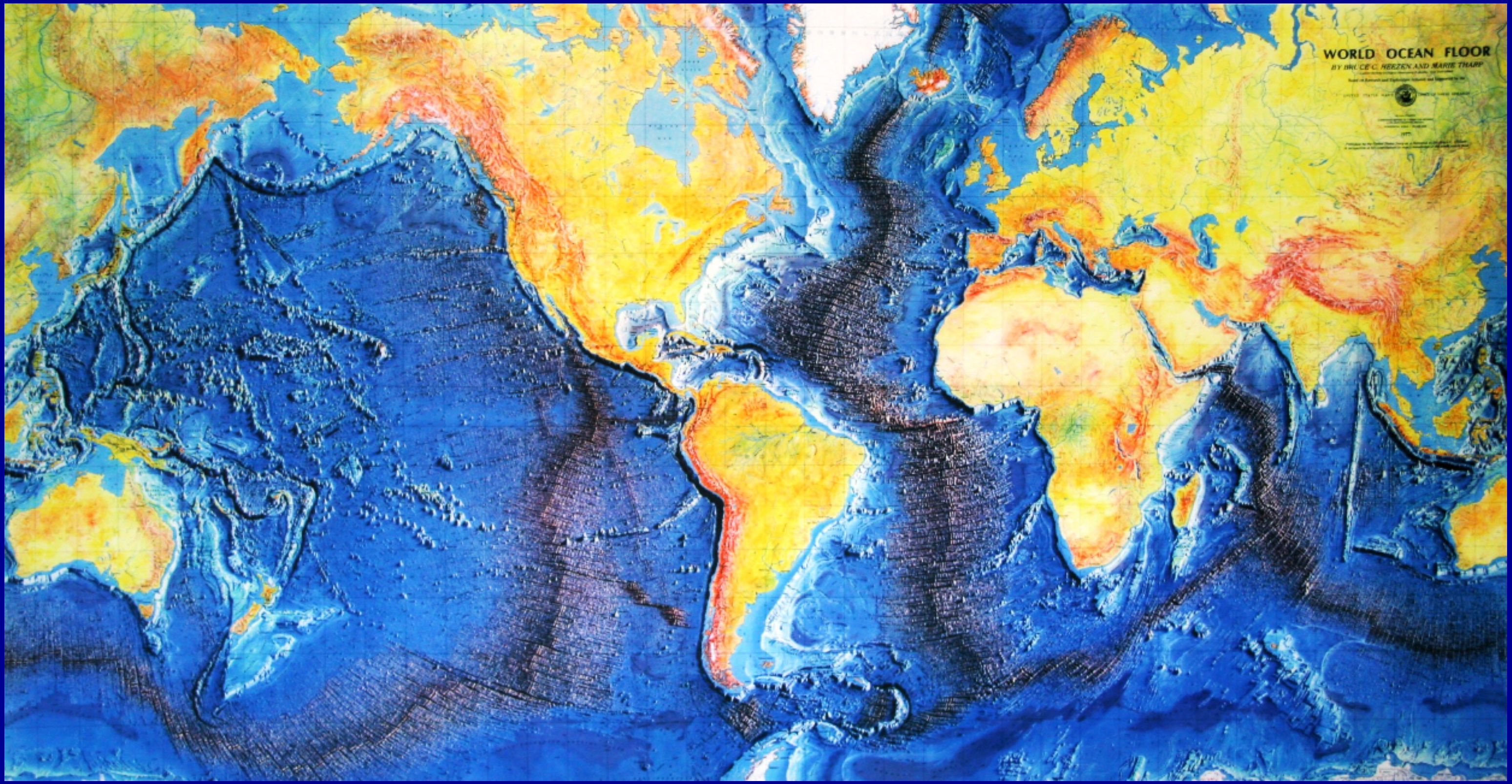
A New Look at Crust-Mantle Differentiation



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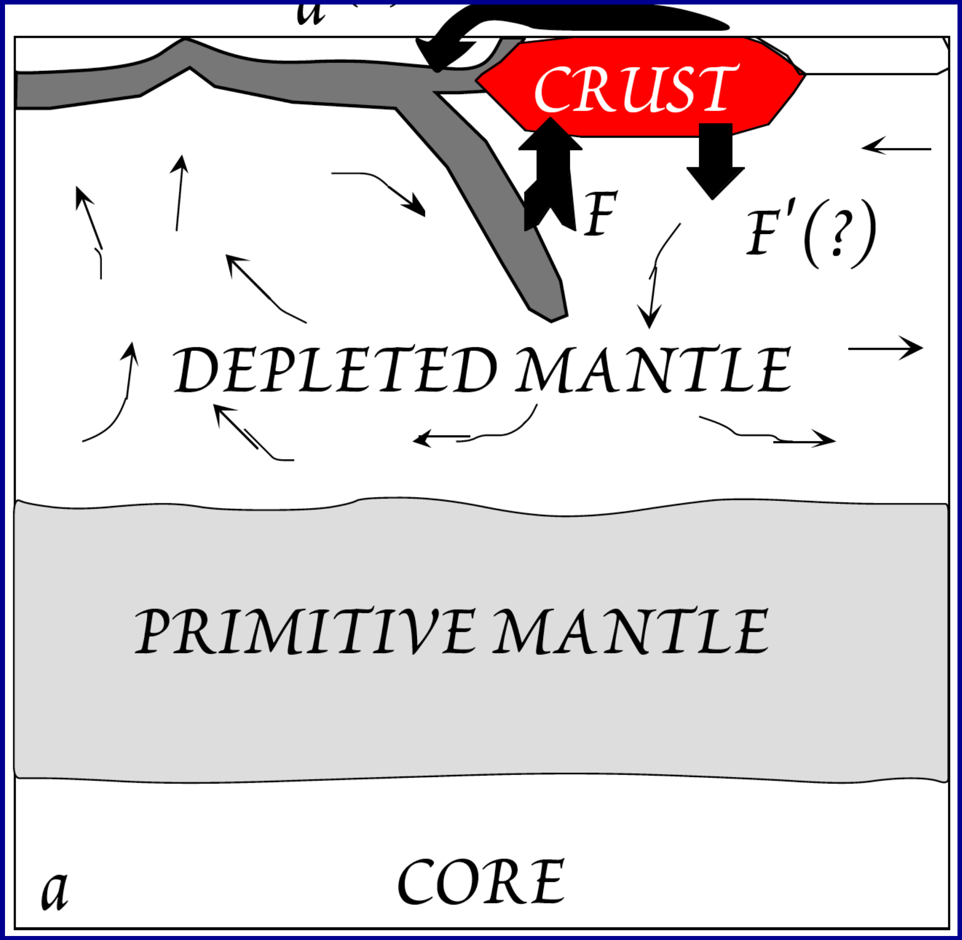
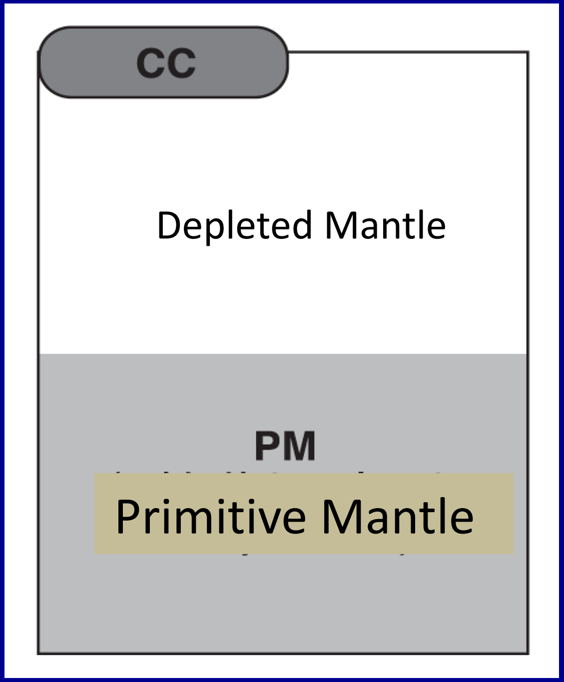
Classical Mantle Differentiation Model



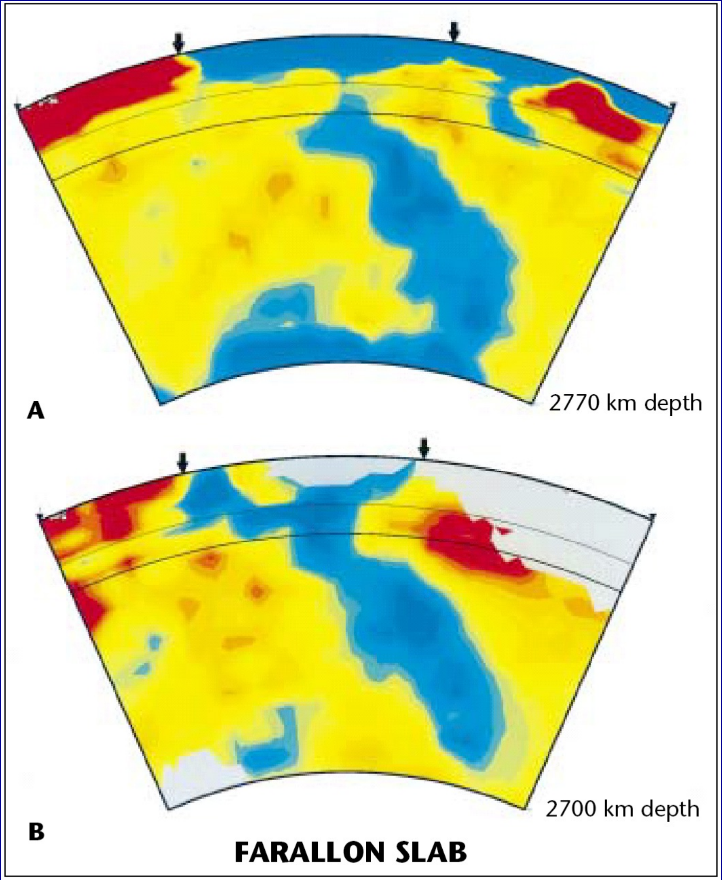


White, W.M. (2009) Geochemistry

The depleted upper mantle reservoir fits the classical two-layer convection model,

but it is *inconsistent* with modern seismic tomography

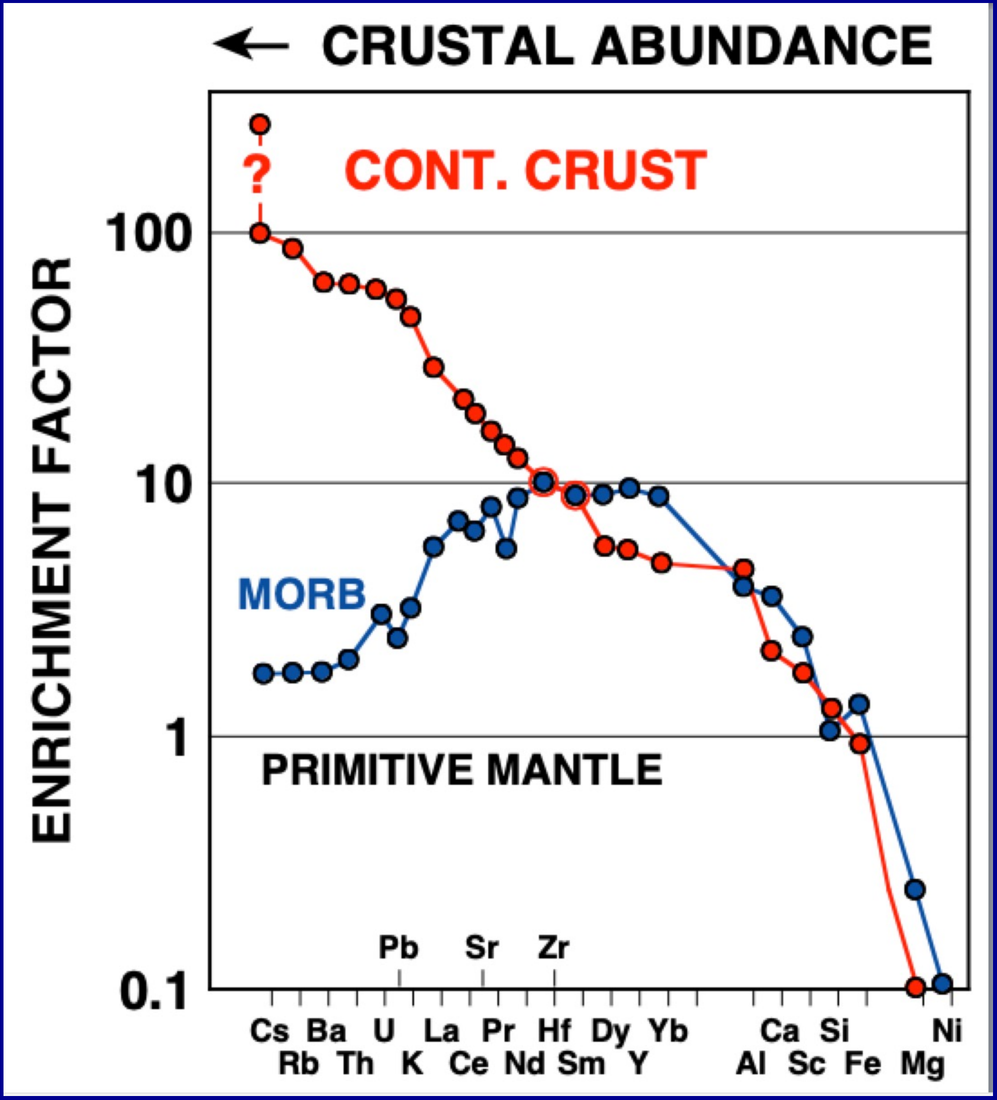
Can we still use a 2-layer mantle model to assess the chemical depletion resulting from extraction of the continental crust?



