

# Composition of bulk silicate Earth and global geodynamics

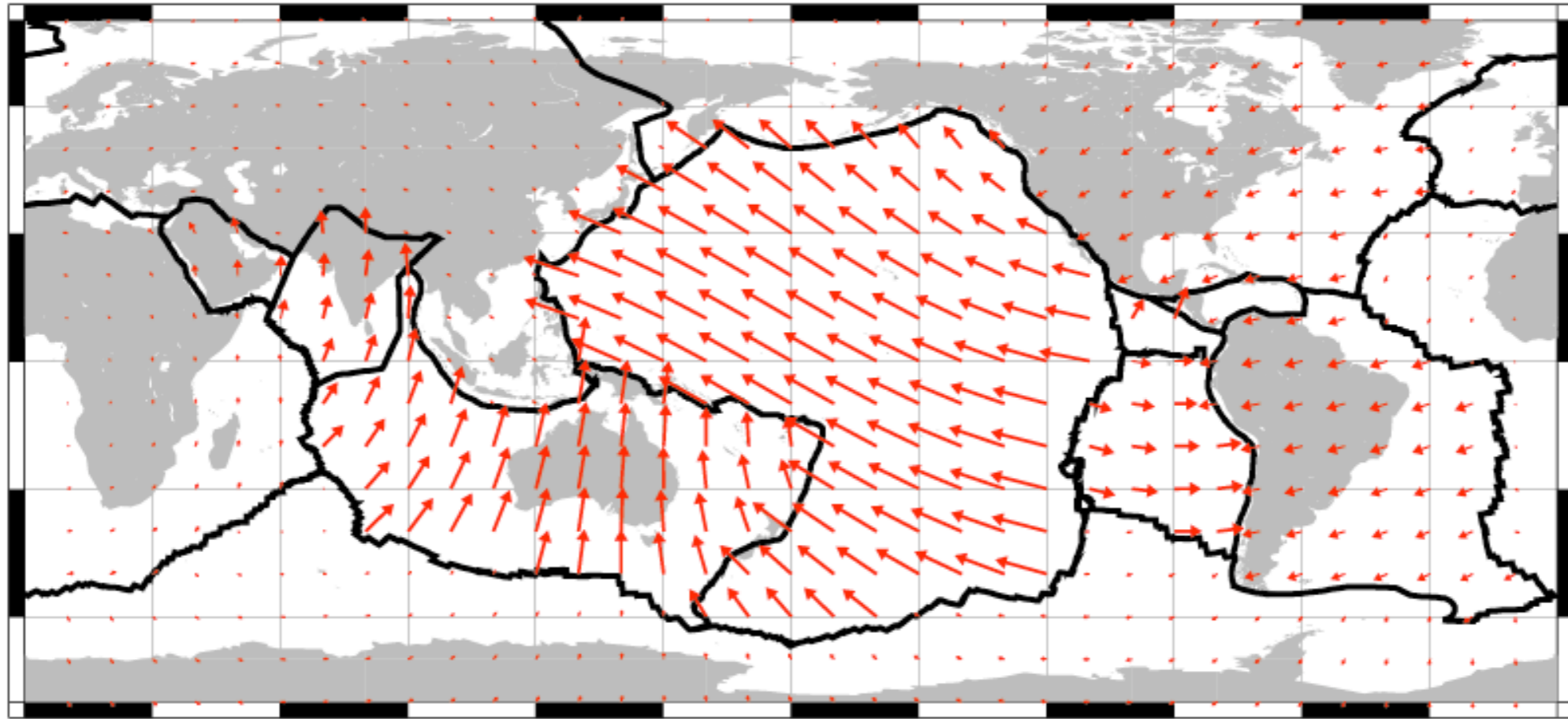
Jun Korenaga  
Department of Geology and Geophysics  
Yale University

March 23, 2007 @ Hawaii Geoneutrino Workshop

# Overview

- Motivation: Thermal evolution of Earth
- Global mass balance and the composition of bulk silicate Earth (BSE)
- Thermal evolution revisited

# Present-day Plate Motion



← 10cm/y.=100km/m.y.

- Average plate velocity  $\sim 4\text{cm/yr}$
- Global heat flux  $\sim 44\text{TW}$

**Q. How was it like in the past?**

# Global heat balance equation

$$C \frac{dT}{dt} = H(t) - Q(t)$$

T - average internal temperature

C - heat capacity of Earth

H - radiogenic heating (easy to specify)

Q - convective heat flux (not straightforward)

$$Q(t) = H(t) - C \frac{dT}{dt}$$

Surface heat flux is a combination of internal heat production and secular cooling.

# Global heat balance equation

$T(0) \sim 1350^\circ\text{C}$

$$C \frac{dT}{dt} = H(t) - Q(t)$$

T - average internal temperature

C - heat capacity of Earth

H - radiogenic heating (easy to specify)

Q - convective heat flux (not straightforward)

$$Q(t) = H(t) - C \frac{dT}{dt}$$

Surface heat flux is a combination of internal heat production and secular cooling.

# Global heat balance equation

$T(0) \sim 1350^\circ\text{C}$

$$C \frac{dT}{dt} = H(t) - Q(t)$$

$H_{\text{total}}(0) \sim 20\text{TW}$

$H_{\text{cc}}(0) \sim 8\text{TW}$

$H_{\text{conv}}(0) \sim 12\text{TW}$

T - average internal temperature

C - heat capacity of Earth

H - radiogenic heating (easy to specify)

Q - convective heat flux (not straightforward)

$$Q(t) = H(t) - C \frac{dT}{dt}$$

Surface heat flux is a combination of internal heat production and secular cooling.

# Global heat balance equation

$$T(0) \sim 1350^\circ\text{C}$$

$$H_{\text{total}}(0) \sim 20\text{TW}$$

$$H_{\text{cc}}(0) \sim 8\text{TW}$$

$$H_{\text{conv}}(0) \sim 12\text{TW}$$

$$C \frac{dT}{dt} = H(t) - Q(t)$$

$$Q_{\text{total}}(0) \sim 44\text{TW}$$

$$H_{\text{cc}}(0) \sim 8\text{TW}$$

$$Q_{\text{conv}}(0) \sim 36\text{TW}$$

T - average internal temperature

C - heat capacity of Earth

H - radiogenic heating (easy to specify)

Q - convective heat flux (not straightforward)

$$Q(t) = H(t) - C \frac{dT}{dt}$$

Surface heat flux is a combination of internal heat production and secular cooling.

# Global heat balance equation

$$T(0) \sim 1350^\circ\text{C}$$

$$H_{\text{total}}(0) \sim 20\text{TW}$$

$$H_{\text{cc}}(0) \sim 8\text{TW}$$

$$H_{\text{conv}}(0) \sim 12\text{TW}$$

$$C \frac{dT}{dt} = H(t) - Q(t)$$

$$Q_{\text{total}}(0) \sim 44\text{TW}$$

$$H_{\text{cc}}(0) \sim 8\text{TW}$$

$$Q_{\text{conv}}(0) \sim 36\text{TW}$$

T - average internal temperature

C - heat capacity of Earth

H - radiogenic heating (easy to specify)

Q - convective heat flux (not straightforward)

$$\text{Urey ratio} \\ = H/Q \sim 0.3$$

$$Q(t) = H(t) - C \frac{dT}{dt}$$

Surface heat flux is a combination of internal heat production and secular cooling.

# How to parameterize $Q(t)$ ?

From the theory of thermal convection:

$$\boxed{\text{Nu} \propto \text{Ra}^\beta}$$

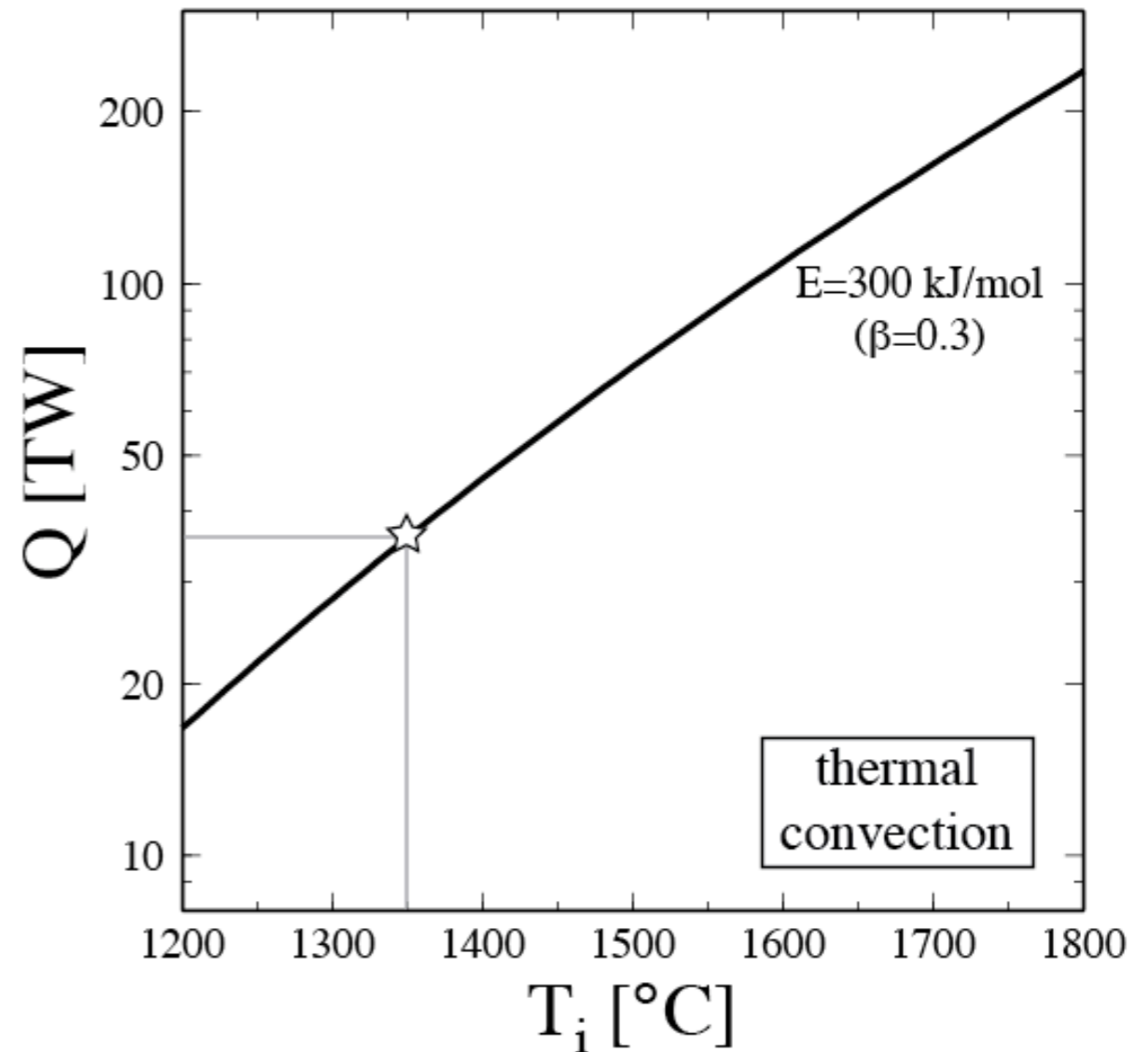
(surface heat flux)  $\propto$  (convective vigor) $^\beta$

Mantle viscosity is strongly temperature-dependent:

$$\text{Ra} \propto \eta(T)^{-1}$$

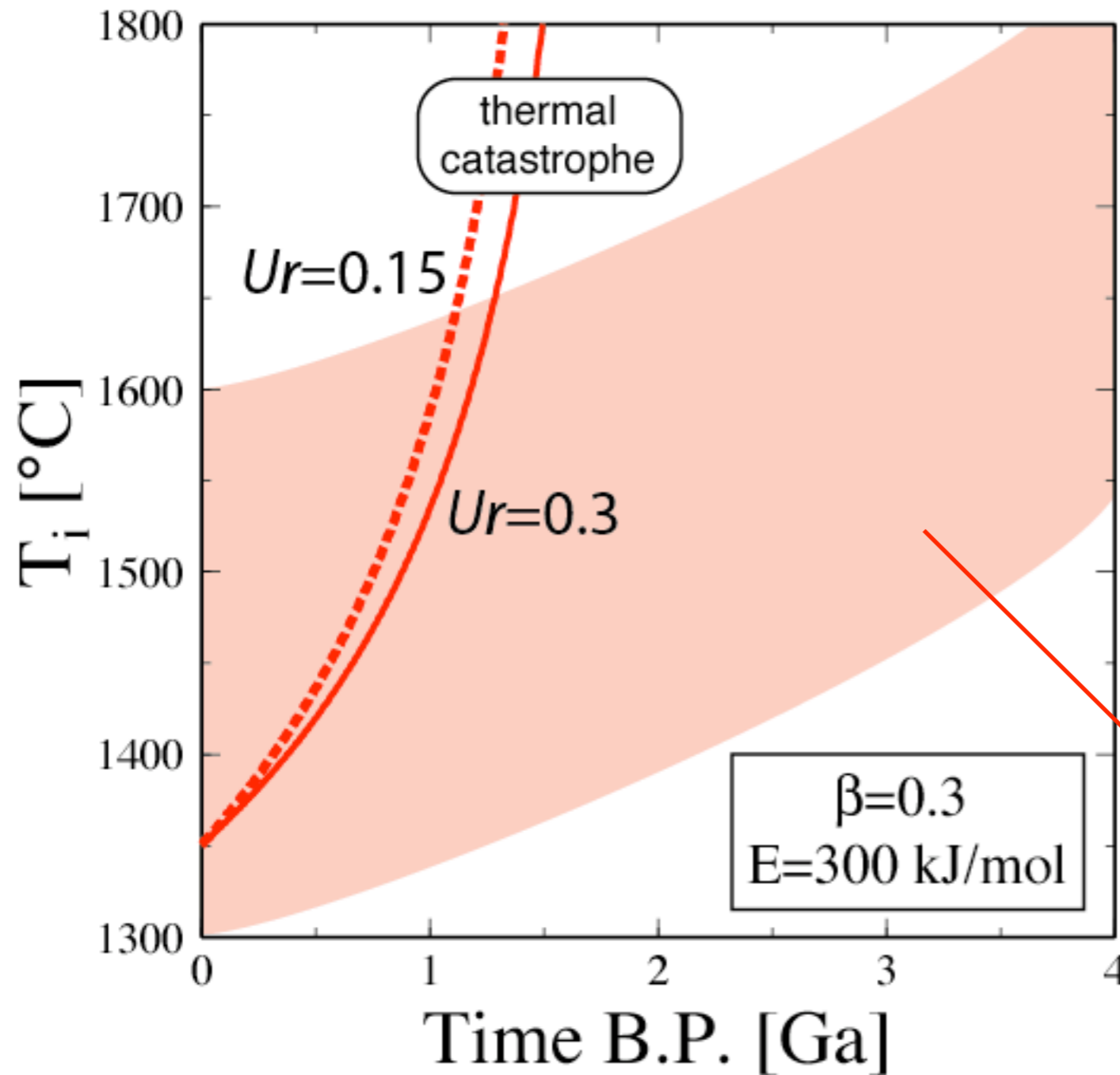
By combining these two relations we may obtain:

$$Q = Q(T(t))$$



Hotter mantle is less viscous, convects faster, and releases more heat.

