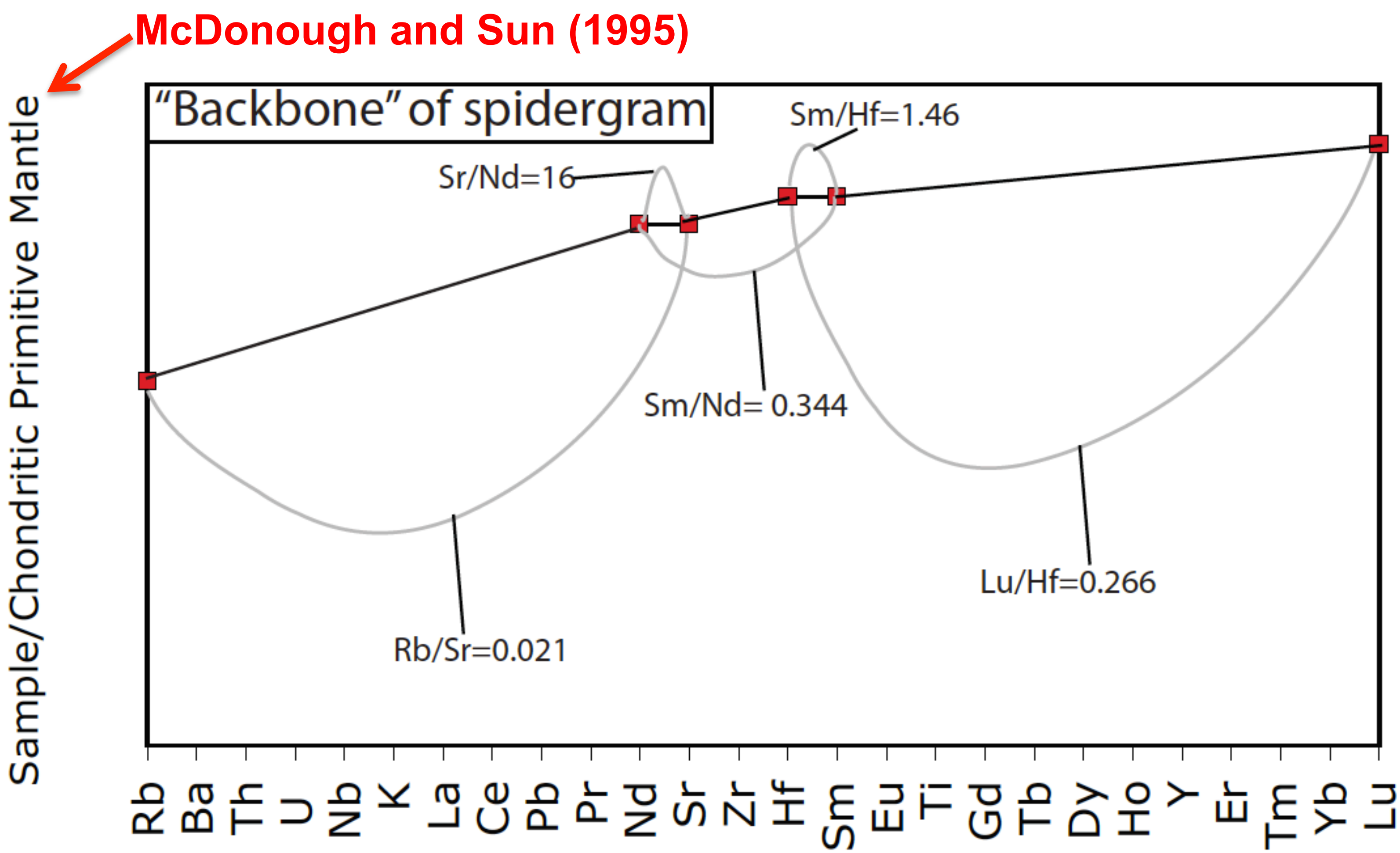
After Caro and Bourdon (2010)