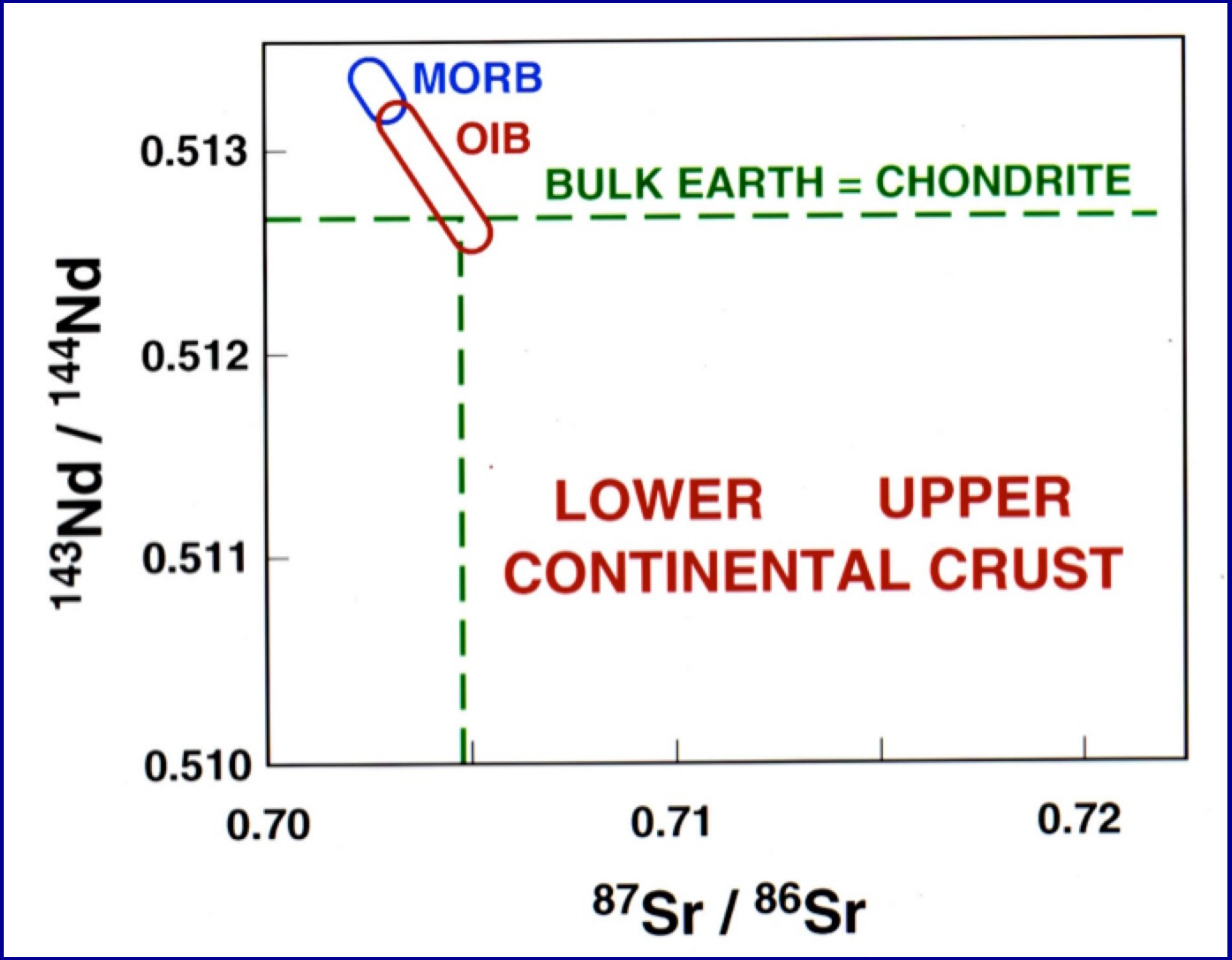
Grand et al., 1997, GSA Today 7, 1-7.

Continental Crust and MORB have apparently complementary trace element abundance patterns

The continental crust is at least partially responsible for the incompatible trace element depletion of the MORB mantle



Isotope data also seem consistent with a simple, 3-reservoir model



Previous assessments assumed crustal growth models to convert isotopic compositions in to element abundances

We use simple mass balance of Davies (1981) applied to present-day crust and mantle compositions

Sum of the mass fractions of reservoirs

$$\sum x_i = 1$$

Mass balance of concentrations C_i (e.g. Nd)

$$\sum x_i C_i = C_0$$

Mass balance of isotopic compositions of element i, ε (Nd)

$$\sum x_i C_i \boldsymbol{\varepsilon}_i = C_0 \boldsymbol{\varepsilon}_0$$

Geoff Davies (1981) Earth´s neodymium budget and structure and evolution of the mantle. Nature 290, 208.

$$\varepsilon = 10000 \cdot \frac{\left({}^{143}Nd/{}^{144}Nd\right) - \left({}^{143}Nd/{}^{144}Nd\right)_{CHUR}}{\left({}^{143}Nd/{}^{144}Nd\right)_{CHUR}}$$

The Epsilon(Nd) solution of the mass balance

- 3 Reservoirs: continental crust, depleted (residual) mantle, primitive mantle

X = Mass fraction of reservoir
Nd = Nd concentration

C = Chemical element concentration

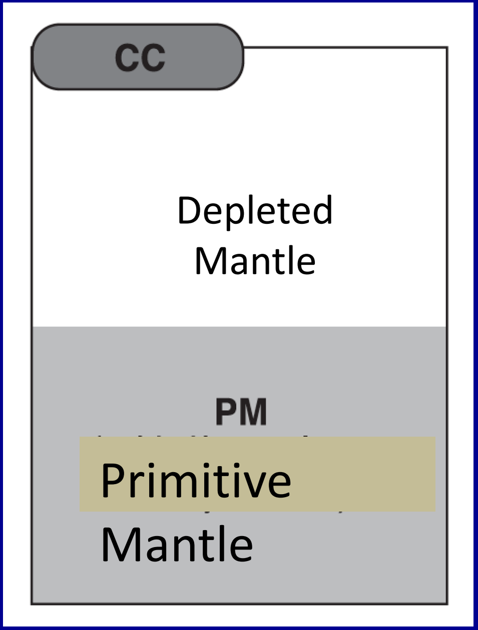
$$X_d = \frac{X_c\, Nd_c\, (\varepsilon_d - \varepsilon_c)}{Nd_p\, (\varepsilon_d - \varepsilon_p)} - X_c$$

$$C_d = \frac{C_p\,(X_d + X_c) - X_c\, C_c}{X_d}$$

c = crust

d = depleted mantle

p = primitive mantle



Input parameters needed to calculate mass fraction of the depleted mantle X_{DMM}

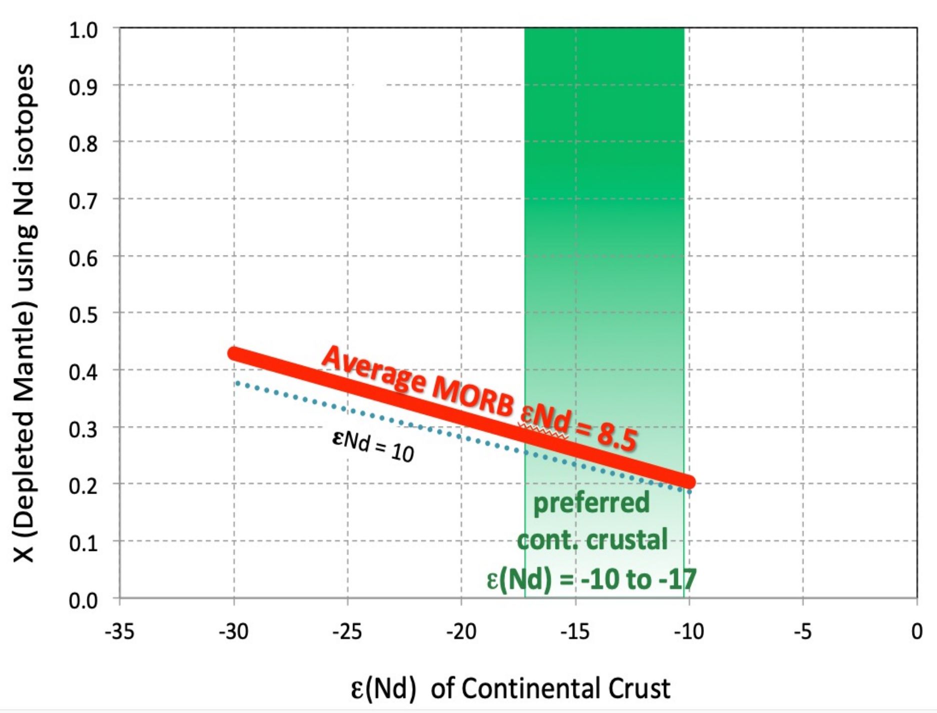
$\varepsilon(Nd)_{MORB}$ = 8.5 (Gale et al. 2013)	Well known
$\varepsilon(Nd)_{Cont.\ Crust}$ = -10 to -17	Poorly known (lower crust??)
$\varepsilon(Nd)_{Primitive\ mantle}$ = 0	Chondritic Earth (assumed)
X_c = 0.006	Well Known mass of cont. crust
Nd_c = 20 to 26 ppm	Relatively well known
Nd_p = 1.25 ppm	Given by chondritic Earth model

X(DMM) = 0.2 to 0.3

Mass fraction of the depleted mantle X(DMM) using $\varepsilon(Nd)_{MORB}$ = 8.5 (Gale et al. 2013)

$$\varepsilon = 10000 \cdot \frac{\left({}^{143}Nd/{}^{144}Nd\right) - \left({}^{143}Nd/{}^{144}Nd\right)_{CHUR}}{\left({}^{143}Nd/{}^{144}Nd\right)_{CHUR}}$$

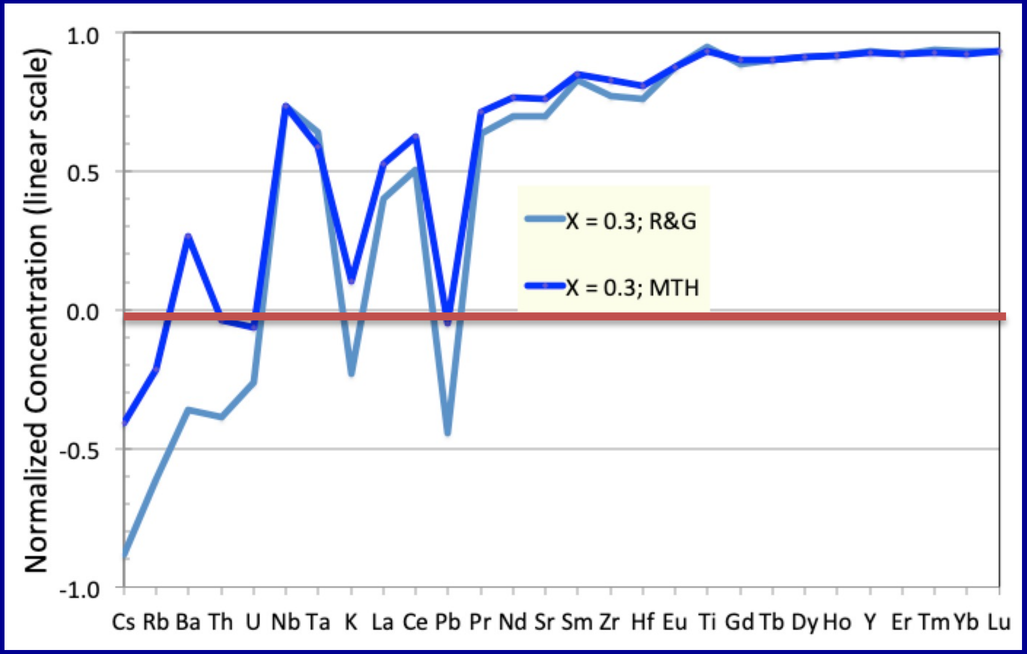
Epsilon(Nd) based mass balance yields the same results as published crustal evolution models (Jacobsen& Wasserburg; Salters & Stracke; Workman & Hart)



Apparent confirmation of classical models, where the $m_{\text{depleted mantle}} \leq 0.3\ m_{\text{total mantle}}$

Published 3-reservoir models based on $\varepsilon(Nd)_{MORB}$ yield **negative** concentrations for Cs, Rb, (Ba), Th, U in the depleted mantle!

