Composition of the Earth

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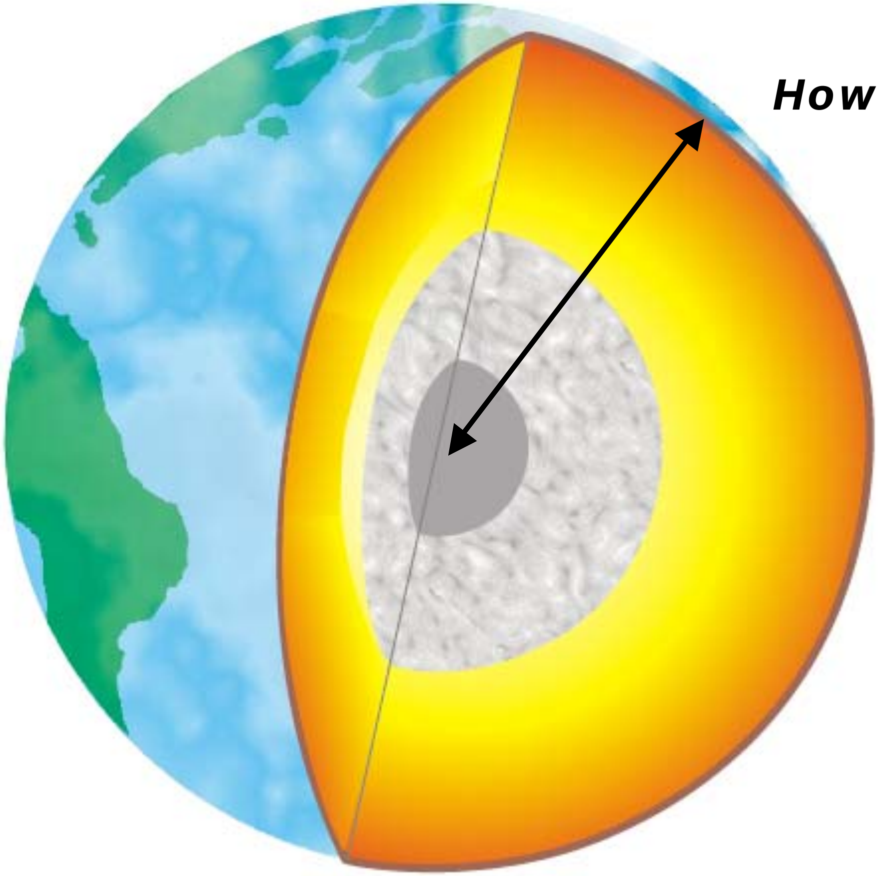
CIDER 2008

Courtesy of NASA/JPL-Caltech



How do we determine the composition of the Earth??

Best Way:

- grind up the Earth.
- take a representative sample.
- analyze in the lab for everything.

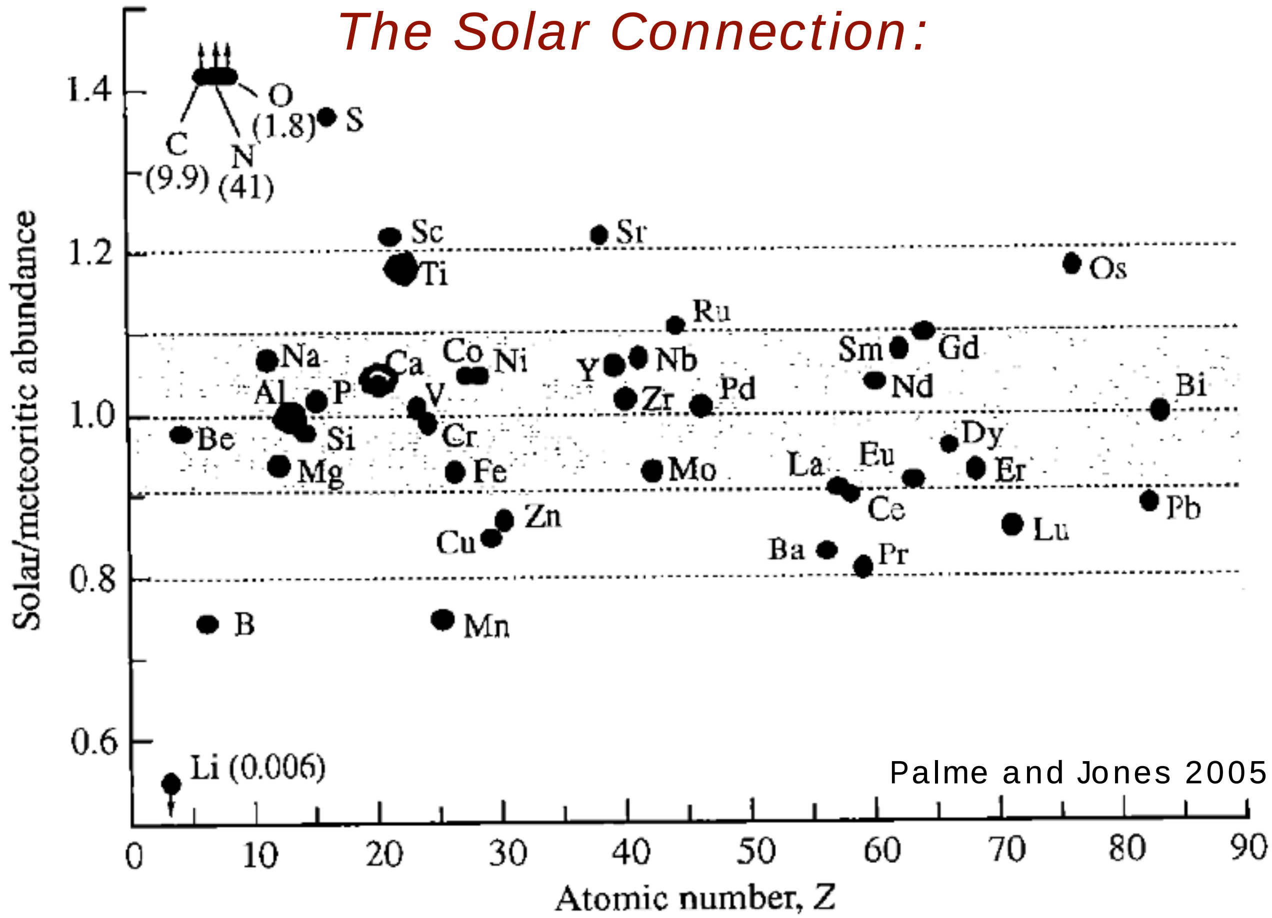
Or we can take a desperate guess (sometimes called the chondrite model).

The problem:

- direct sampling to only ~15 km.
- eruptive “entrainment” sampling to 200 km, and possibly to 500 km.
- mantle plume advection from the base of the mantle (2900 km). If plumes exist.
- no *bona fide* samples yet from the core.

Why do we think meteorites have anything to do with the Earth?

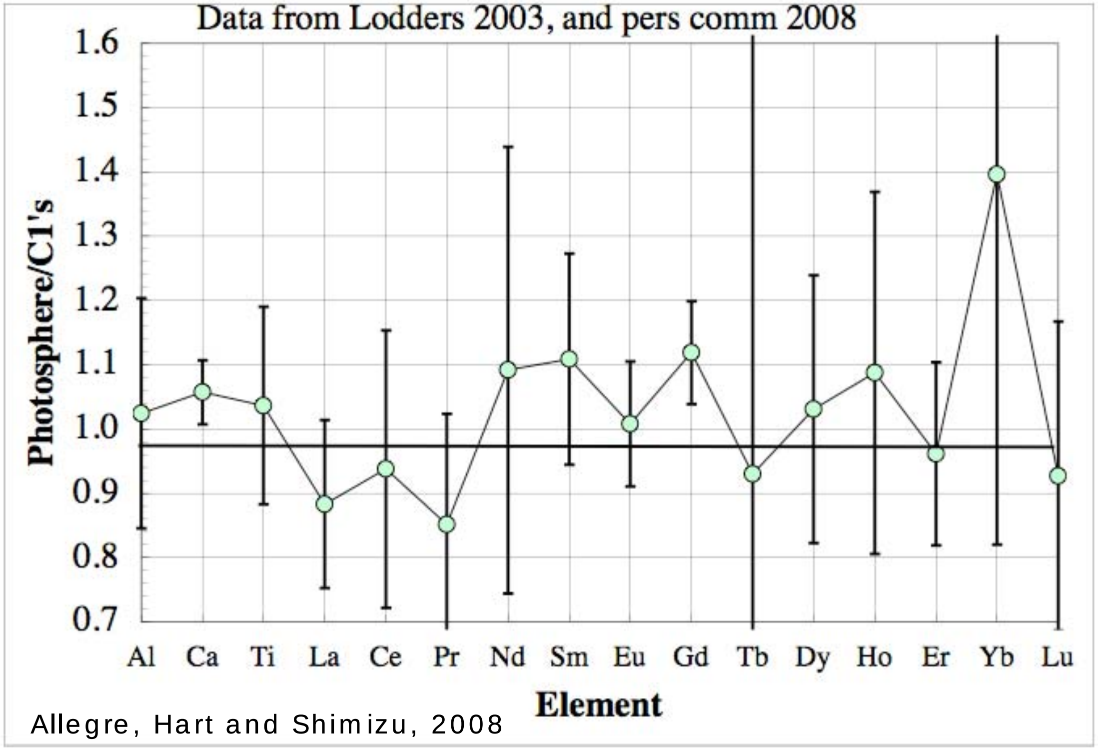
The Solar Connection:



Palme and Jones 2005

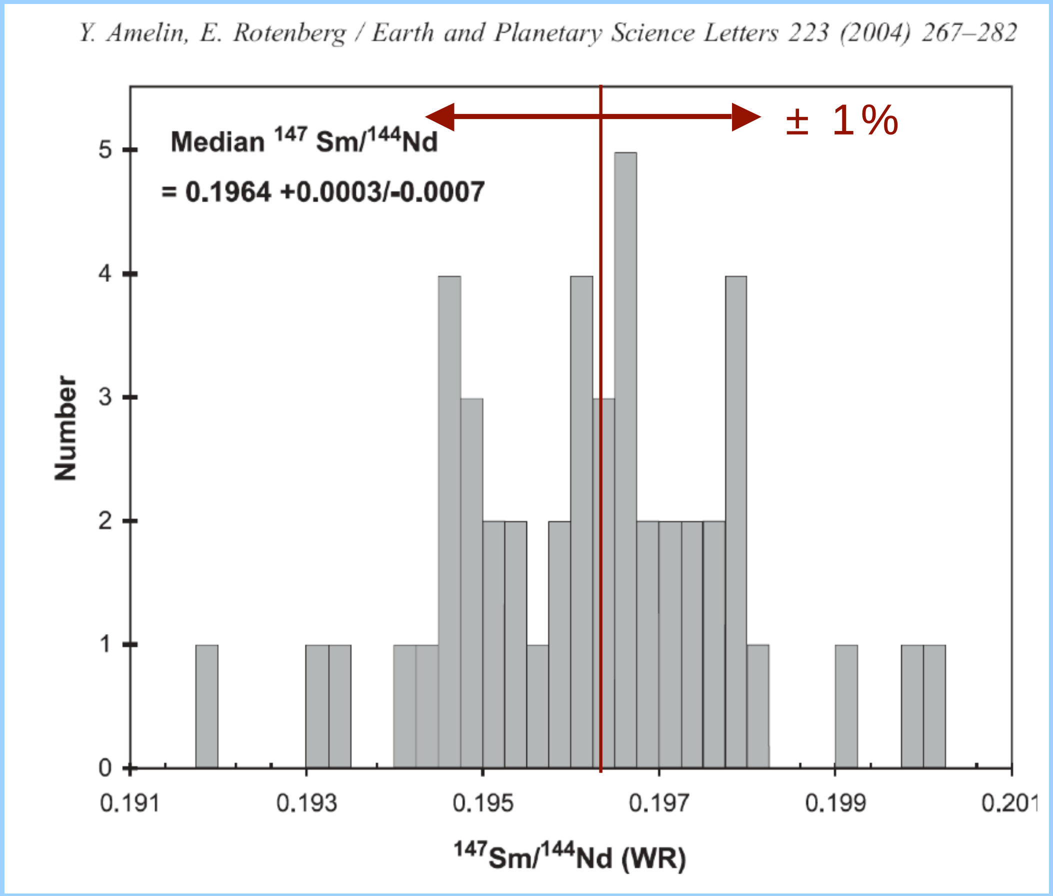
Chondrites ~ Solar Nebula, to within ± 20%

The Solar Connection:



C1 Chondrites ~ Solar Nebula, to within the uncertainties of the solar spectroscopic measurements.

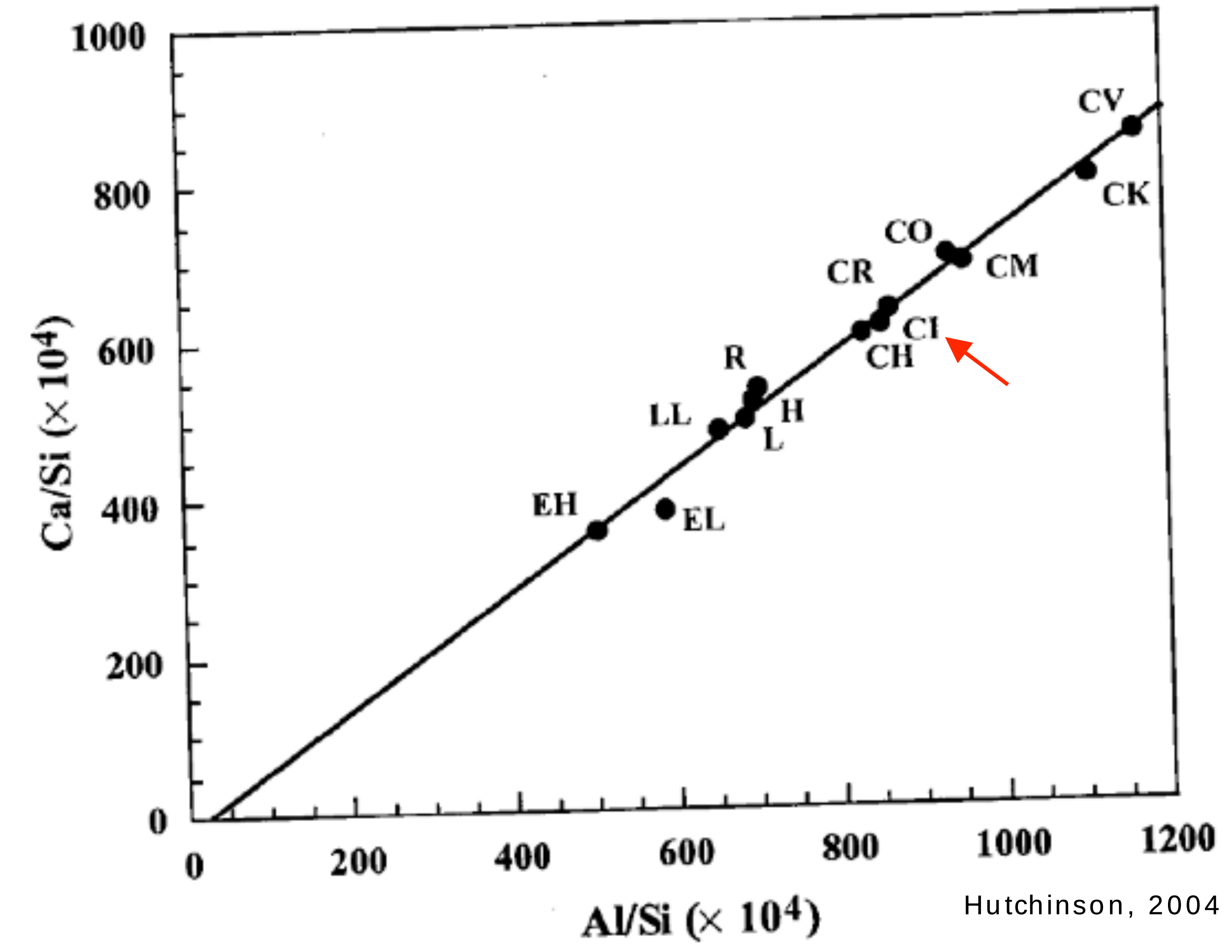
The Chondritic Earth model



All classes of Chondrites have the same Sm/Nd ratio (±1%!)
- maybe the Earth is also the same?

