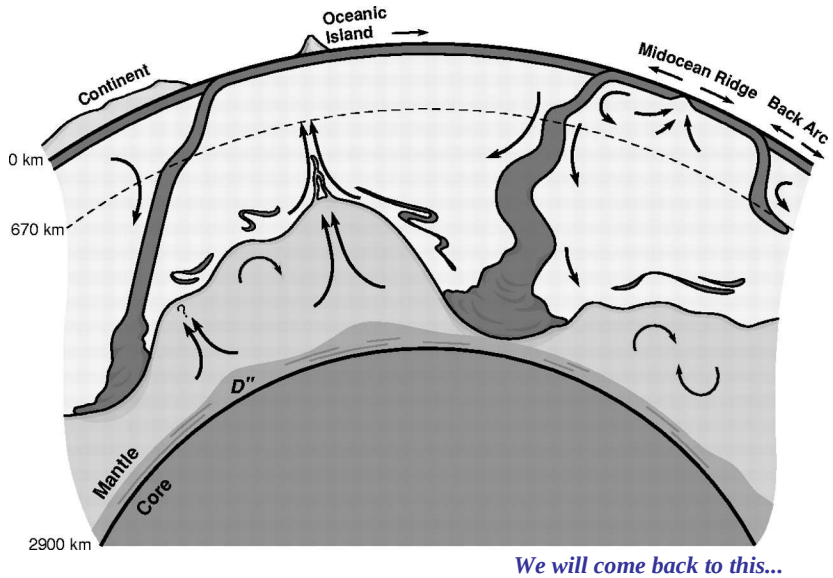
Mantle evolution models

- Some broad generalizations about isotopes in the mantle
- Isotopic evolution and mass balance - the Sm-Nd system and 670km coincidence; ε_{Nd} notation
- Box models for average isotopic composition of mantle and crust - limits on continental recycling and upper-lower mantle exchange
- Heterogeneity and sampling incorporated into a box model (Kellogg et al. approach)
- (Brief) comments on rare gases

What is wrong with this picture?

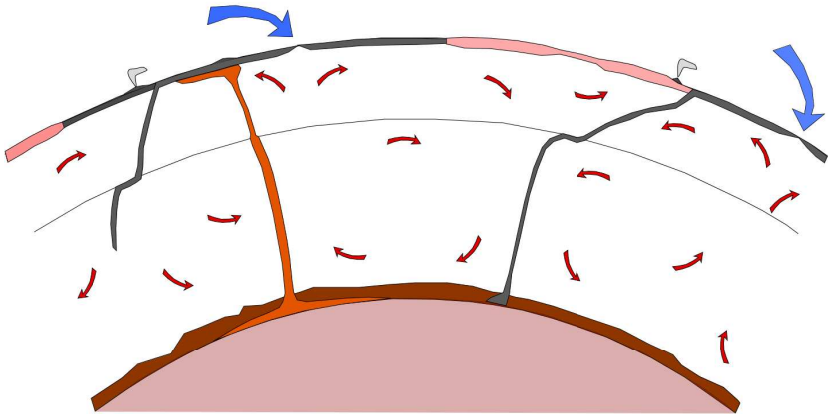


We will come back to this...

Mid-ocean Ridge Basalts.....

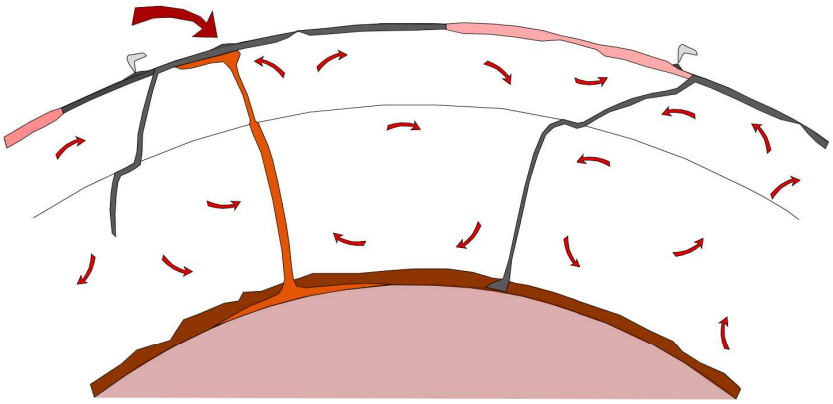
The typical mantle that melts at MOR's...