$$C_{dmm} = \frac{C_{pm}\,(X_{dmm} + X_{cc}) - X_{cc}\,C_{cc}}{X_{dmm}}$$

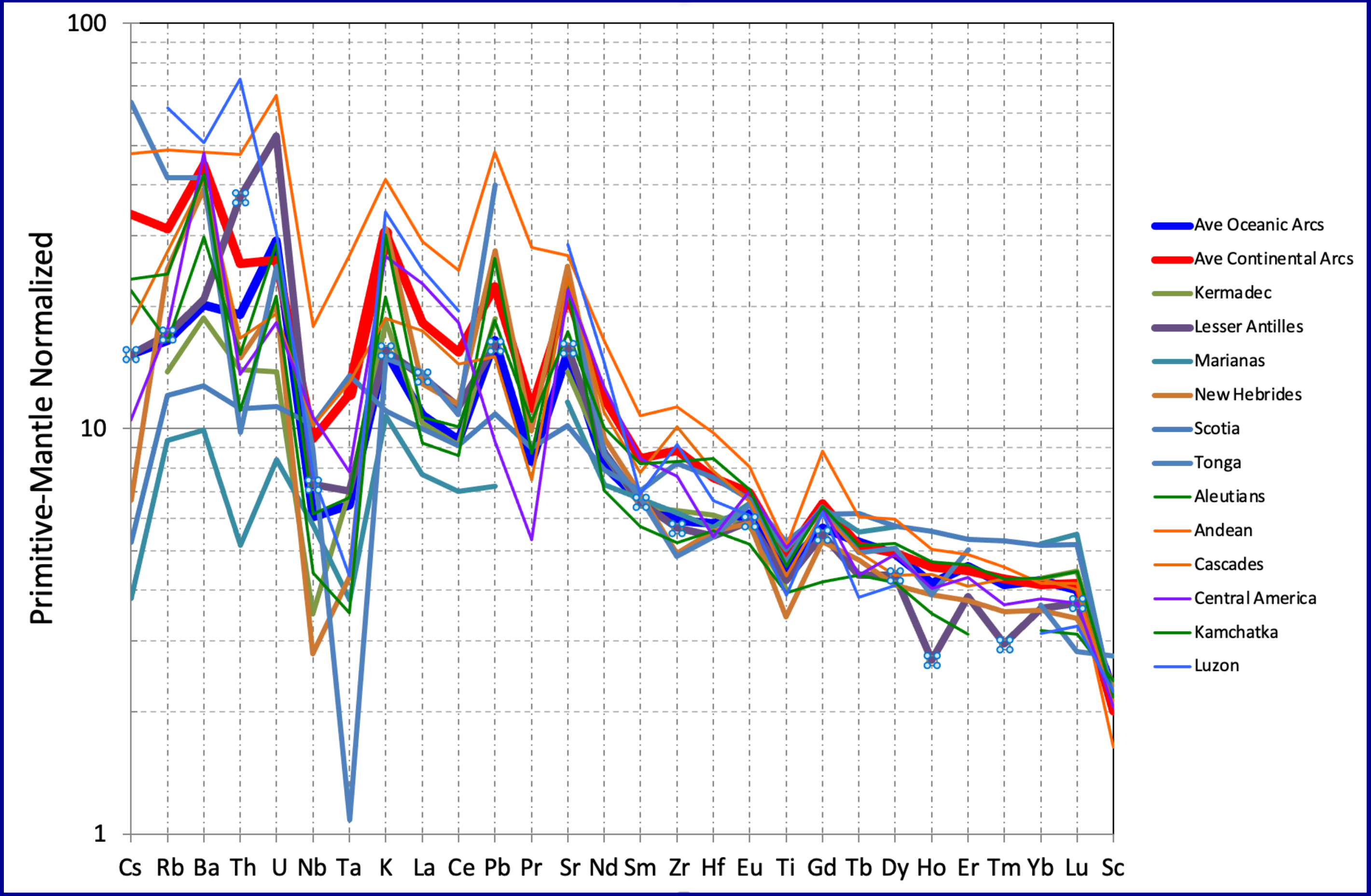


Mass balance based on ε(Nd) delivers nonsense for highly incompatible elements

Nb and Ta are the best tracers

for crust-mantle differentiation

All island arc rocks
have large negative
Nb-Ta anomalies

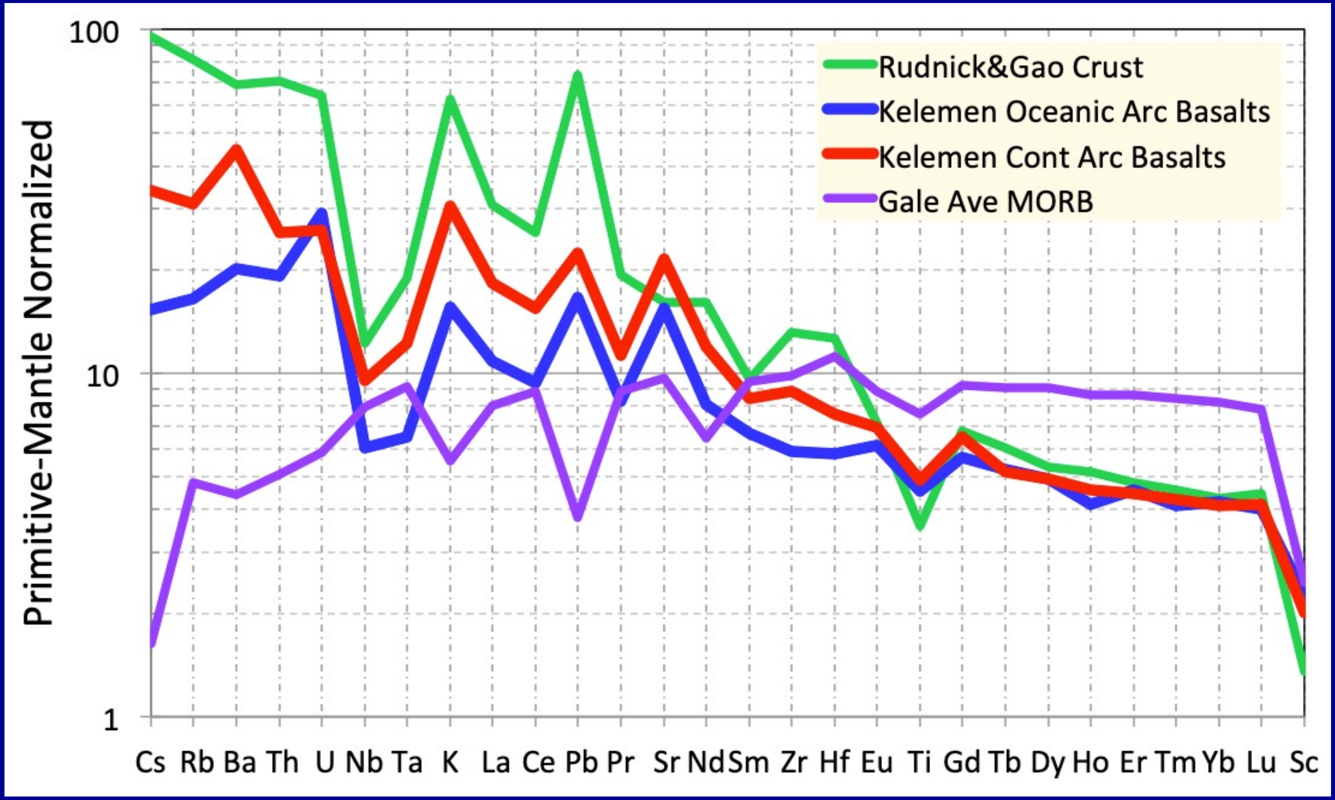


Kelemen & Hanghoj (2003) Treatise on Geochemistry Vol 3.18

Nb and Ta are better tracers for crust-mantle differentiation

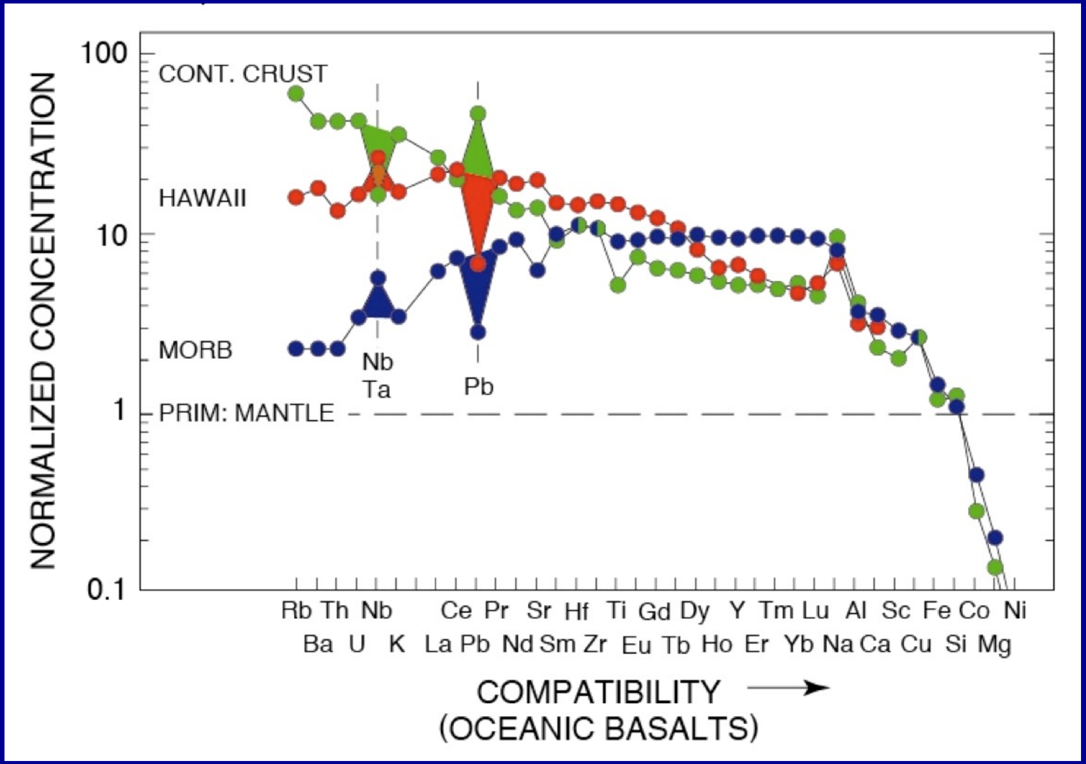
Continental crust has similar negative Nb-Ta anomalies as arc rocks.

This contrasts with positive Nb/Ta anomalies of oceanic basalts



Kelemen & Hanghoj (2003) Treatise on Geochemistry Vol 3.18

Ocean Island basalts also have positive Nb-Ta anomalies



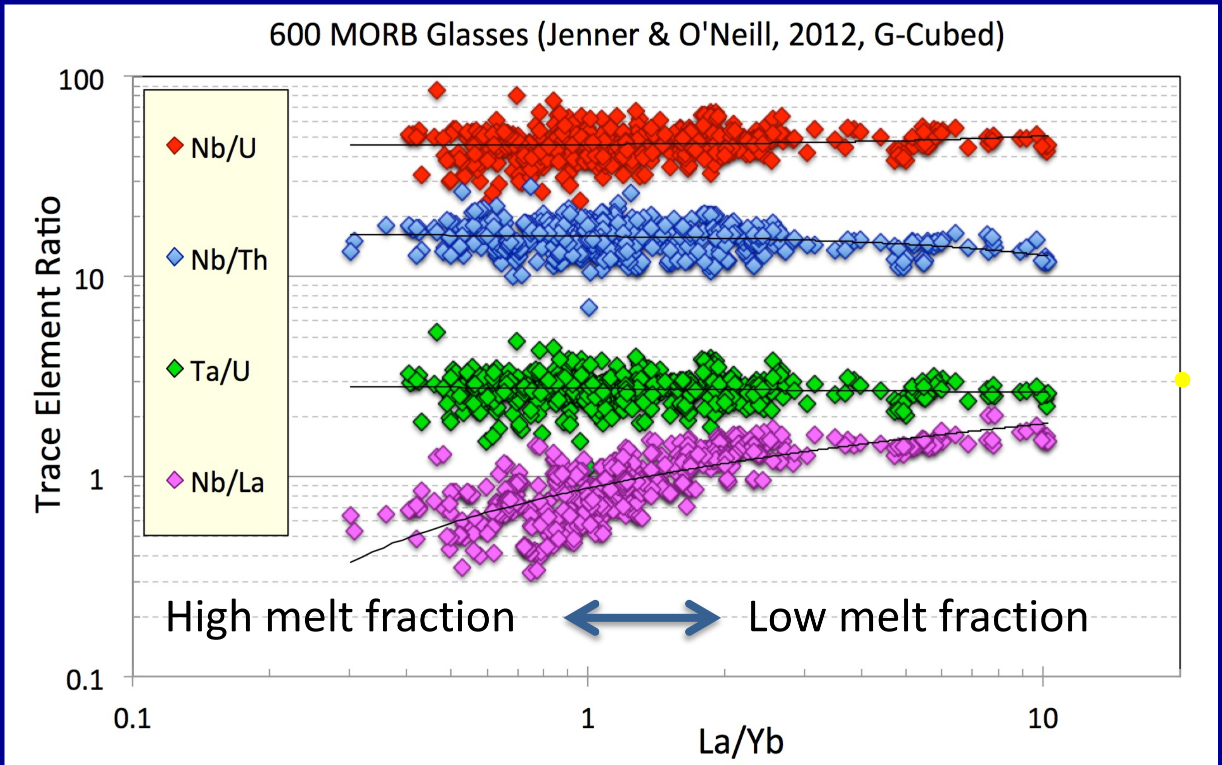
How can we use these "anomalies" as quantitative tools to assess crust-mantle differentiation?

Strategy of using “canonical” trace element ratios

Criterion: The ratio of Nb with another trace element must remain constant and independent of the degree of melting, which governs the absolute concentrations of the incompatible elements involved.

In this case, the two elements will have identical partition coefficients.
And the ratio of the two elements will be identical in the melt as in the source.