(note: Sm/Nd weight ratio is directly proportional to $^{147}Sm/^{144}Nd$)

The Chondritic Earth model

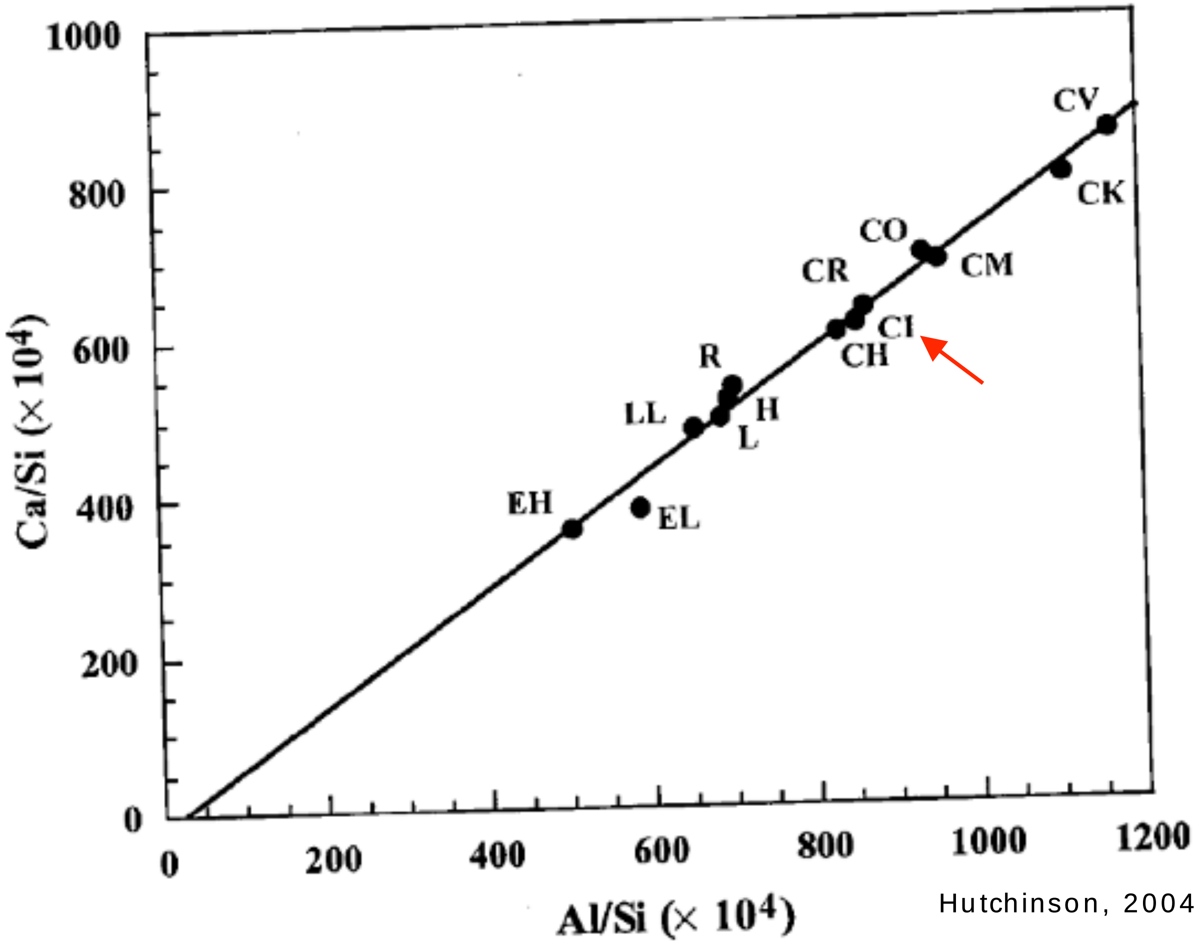


Hutchinson, 2004

Chondrites have variable Ca/Si and Al/Si but all classes of chondrites have the same Ca/Al ratio -

Maybe the Earth also has the same Ca/Al?

The Chondritic Earth model



Hutchinson, 2004

Condensation temperatures of the elements, °K:

Al - 1655°
Ca - 1520°
Mg - 1340°
Fe - 1335°
Si - 1310°

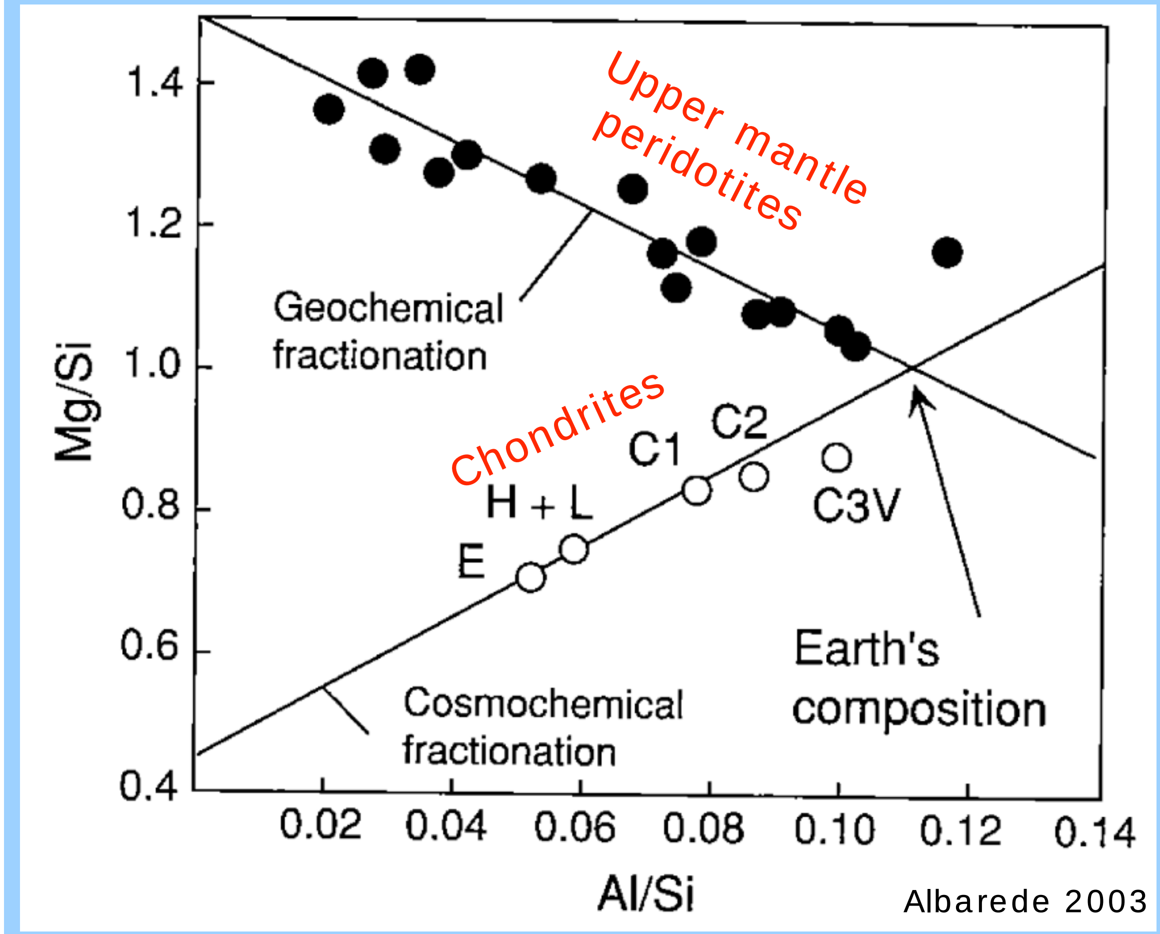
Why is Ca/Si and Al/Si variable between chondrite classes?

Because Si has a lower condensation temperature than Ca and Al.

Then what is the Earth's Ca/Si and Al/Si?

The chondritic Earth model

The first “fuzzy” step -



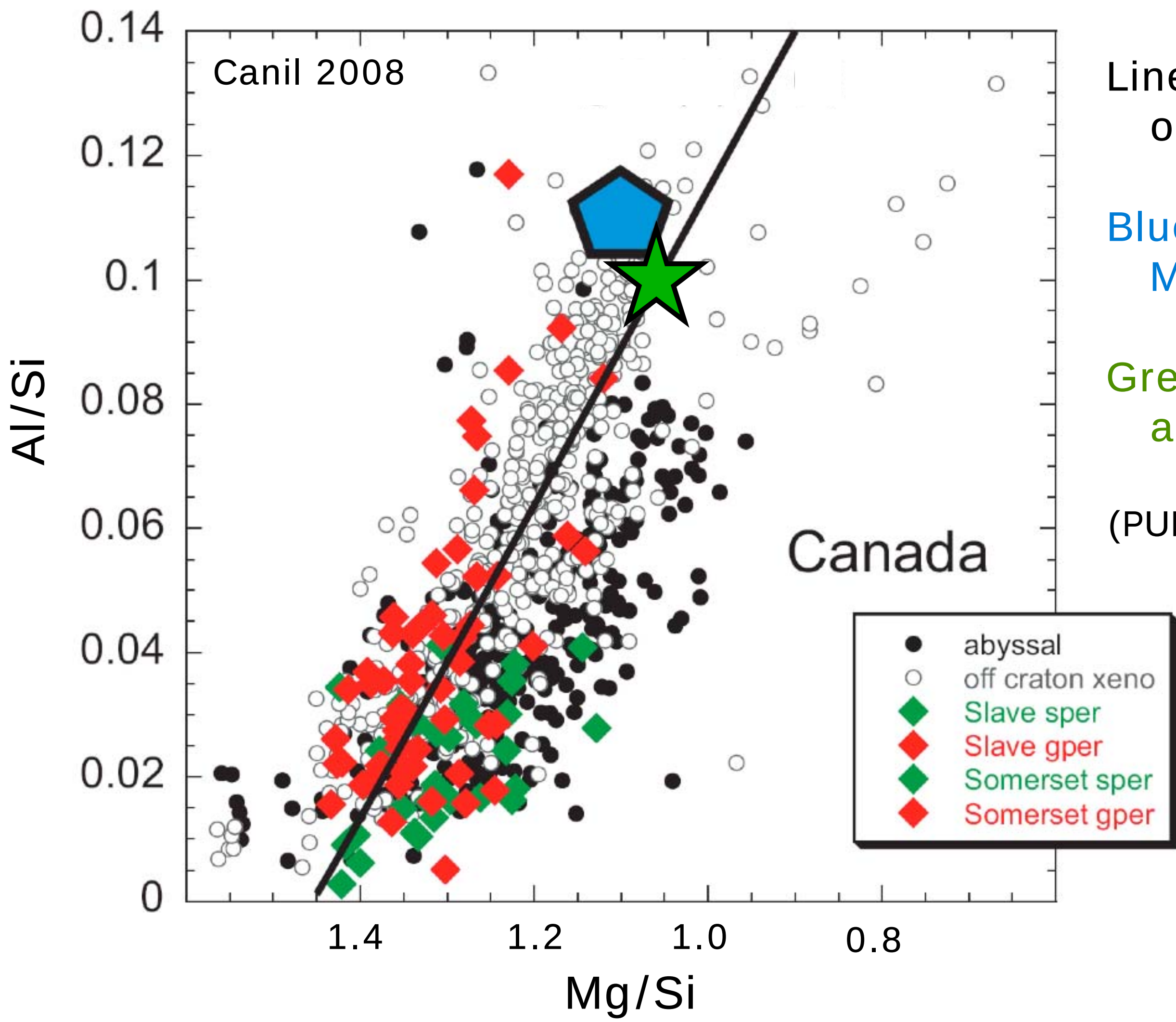
Peridotites represent residues of partial melting.

Chondrites represent differing condensation temperatures.

Intersection defines the composition of the primitive upper mantle (PUM) and suggests Earth had a higher condensation temperature than chondrites.

QED - we know the relative Al, Mg and Si contents of the Earth.

The more the data, the fuzzier it gets!



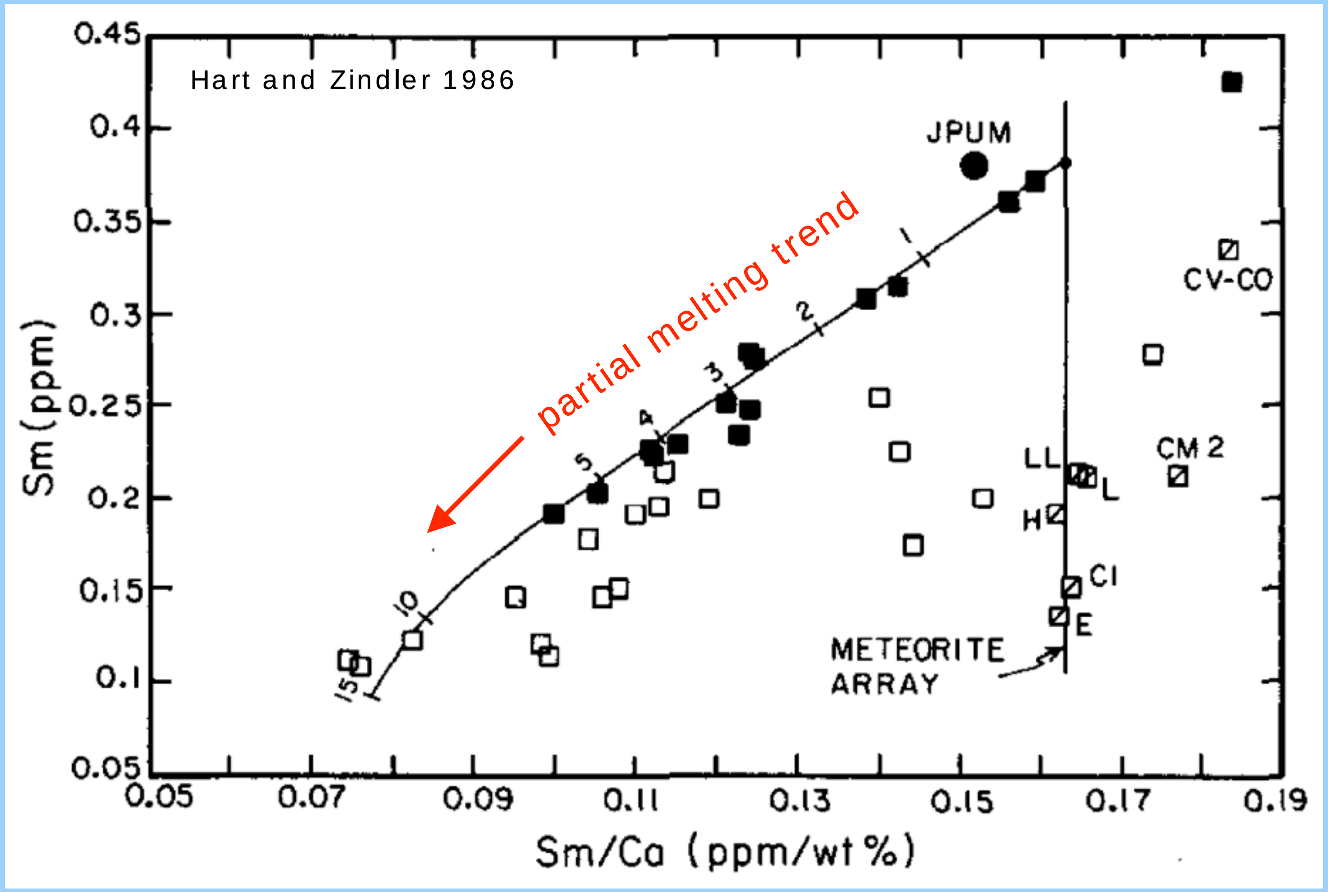
Line is Canil's best fit to the off-craton xenoliths.