# Thermal catastrophe



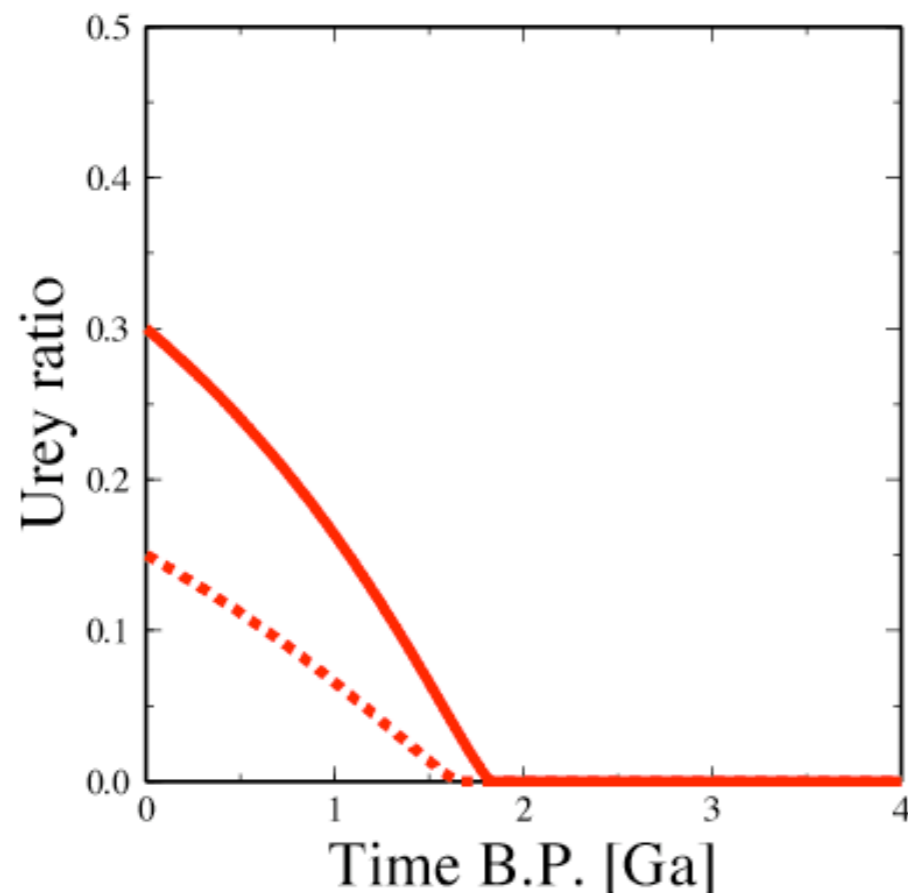
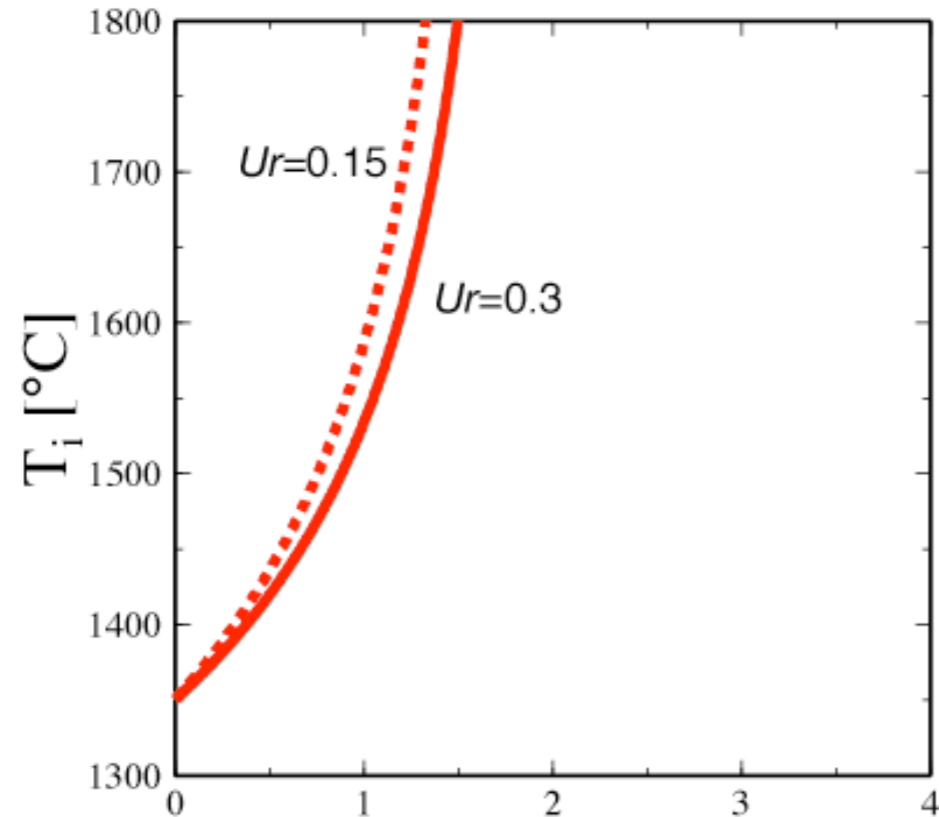
Whole-mantle convection does not produce a reasonable thermal history **when combined with what we know about global heat budget!**

Range of upper mantle temperature  
[Abbott et al., 1994]

**Why does this happen?**

Note: we are back-tracking a thermal history from the present time.

# Why thermal catastrophe?



Positive feedback loop:

$Ur=0.3$

- ⇒ 70% secular cooling
- ⇒ higher mantle temperature
- ⇒ hotter mantle convects faster
- ⇒ higher heat flux (more rapid than increase in internal heating)
- ⇒ even lower  $Ur$

# How to avoid catastrophe?

- A. Whole-mantle convection with  $Ur=0.7$   
(‘standard’ geophysical model)
- B. Layered-mantle convection?
- C. Different  $Q(T)$ ?

# Global mass (im)balance arguments for layered convection

- Missing argon paradox
- Missing heat-source paradox (including U-Th systematics)
- Refractory lithophile mass balance (REE, Ca, Al, Ti, U, Th, ...)
- Nd isotope mass balance

All of these arguments are based on the following *negative* result:

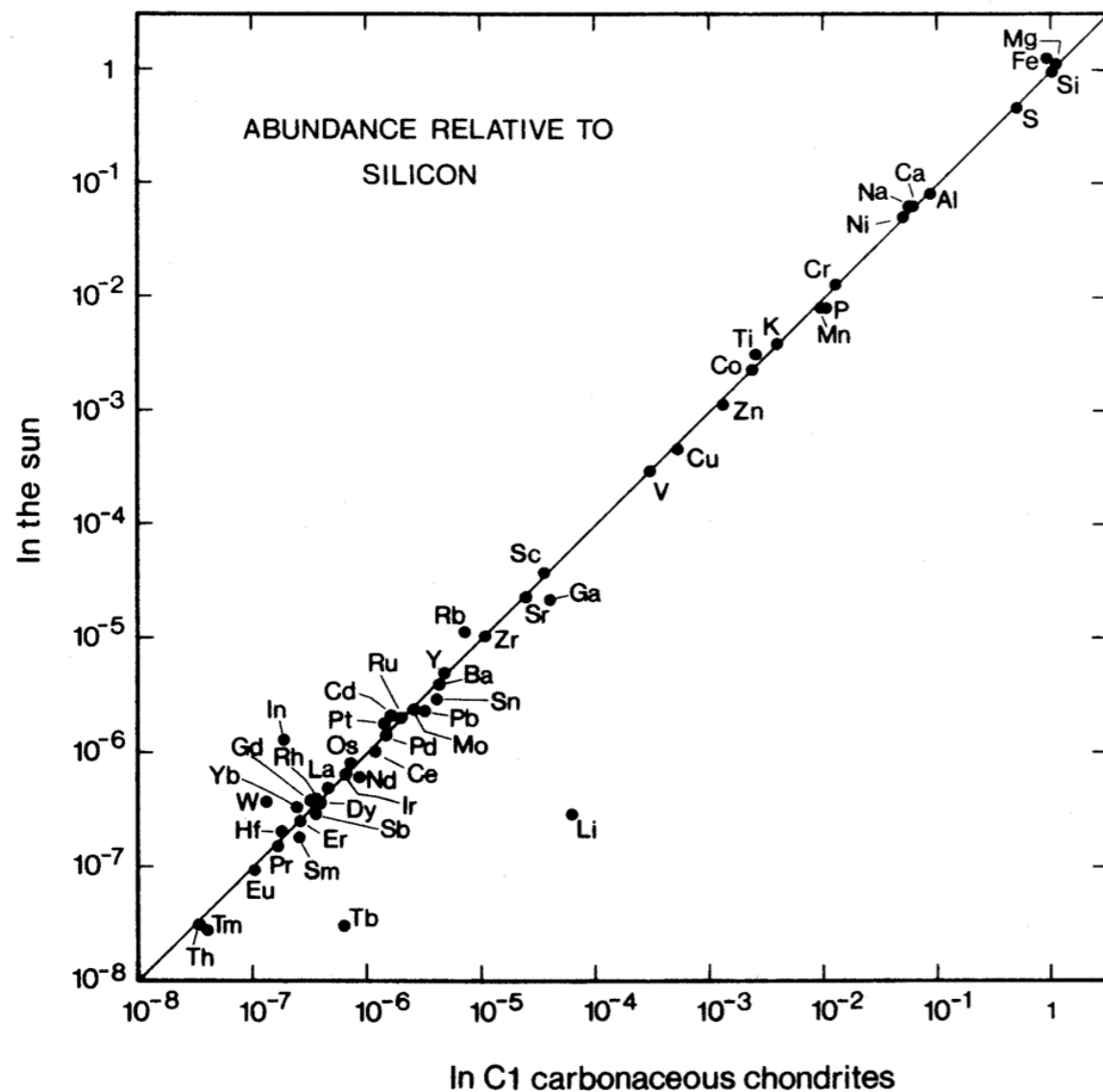
$$CC+DM \neq BSE$$

(i.e., failure to reconstruct BSE from CC and DM)

But how do we know about BSE??

# Chondrite-Sun coincidence

Carbonaceous chondrites = the most 'primitive' kind of meteorite



Chondrites are the 'hand sample' of the bulk solar system, which we can analyze in great details (to figure out the age of the solar system, etc).

# Cosmochemical and geochemical jargons for element behavior

- Regarding condensation temperatures
  - **Volatile** - low condensation T
  - **Refractory** - high condensation T
- Regarding chemical partitioning
  - **Lithophile** - like to be with silicates (crust and mantle)
  - **Chalcophile** - like to be with sulfur
  - **Siderophile** - like to be with iron (core)
  - **Atmophile** - like to be in the atmosphere

# Composition of Bulk Silicate Earth (=crust + mantle)

- Should be *similar* to that of carbonaceous chondrites in terms of **refractory lithophile elements** (Al, Ca, Ti, Sc, V, REE, U, Th, ...)
- But *how* similar?
- Sm-Nd & Lu-Hf isotope systems tell us BSE's Sm/Nd and Lu/Hf should not deviate from chondritic values by more than 5%.

# Nailing down the **absolute** abundance of RLEs

McDonough & Sun [1995] - the de facto standard model

Two (and only two) assumptions:

- Compositional trend in mantle peridotites is 'melting' trend. Along such a trend should exist the primitive mantle (or BSE).
- By imposing chondritic constraints on the ratio of RLE, we should be able to find the location of BSE on the trend.

Note: Other studies employ more assumptions, the validity of which are often questionable.

# Nailing down the **absolute** abundance of RLEs

## McDonough & Sun [1995]

- Compositional trends in mantle peridotites are 'melting' trends. Along these trends should exist primitive mantle (or BSE).
- BSE contents of Ti, Al, & Ca are estimated using chondritic RLE ratios (see figure).
- Their concentrations are ~2.75 times more than those in CI-chondrite.
- This enrichment factor (~2.75) fixes the absolute concentrations of all RLEs in BSE.