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



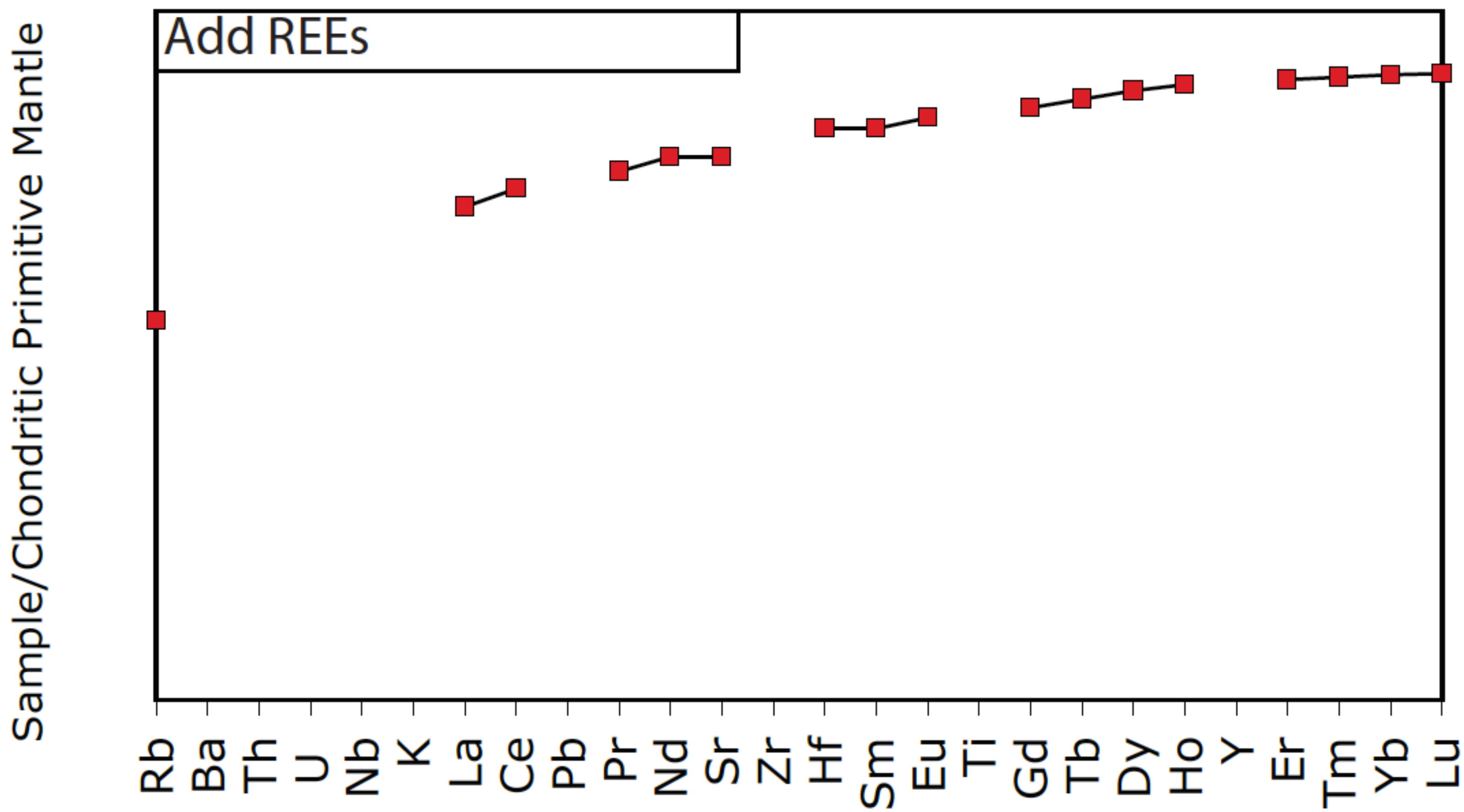
After Caro and Bourdon (2010)