Blue pentagon is PUM from McDonough and Sun 1995.

Green star is PUM from Hart and Zindler 1986 (aka HaZi).

(PUM = primitive upper mantle)

Chondrite model can also be used for trace elements:

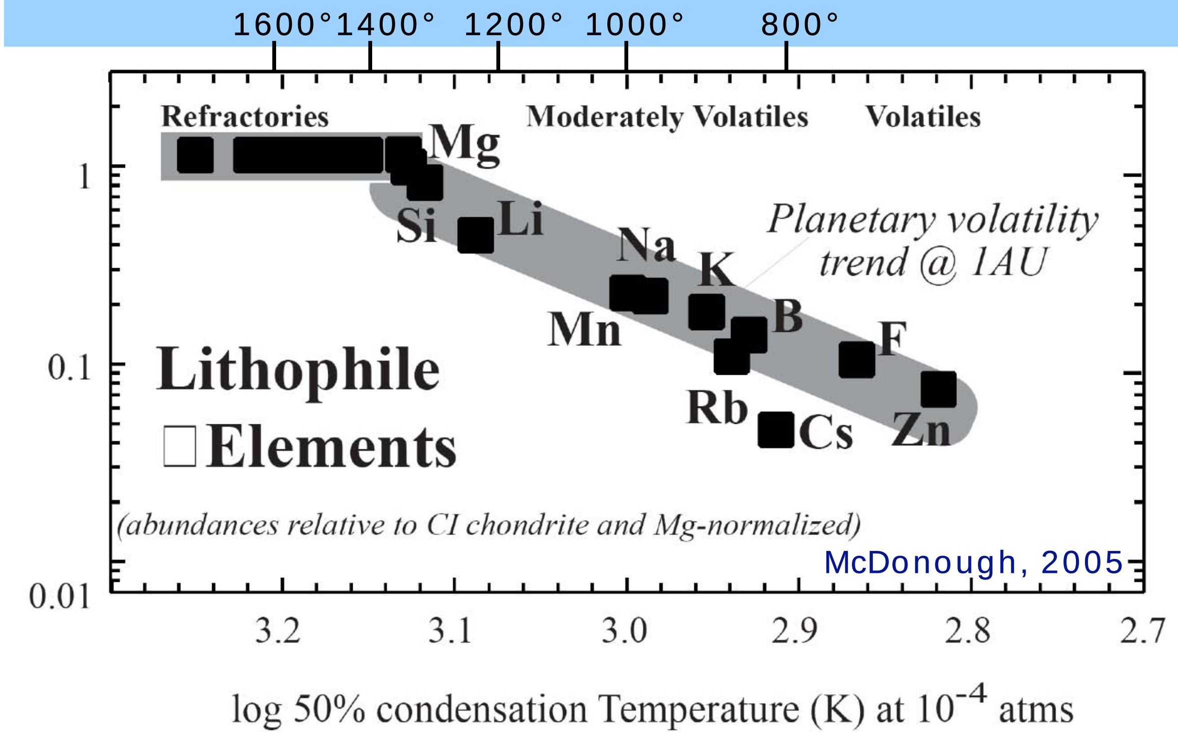


Like Sm/Nd, Sm/Ca appears constant in chondrites (excepting some "cooked" carbonaceous chondrites).

Ignore the open squares (metasomatized upper mantle peridotites).

Tic marks on melting curve are % increments of melt removal.

Estimated Earth Composition relative to C1 chondrites



Refractory Element Condensation Temps

Re - 1820°K
W - 1790
Zr - 1740
Th - 1660
REE -1660 - 1490 (Yb)
Al - 1655
U - 1610
Ti - 1580
Ca - 1520

Semi-refractory

Mg - 1340
Fe - 1335
Si - 1310

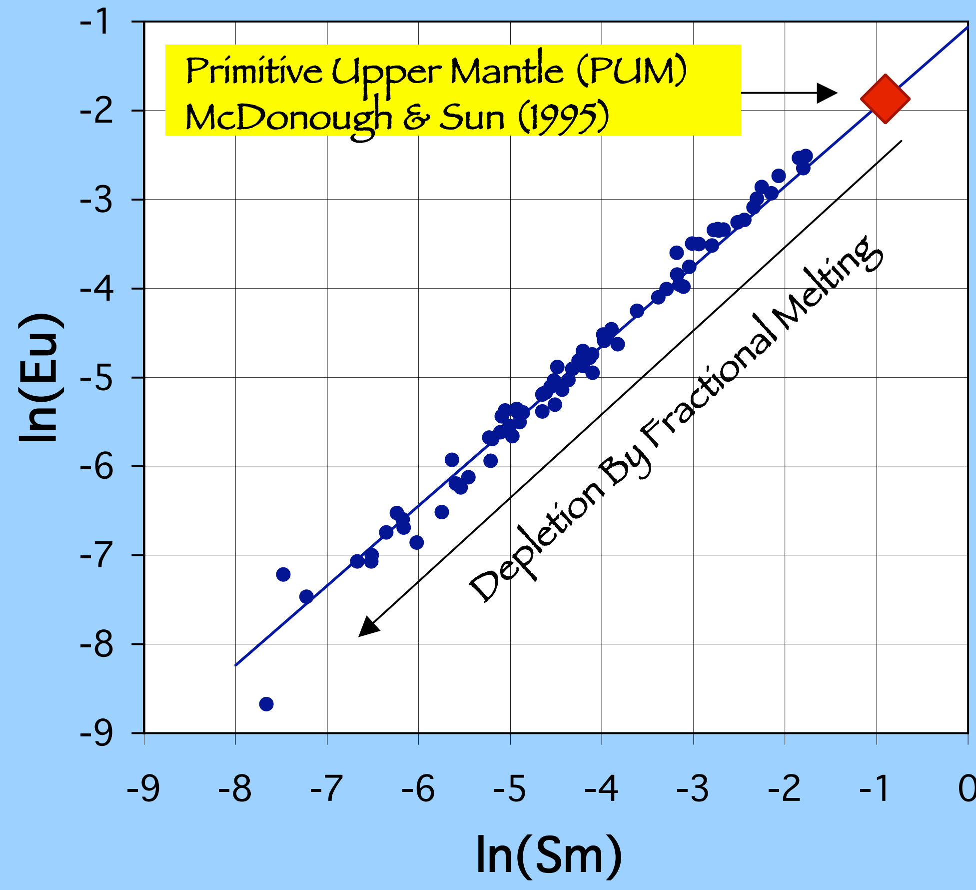
Good match for Refractory Elements (Tcond. >1500°K)

Abyssal Peridotites = Simple Residues of DMM Melting

Linearized relationship between two elements, A & B, in a residue of fractional melting:

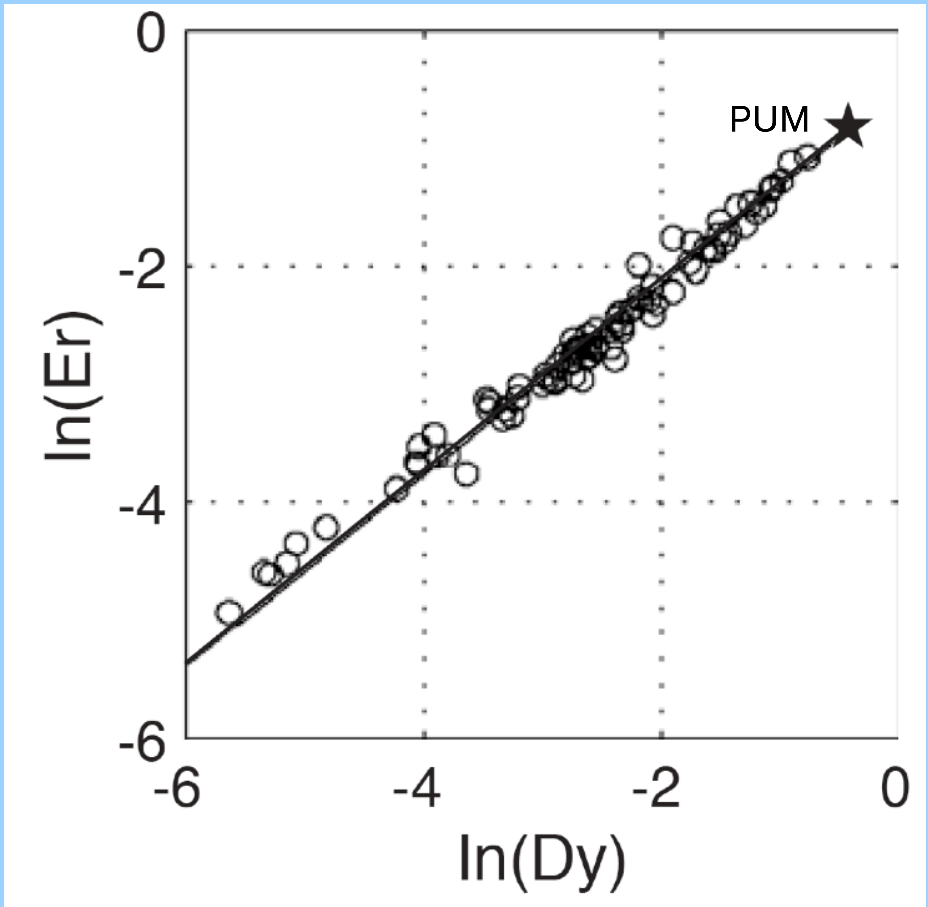
$$\ln\left(C_s^A\right) = R\ln\left(C_s^B\right) + \ln\left(\frac{C_o^A}{\left(C_o^B\right)^R}\right)$$

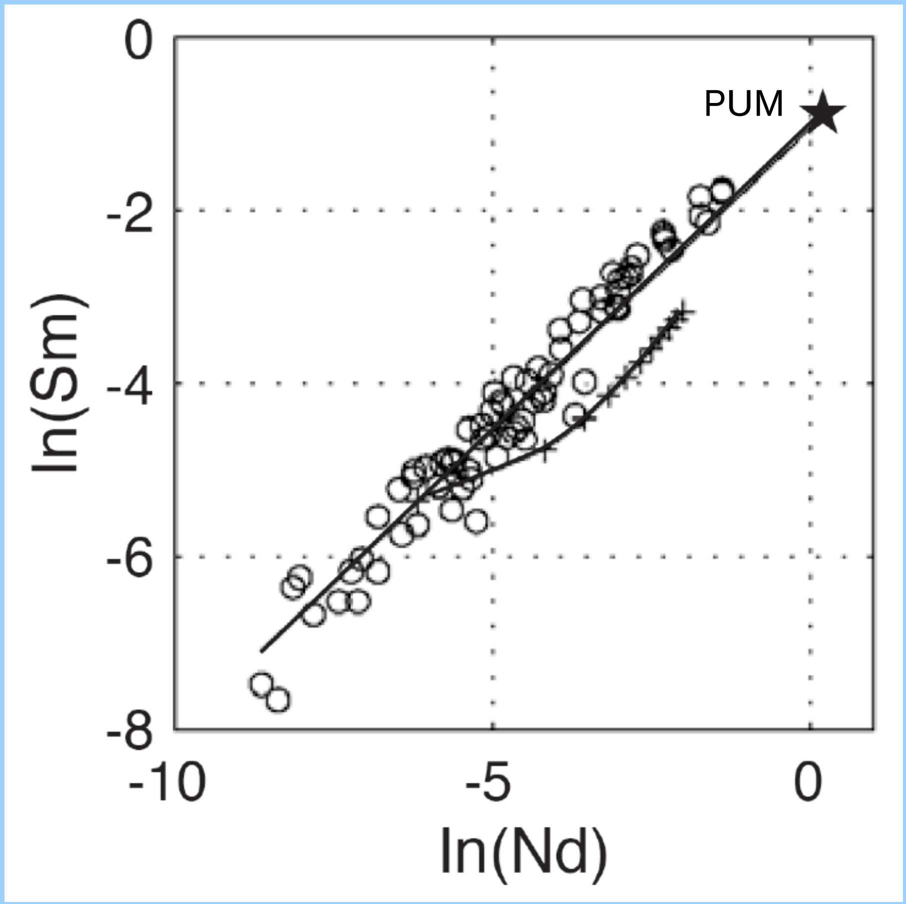
Where slope, R $= \dfrac{D_B(1-D_A)}{D_A(1-D_B)}$