- is not average mantle material; it is too depleted in LILE
- represents a small fraction of the total mantle (10 - 20%)
- probably contains recycled continental + oceanic crustal material



Mantle Plumes...

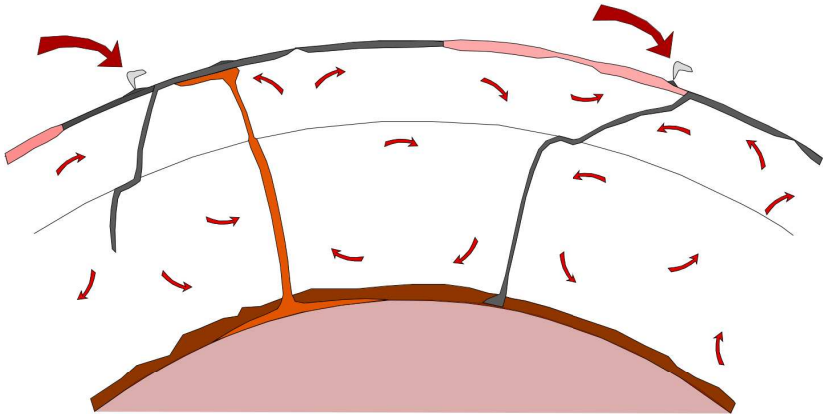
- Exist
- Bring materials up from depth that are different from the ambient upper mantle
- Consist of material that is not primitive (usually "less depleted" than MORB)
- Sometimes contain Helium that looks primitive (but with Nd, Sr, Pb, Hf that does not look primitive)



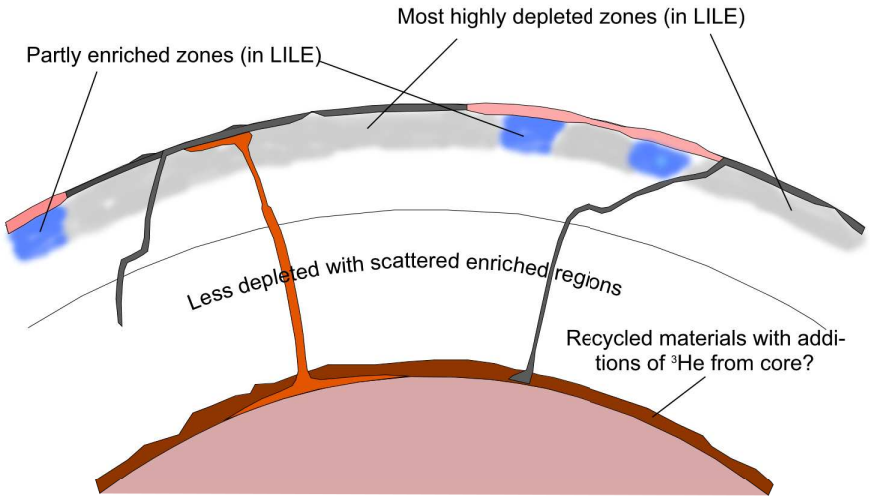
Island Arcs and Backarcs.....

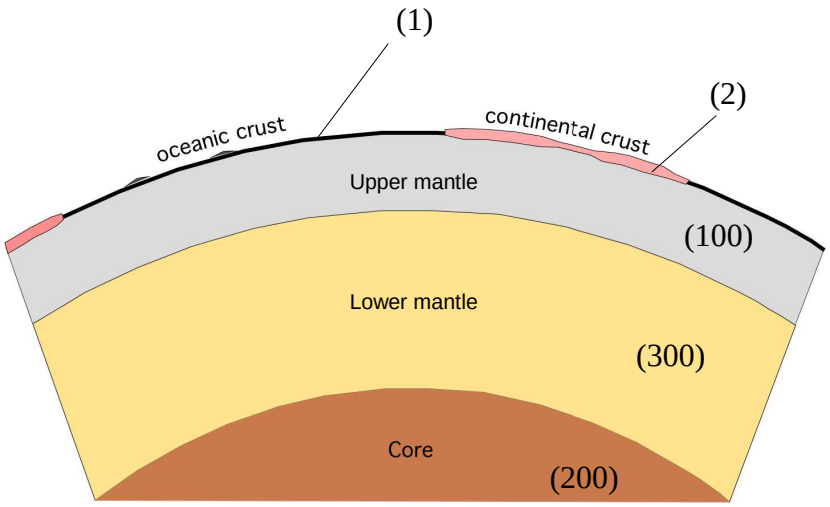
The typical mantle that melts at arcs...