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



Jackson & Jellinek, 2012

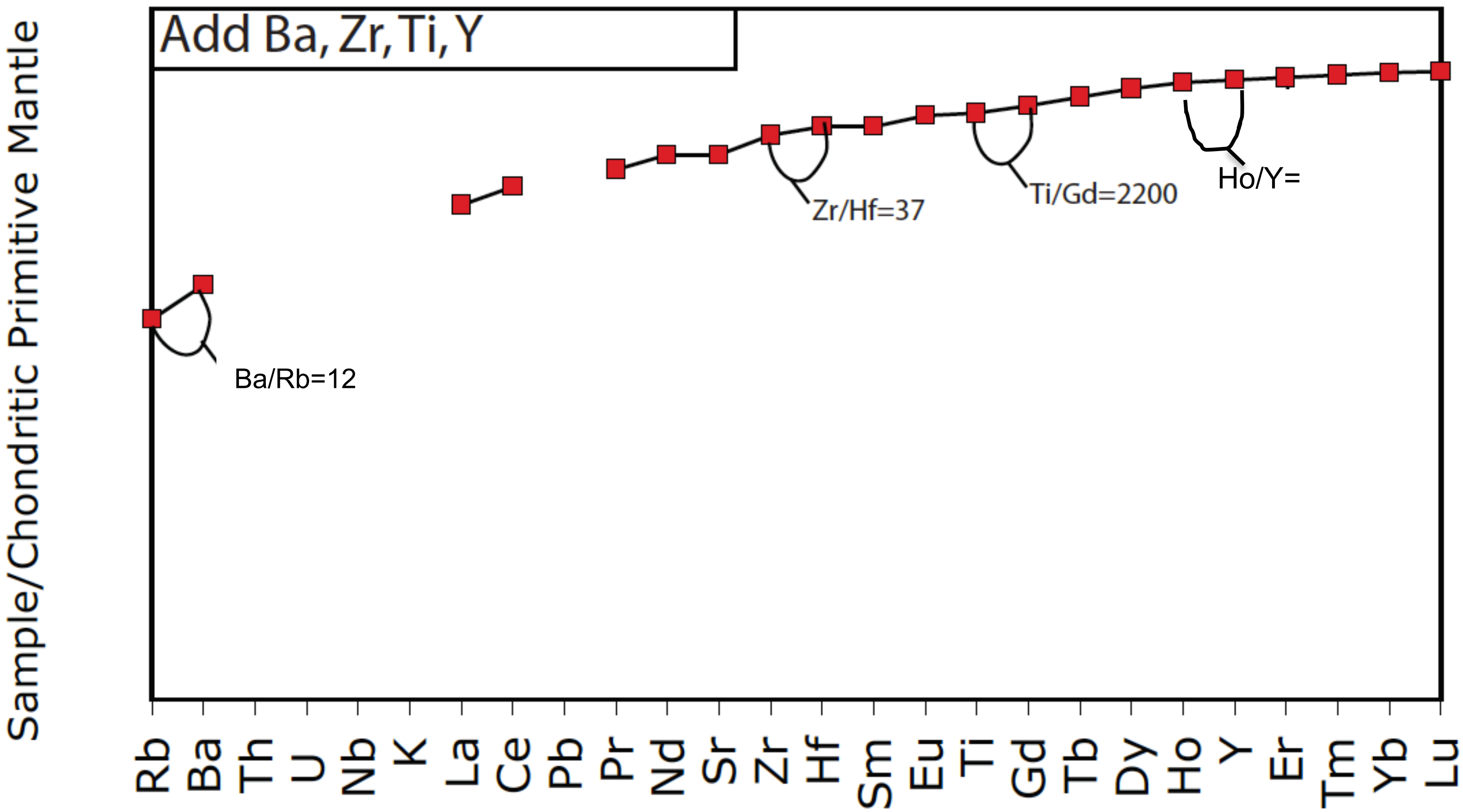
“Splice” in the Rare Earth’s