Workman and Hart, 2005

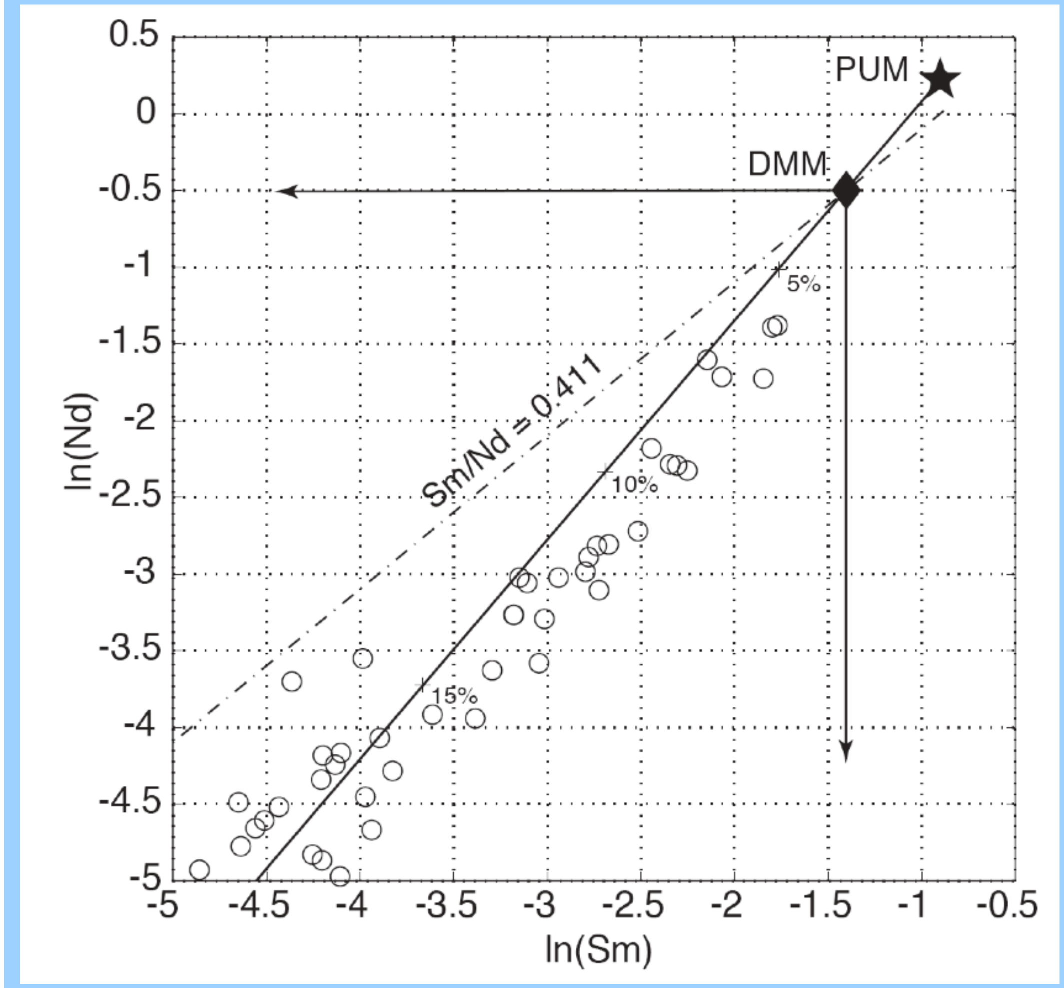
Some other trace element trends in abyssal peridotites:





We know the composition of DMM is somewhere on the regression between PUM and the least depleted abyssal peridotite - but where?

Workman and Hart, 2005



We work backward from the average $^{143}Nd/^{144}Nd$ of melts from the depleted upper mantle (=0.51317).

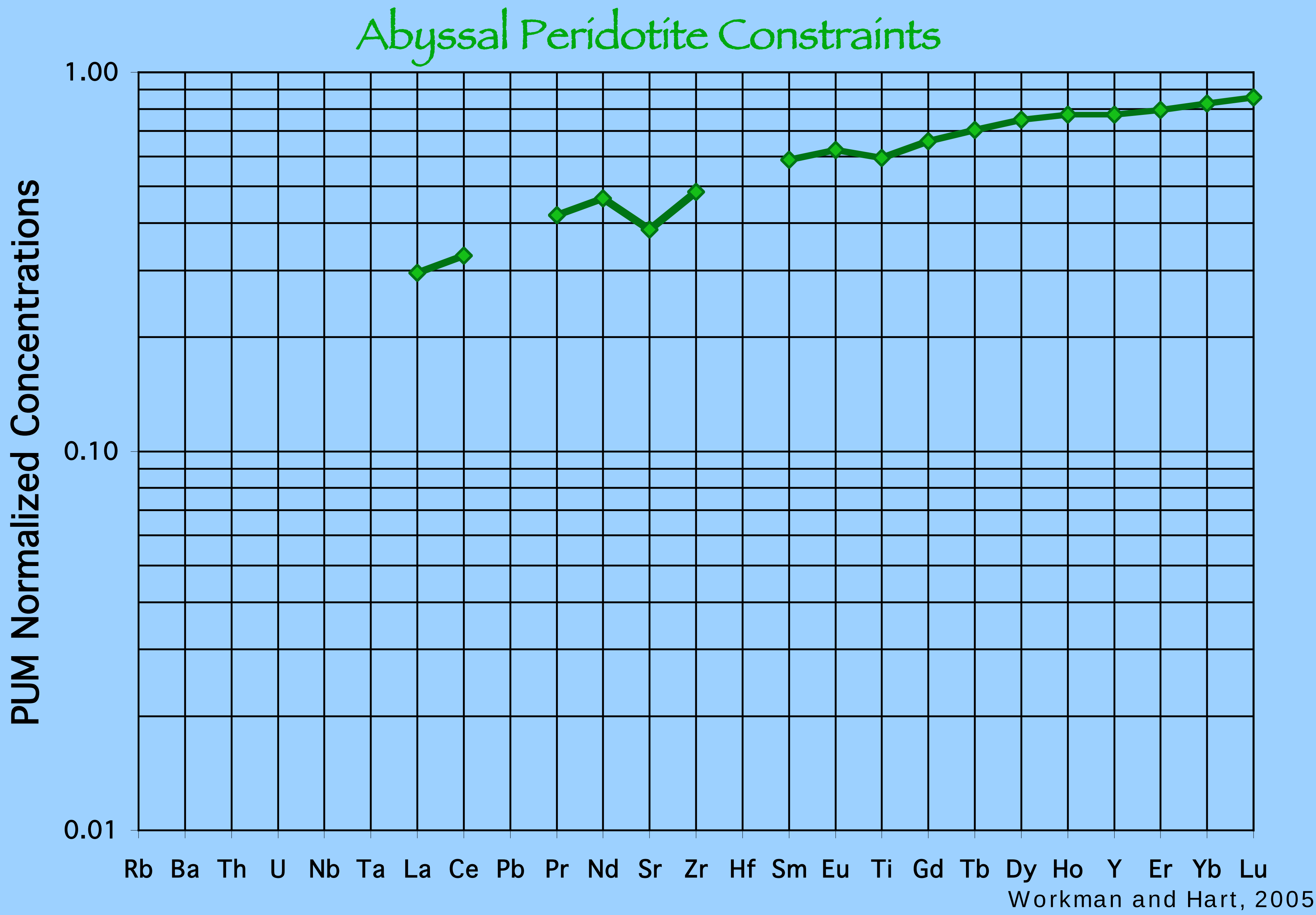
Given the Sm/Nd of PUM, we can model the evolution of a continuously depleting reservoir that ends at this present day $^{143}Nd/^{144}Nd$ of N-MORB.

From this model, we can estimate the present day Sm/Nd of DMM (=0.411).

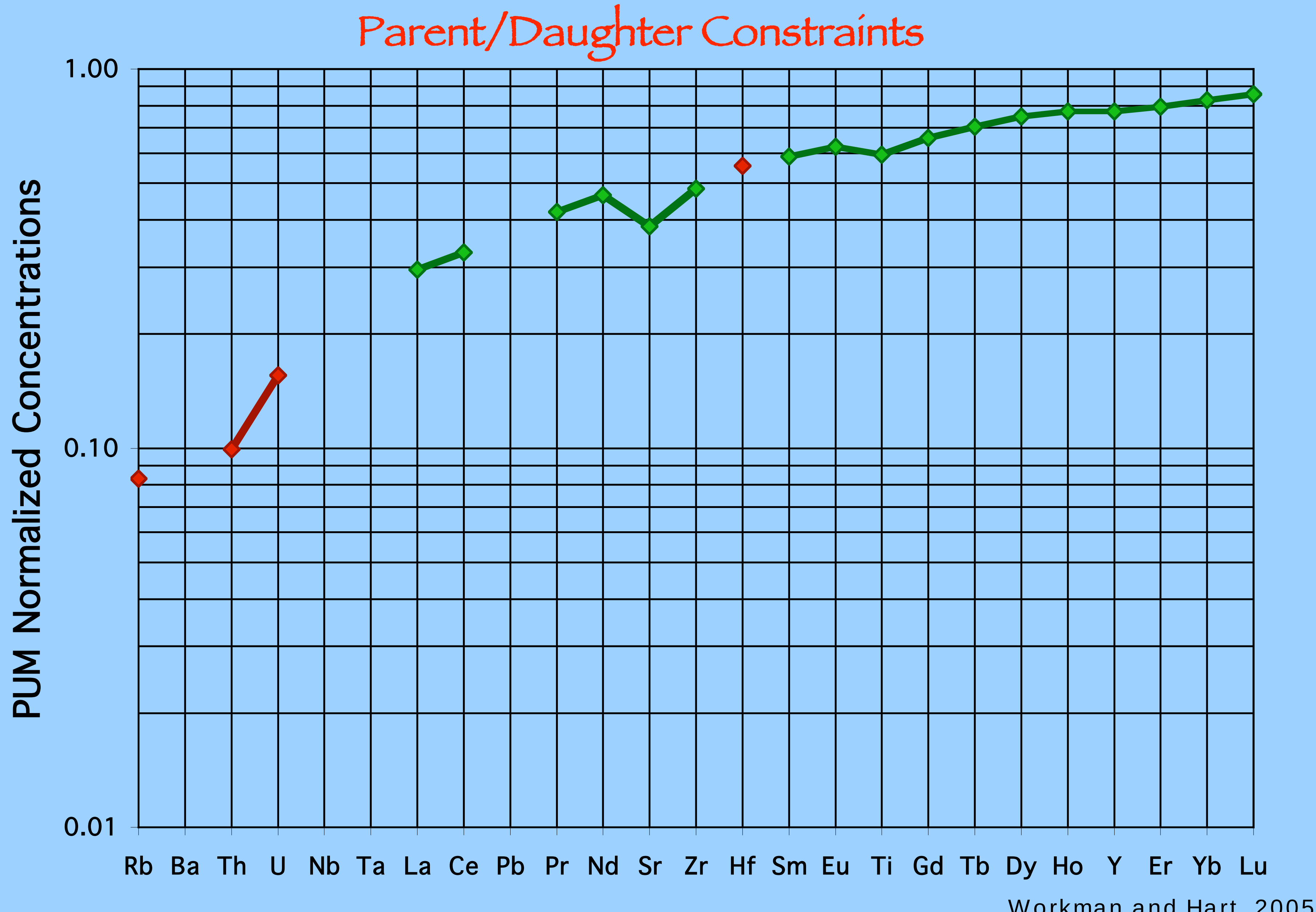
The intersection of this line with the abyssal peridotite trend defines the Sm and Nd concentration of DMM.