- is depleted in LILE but less so than for MORB
- is typically affected by subducted materials via fluids

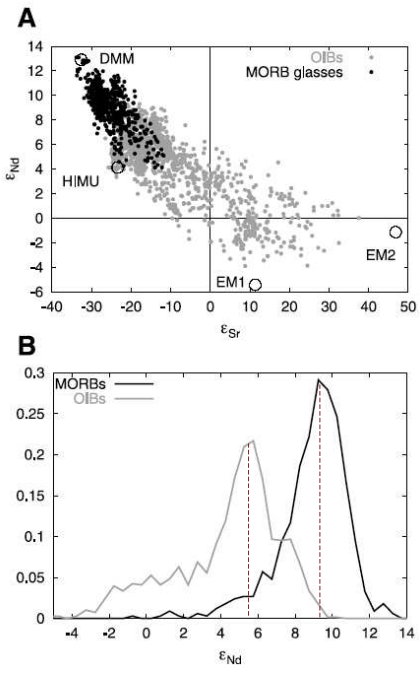


Mantle map in terms of what is "depleted" or "enriched" in incompatible elements:



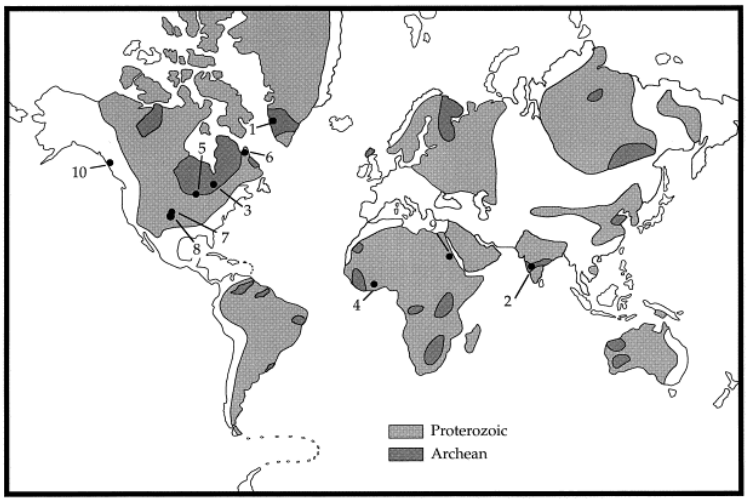


Mass in units of 10^{25}g



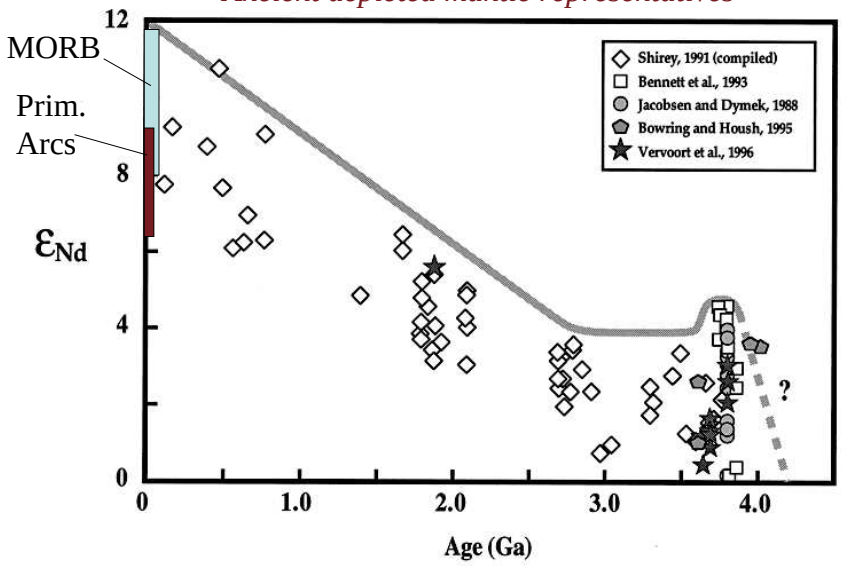
Modern distribution of isotope ratios in oceanic basalts