Jackson & Jellinek, 2012

Ba, Zr, Ti, Y

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



Jackson & Jellinek, 2012

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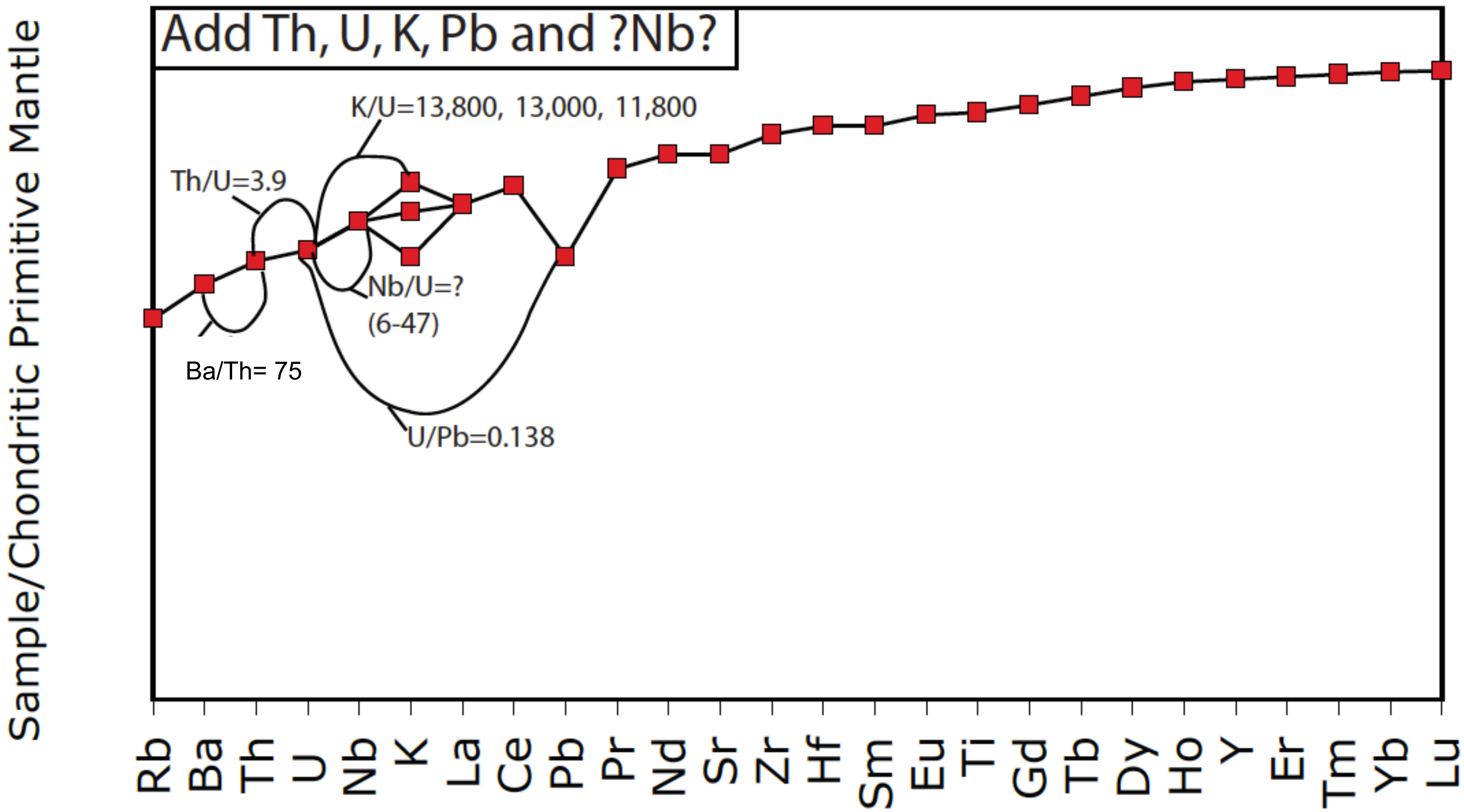
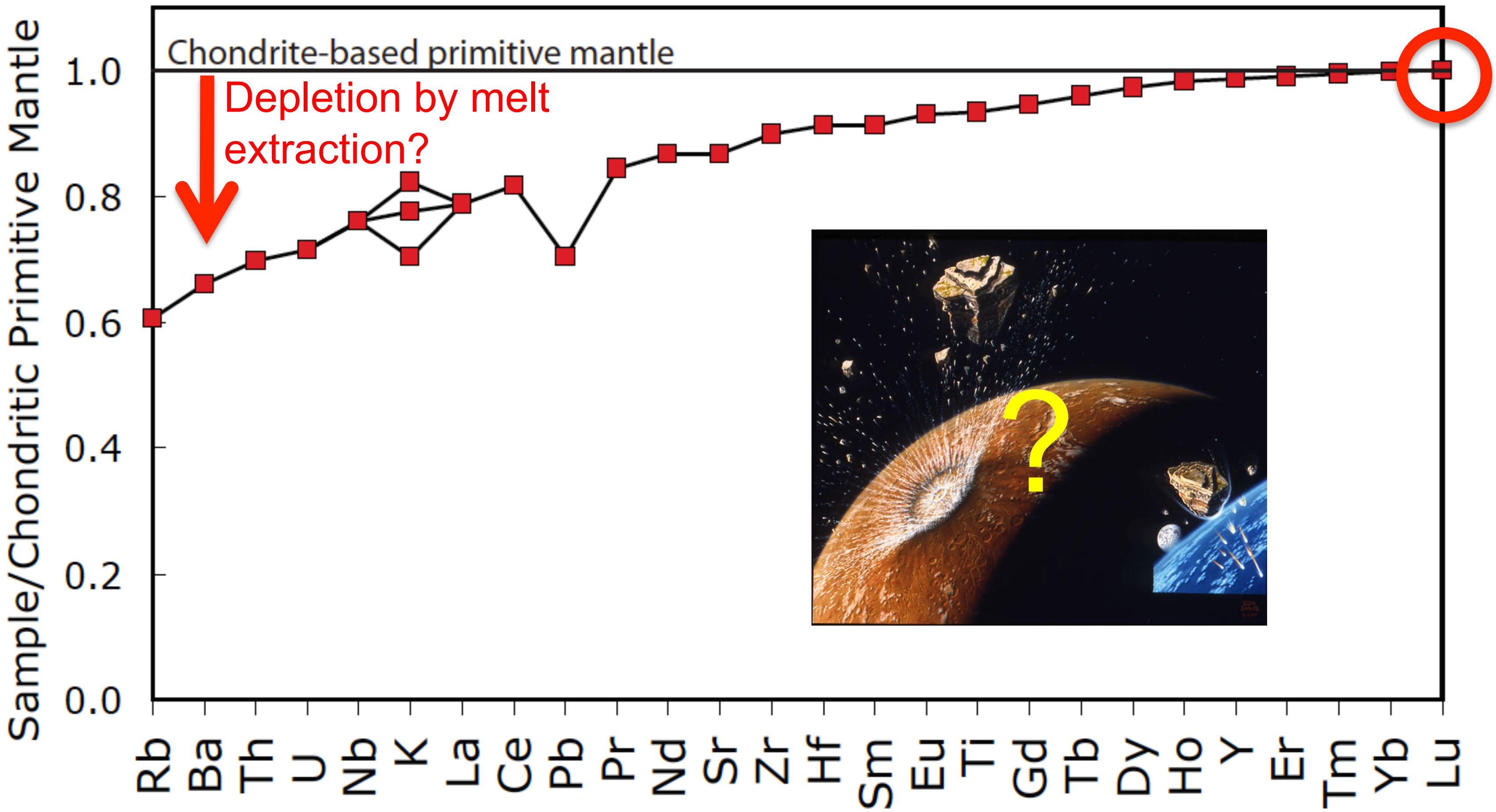
Th-U-K-Pb and Nb