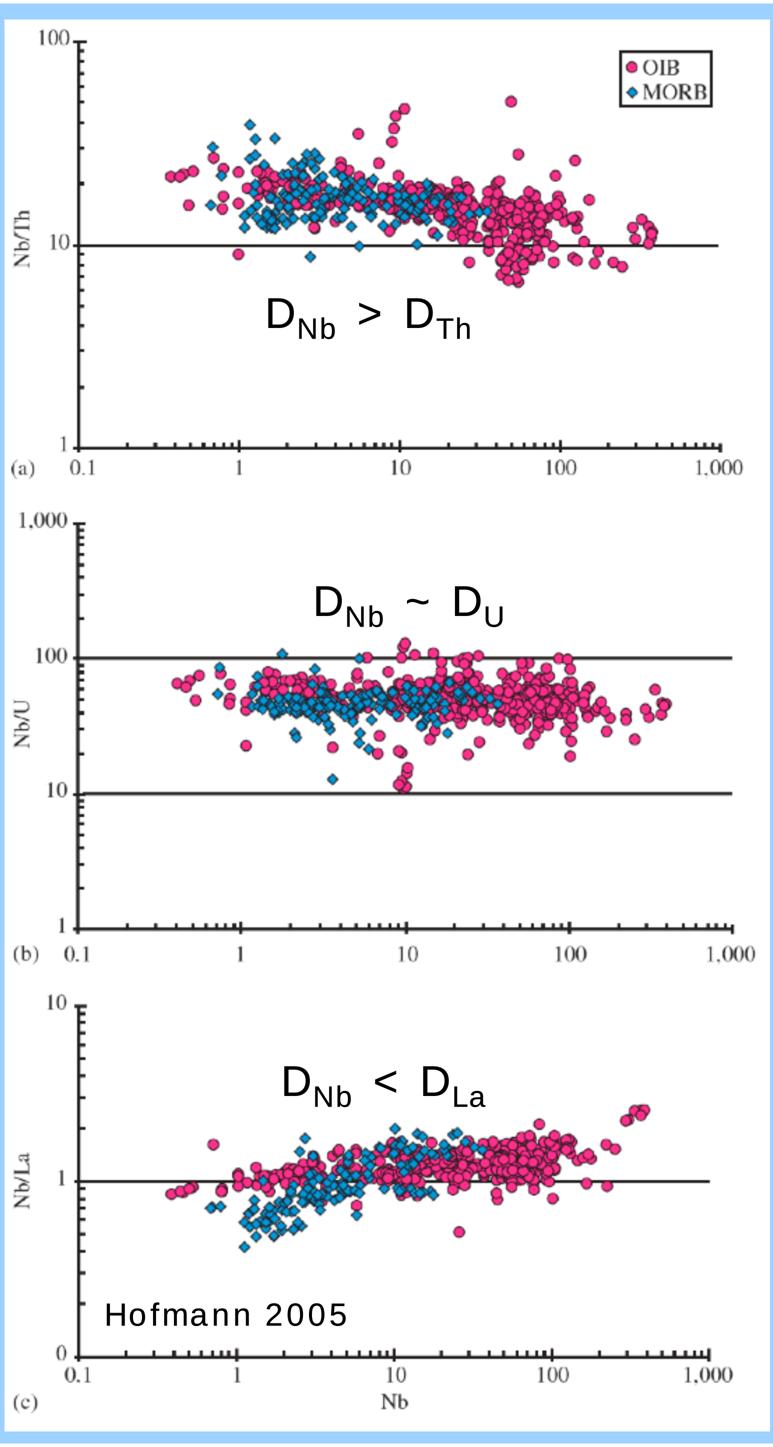
Workman and Hart, 2005

Composing Trace Element Composition of DMM



Composing Trace Element Composition of DMM





"Canonical" Ratios

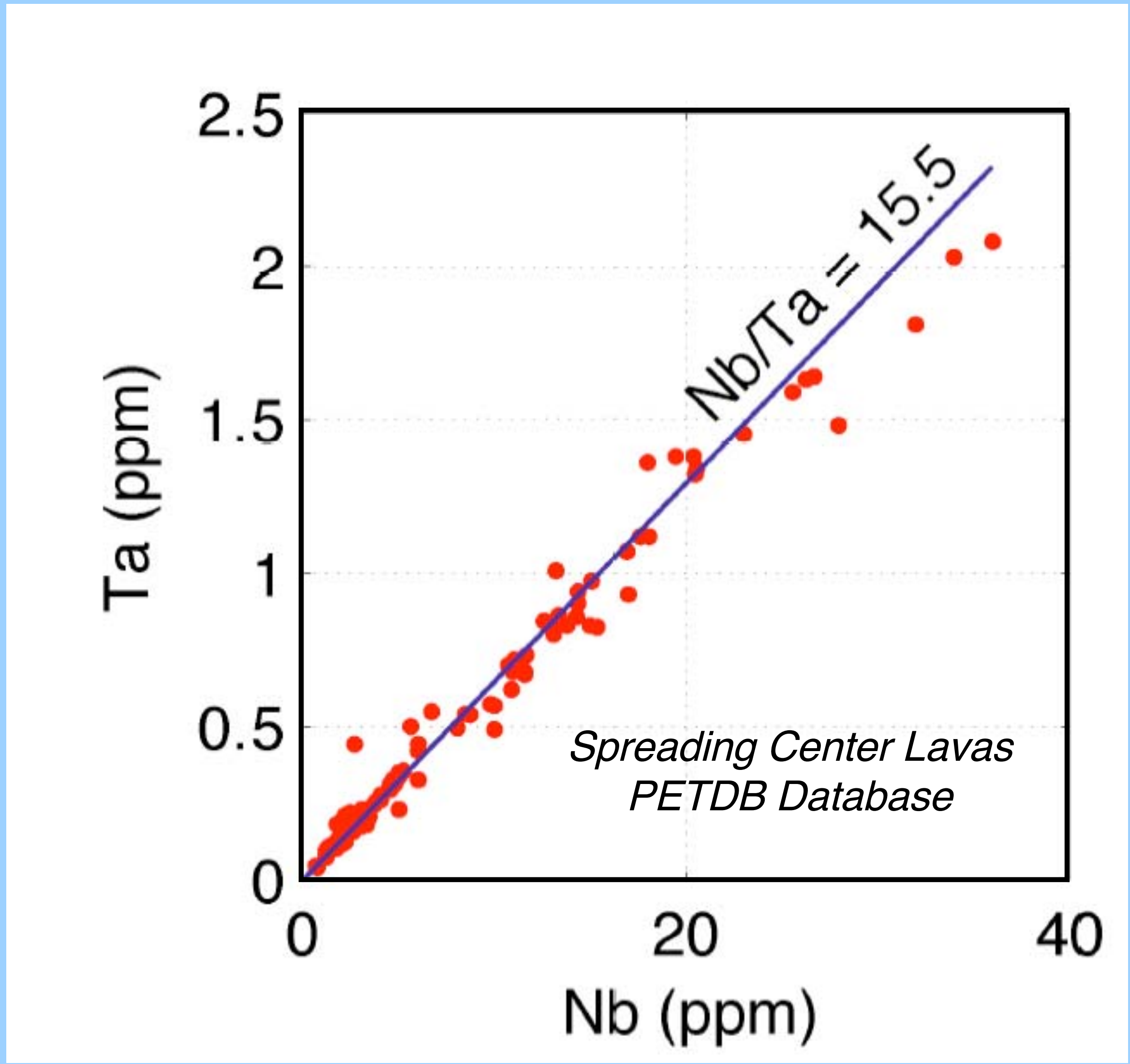
Negative slope means numerator element is more compatible than denominator element.

i.e mineral/melt partition coefficient D_i is larger

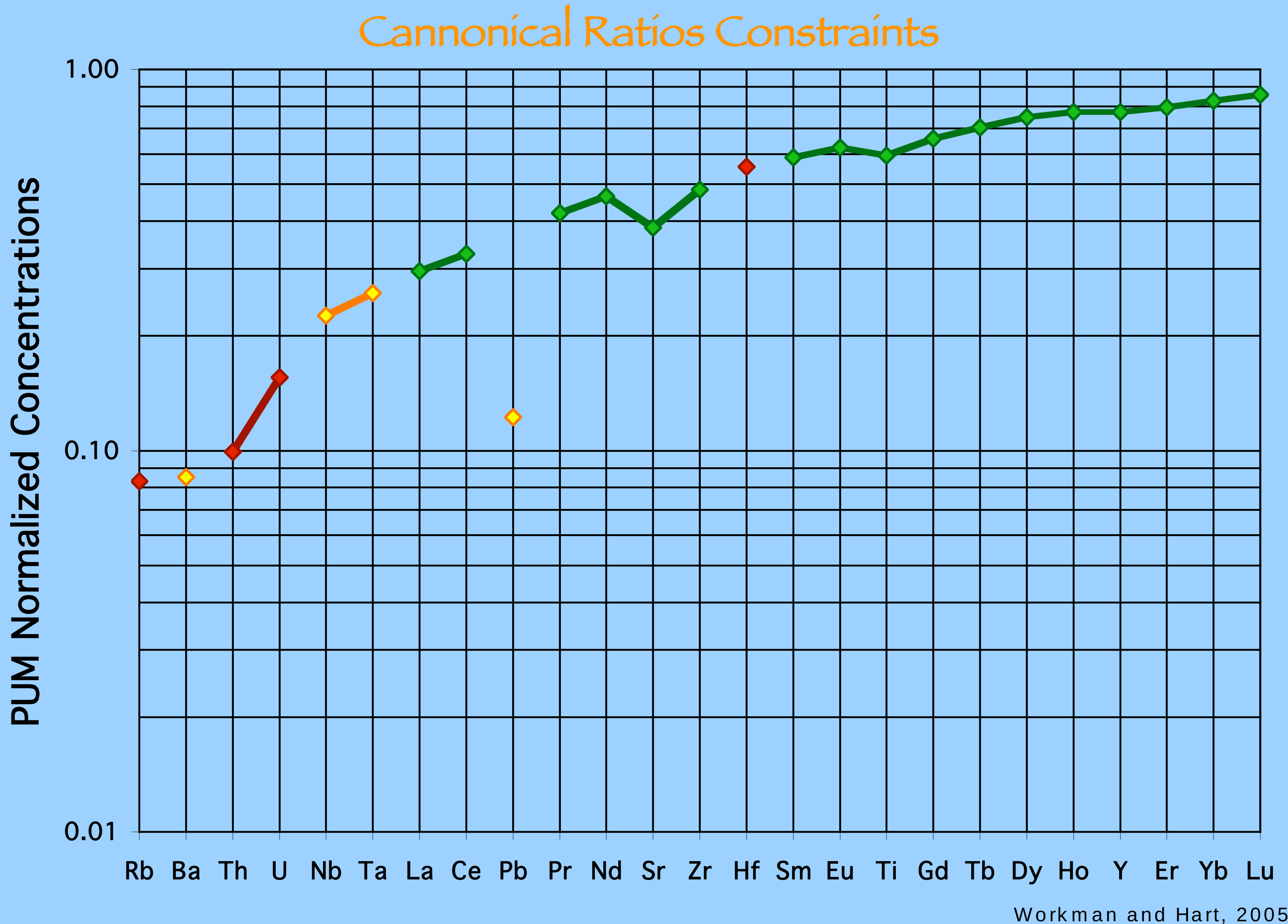
Horizontal slope means both elements have the same partition coefficient.

"Canonical" ratios

Some trace elements don't fractionate from each other!
So ratio in melt equals ratio in residue