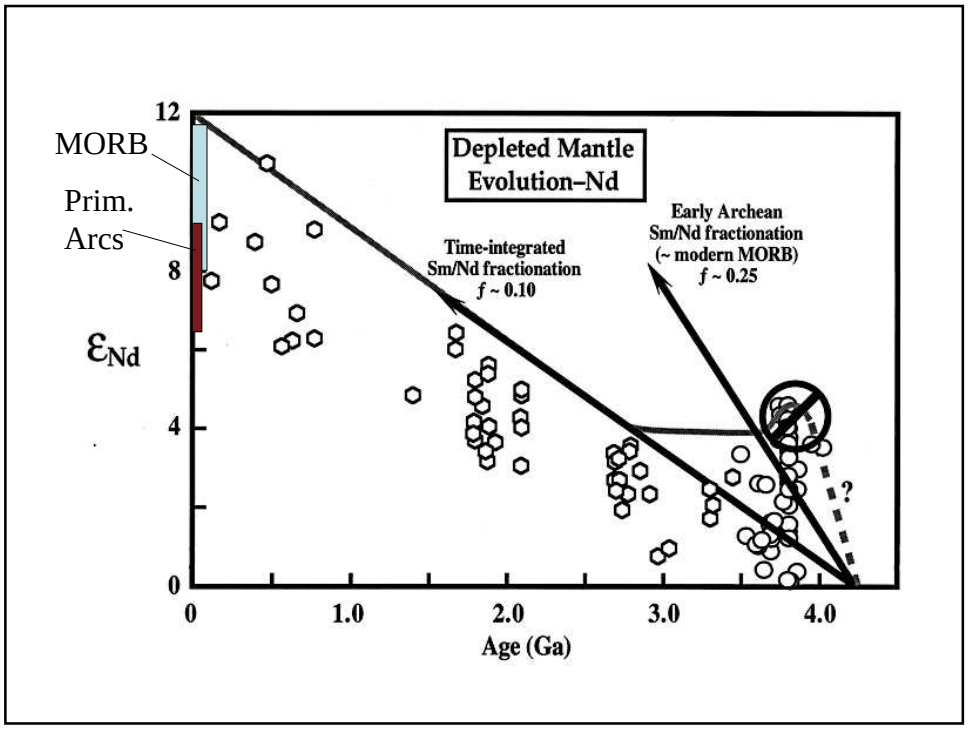
To trace back through time we need older rocks