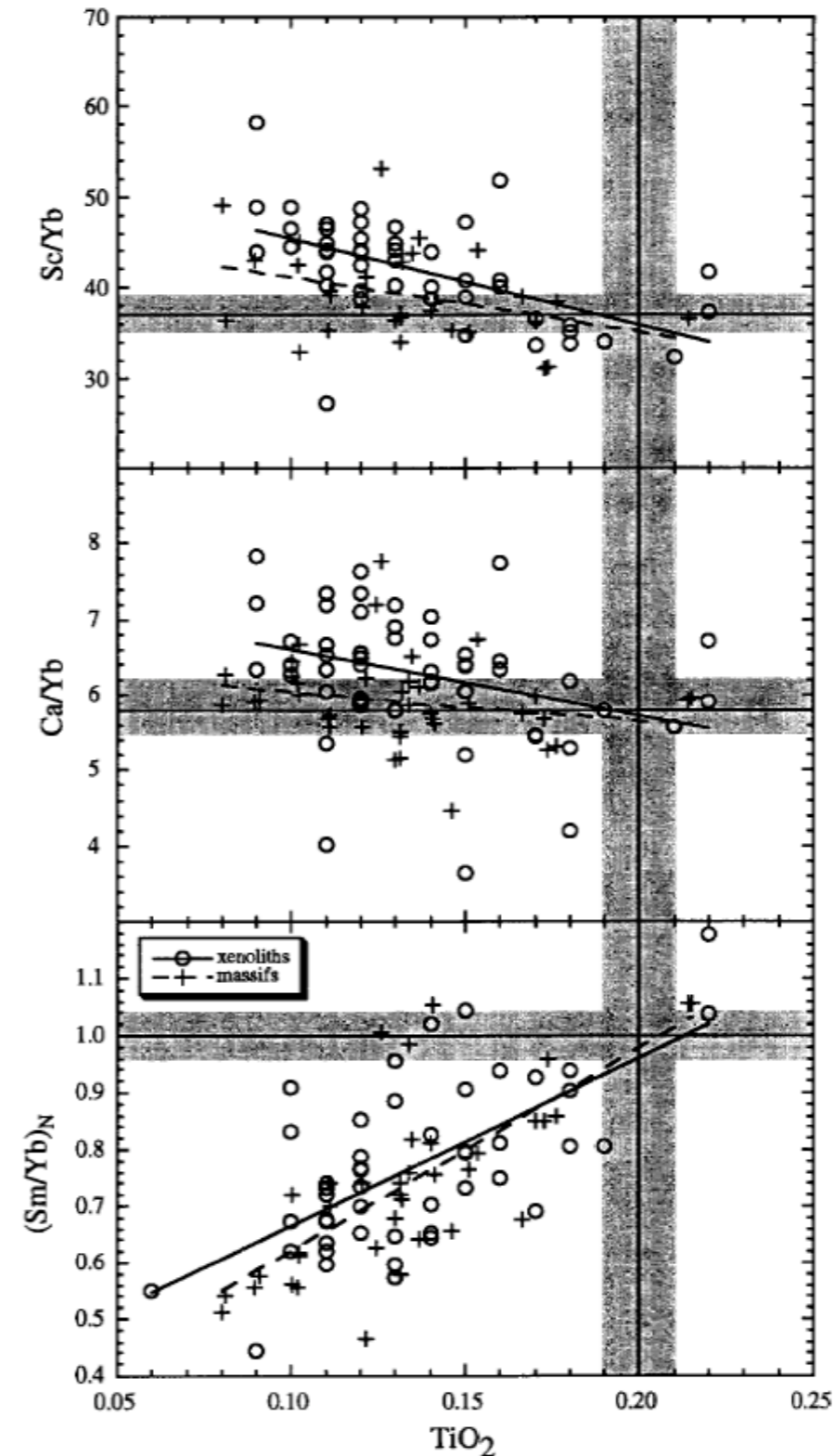


Fig. 6.  $\text{TiO}_2$  vs.  $\text{Sc/Yb}$ ,  $\text{Ca/Yb}$  and  $(\text{Sm/Yb})_N$  in peridotite massifs (crosses) and peridotite xenoliths (open circles). The horizontal lines and shaded areas show the chondritic ratio and an estimate of its variation in chondritic meteorites, respectively. The vertical line and its shaded area is our estimate of the  $\text{TiO}_2$  content of the Silicate Earth and the precision of this estimate, respectively. Linear regression lines are given for peridotite massifs (dashed line) and peridotite xenoliths (solid line); see text for further discussion. Data are shown for fertile peridotites with  $\leq 40.5$  wt% MgO.

# Problems with previous BSE models

- Defining ‘melting trends’ in the multi-dimensional compositional space is difficult.
- Different chondritic RLE ratios often yield different BSE estimates.
- Peridotite data have large scatters and outliers, which must influence geochemical inference.

These issues make it difficult to estimate model uncertainty (“How much should we trust one particular BSE model?”).

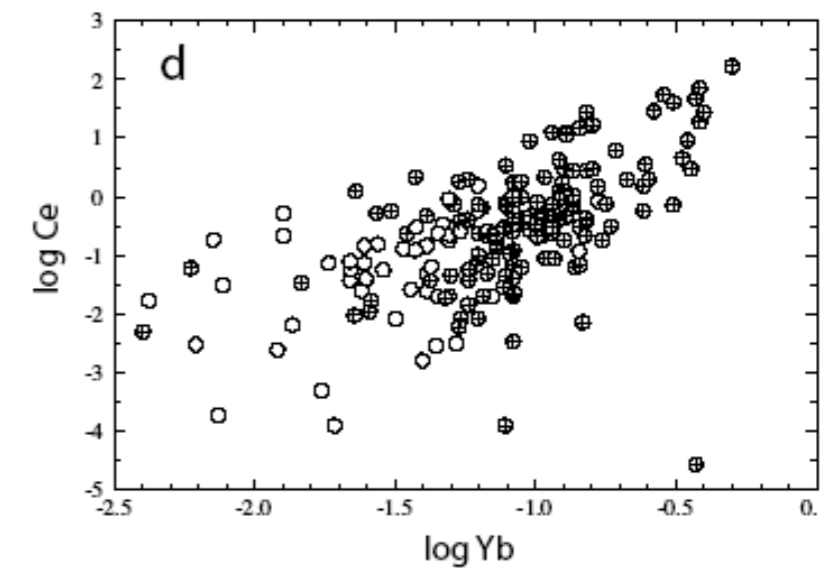
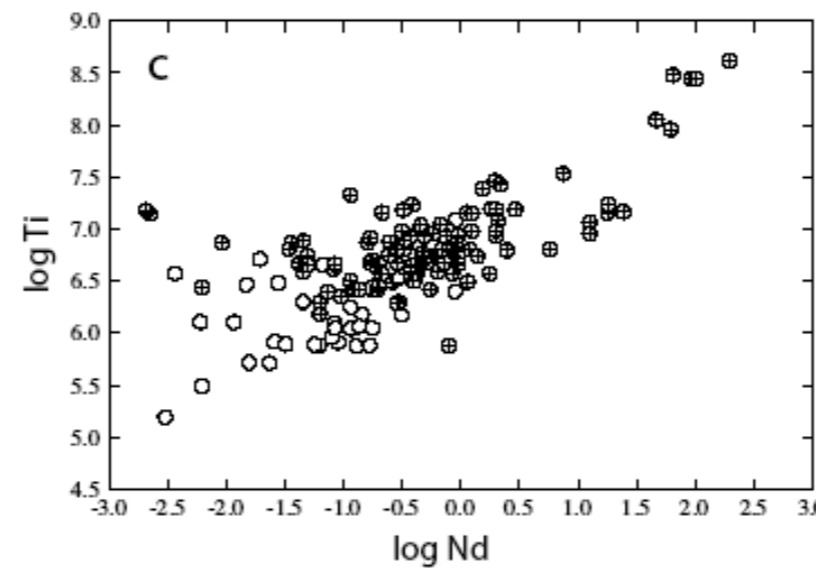
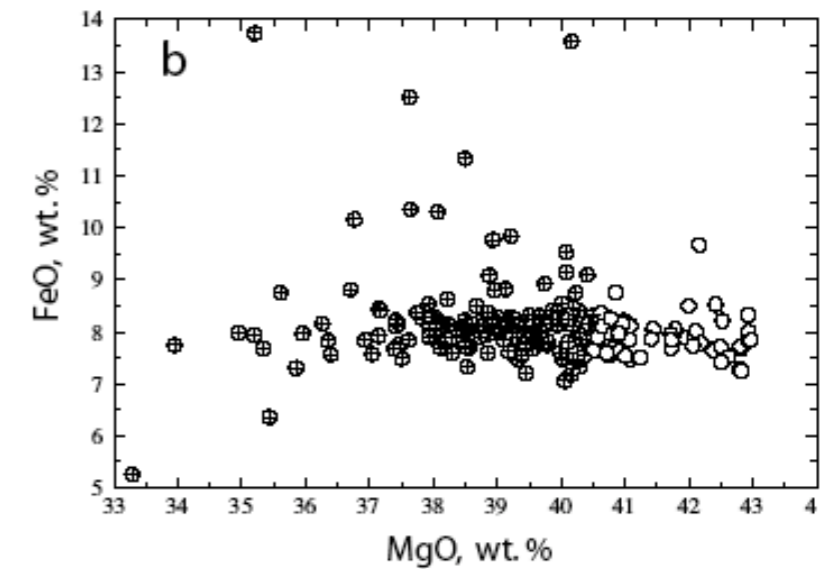
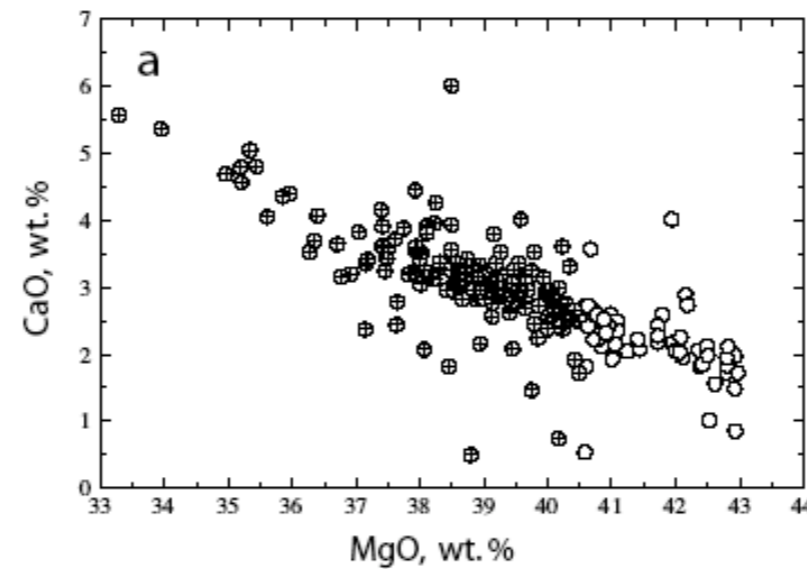
# A new approach

[Lyubetskaya and Korenaga, JGR, 2007]

- Defining linear and nonlinear ‘melting trends’ in the multi-dimensional compositional space: **the principal component analysis in the lognormalized data space**
- Different chondritic RLE ratios: **stochastic least-squares inversion to impose all constraints simultaneously**
- Large scatters and outliers: **the bootstrap resampling method to propagate data uncertainty to model uncertainty**

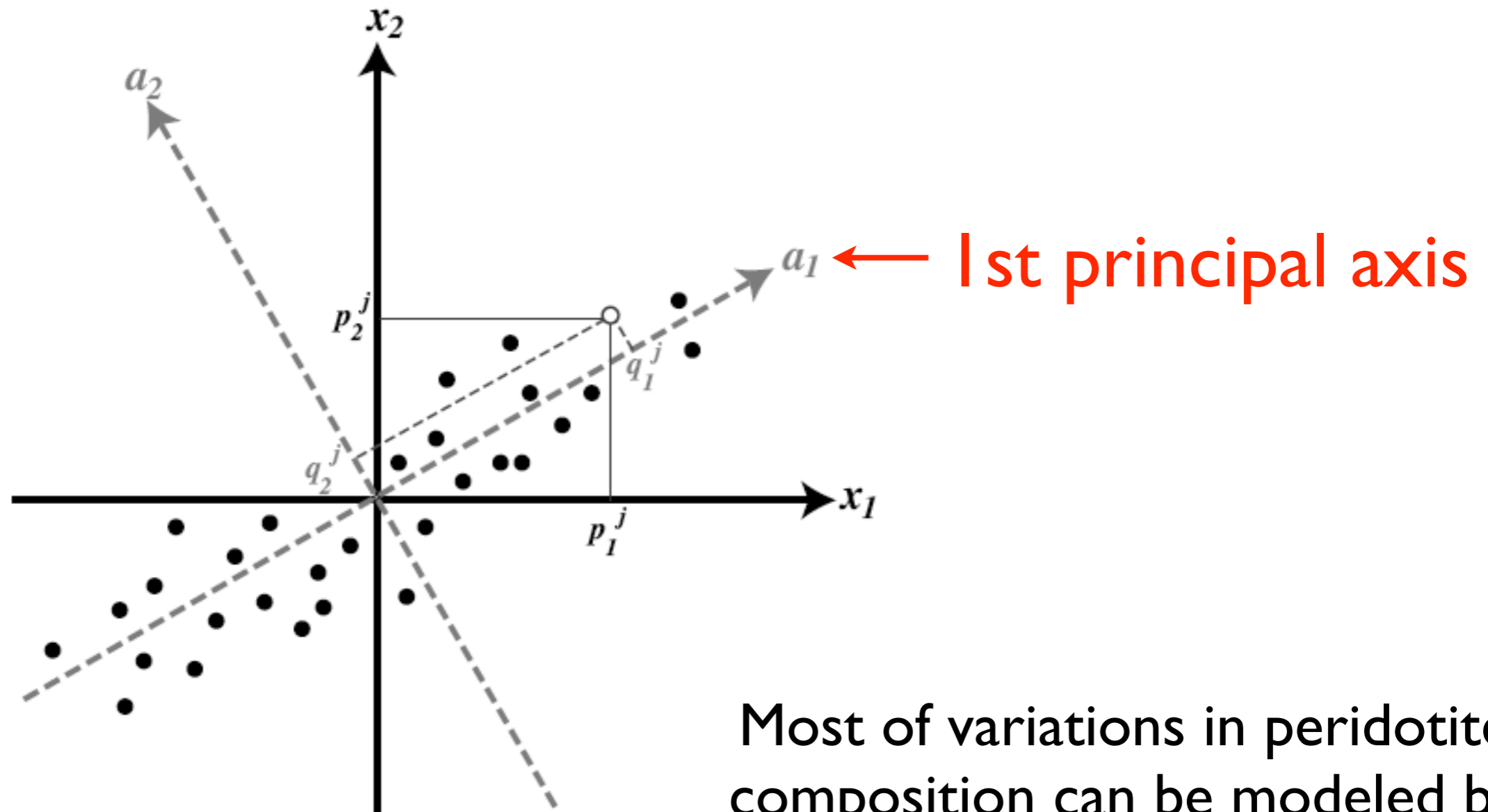
# Compositional covariation in multidimensions

- MgO  $\leq$  43 wt%
- $[La/Yb]_N \leq 2$
- no garnet peridotites
- no cratonic peridotites (Mg# < 91)