Composing Trace Element Composition of DMM

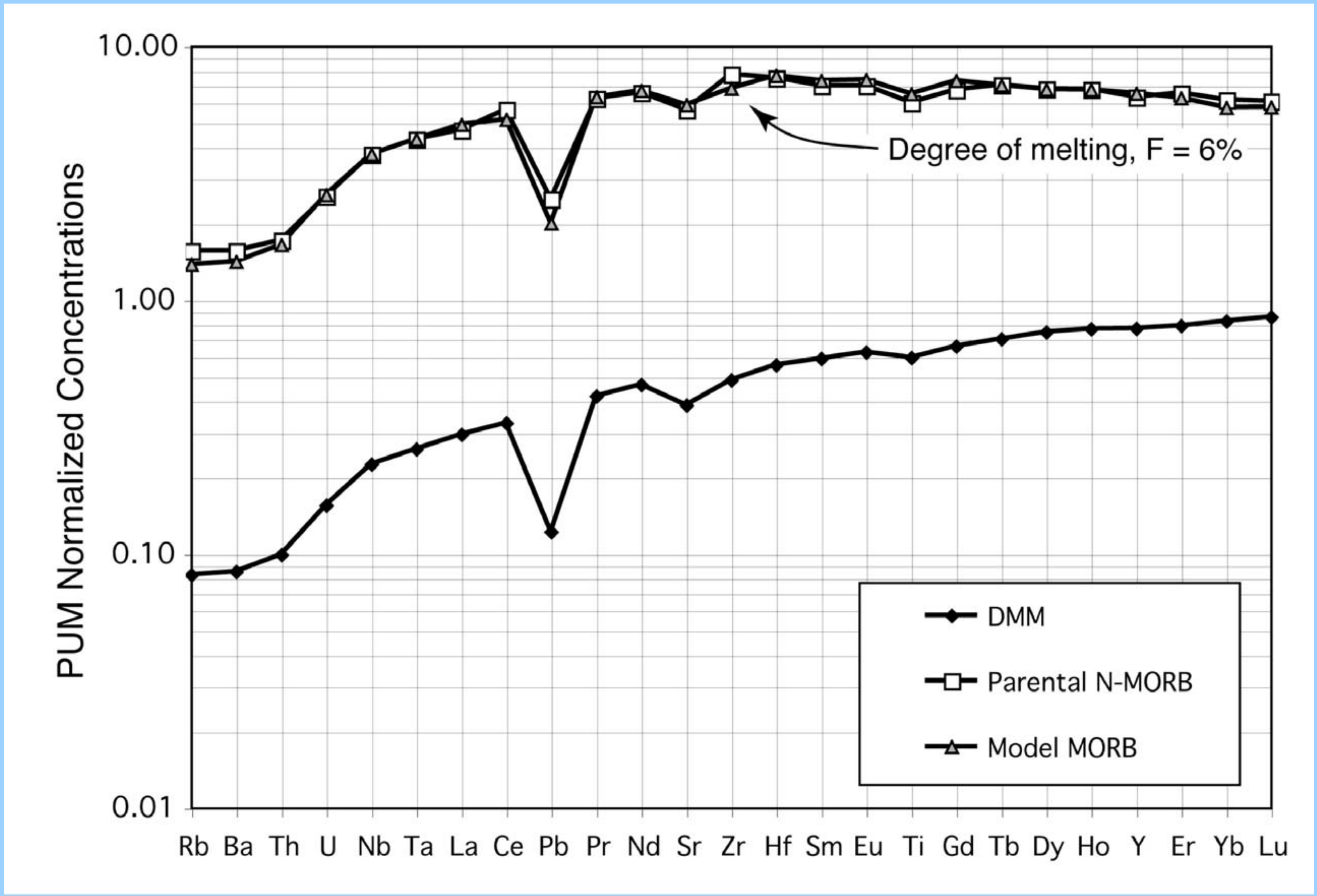


Composing Trace Element Composition of DMM

Connecting the Dots…

Workman and Hart, 2005

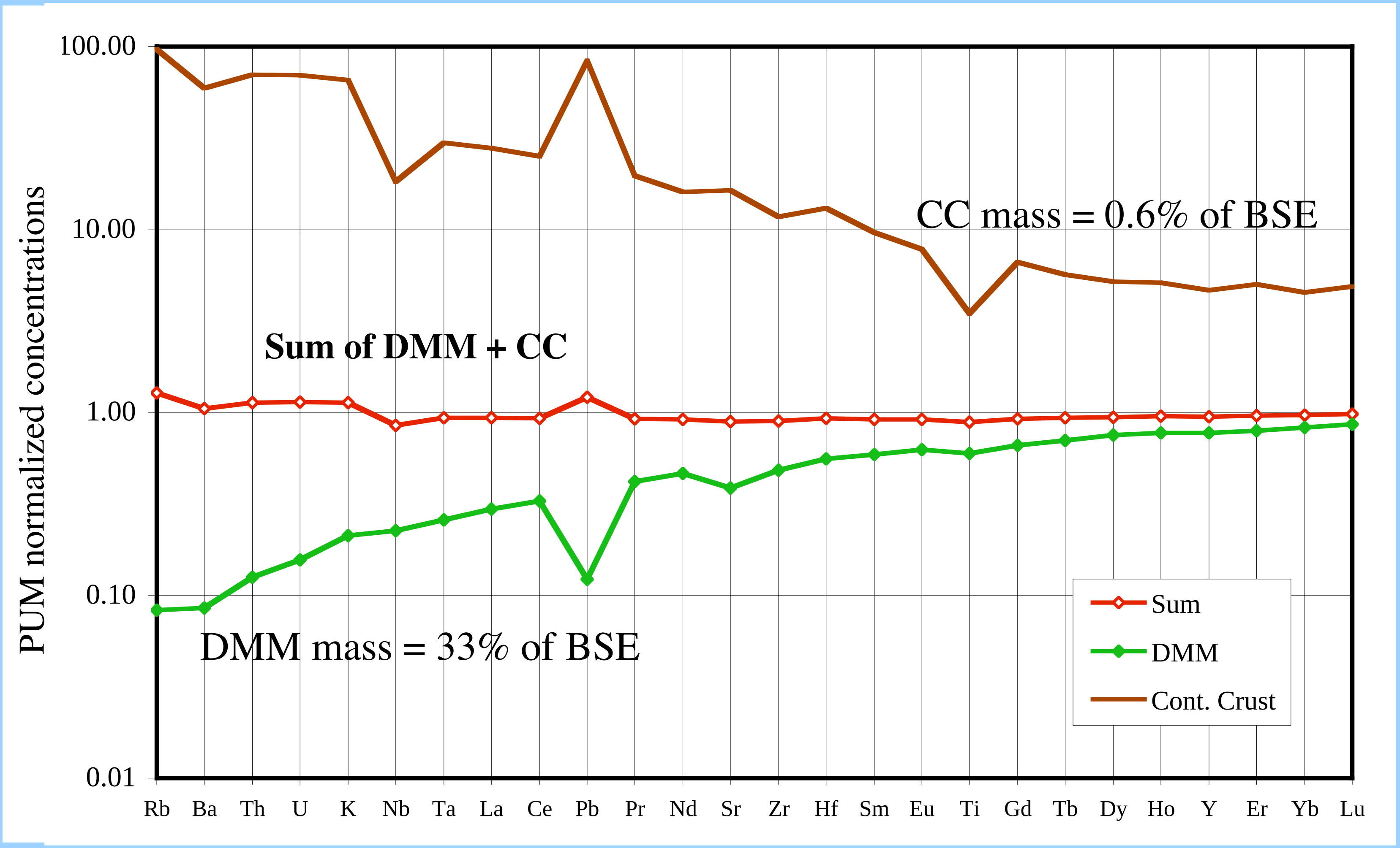
MORB Generation from model DMM



Workman and Hart, 2005

Crust-Mantle Mass Balance - I

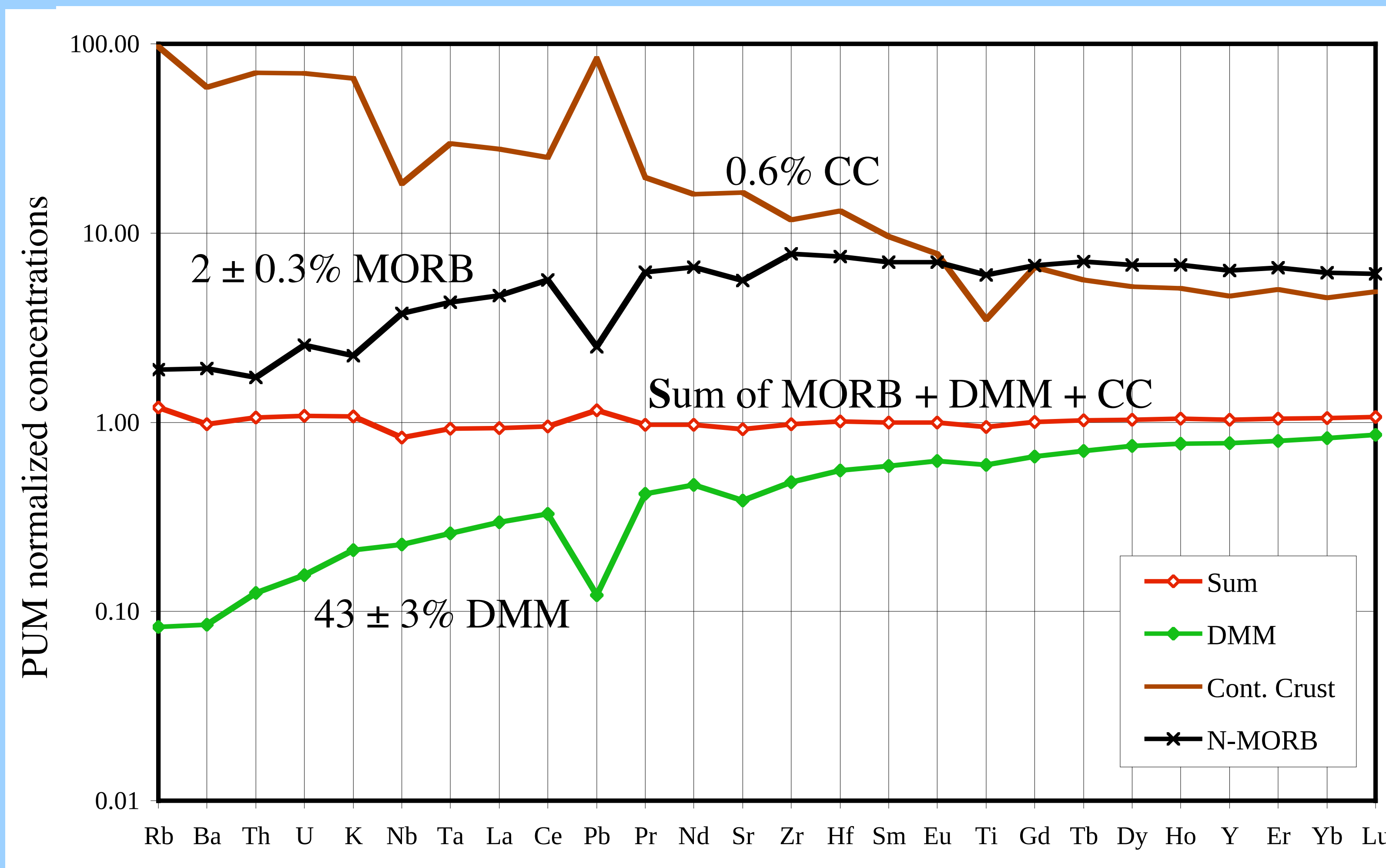
How much DMM does it take to balance JUST Continental Crust?



Bulk Continental Crust from Rudnick and Fountain (1995)

Crust-Mantle Mass Balance - II

Adding Oceanic Crust into the Balance
Most element fit to within 8%



Bulk Continental Crust from Rudnick and Fountain (1995)

Table 3. Modal abundances and major element composition of DMM.

	Modal Abundances in DMM (%):					
	Olivine	Opx	Cpx	Spinel		
	57	28	13	2		
	Mineral compositions:					
	Olivine	Opx	Cpx	Spinel	Bulk DMM	PUM [a]
SiO_2	40.70	53.36	50.61		44.71	44.90
Al_2O_3		6.46	7.87	57.54	3.98	4.44
FeO*	10.16	6.27	2.94	12.56	8.18	8.03
MnO	0.14	0.12	0.09	0.16	0.13	0.13
MgO	48.59	30.55	16.19	19.27	38.73	37.71
CaO	0.05	2.18	19.52		3.17	3.54
Na_2O		0.05	0.89		0.13	0.36
Cr_2O_3		0.76	1.20	10.23	0.57	0.38
TiO_2		0.16	0.63		0.13	0.20
NiO	0.36	0.09	0.06	0.24	0.24	0.25
K_2O					0.006 [c]	0.029
P_2O_5					0.019 [d]	0.021
Total	100.00	100.00	100.00	100.00	100.00	100.00
Mg # [e]	89.5	89.7	90.8	73.2	89.4	89.3
Cr # [f]				10.7		
CaO/Al_2O_3		0.34	2.48		0.80	0.80

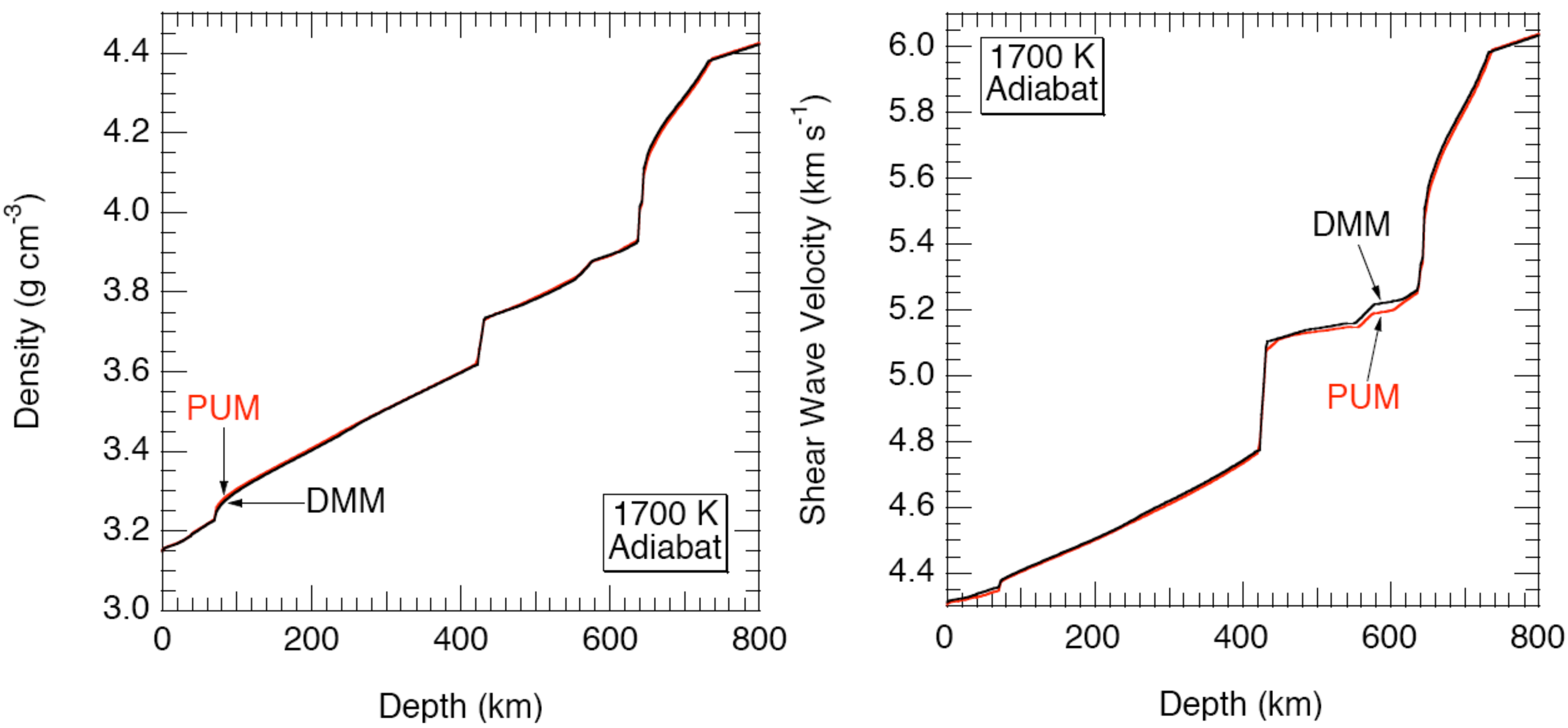
Workman and Hart, 2005

Summary of Upper Mantle Composition

- DMM ~ PUM minus -3% melt
- N-MORBs are ~ 6% melts of DMM.
- DMM mineralogy is still a lherzolite.
- DMM physical properties are like PUM.
- Heat production is only 15% of PUM. (2.4 pW/m^3)

Deplete the primitive upper mantle to make a depleted MORB mantle:

- produces a huge effect on isotopes, heat production and some trace elements but an insignificant effect on density and shear wave velocity!



Physical properties calculated with model of Stixrude and Lithgow-Bertelloni 2005

So we’re done, right?

hmmmmmm

^{142}Nd is the daughter of ^{146}Sm, an extinct parent.

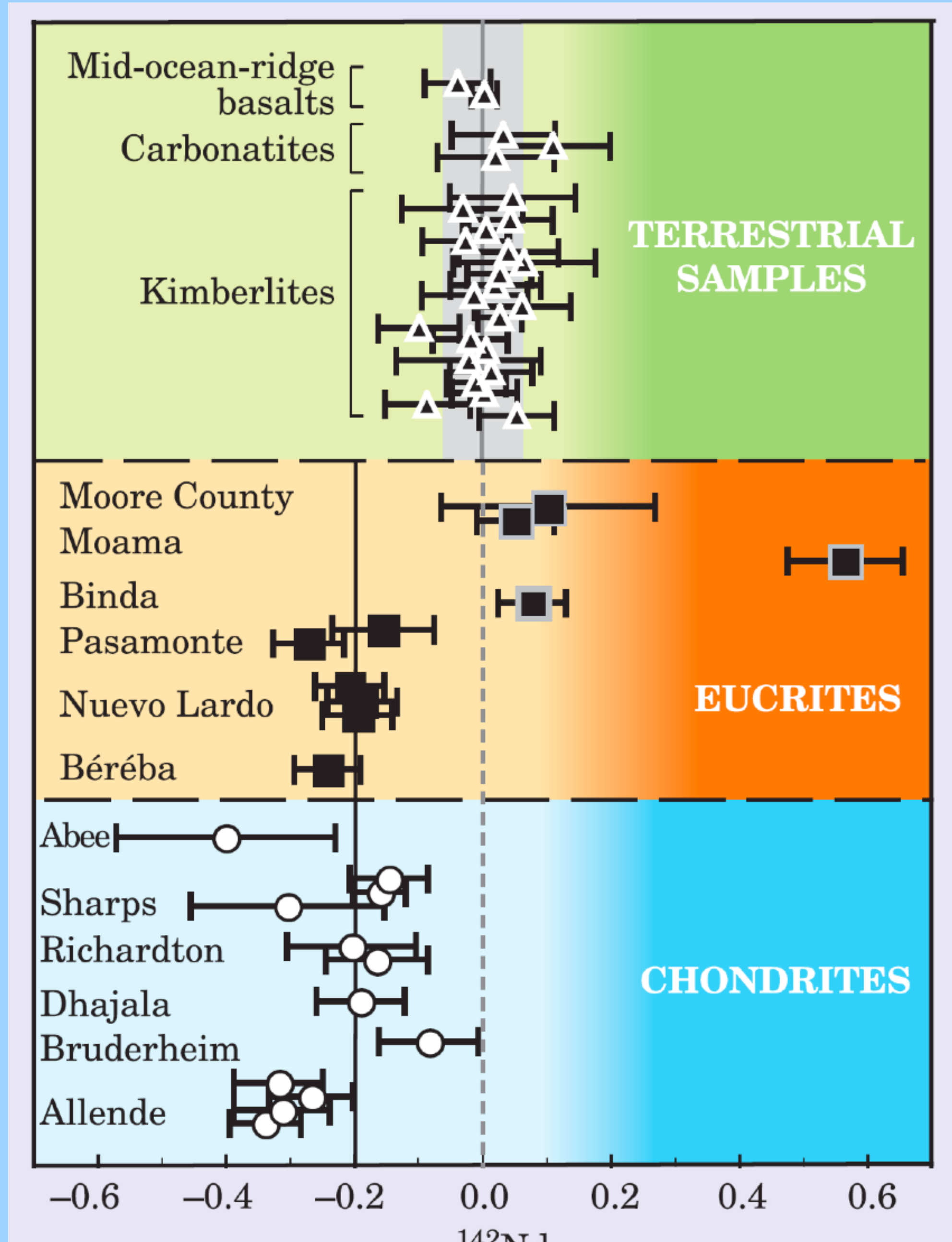
^{142}Nd in the accessible Earth is 20 ppm higher than in chondrites.

Only two simple choices:
- the earth is not chondritic.
- there is a hidden terrestrial low Sm/Nd reservoir we've not yet seen.

All consequences are drastic!

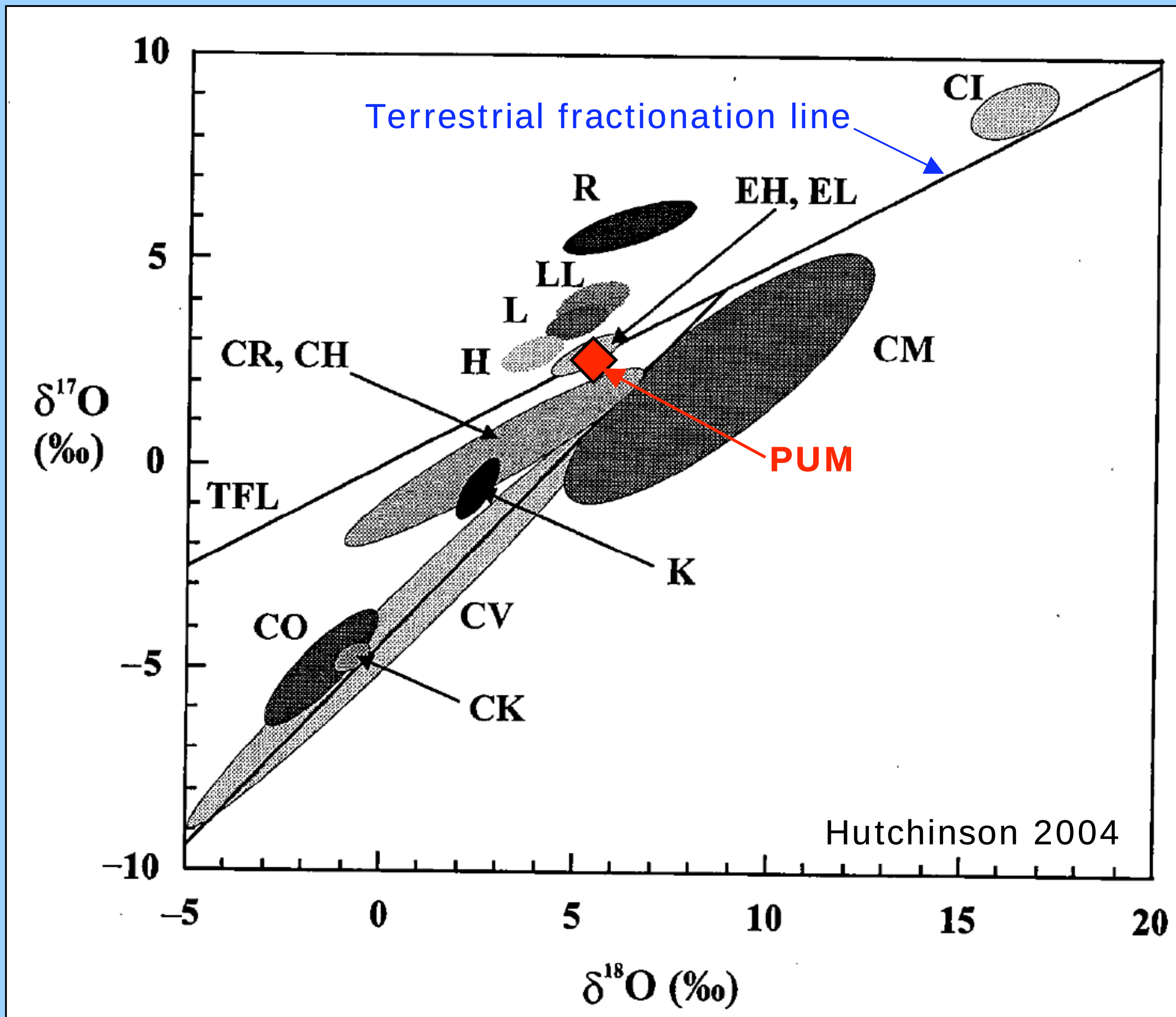
So is the chondritic model for the Earth wrong?