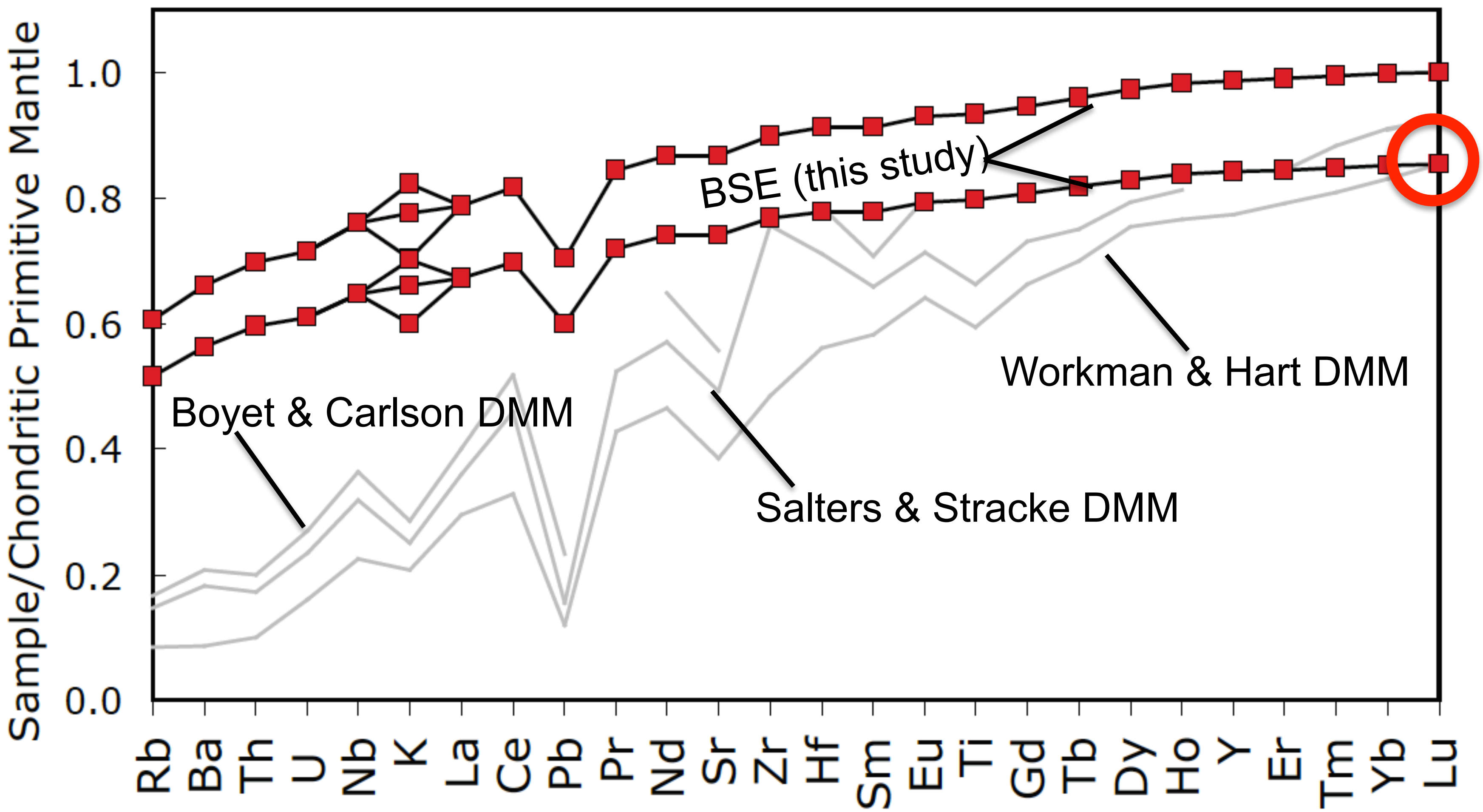
Jackson & Jellinek, 2012

-Spidergram has a shape, but no absolute concentrations.
-Can't be more enriched than chondrite-based model………" **So, anchor" to Lu!**