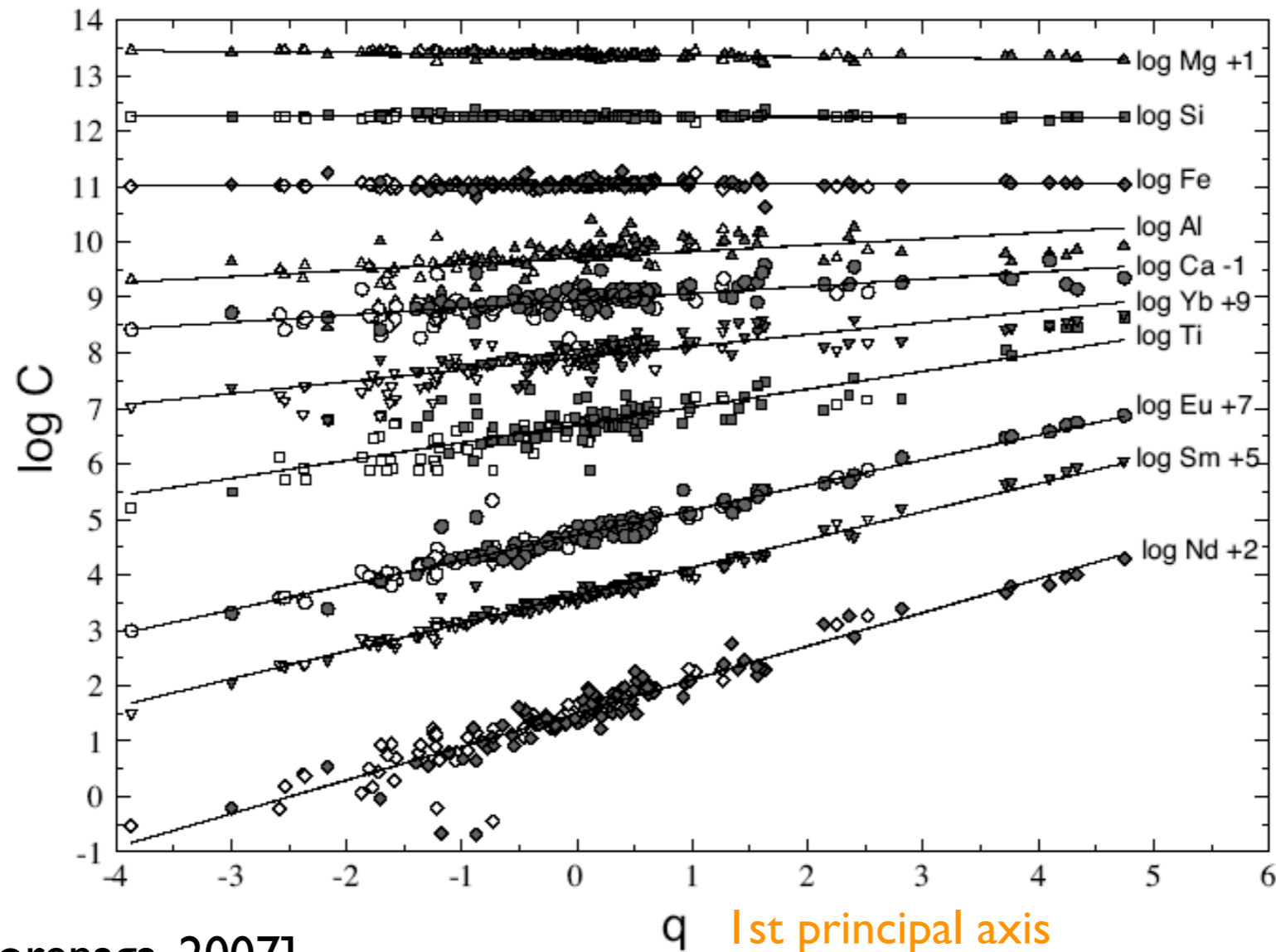
# Principal component analysis

= rotation of coordinate axes



Most of variations in peridotite composition can be modeled by the 1st principal component only (i.e., “melting” trend)

# Principal component analysis



>80% of total variance is explained by the first principle component

[Lyubetskaya and Korenaga, 2007]

$$\log C_i(q) \approx qa_i + \mathcal{E}(\log C_i) + \omega_i$$

1st principal component

log-mean

noise component

# Stochastic inversion

[Lyubetskaya and Korenaga, 2007]

logarithmic enrichment factor  
w.r.t CI chondrites:

$$\varepsilon_i = \log C_i(q) - (\log C_i)_{CI}$$

If you have N refractory lithophile elements, there are N enrichment factors, and we seek to obtain the most consistent set of enrichment factors by minimizing the following cost function:

$$\chi^2(q) = \sum_i (\varepsilon_i - \bar{\varepsilon})^2 \quad \text{where } \bar{\varepsilon} = \frac{1}{N} \sum_i \varepsilon_i$$

Formula for best-fit q:

$$q_{PM} = -\frac{\sum_i b_i d_i}{\sum b_i^2}$$

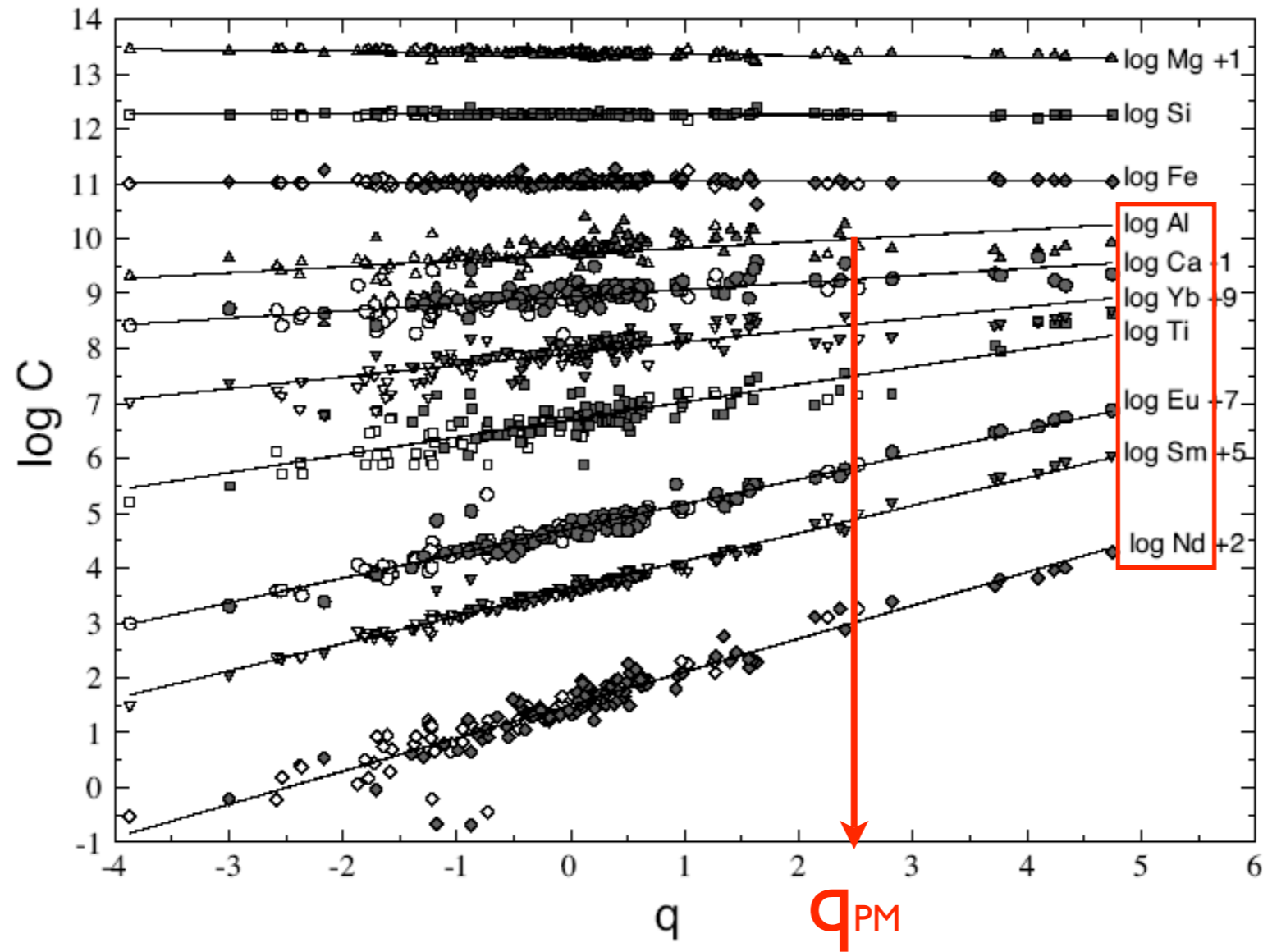
This determines the absolute concentration of RLEs.

$$b_i = a_i - \frac{1}{N} \sum_i a_i$$

$$d_i = \mathcal{E}(\log C_i) - (\log C_i)_{CI} + \omega_i$$

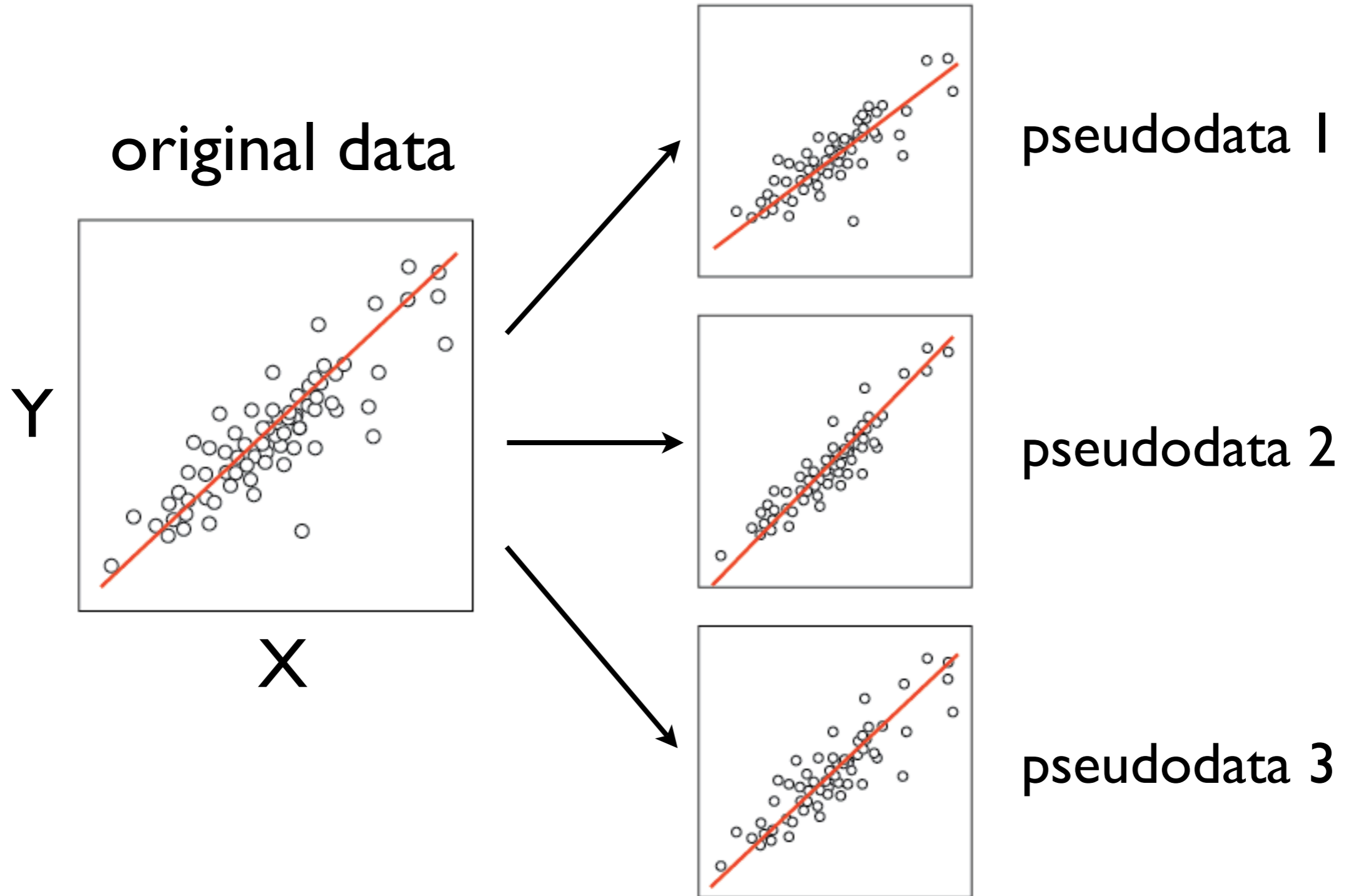
$$\frac{1}{N} \sum_i (\mathcal{E}(\log C_i) - (\log C_i)_{CI} + \omega_i)$$