Such a ratio can be used like an isotope ratio

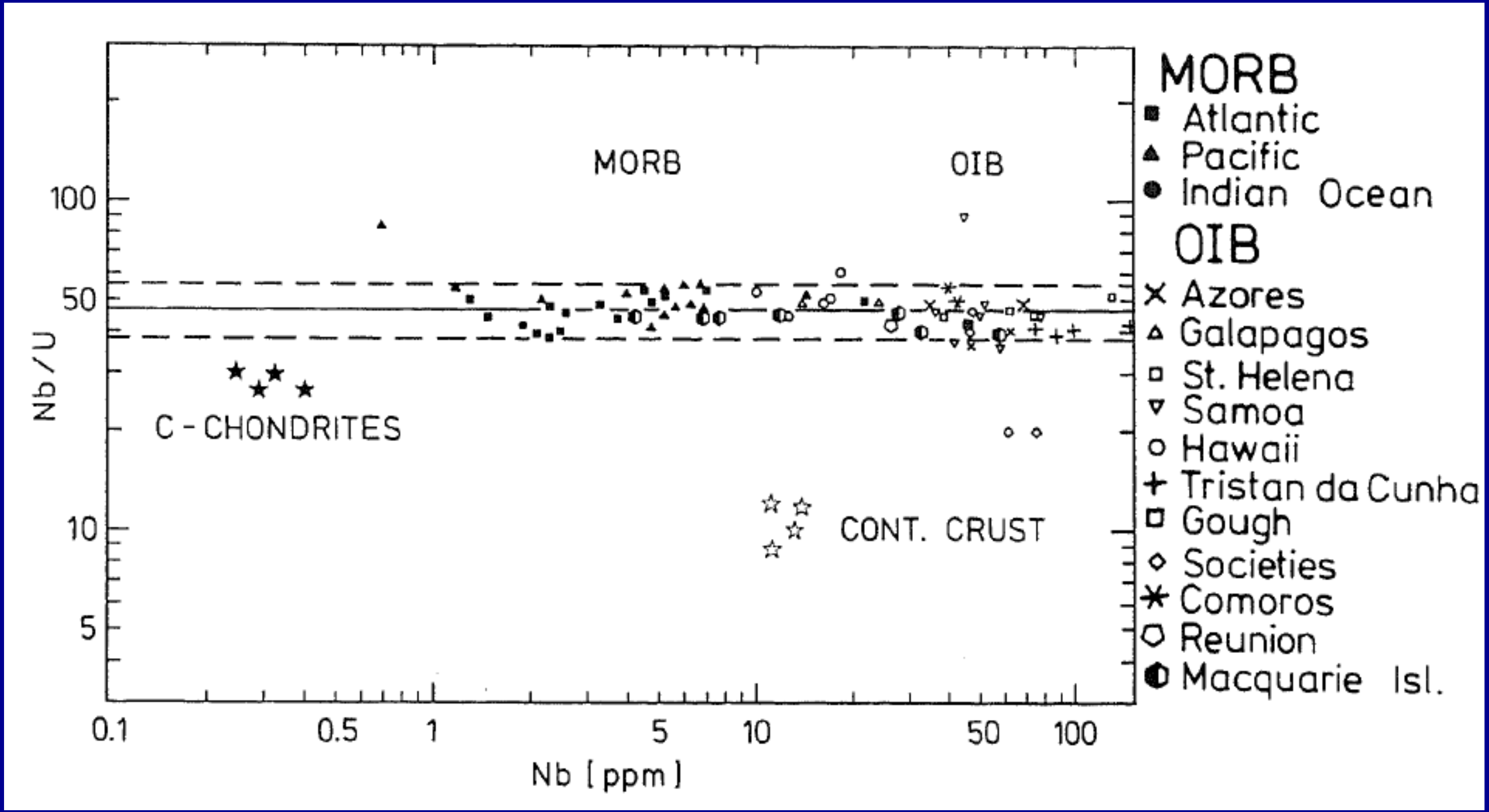


$Nb/U_{melt} = Nb/U_{source}$

$Ta/U_{melt} = Ta/U_{source}$

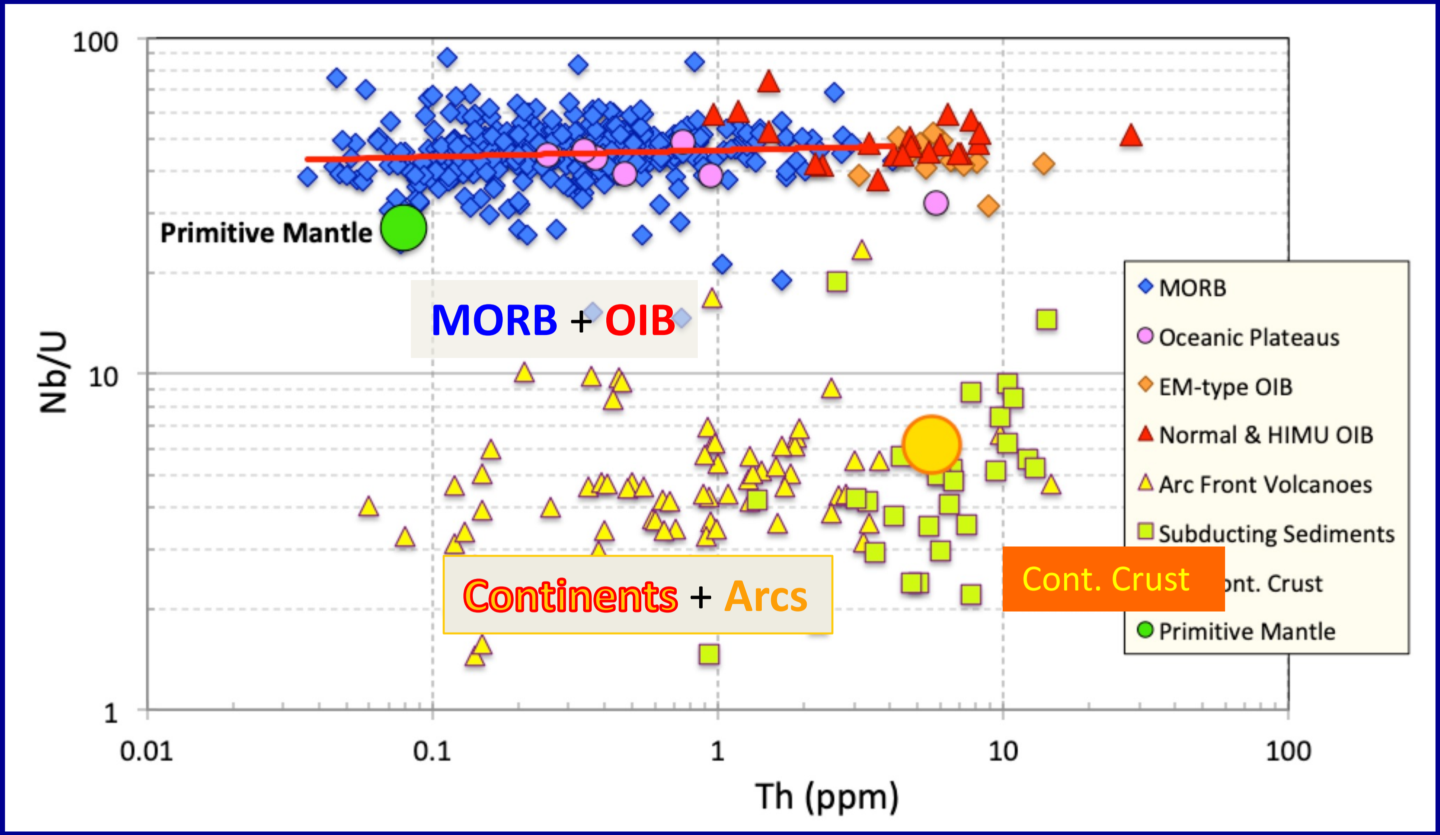
$Nb/La_{melt} \neq Nb/La_{source}$

Serendipitous discovery 36 years ago



Hofmann et al., 1986, Nb and Pb in oceanic basalts: new constraints on mantle evolution. EPSL 79, 33-45.

Confirmation 2022

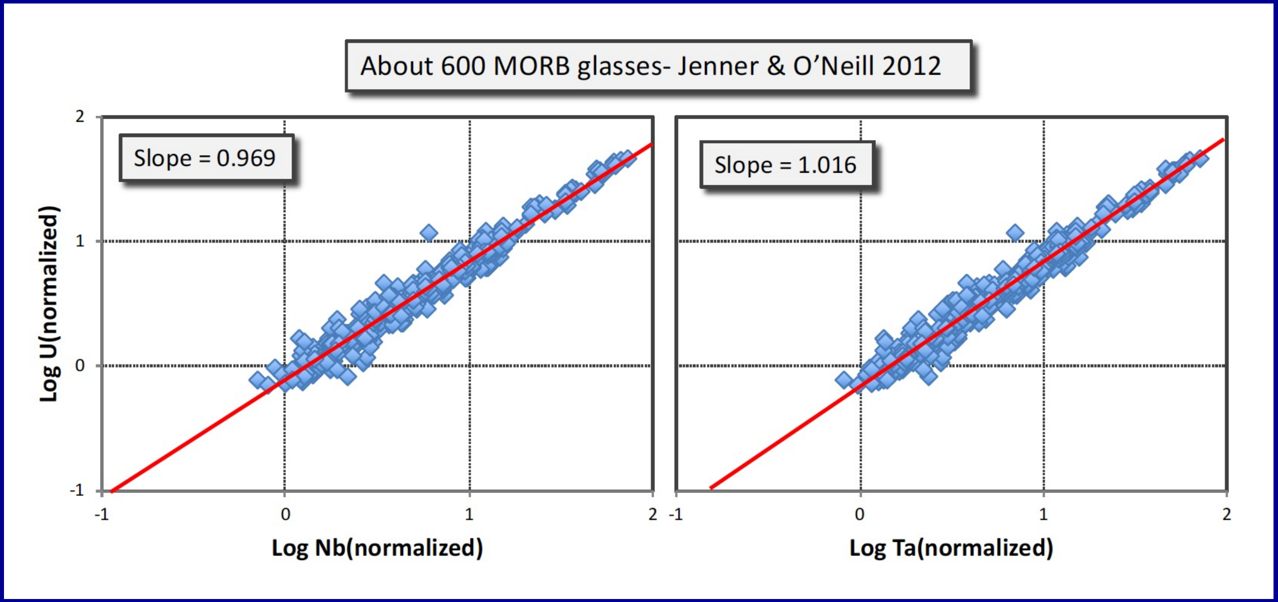


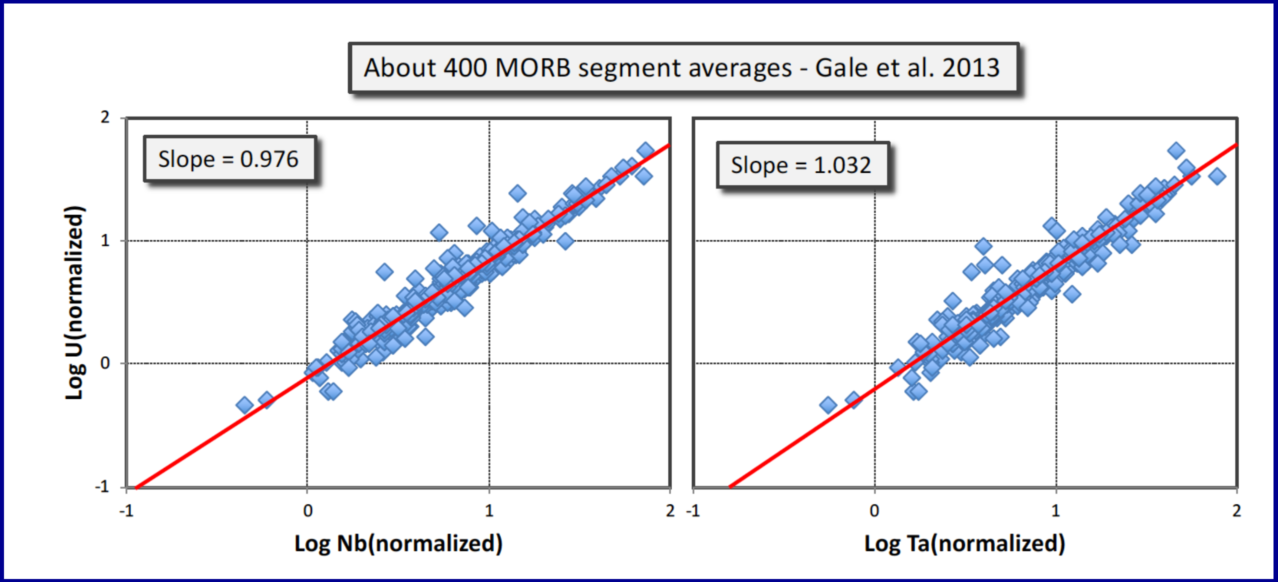
Nb/U discriminates between
oceanic crust + OIBs and
continental crust + sediments + island arcs

Ideally: Log-log plots with slope = 1.0 Assures that ratio is constant

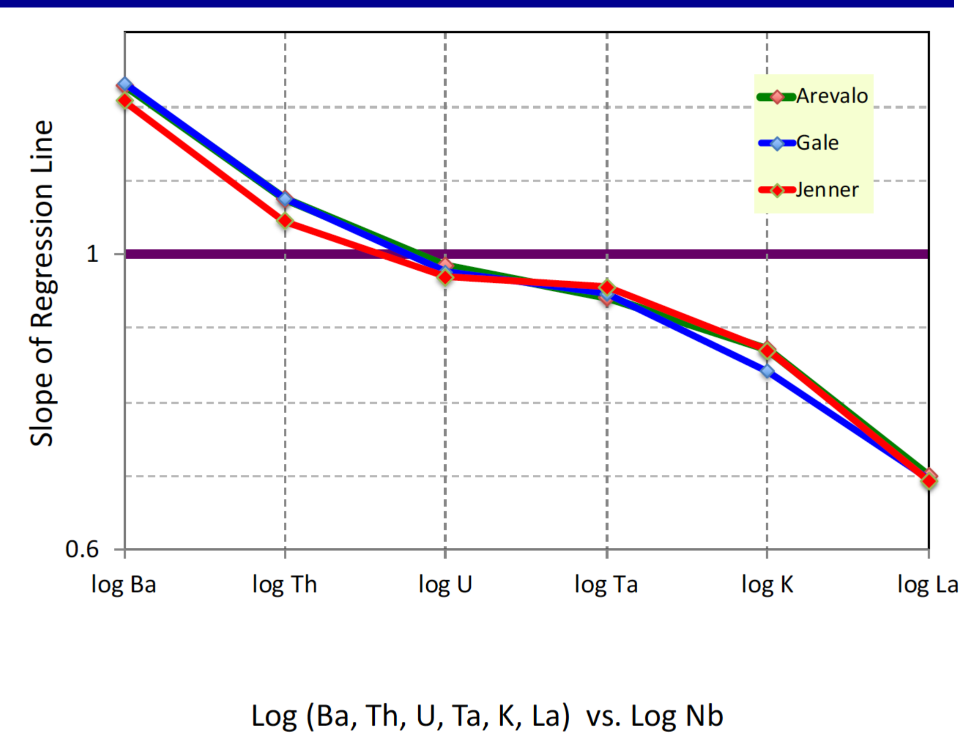
An element with partitioning properties between Nb and Ta should have a log-log correlation with slope = 1.000

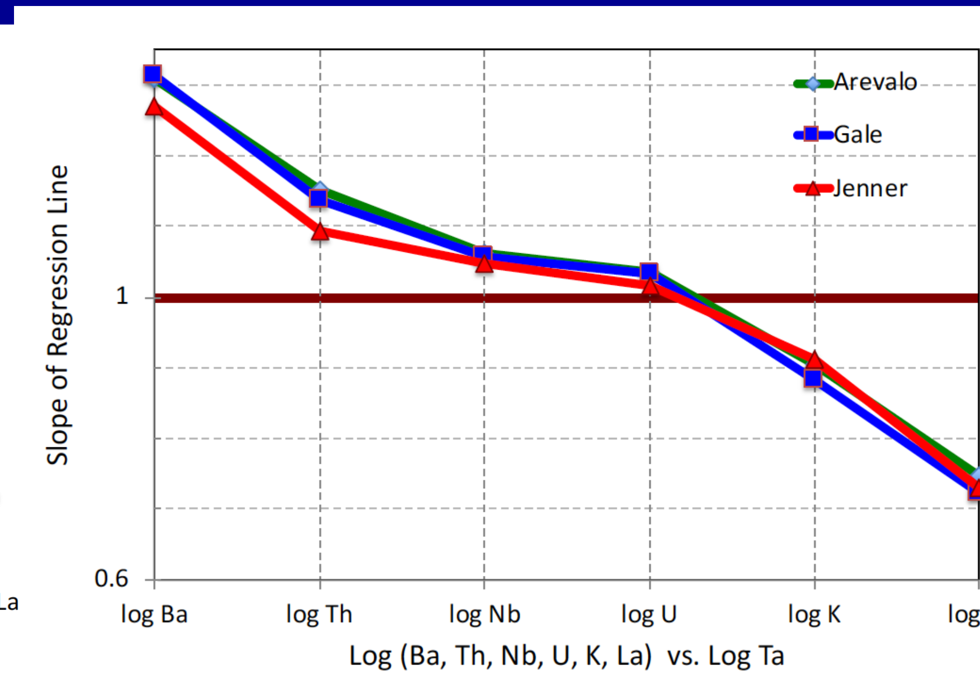
But both Nb/U and Ta/U ratios are very close constant over 2 orders of magnitude of absolute concentrations