Jackson & Jellinek, 2012

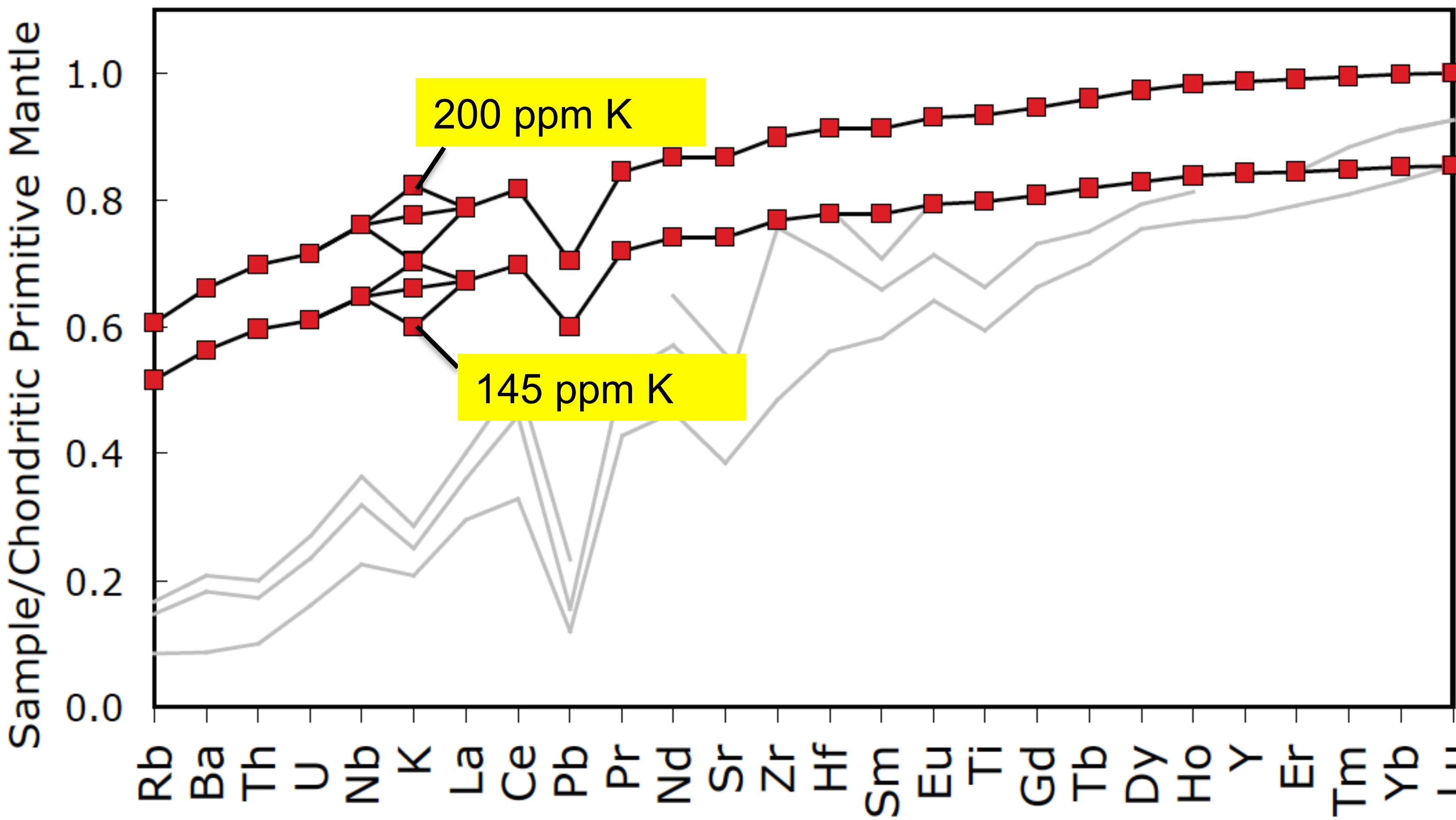
Can't be more depleted than DMM (upper and lower limits established)