# $q_{PM}$ for primitive mantle (BSE)

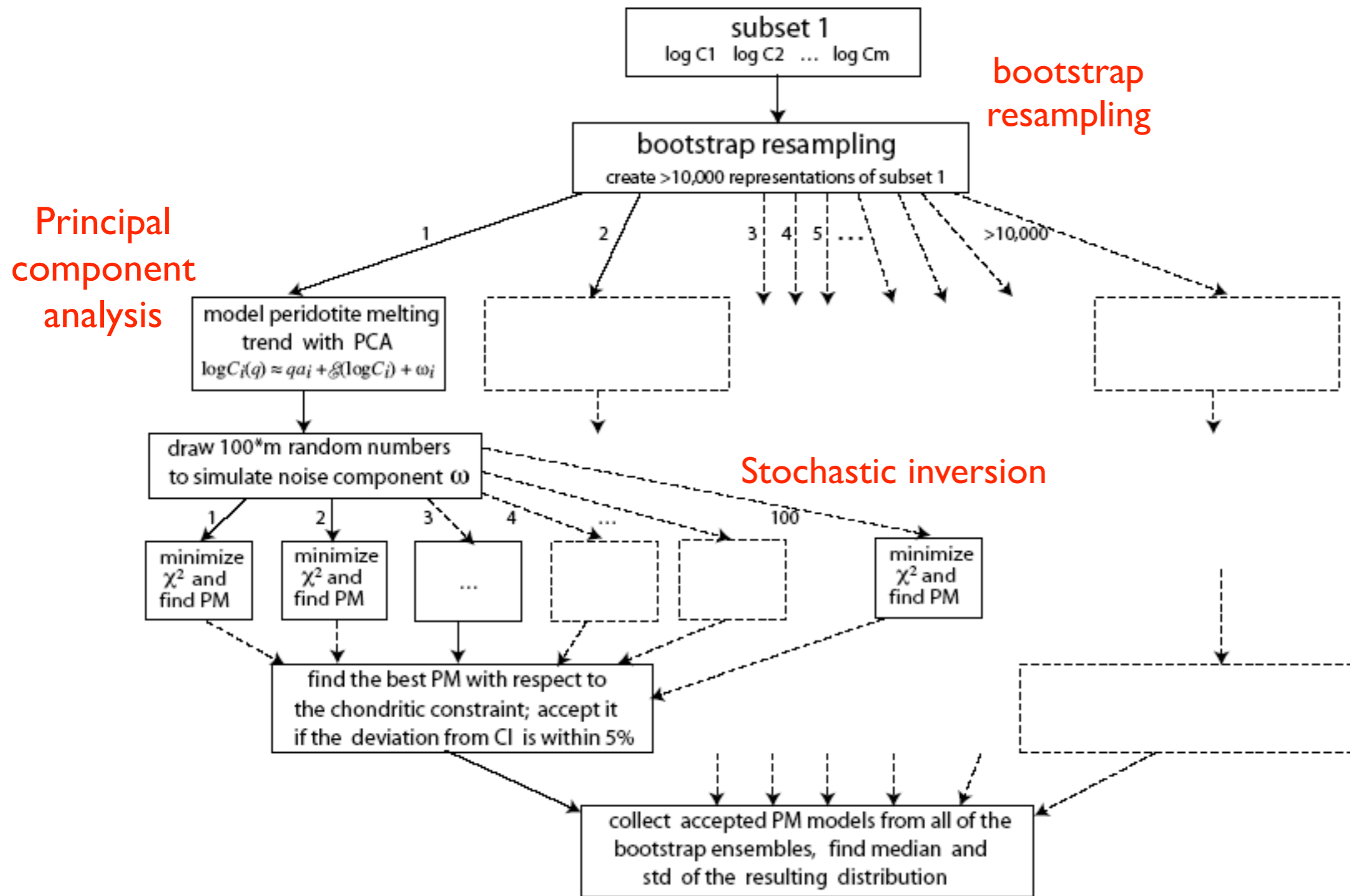


# Bootstrap resampling

Create pseudodata by sampling randomly from N data, by N times with repetitive sampling allowed



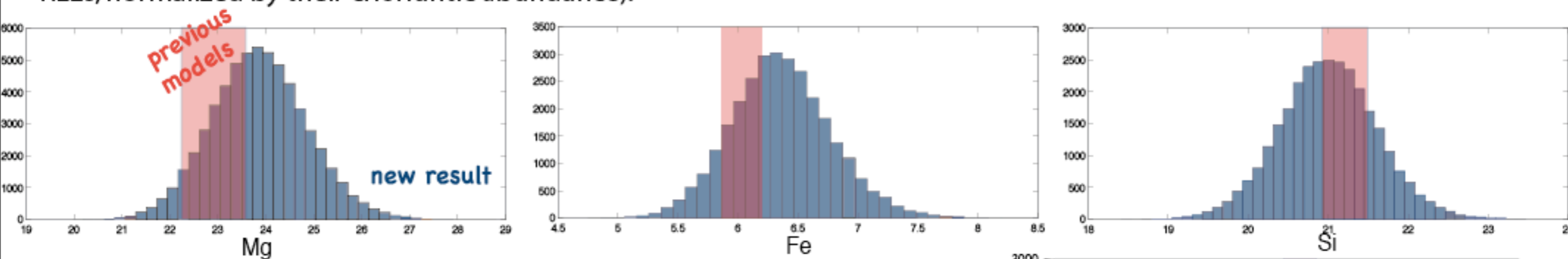
# How we actually implement the whole thing



# New BSE Model

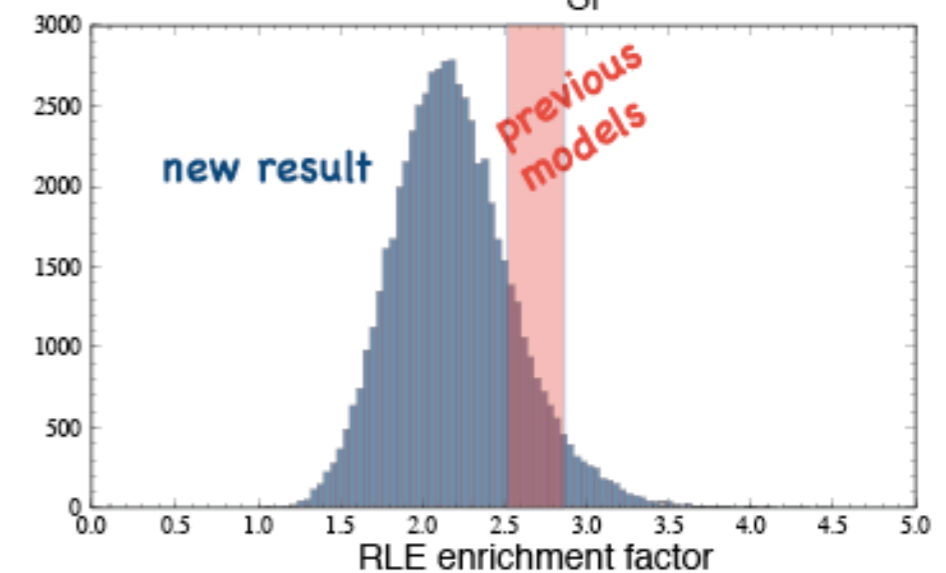
Lyubetskaya and Korenaga [2007]

The new model of the primitive mantle is **similar** to the previous models in terms of **major elements** concentrations, Mg, Si, Fe, and is **different** from the previous models in terms of the **RLE enrichment factor** (Earth's abundance of the RLEs, normalized by their chondritic abundance).



The new estimate of the enrichment factor predicts **~20% lower** bulk Earth abundances of

- Ca, Al, Ti
- REE elements
- heat producing elements K, Th, U
- volatile elements Rb, Na, Ba, As, B, etc.



# BSE composition

Old and new models

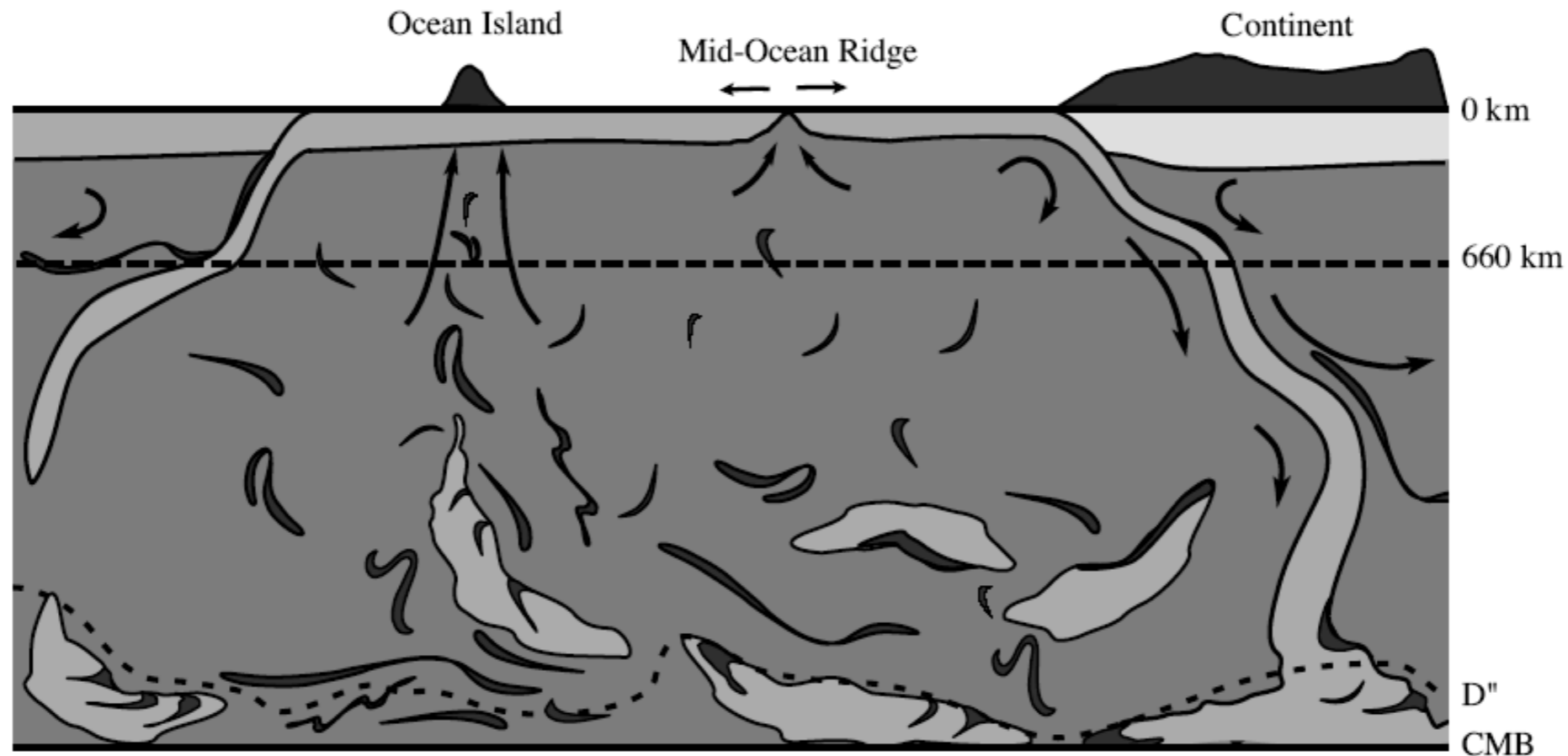
	McDonough and Sun [1995]	Lyubetskaya and Korenaga [2007]
U	20.3 ppb	$17 \pm 3$ ppb
Th	79.5 ppb	$63 \pm 10$ ppb
K	240 ppm	$190 \pm 40$ ppm

**Now, CC+DM ~ BSE**

This (subtle) difference in model revision turns out to be sufficient to resolve the missing heat-source and missing argon paradoxes.

# Whole-mantle convection

‘Low-CaRb’ marble-cake mantle



[Lyubetskaya and Korenaga, 2007]

- Given its uncertainty, the new BSE model still *allows* the presence of a hidden reservoir, but *doesn't require* it; its size is probably small and exists as small-scale heterogeneities.
- The convecting mantle as a whole ('interactive mantle') may be more enriched than the pure MORB source mantle, and a recent estimate by Langmuir indicates petrological  $U_r \sim 0.3$  ( $\pm?$ ).

# How to avoid catastrophe?

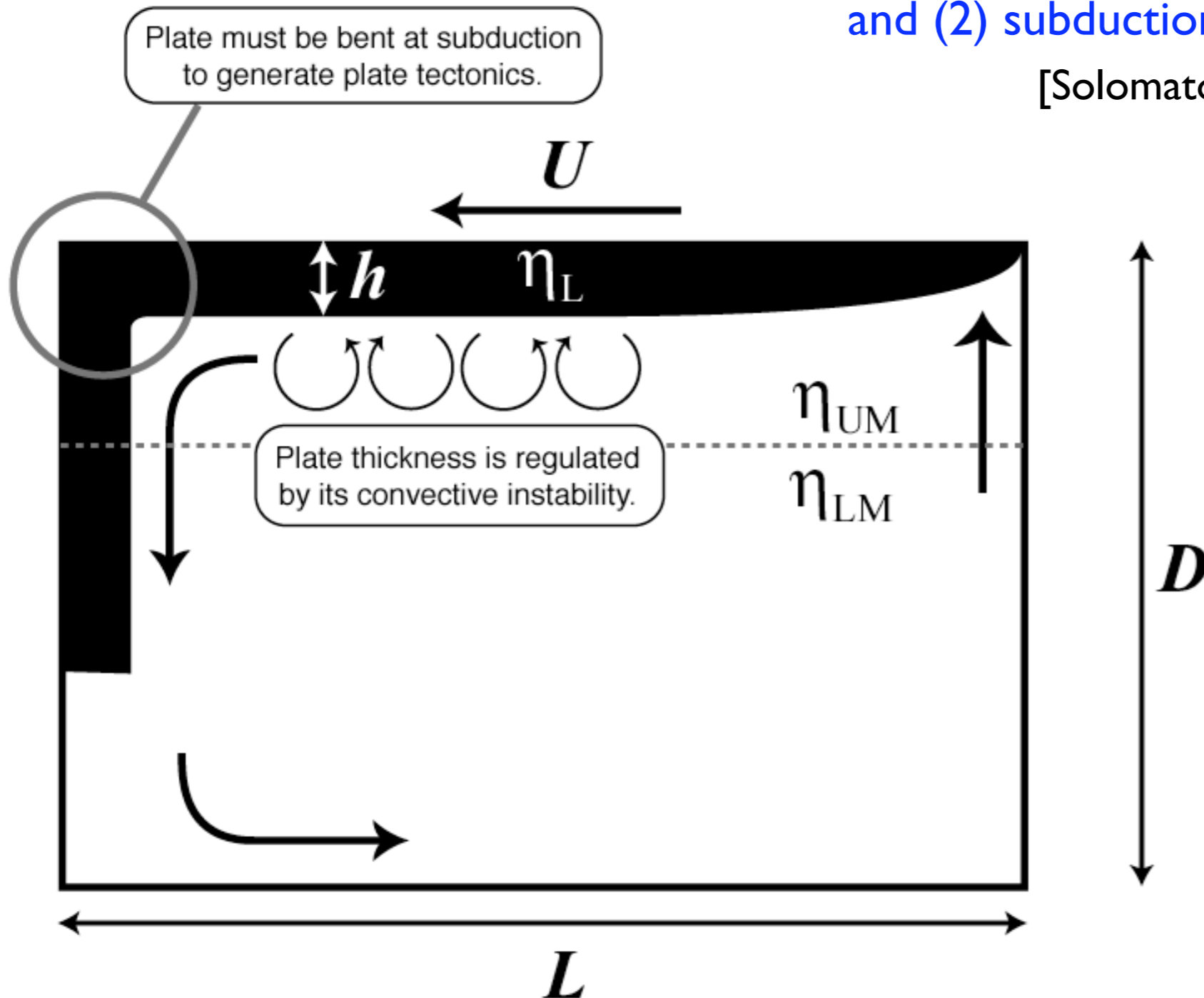
- A. Whole-mantle convection with  $Ur=0.7$
- B. Layered-mantle convection
- C. Different  $Q(T)$  for plate-tectonic convection