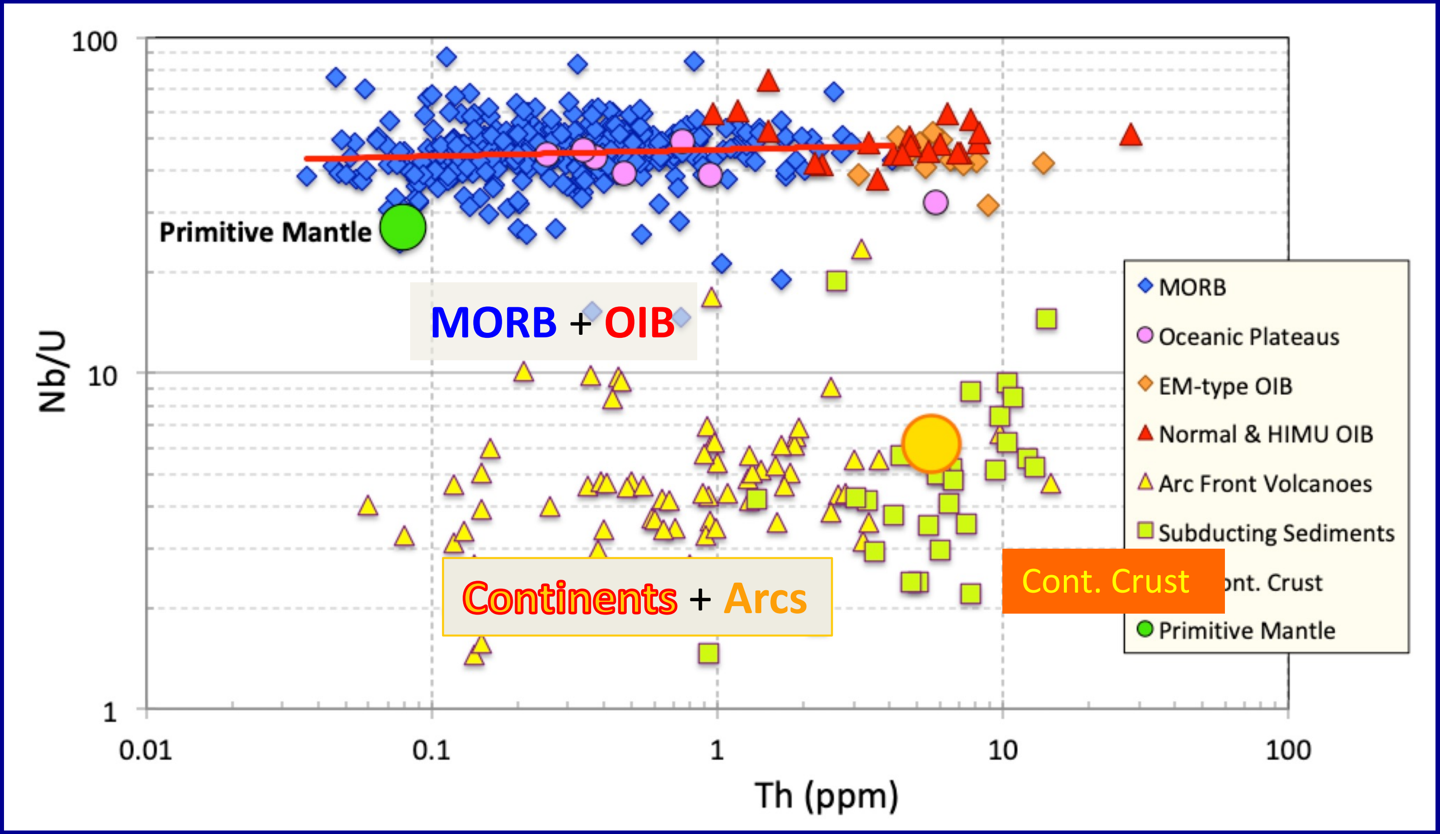
Slopes of log-log plots vary systematically in global MORBs going from Ba-Nb to La-Nb, also from Ba-Ta to La-Nb





Demonstrates that Ba/Nb or La/Nb are less suitable as “canonical” ratios for use as tracers of source ratios than Nb/U.

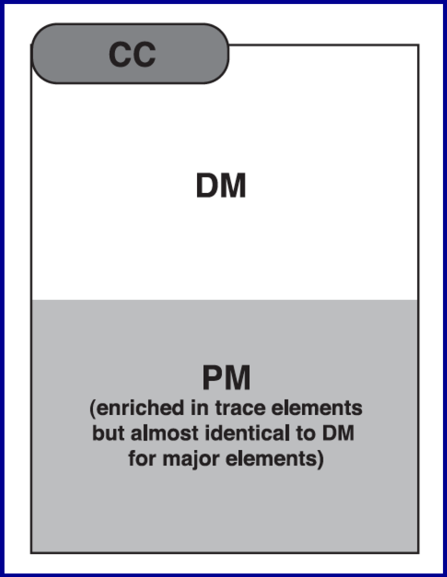
Confirmation 2022



Nb/U discriminates between
oceanic crust + OIBs and
continental crust + sediments + island arcs

New Mass Balance using Nb/U (or Ta/U) ratios

- 3 Reservoirs: Primitive mantle, Residual mantle, Continental crust



$$X_r = \frac{X_c\,\mathrm{U}_c\,((\mathrm{Nb/U})_r - (\mathrm{Nb/U})_c)}{\mathrm{U}_p\,\left((\mathrm{Nb/U})_r - (\mathrm{Nb/U})_p\right)} - X_c$$

$$U_r = \frac{\mathrm{U}_p\,(X_r + X_c) - X_c\,\mathrm{U}_c}{\mathrm{X}_r}$$

X = Mass fraction

U = U concentrations

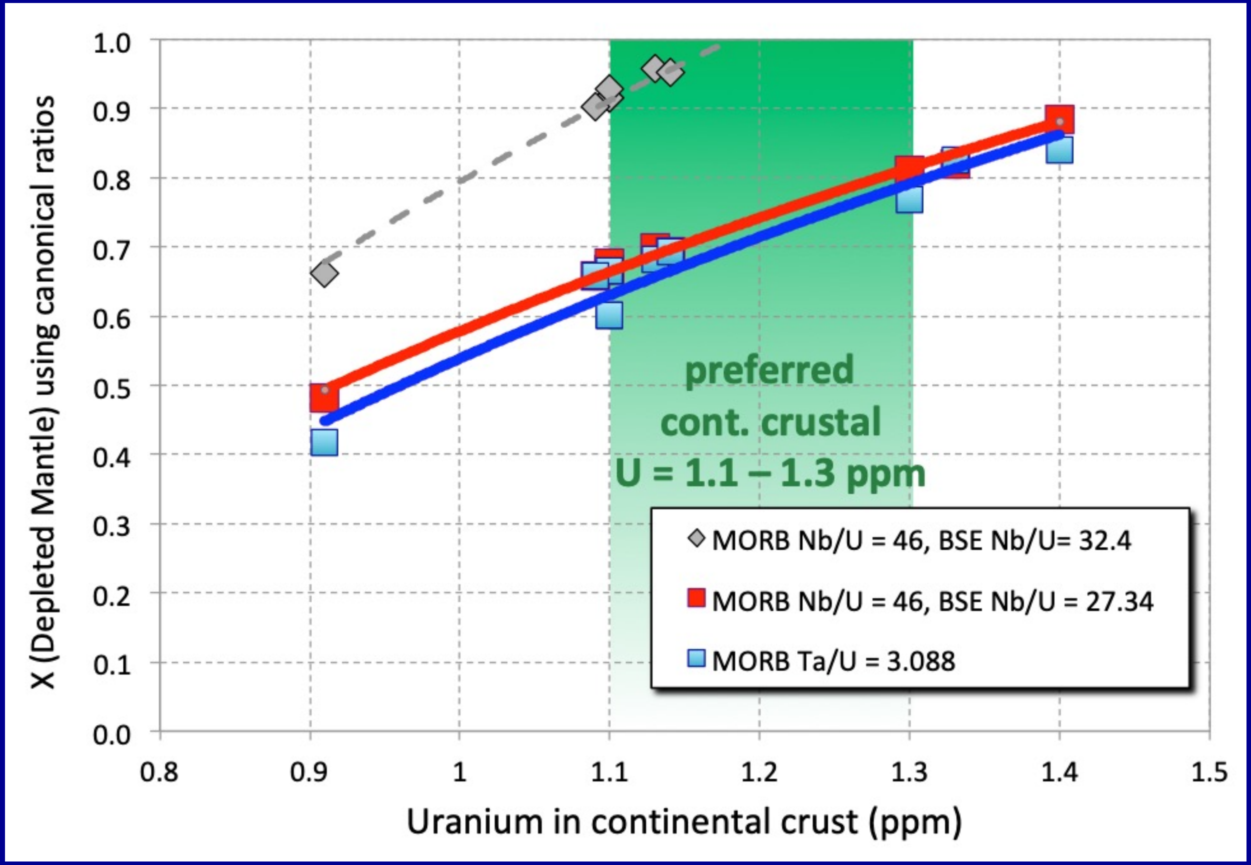
c = crust

r = residual mantle

p = primitive mantle

Mass balance using the Nb/U tracer:

The residual mantle occupies 60 to 80 % of the total mantle



Crustal U values from:

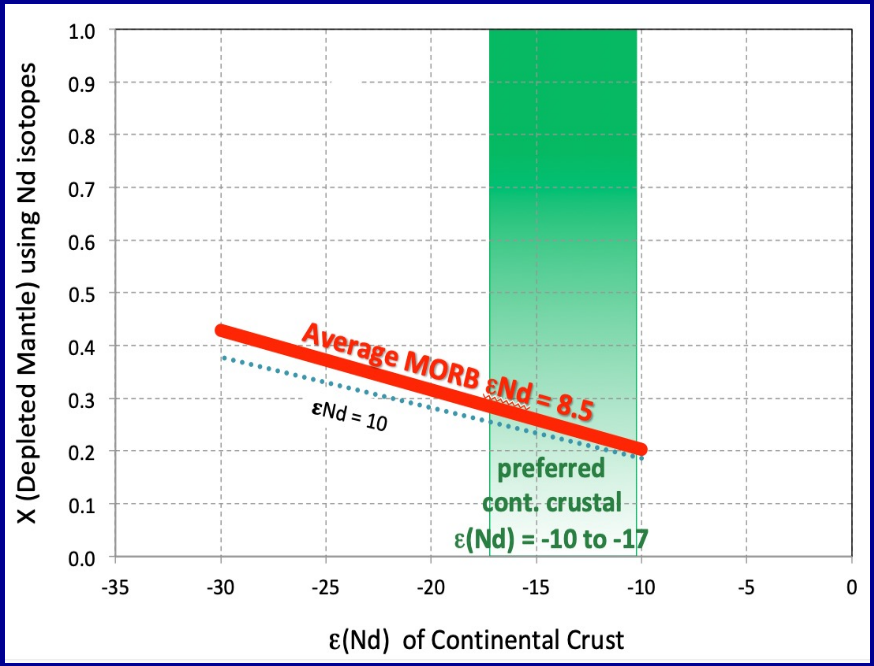
Taylor & McLennan 1985
Rudnick & Gao 2003
McLennan et al. 2006
Hacker et al. 2015

Red squares: The assumed BSE Nb/U = 27.85 is based on Nb/Ta ratios of MORB & OIB, plus experimental data on Nb partitioning in the core. This Nb/U ratio is lower than the chondritic value of 32.4.

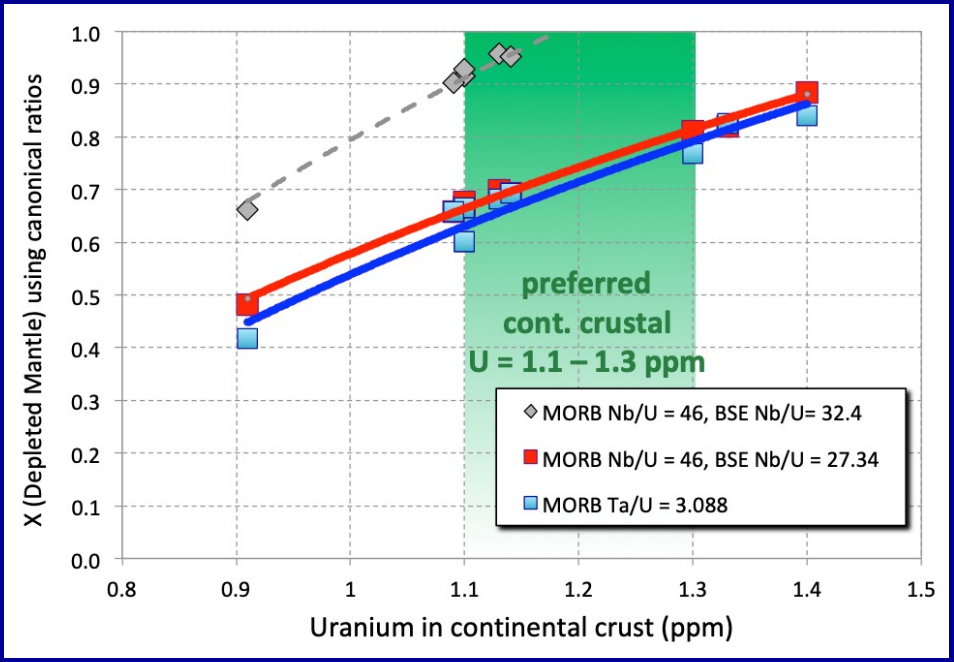
Comparison of the two mass balances: ε(Nd) and (Nb,Ta)/U.