Maybe!



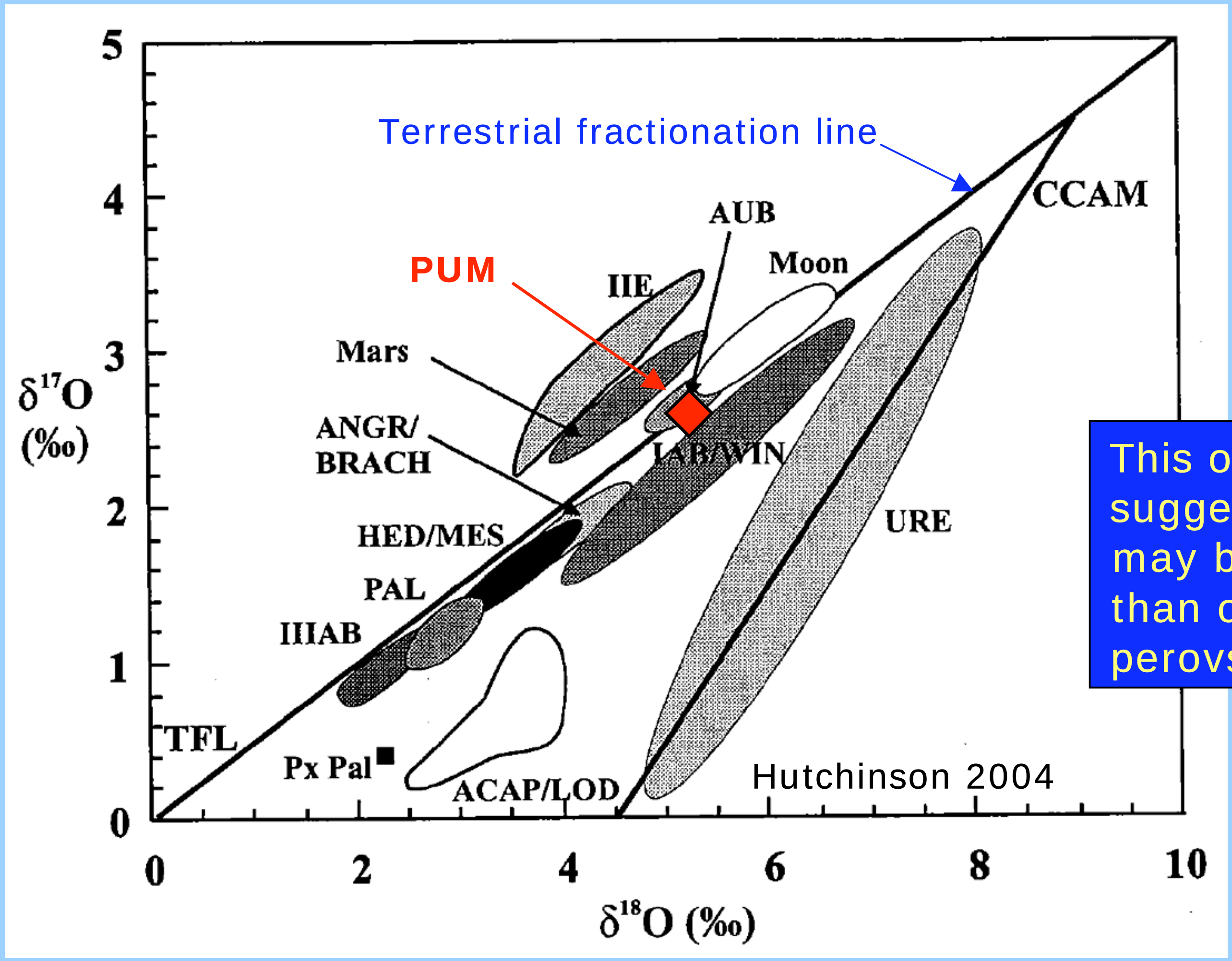
Boyet and Carlson 2006

Oxygen isotope compositions of Earth, Ordinary chondrites (H, L LL), Enstatite chondrites (EH, EL), and Carbonaceous chondrites (C1, CM, etc).



Earth is similar only to the Enstatite Chondrites.

Oxygen isotope compositions of Earth, Moon, Mars, Iron meteorites and differentiated meteorites

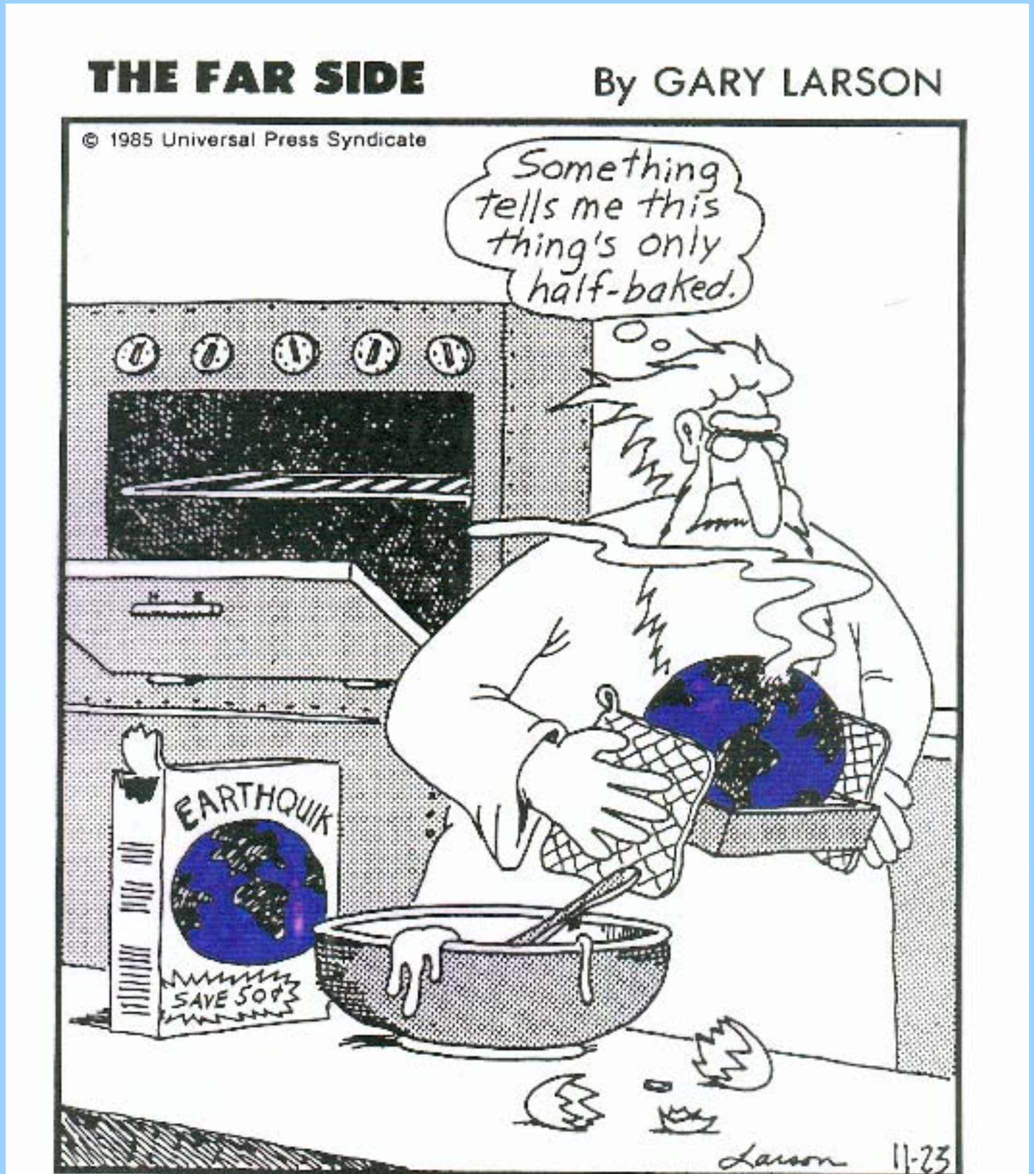


Earth is similar only to the Moon, and Aubrites (Enstatite achondrites).

This oxygen "DNA" test suggests the deep Earth may be richer in enstatite than olivine (higher perovskite/periclase ratio).

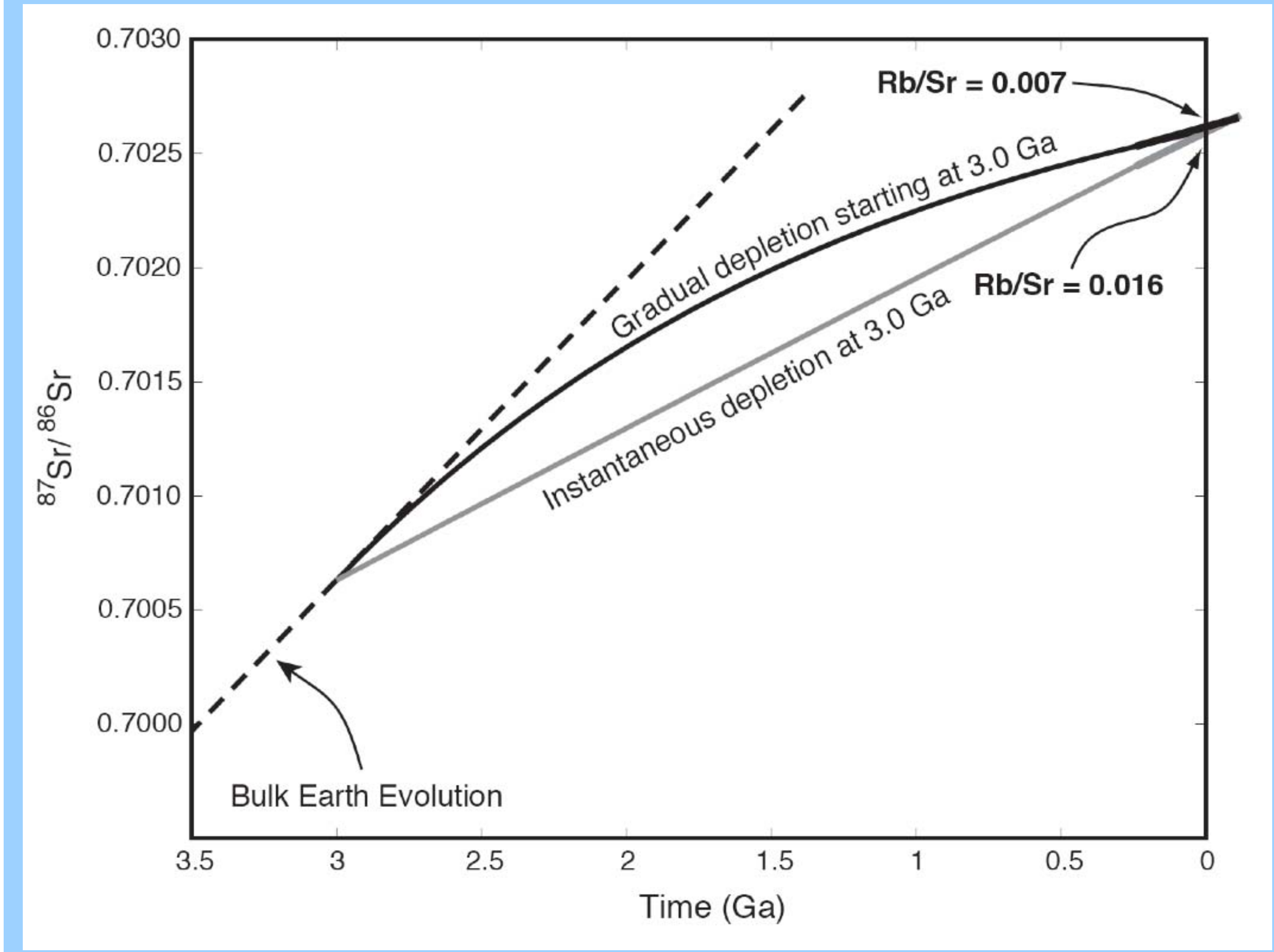
Seismologists and mineral physicists to the rescue??

I'm done!