$$C \frac{dT}{dt} = H(t) - Q(t)$$

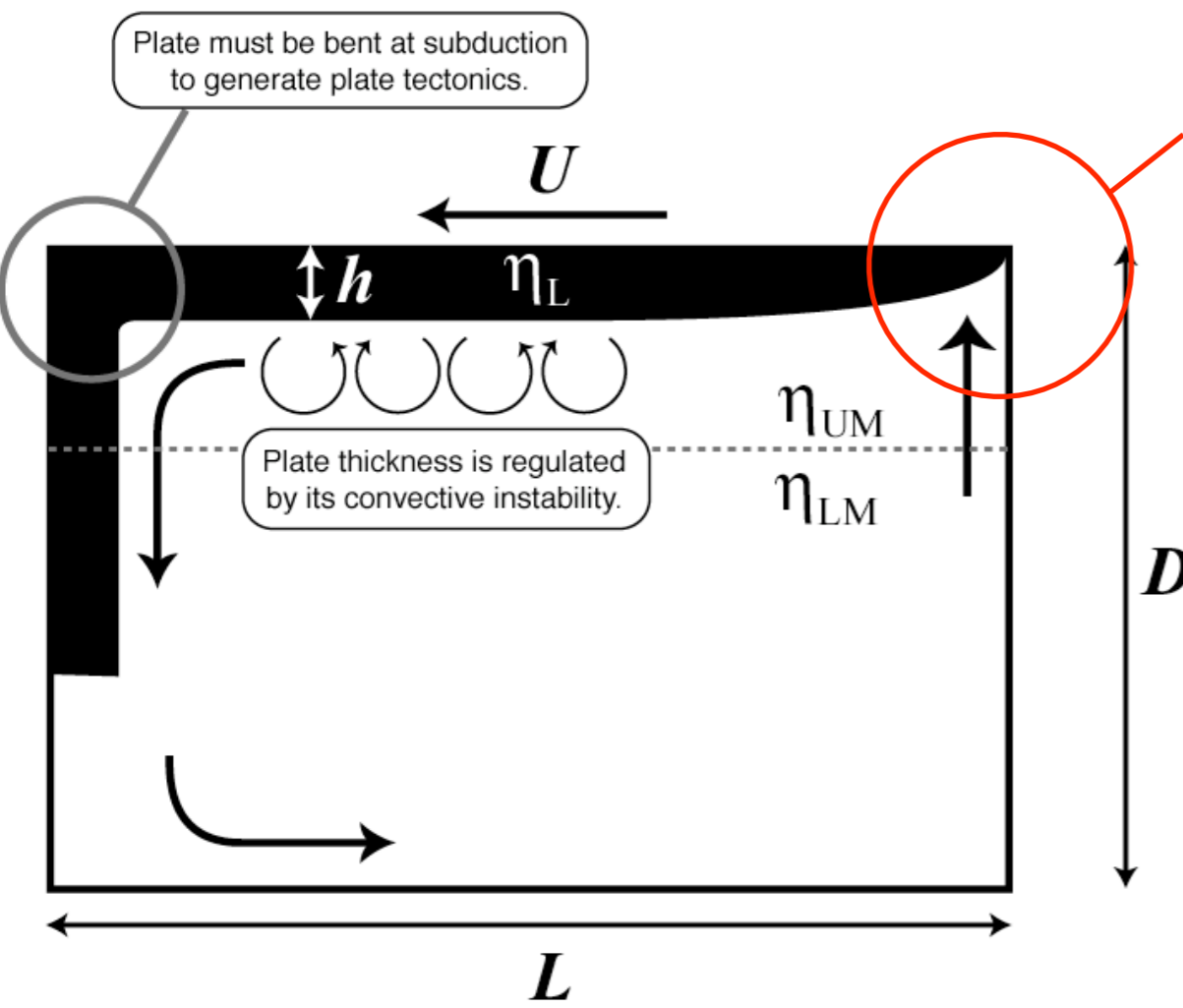
# Plate-tectonic convection

- Energy input from descending slab
- Energy output by dissipation at (1) bulk mantle and (2) subduction zone

[Solomatov, 1995; Conrad and Hager, 1999]



# Mantle not only convects but also **melts**

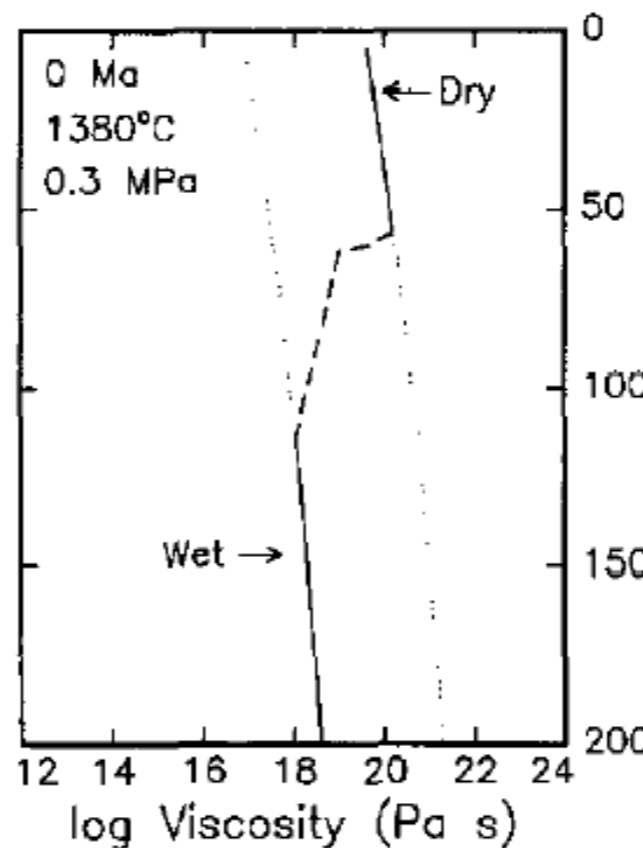


... and this melting removes impurities (e.g.,  $H_2O$ ), leaving *stiffer* residual mantle (dehydration stiffening)

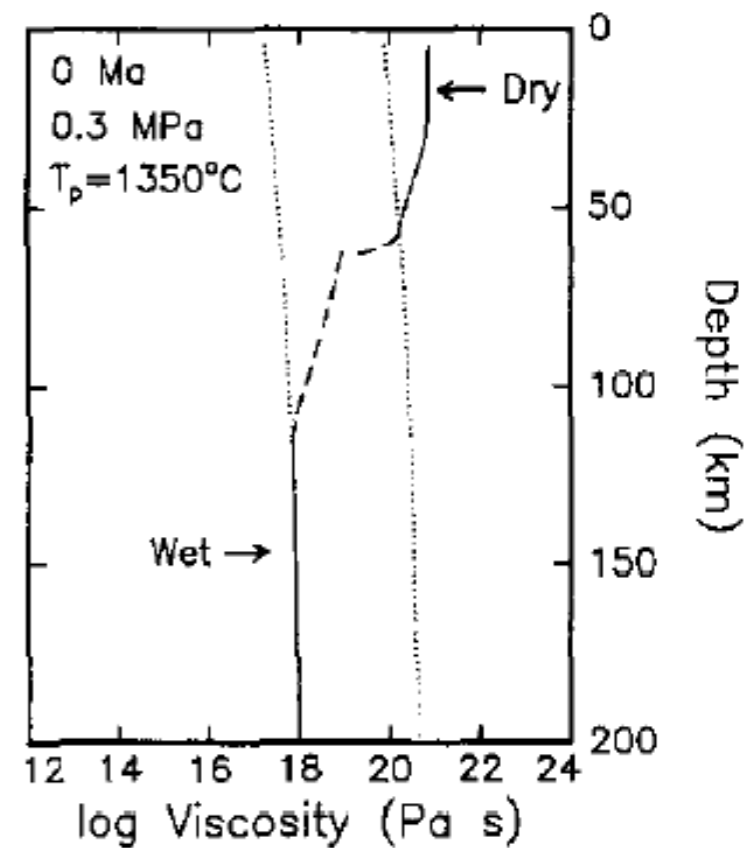
[Karato, 1986; Hirth and Kohlstedt, 1996]

Viscosity profiles for mantle beneath a mid-ocean ridge [Hirth and Kohlstedt, 1996]

a: Isothermal

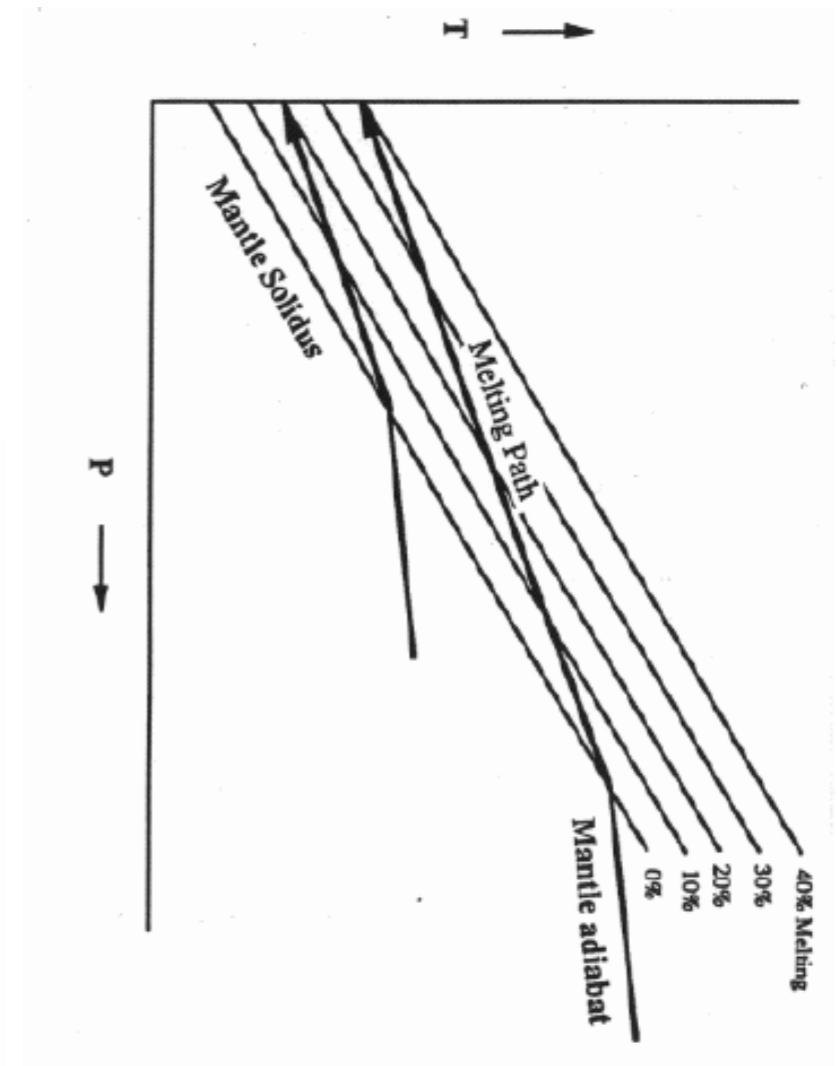
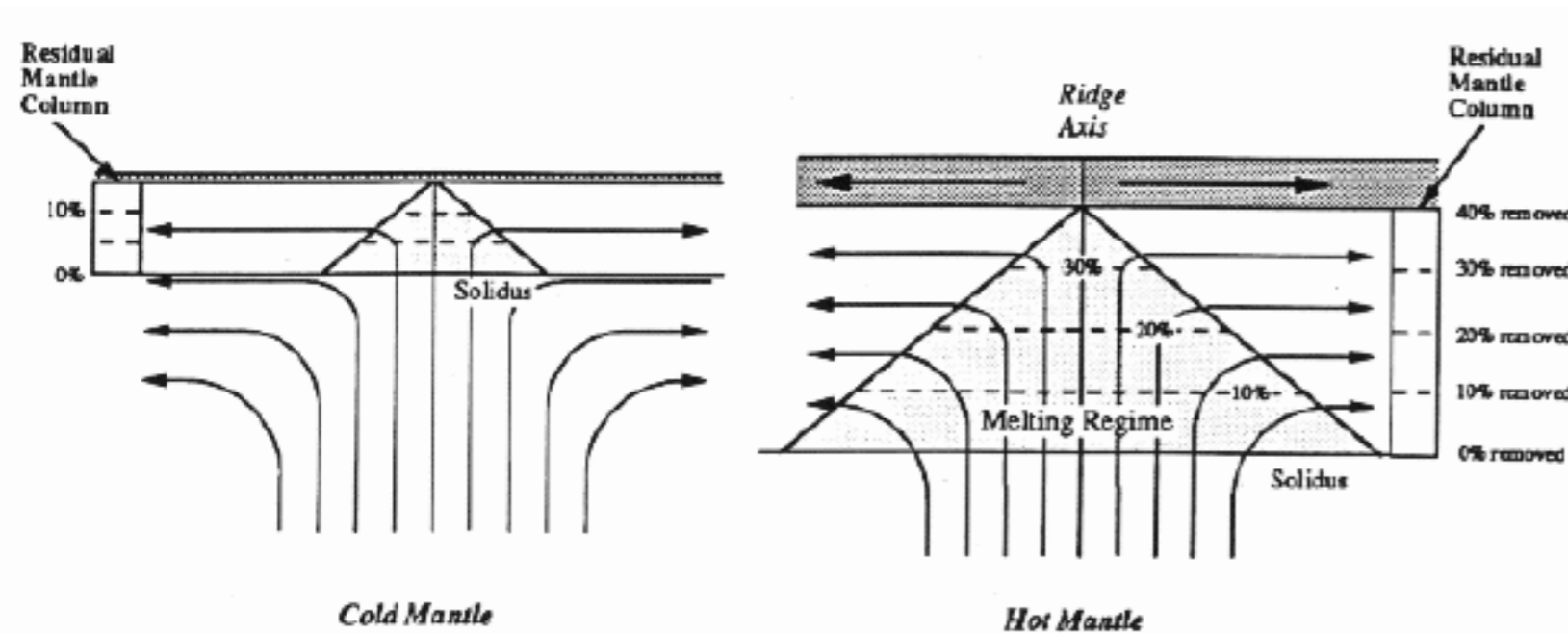