But: ε-based balance uses only MORB mantle

(Nb,Ta)/U-base balance includes MORB + OIB sources



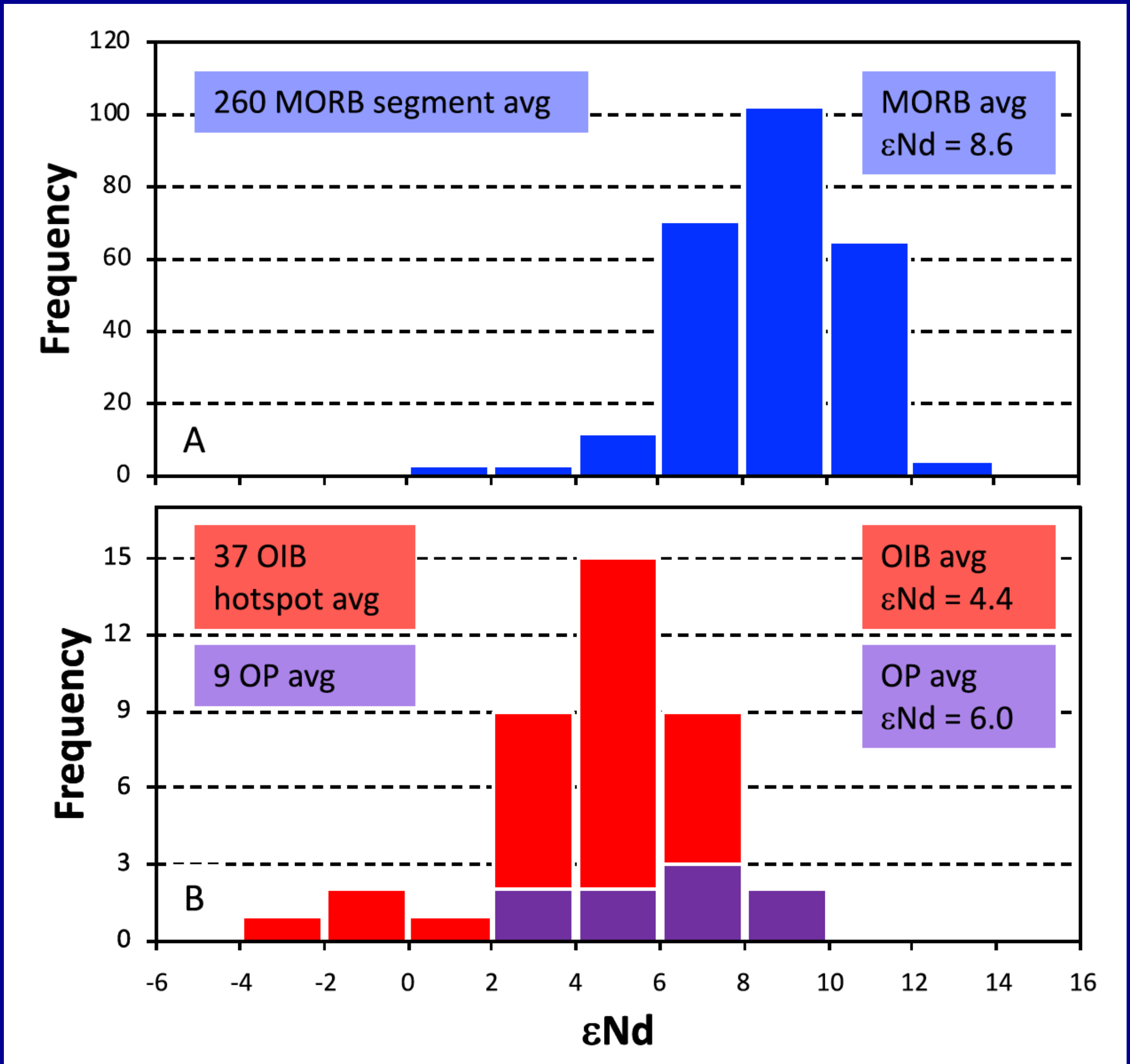
ε-based mass balance



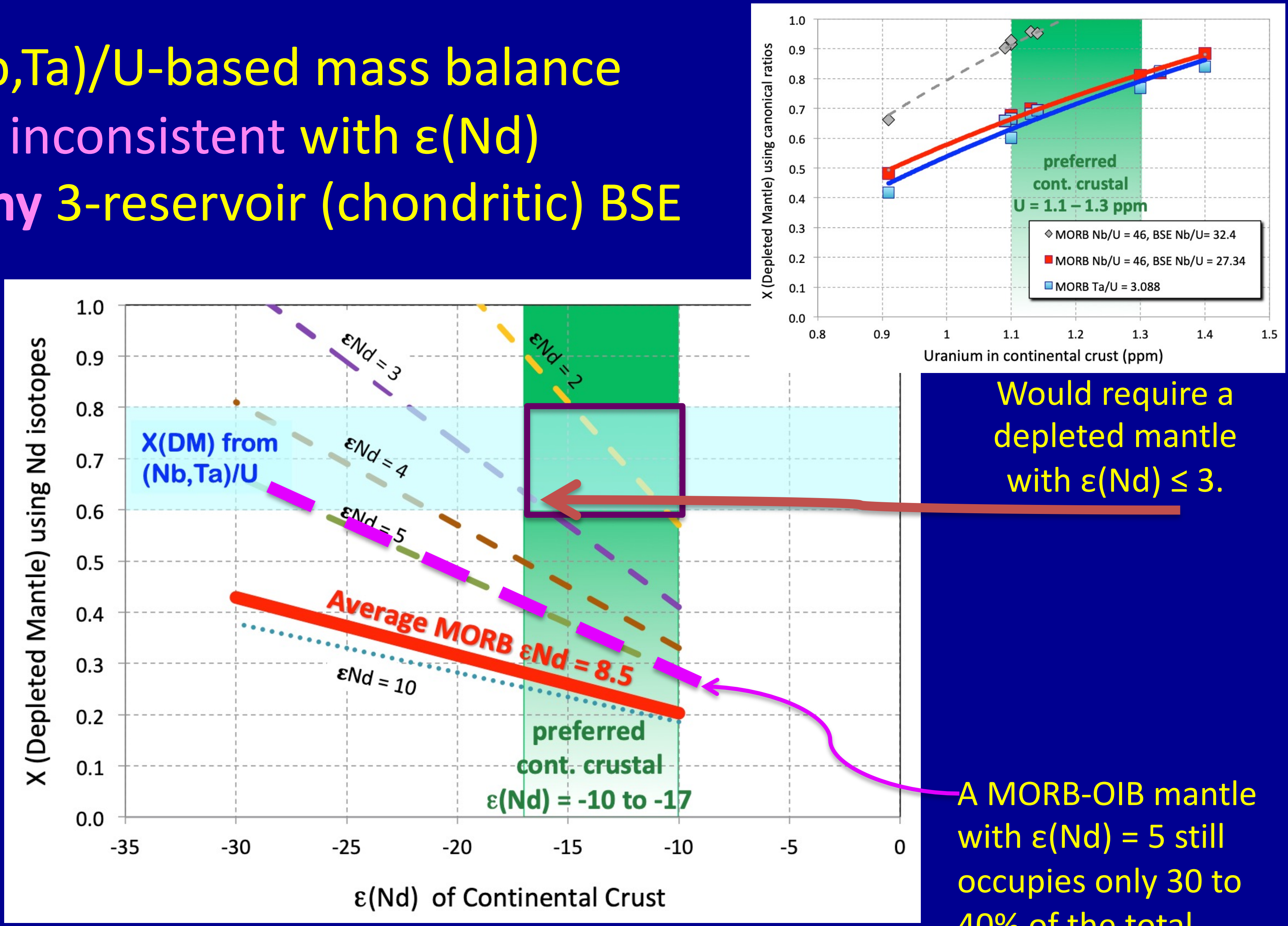
(Nb,Ta)/U-based mass balance

The bulk epsilon(Nd) value of the combined MORB + OIB source mantle is

$5 < \varepsilon(Nd) < 8.6$



(Nb,Ta)/U-based mass balance inconsistent with ε(Nd) for any 3-reservoir (chondritic) BSE



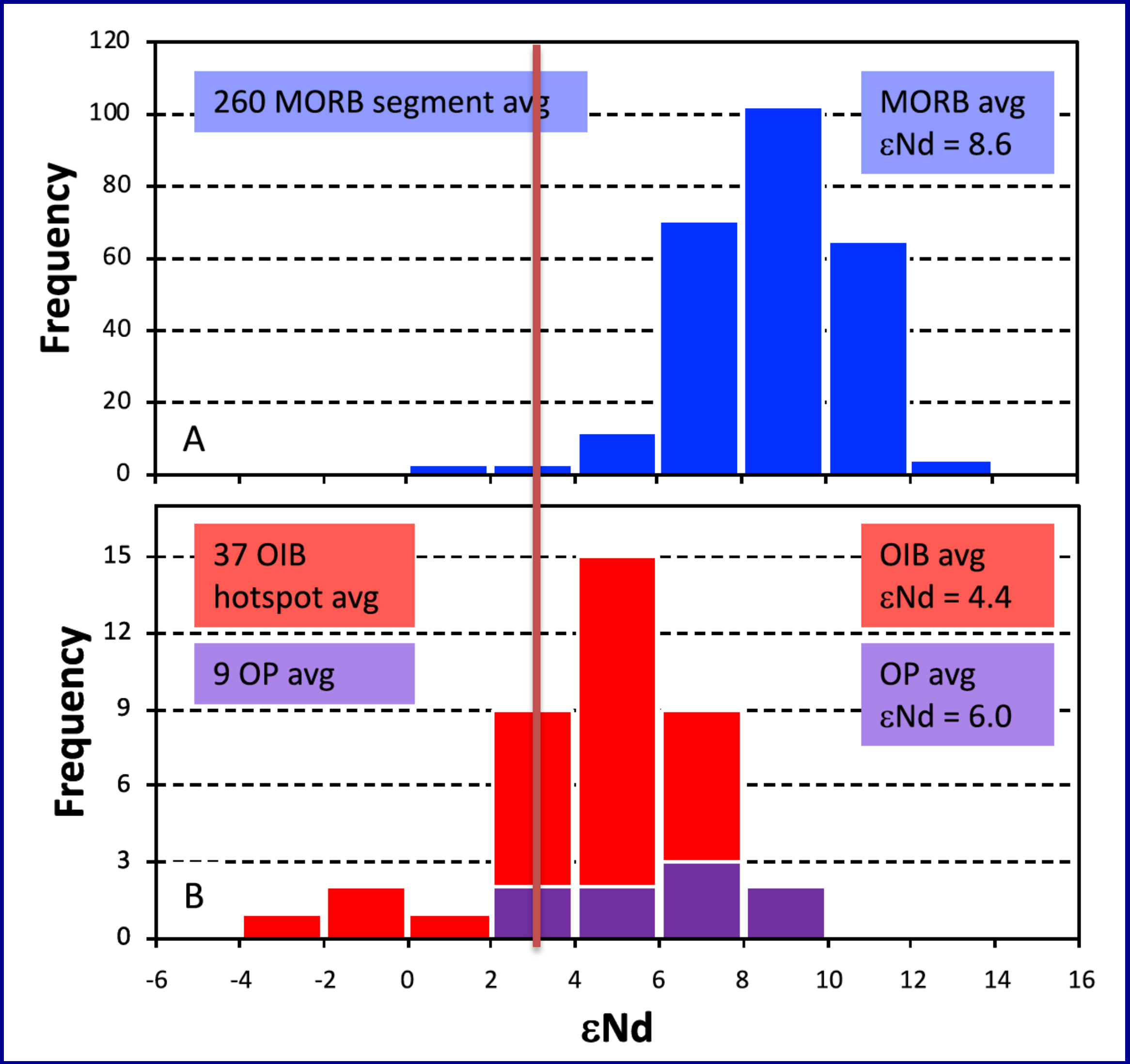
Would require a depleted mantle with ε(Nd) ≤ 3.

A MORB-OIB mantle with ε(Nd) = 5 still occupies only 30 to 40% of the total mantle

The **bulk** ε(Nd) value of the residual mantle would have to be

ε(Nd) < 3

This is much lower than observed mantle rocks



Simplest Solution:

A fourth, *hidden* reservoir, leaving behind an
"Early Depleted Reservoir" (EDR)
or simply a non-chondritic BSE

Replace chondritic Bulk Silicate Earth by EDR:

Mass fraction of the Residual Mantle (RM) given by:

$$X_{\mathrm{RM}} = \frac{X_{\mathrm{CC}}\, Nd_{\mathrm{CC}}\; (\varepsilon_{\mathrm{RM}} - \varepsilon_{\mathrm{CC}})}{Nd_{\mathrm{EDR}}\; (\varepsilon_{\mathrm{RM}} - \varepsilon_{\mathrm{EDR}})} - X_{\mathrm{CC}}$$

$$X_{\mathrm{RM}} = \frac{X_{\mathrm{CC}}\, U_{\mathrm{CC}}\; (Nb/U_{\mathrm{RM}} - Nb/U_{\mathrm{CC}})}{U_{\mathrm{EDR}}\; (Nb/U_{\mathrm{RM}} - Nb/U_{\mathrm{EDR}})} - X_{\mathrm{CC}}$$

Two equations with 4 unknowns:

$$X_{\mathrm{RM}} = \frac{X_{\mathrm{CC}}\, Nd_{\mathrm{CC}}\ (\varepsilon_{\mathrm{RM}} - \varepsilon_{\mathrm{CC}})}{Nd_{\mathrm{EDR}}\ (\varepsilon_{\mathrm{RM}} - \varepsilon_{\mathrm{EDR}})} - X_{\mathrm{CC}}$$

$$X_{\mathrm{RM}} = \frac{X_{\mathrm{CC}}\, U_{\mathrm{CC}}\ (Nb/U_{\mathrm{RM}} - Nb/U_{\mathrm{CC}})}{U_{\mathrm{EDR}}\ (Nb/U_{\mathrm{RM}} - Nb/U_{\mathrm{EDR}})} - X_{\mathrm{CC}}$$

Model the EDR by extracting and permanently removing an amount of X_{EER} of mafic "primordial" crust (= sequestration or accretional "erosion."