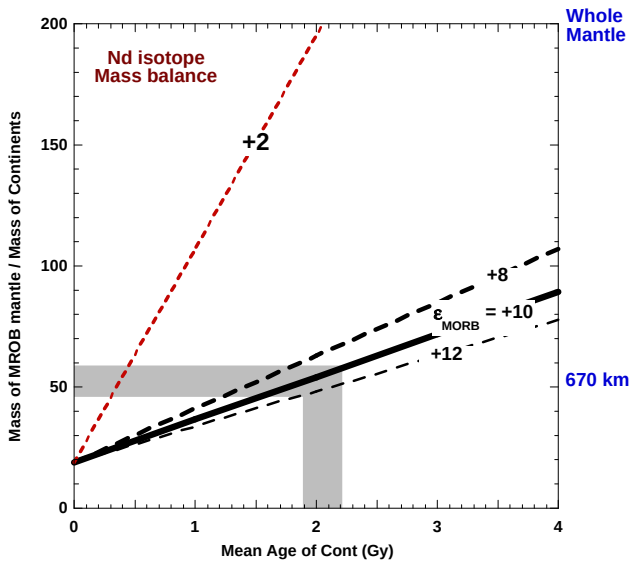


Not many MORB analogues; must use island arc analogues

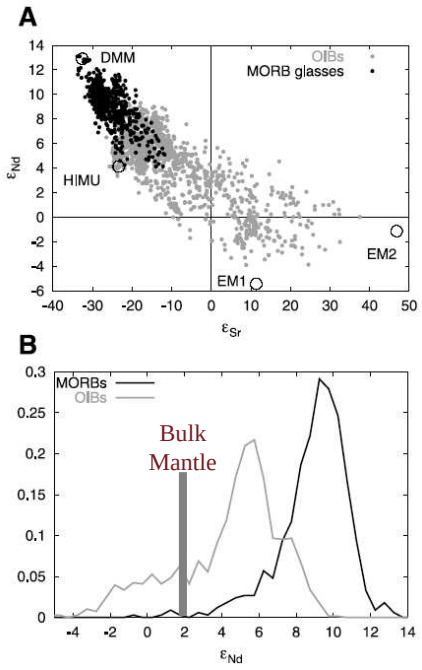
Ancient depleted mantle representatives







Assumes no other depleted reservoirs



A major problem is that most everything appears to be too depleted

The general (simplified) equation for mantle isotopic evolution, expressed in terms of epsilon values relative to a bulk earth reservoir, can be written in the form (DePaolo, 1983; 1988; Jacobsen, 1988a)

$$\frac{d\varepsilon_m}{dt} \approx f_m Q - \frac{m_d}{M_c X_m}\varepsilon_m$$

where:

$$f_m = \frac{(P/D)_m}{(P/D)_{BE}} - 1 \qquad \text{and} \qquad Q = \frac{10^4 \lambda_P (P/D)_{BE}}{(D^*/D)_{BE}}$$

X_m = fraction of daughter element remaining in the depleted mantle (m)
m_d = rate of return of crustal material to the mantle (recycling rate in units mass/time)
M_c = mass of crust at time t
D*/D = daughter isotope ratio ($^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, etc.)

For Sm-Nd, Q =25.1, $f_m \approx 0.25$ for present day Earth
So $f_m Q \approx 6$ Gy^{-1} whereas $d\varepsilon_m/dt \approx 2$ Gy^{-1}

COMPOSITION OF THE CONTINENTAL CRUST

MAJOR OXIDES (weight percent)

	R & F	T & M
SiO_2	59.1	57.3
TiO_2	0.7	0.9
Al_2O_3	15.8	15.9
FeO	6.6	9.1
MnO	0.1	0.18
MgO	4.4	5.3
CaO	6.4	7.4
Na_2O	3.2	3.1
K_2O	1.88	1.1
P_2O_5	0.2	

TRACE ELEMENTS (in ppm except where noted)

	R & F	T & M		R & F	T & M
Li	11	13	Ba	390	250
Be		1.5	La	18	16
B		10	Ce	42	33
Sc	22	30	Pr	5	3.9
V	151	230	Nd	20	16
Cr	119	185	Sm	3.9	3.5
Co	25	29	Eu	1.2	1.1
Ni	51	105	Gd	3.6	3.3
Cu	24	75	Tb	0.56	0.6
Zn	73	80	Dy	3.5	3.7
Ga	16	18	Ho	0.76	0.78
Ge		1.6	Er	2.2	2.2
As		1	Tm		0.32
Se		0.05	Yb	2	2.2
Rb	58	32	Lu	0.33	0.3
Sr	325	260	Hf	3.7	3
Y	20	20	Ta	1.1	1
Zr	123	100	W		1
Nb	12	11	Re, ppb	0.4	
Mo		1	Os, ppb	0.005	
Pd, ppb		1	Ir, ppb		0.1
Ag, ppb		80	Au, ppb	3	
Cd, ppb		98	Tl, ppb		360
In, ppb		50	Pb	12.6	8
Sn		2.5	Bi, ppb		60
Sb		0.2	Th	5.6	3.5
Cs	2.6	1	U	1.42	0.91

Sources:

R & F: Rudnick, R. L. and D. M. Fountain. 1995. *Rev. Geophys.* 33: 267-309.

T & M: Taylor, S. R. and S. M. McLennan, 1985. *The Continental Crust: its composition and evolution*. Blackwell Scientific Publishers, Oxford;
Taylor, S. R. and S. M. McLennan. 1995. *Rev. Geophys.* 33: 241-265.