b: Adiabatic Geotherm



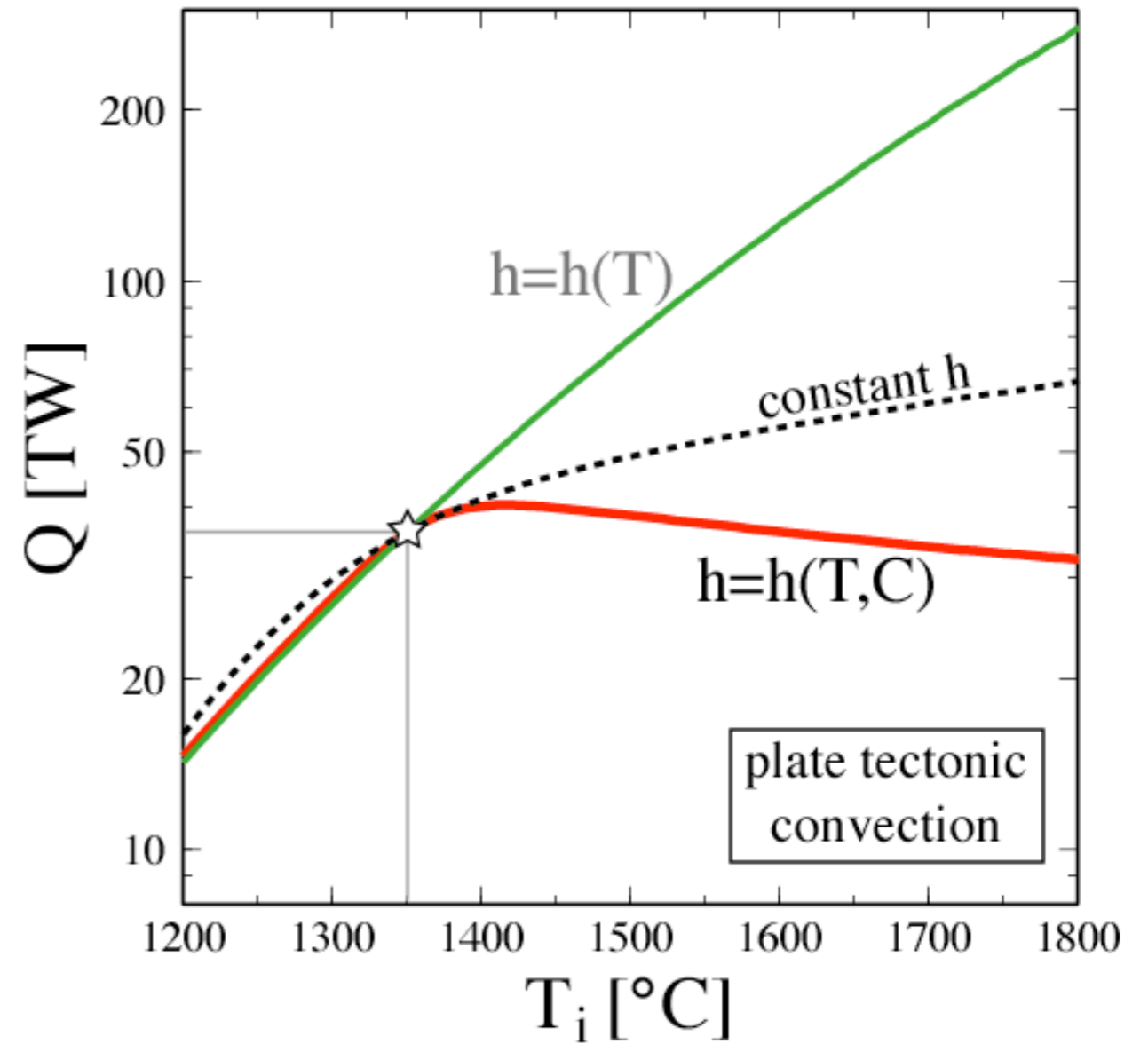
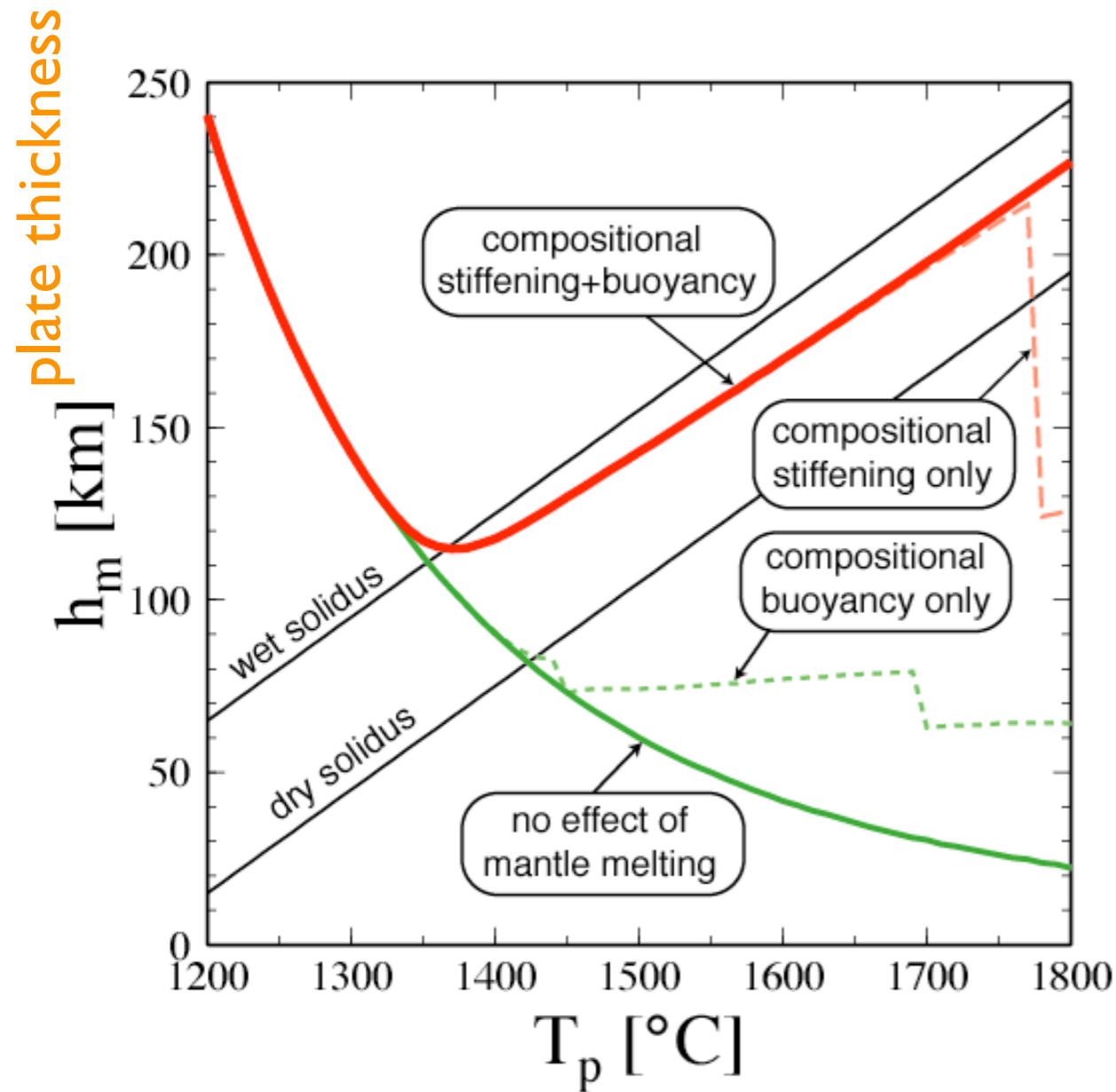
# Hotter mantle starts to melt deeper

Hotter mantle creates thicker oceanic crust and **thicker depleted lithospheric mantle**.



[Langmuir et al., 1992]

# Plate-tectonic $Q(T)$

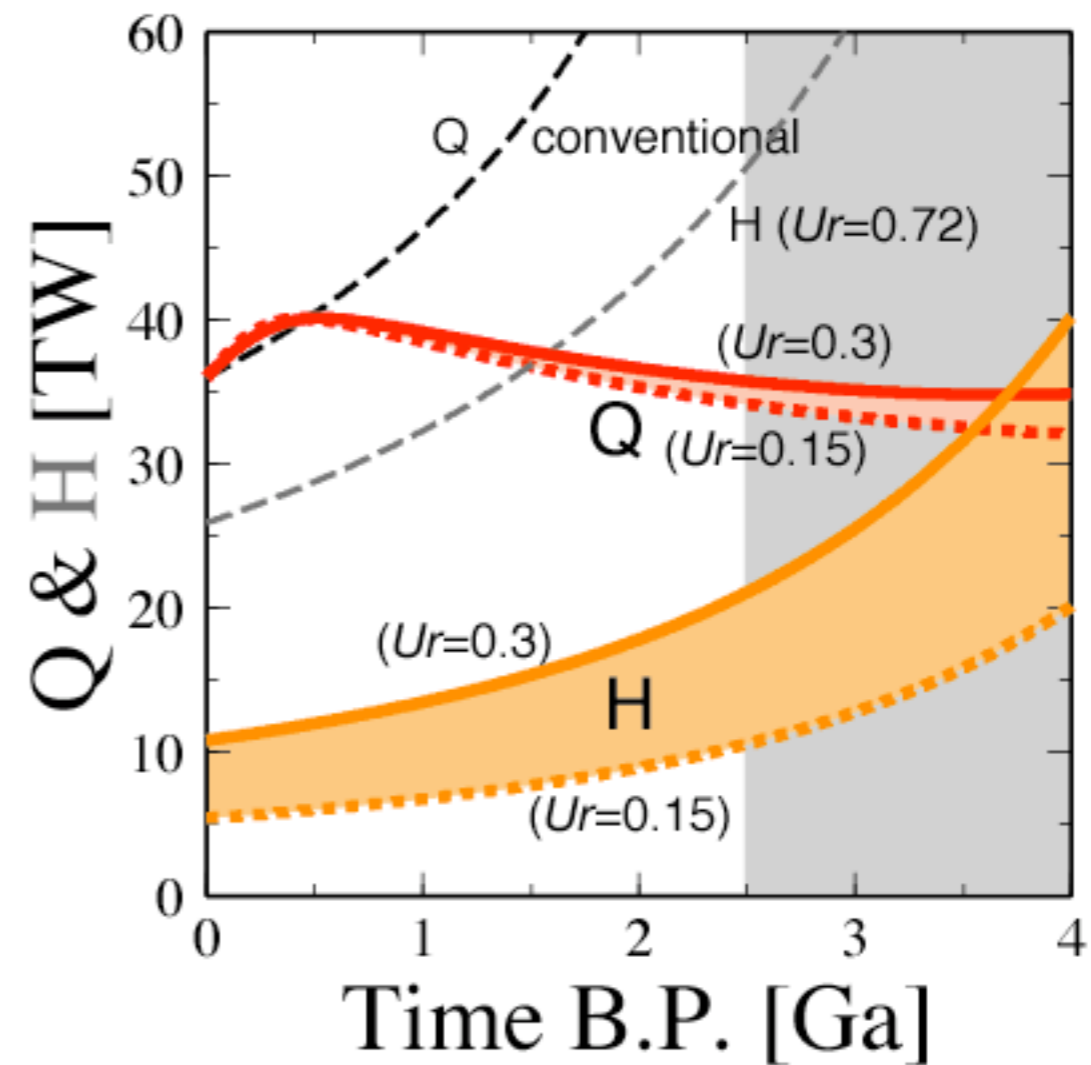
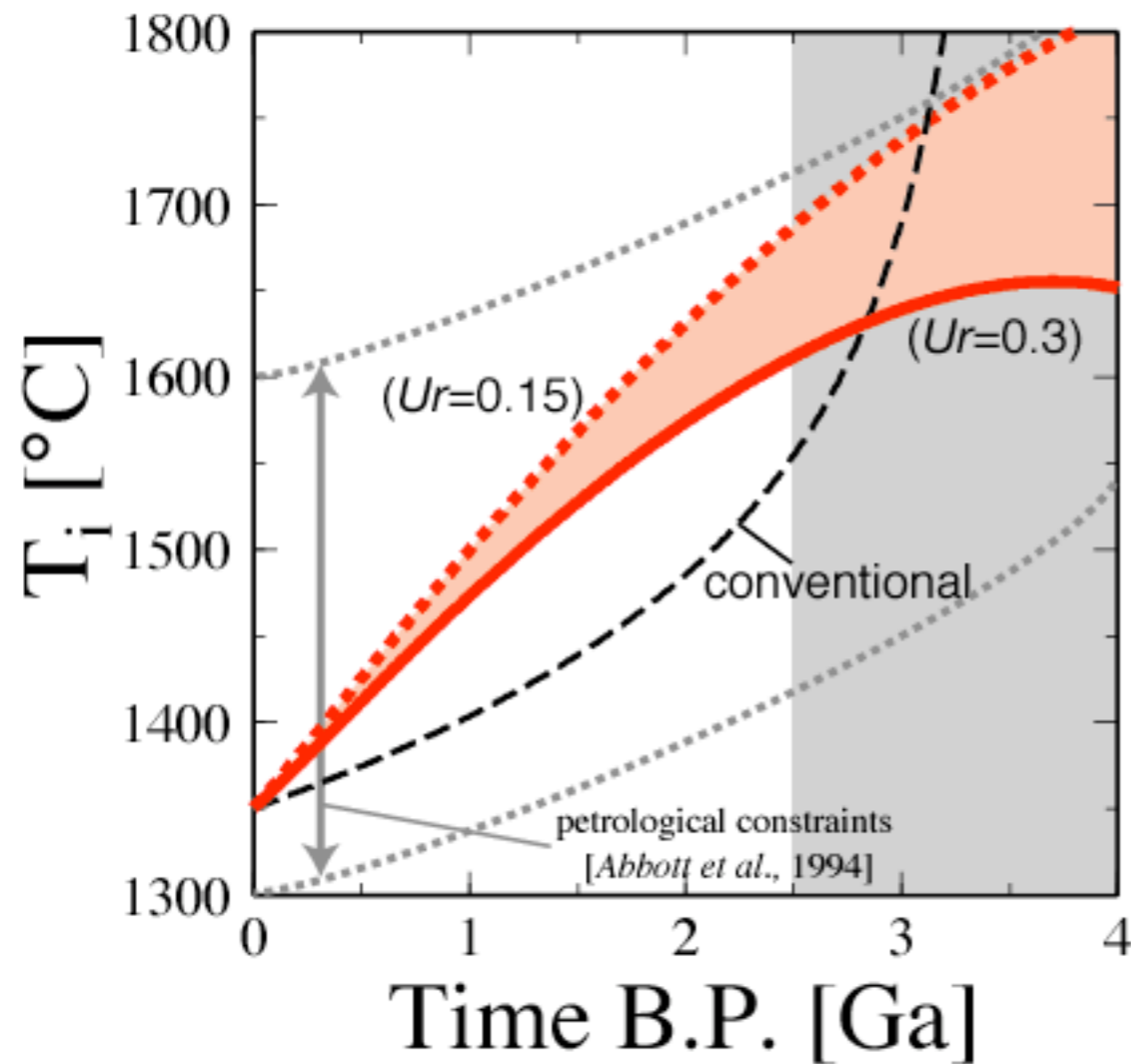