Jackson & Jellinek, 2012

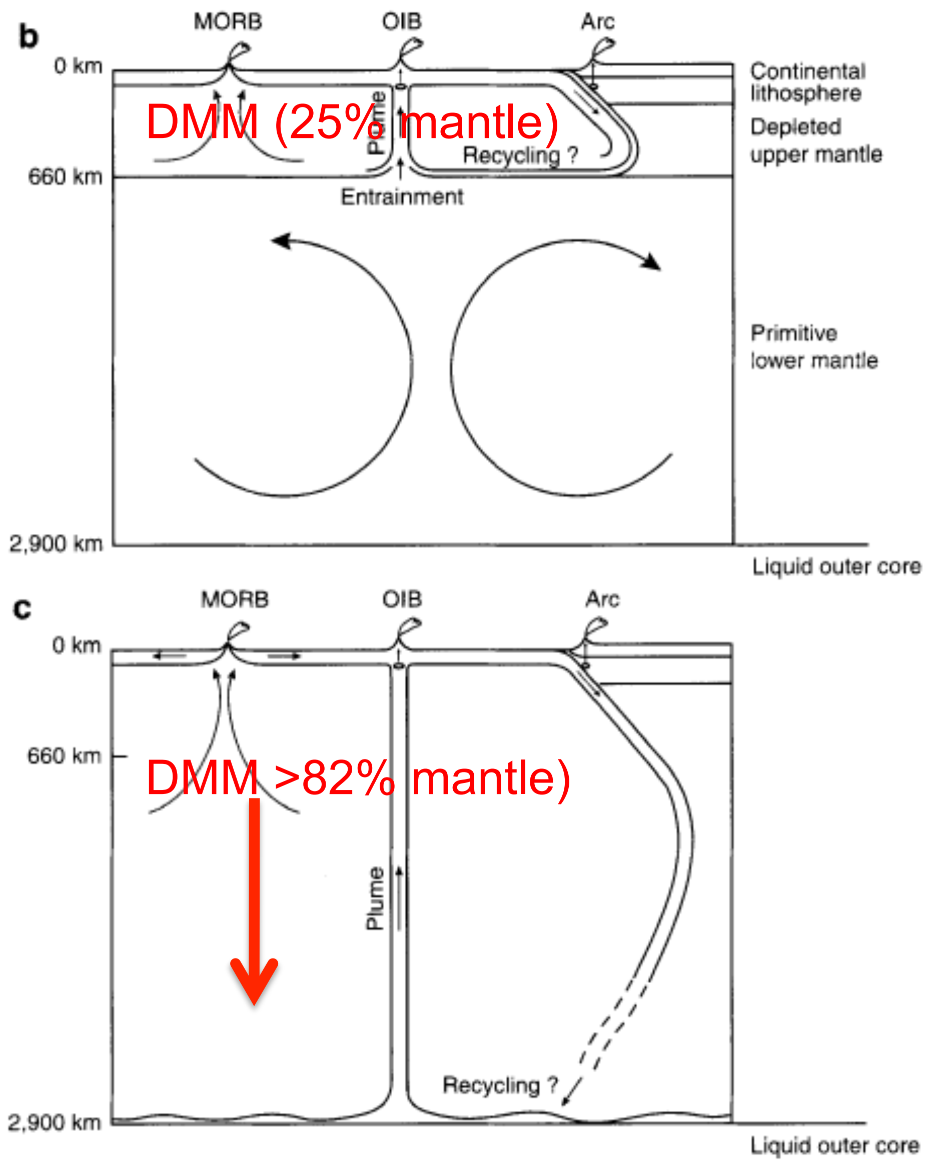
Solution to “missing” Ar?

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



Jackson & Jellinek, 2012

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]

Conclusions

- If Earth isn't "chondritic", then FOZO represents our best bet for primitive mantle.
- If terrestrial primitive mantle is FOZO-like, then it is possible to construct a trace element composition for this reservoir.
- Solution to "missing Ar" problem
- DMM is >80% of mantle.
- Lower Ur number…new generation of thermal models.

In God's kitchen