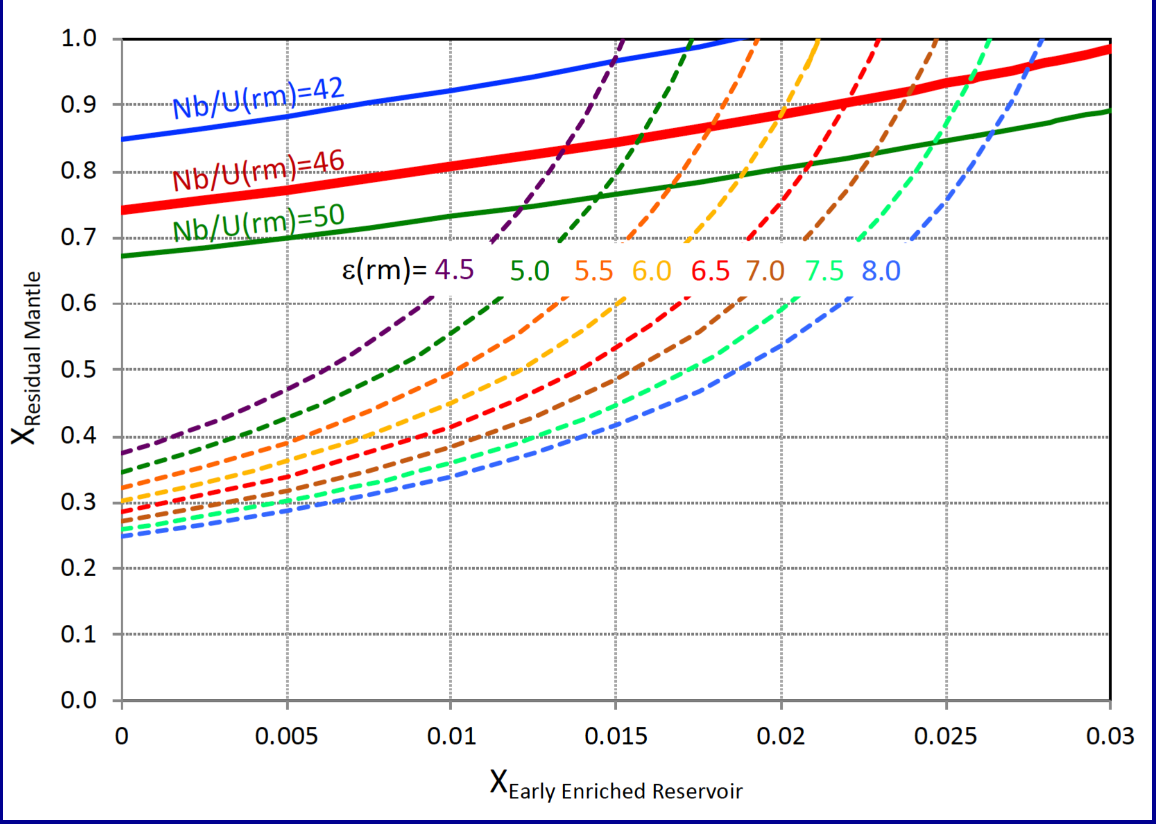
Use simple partial melting model of BSE in spinel peridotite facies, similar to MORB melting, varying melt fraction F = 0.08 to 0.12.

This melting model does not change Nb/U, therefore $(Nb/U)_{EDR} = (Nb/U)_{EER} = (Nb/U)_{BSE} = 27.85$

For a given value of e.g. F = 0.10, a unique mass fraction of the EER, X_{EER}, satisfies both equations

Mass of the Residual Mantle depends on knowledge of crustal composition.

Case for $F_{EER} = 0.10$, $U_{CC} = 1.2$ ppm, $\varepsilon_{CC} = -13$



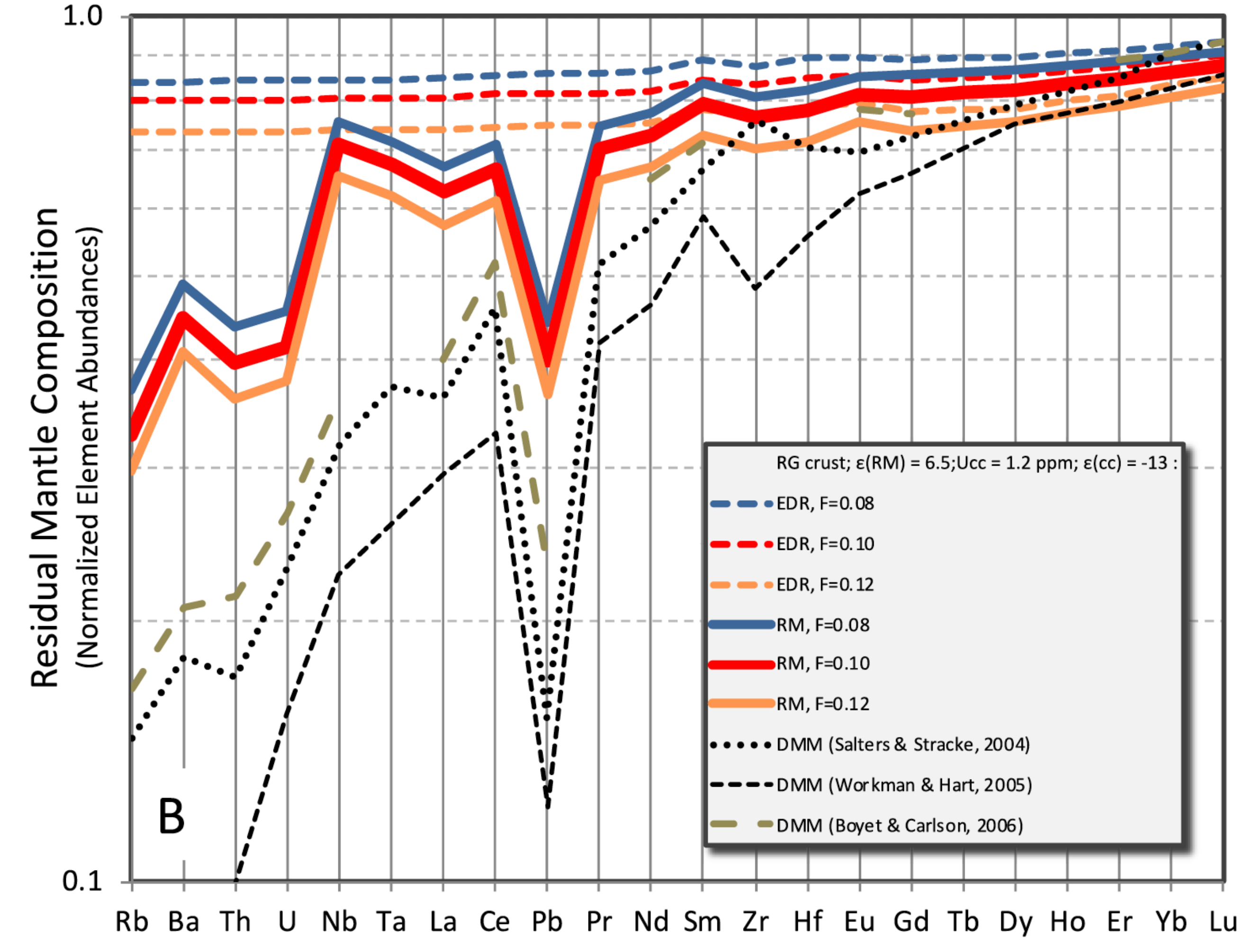
The residual mantle occupies > 70% of the total mantle

The mantle residue of continental crust extraction contains both MORB and OIB sources.
It is much less depleted than published estimates of the Depleted Mantle

$\varepsilon_{\text{Residual mantle}} = 6.5$

$U_{CC} = 1.2$ ppm

$\varepsilon_{CC} = -13$



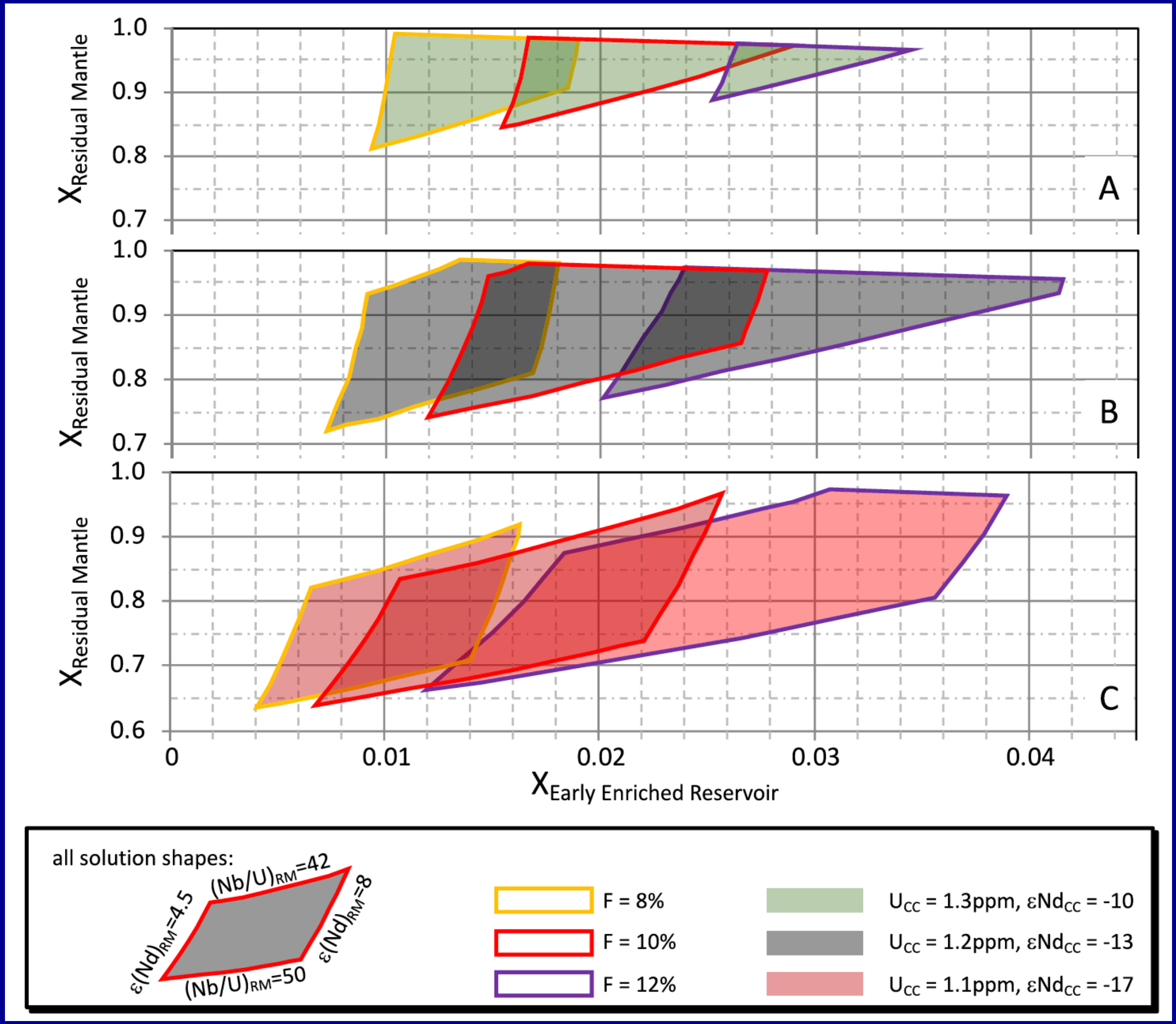
Covering the full range of parameters

F = 0.08 to 0.12; U_{cc} = 1.1 to 1.3 ppm; $\varepsilon(Nd)_{CC}$ -10 to -17

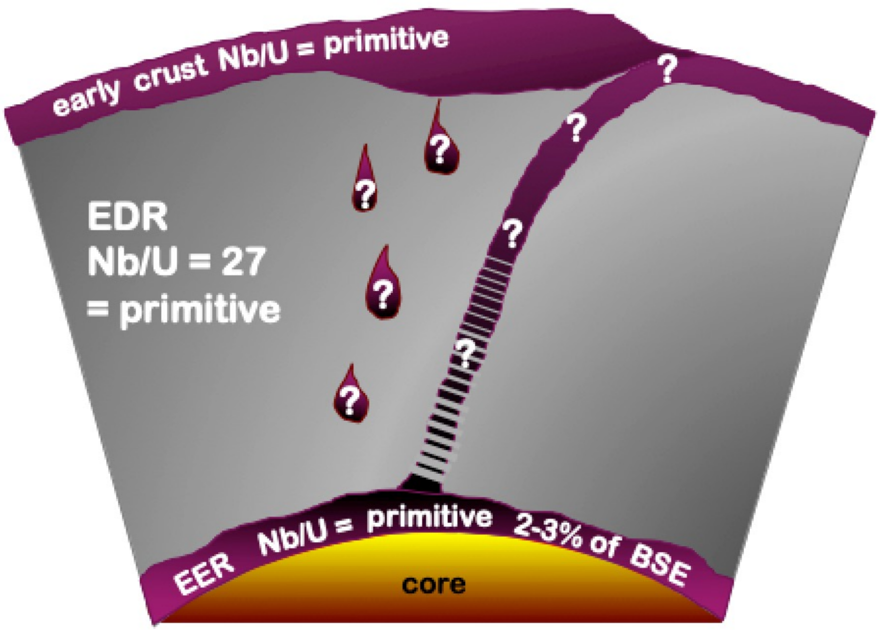
Mass fraction of residual mantle:

$X_{RM} \geq 0.65$

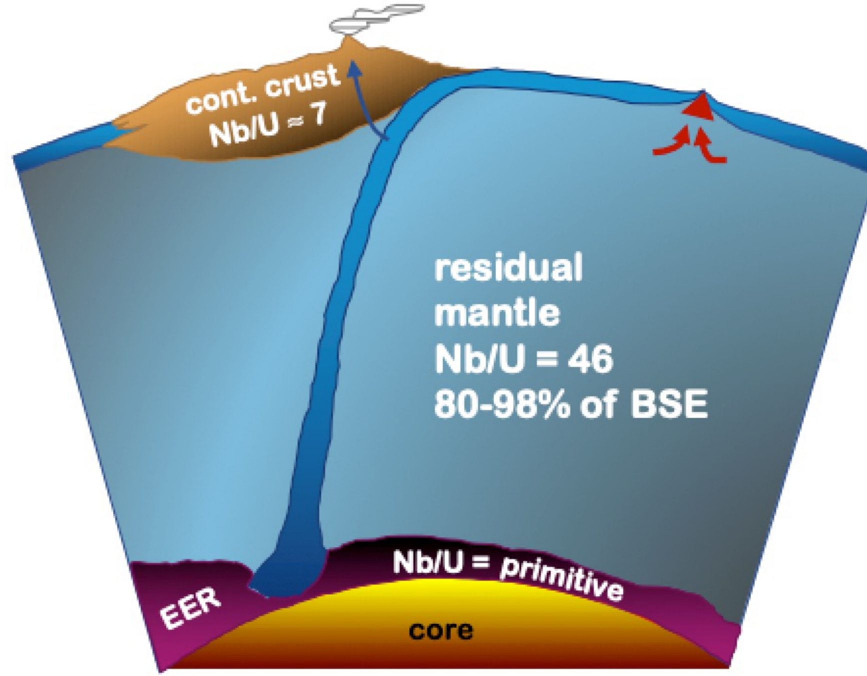
The *Residual Mantle* may occupy all of the mantle!