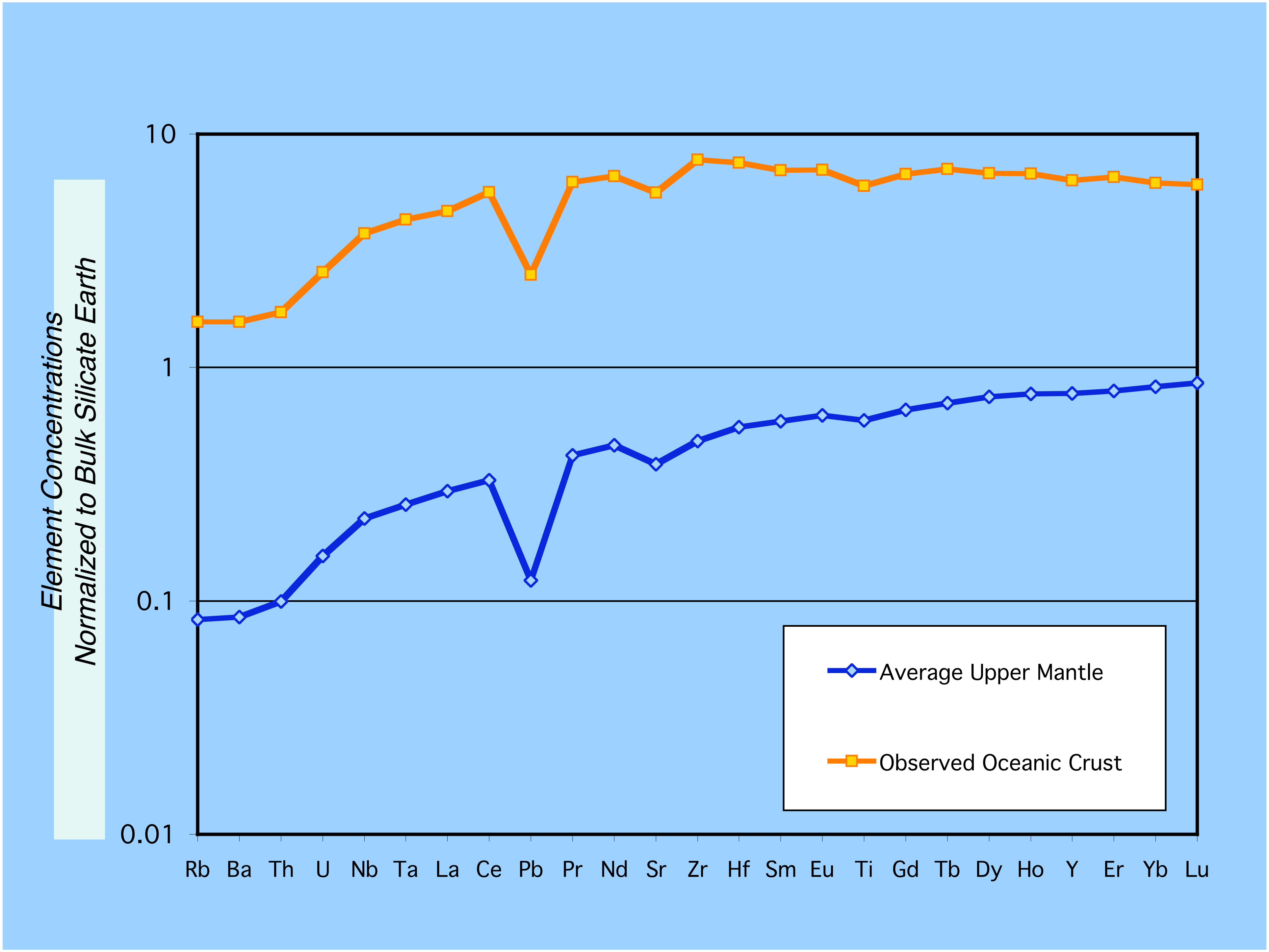


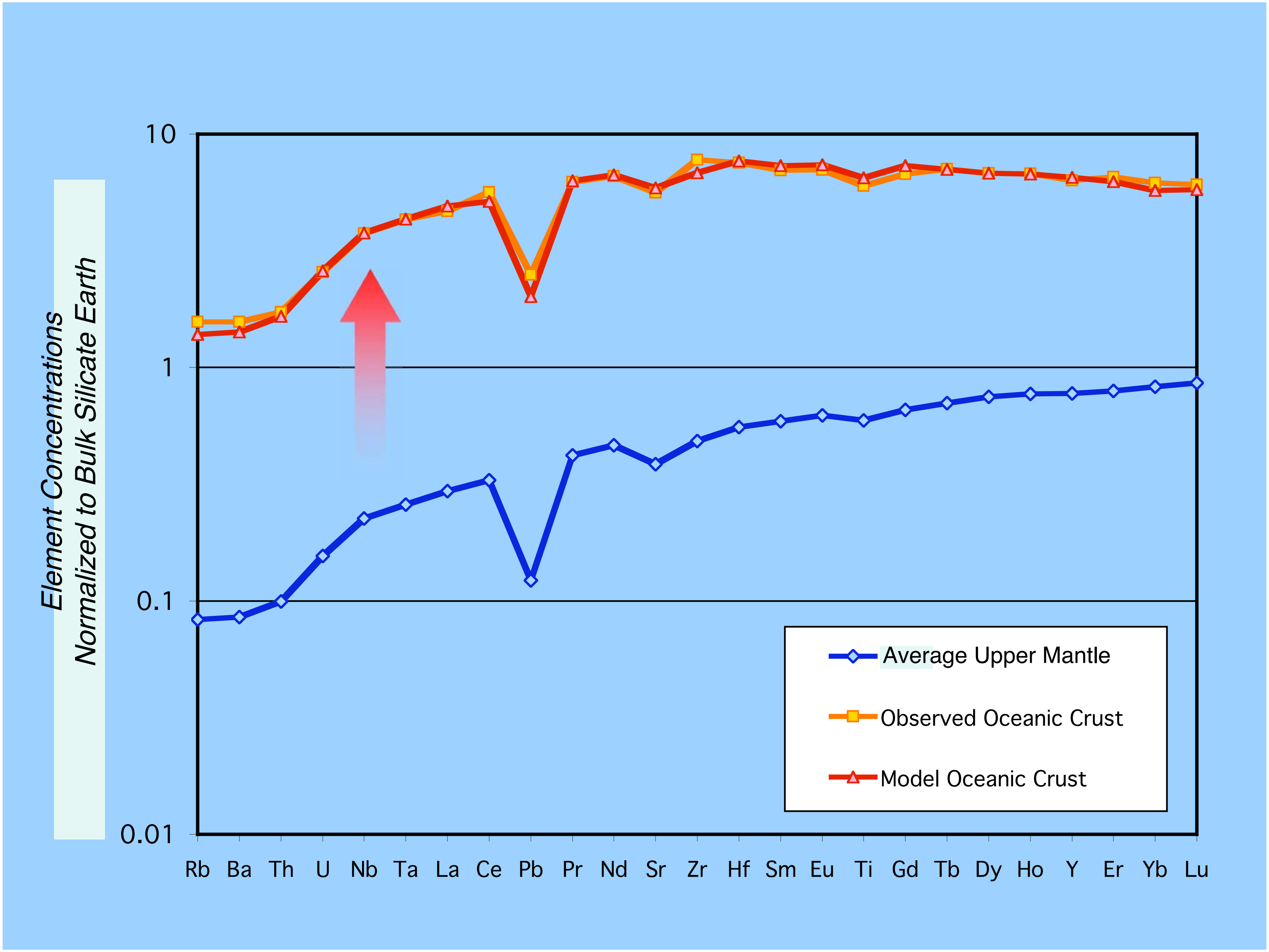
In God's kitchen

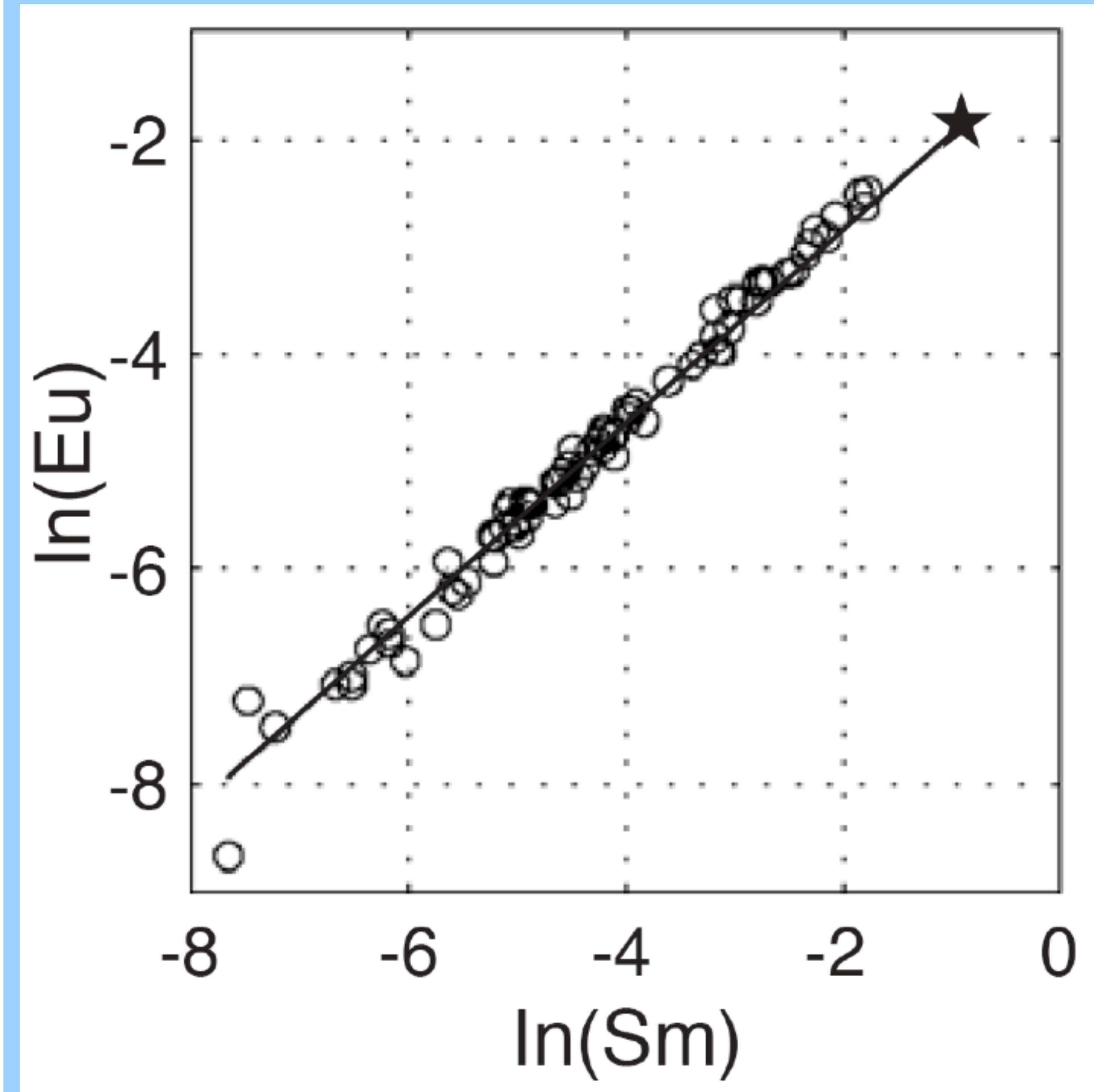
Stay tuned -



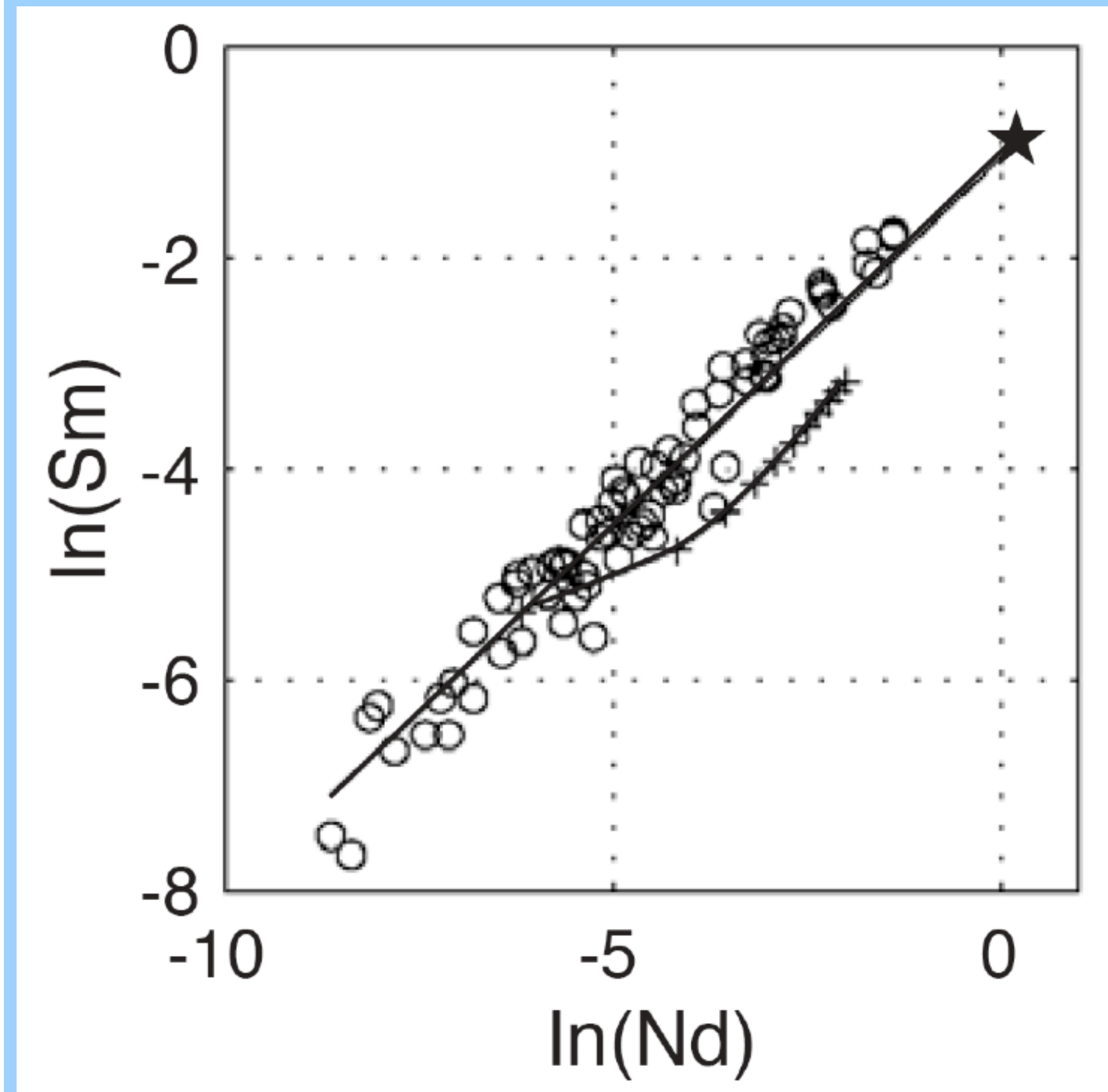
0.7030
0.7025
0.7020
0.7015
0.7010
0.7005
0.7000
$^{87}Sr/^{86}Sr$
Rb/Sr = 0.007
Gradual depletion starting at 3.0 Ga
Rb/Sr = 0.016
Instantaneous depletion at 3.0 Ga
Bulk Earth Evolution
3.5
3
2.5
2
1.5
1
0.5
0
Time (Ga)


Element Concentrations
Normalized to Bulk Silicate Earth
10
1
0.1
0.01
Rb
Ba
Th
U
Nb
Ta
La
Ce
Pb
Pr
Nd
Sr
Zr
Hf
Sm
Eu
Ti
Gd
Tb
Dy
Ho
Y
Er
Yb
Lu
Average Upper Mantle
Observed Oceanic Crust


Element Concentrations
Normalized to Bulk Silicate Earth
10
1
0.1
0.01
Rb Ba Th U Nb Ta La Ce Pb Pr Nd Sr Zr Hf Sm Eu Ti Gd Tb Dy Ho Y Er Yb Lu
Average Upper Mantle
Observed Oceanic Crust
Model Oceanic Crust



-2
-4
-6
-8
ln(Eu)
-8
-6
-4
-2
0
ln(Sm)


0
-2
-4
-6
-8
-10
-5
0
ln(Nd)
ln(Sm)

Defining a unique position on the mantle depletion trends