[Korenaga, 2006]

Effects of mantle melting on plate dynamics may have resulted in **reduced heat flux in the past.**

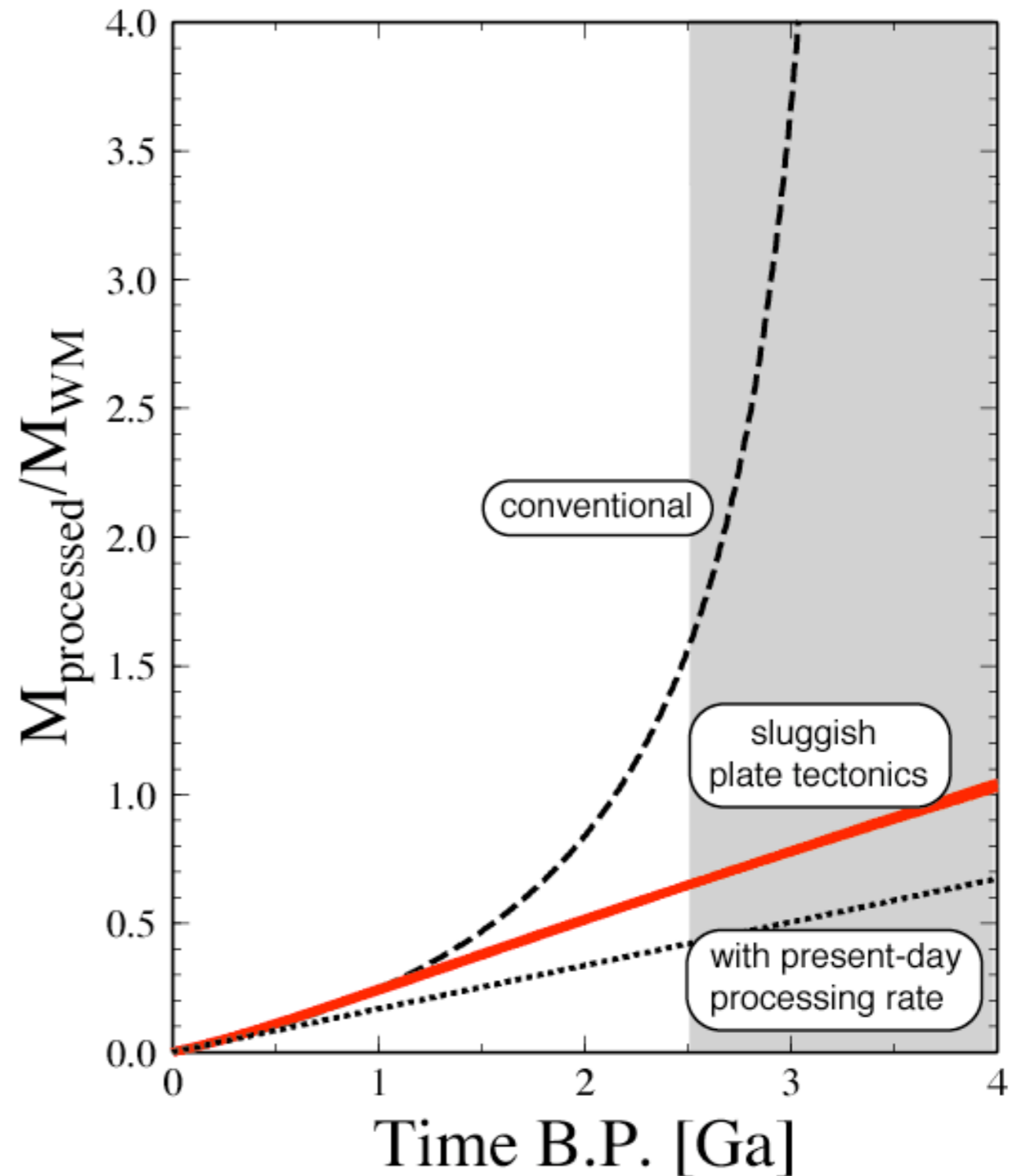
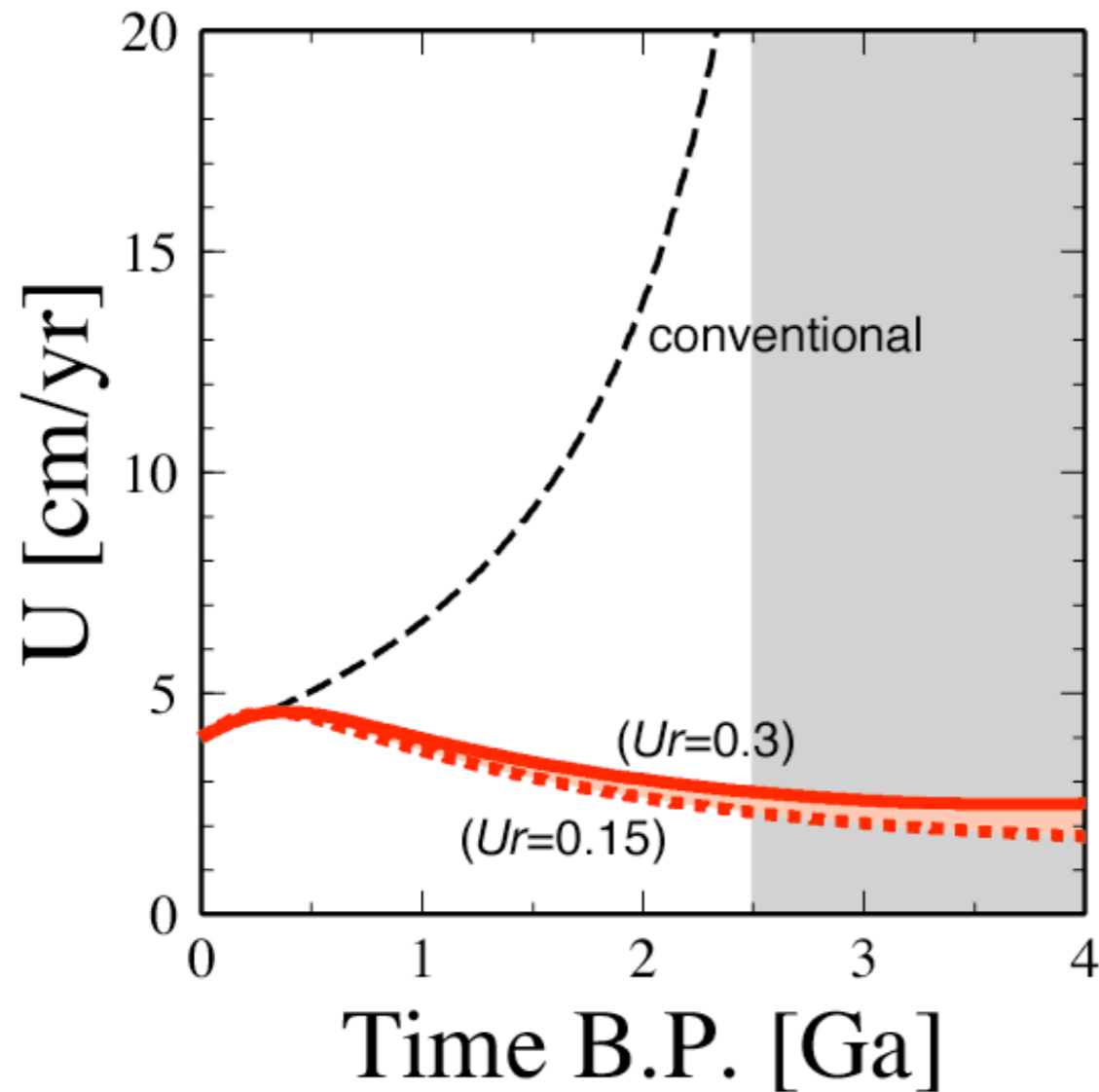
# New evolution model

[Korenaga, 2006]

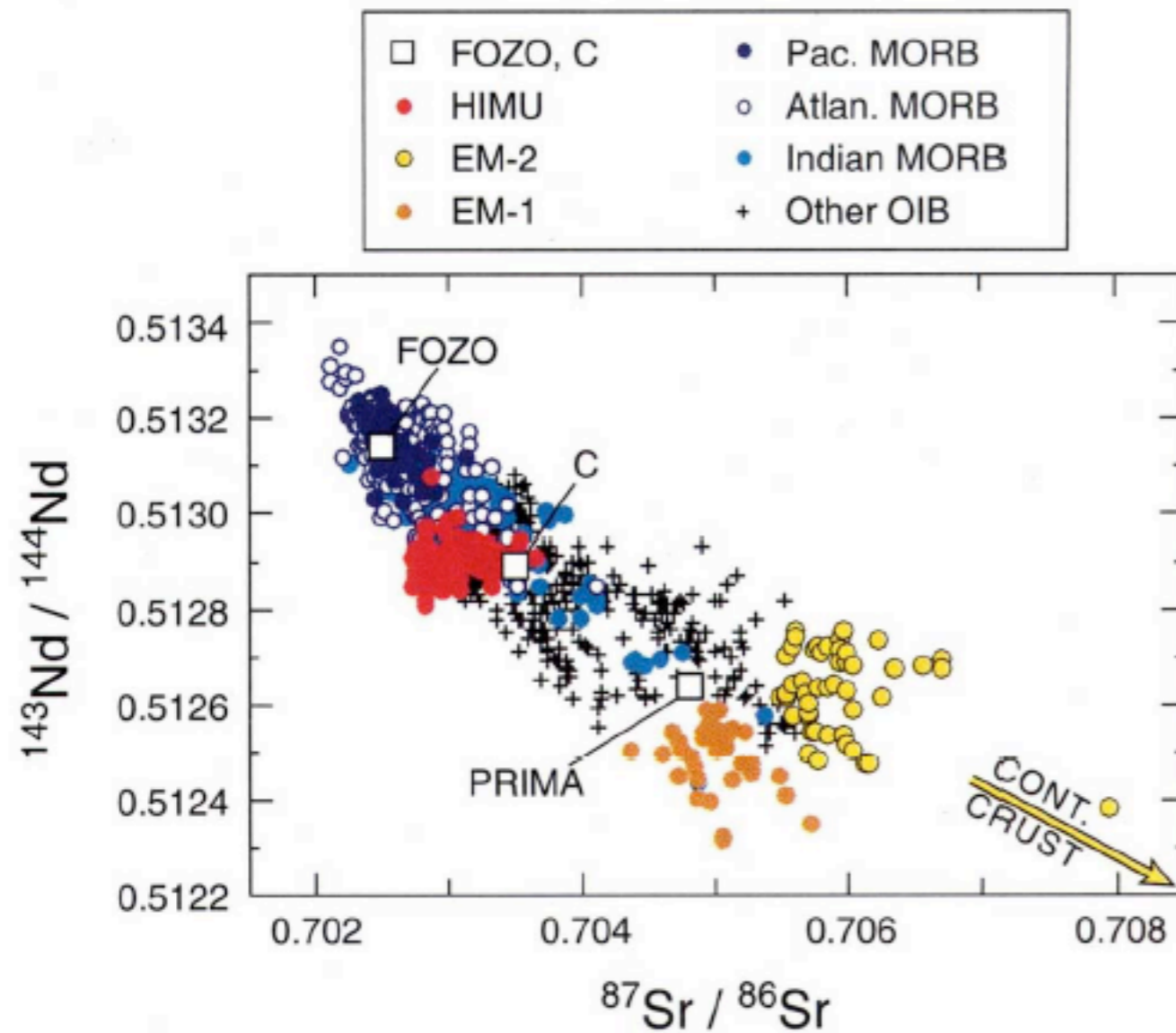


Reduced heat flux for hotter mantle breaks the positive feedback loop. Even  $Ur=0.15$  (with whole-mantle convection) results in a reasonable thermal history.

# Past plate motion and mantle mixing



# MORB and OIB



[Hofmann, 1997]

**Q.** Does observed isotope heterogeneity require a special mechanism (other than whole-mantle convection)?

**A.** Probably no. Sluggish plate tectonics in the past implies inefficient mantle mixing even with whole-mantle convection.

# Conclusion

- Whole-mantle convection can satisfy a wide range of geophysical and geochemical constraints on the structure and evolution of Earth's mantle, if we take into account the revised BSE composition and the new heat-flow scaling law for plate-tectonic convection.
- Archean dynamics is probably characterized by sluggish plate tectonics. Mantle has been mixed slowly, which has probably resulted in the presence of compositional heterogeneities with various spatial scales.