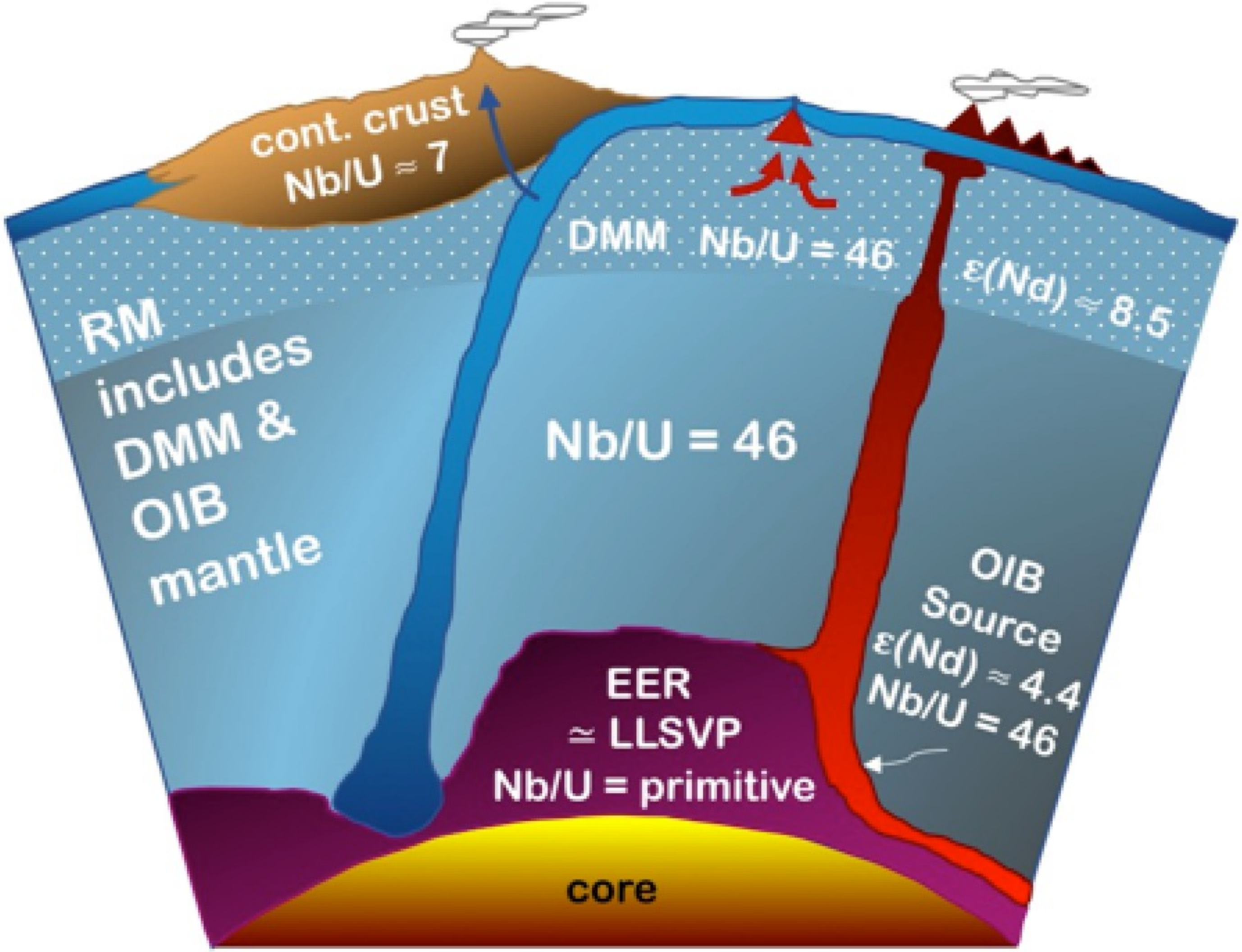
Early EER-EDR differentiation (> 4 Ga ago)



Formation of continental crust and residual mantle



Present-day silicate Earth



What is the Early Enriched Reservoir?

- Primordial crust now at the base of the mantle?

  Tolstikhin and Hofmann (2005)

- Fractionation and overturn of early magma ocean?

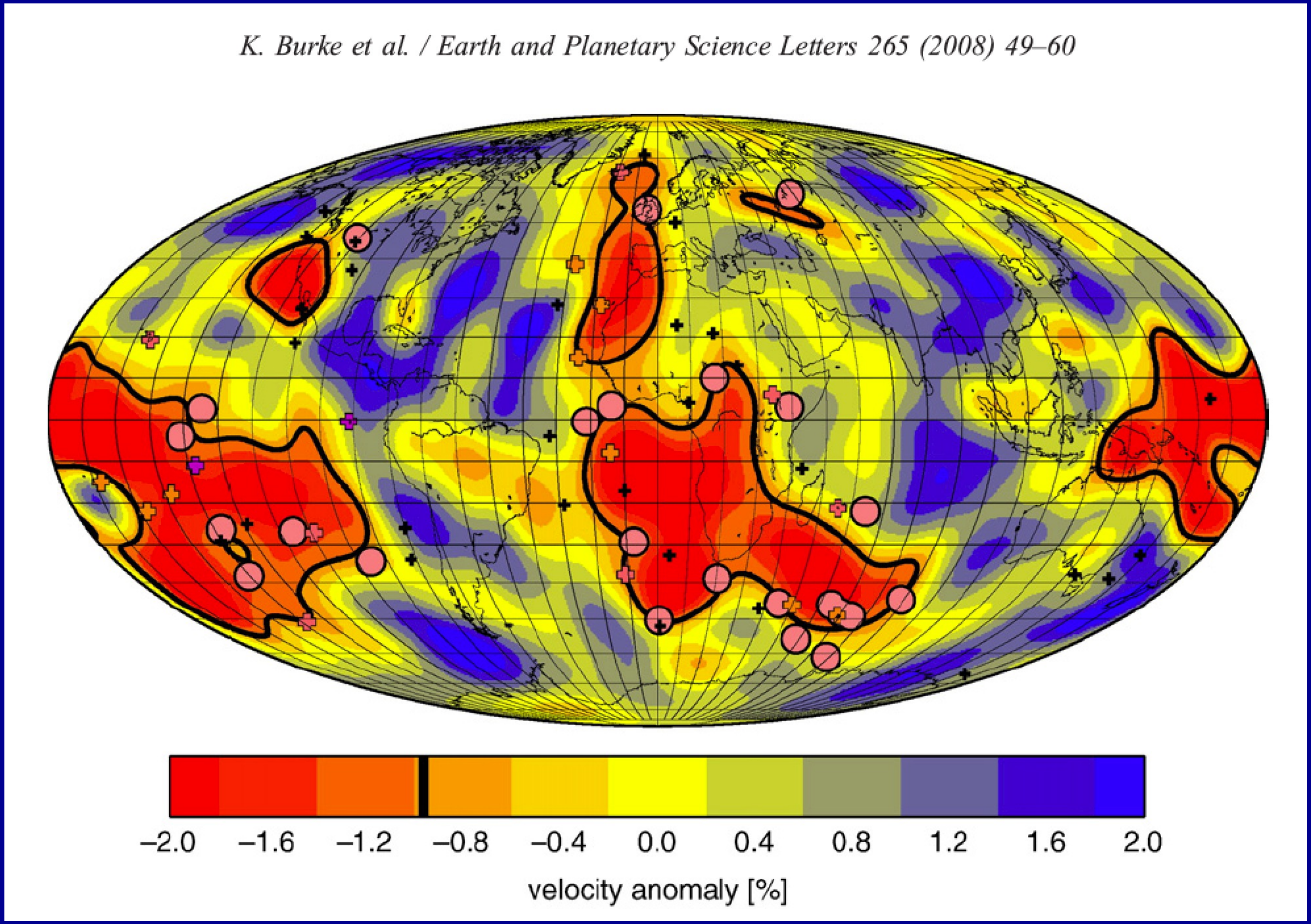
  Brown et al. (2014)

- Lost to space by collisional erosion?

  O'Neill and Palme (2008)

Are LLSVPs the hosts for the Early-Enriched Reservoir(s) ?

Maybe

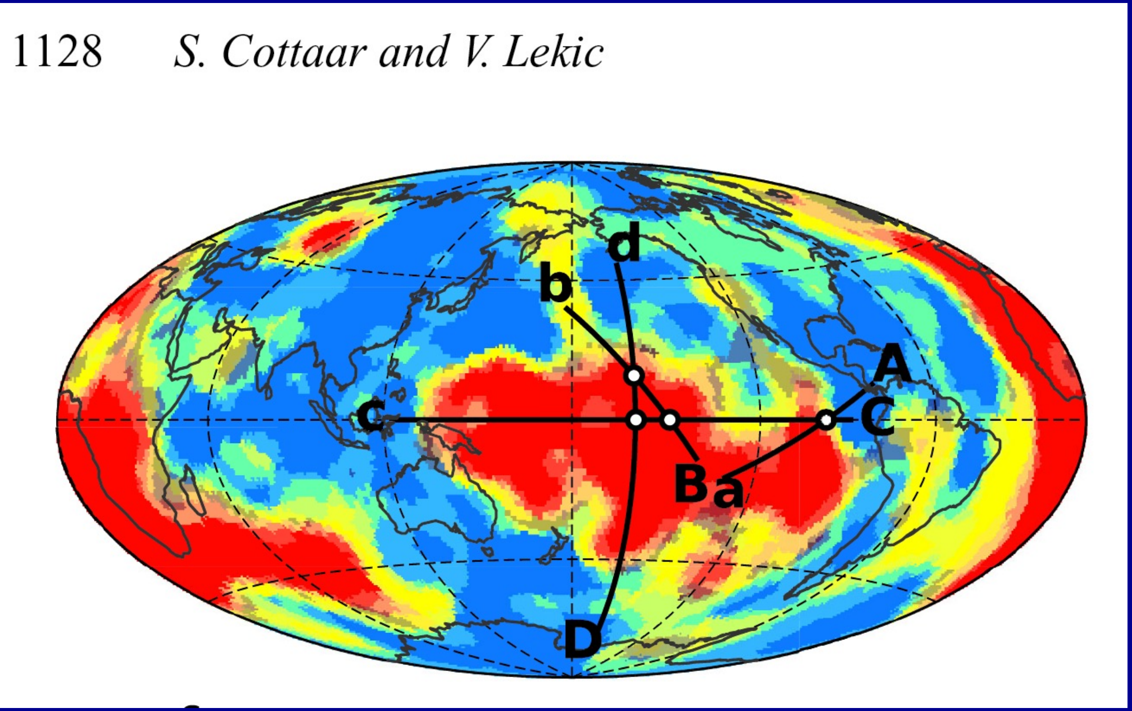


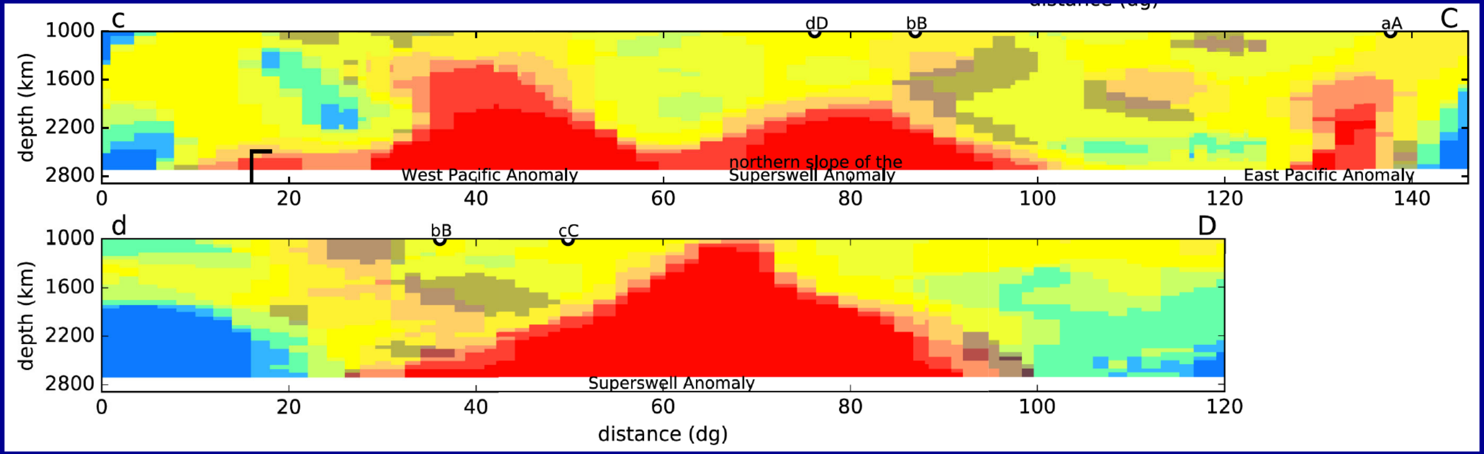
Burke et al., 2008, EPSL

Large Low Shear Velocity Provinces:

9% of the total mantle

LLSVPs dominate the lower mantle





Cottaar & Lekic, 2016, Geophys. J. Int.

Take home messages

Isotope-based evaluations of the depleted mantle reservoir are fundamentally incorrect:

They systematically underestimate the size of the depleted reservoir

Overestimate the degree of depletion

No 3-reservoir crust-mantle model can account for crust-mantle differentiation of a <u>chondritic</u> Earth.

An early depletion event is required

either by sequestration of an early-enriched reservoir

or by creating a non-chondritic BSE via collisional erosion

Sampling Earth's Interior