Kellogg et al., 2002

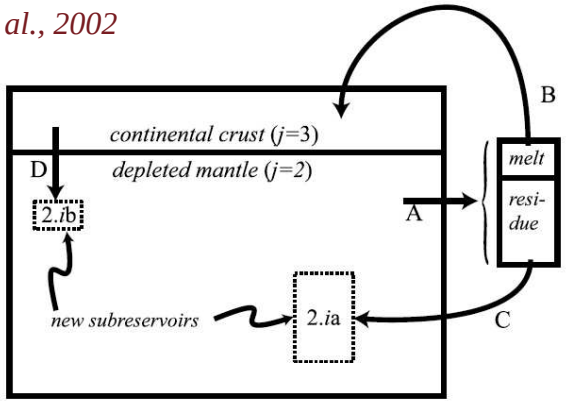
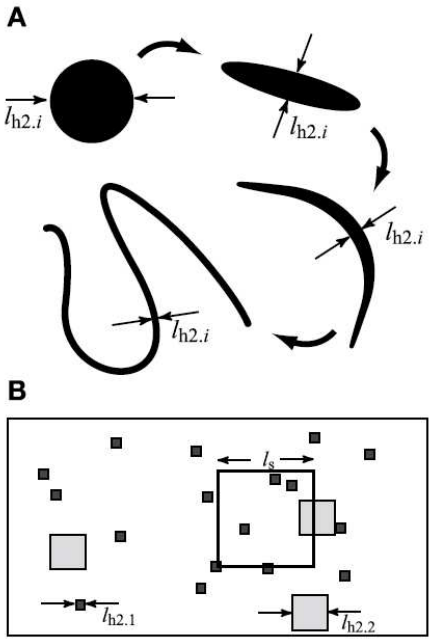


Fig. 4. Cartoon illustrating our model for the creation of subreservoirs in the depleted mantle. (A) At each time step, we partially melt a portion of the bulk depleted mantle (Reservoir 2) to create a chemically fractionated melt and residue. (B) The melt is added to the mean crust (Reservoir 3), whereas (C) the residue is put back into the depleted mantle, resulting in the creation of a new subreservoir (2.*i*a). (D) In addition, continental crust may be recycled into the depleted mantle, creating another subreservoir (2.*i*b).



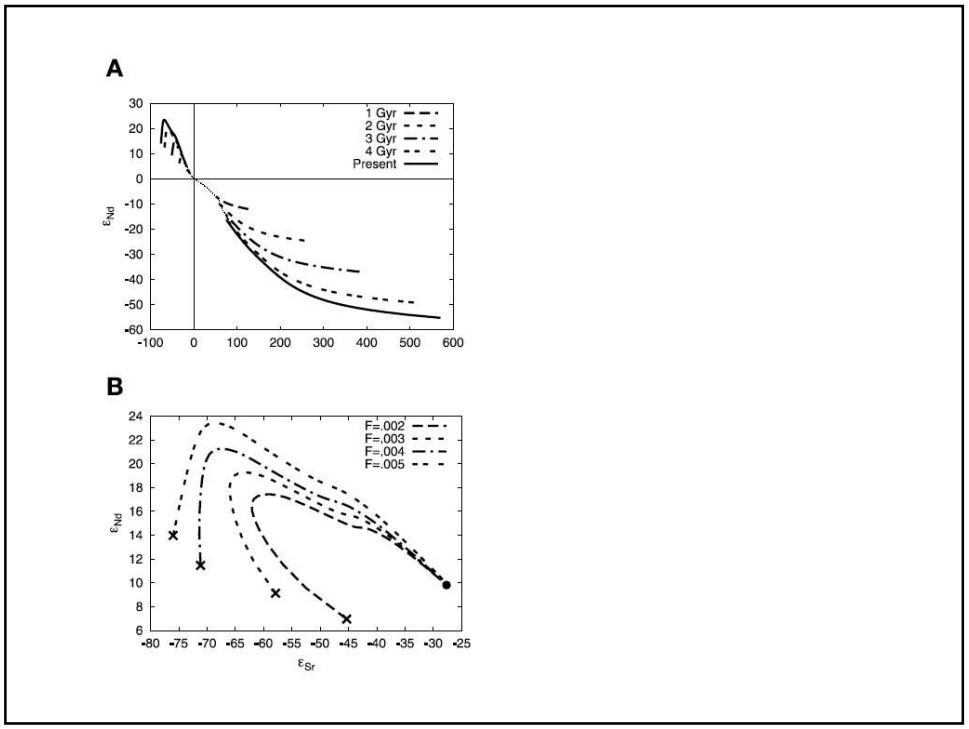
Stirring effect:

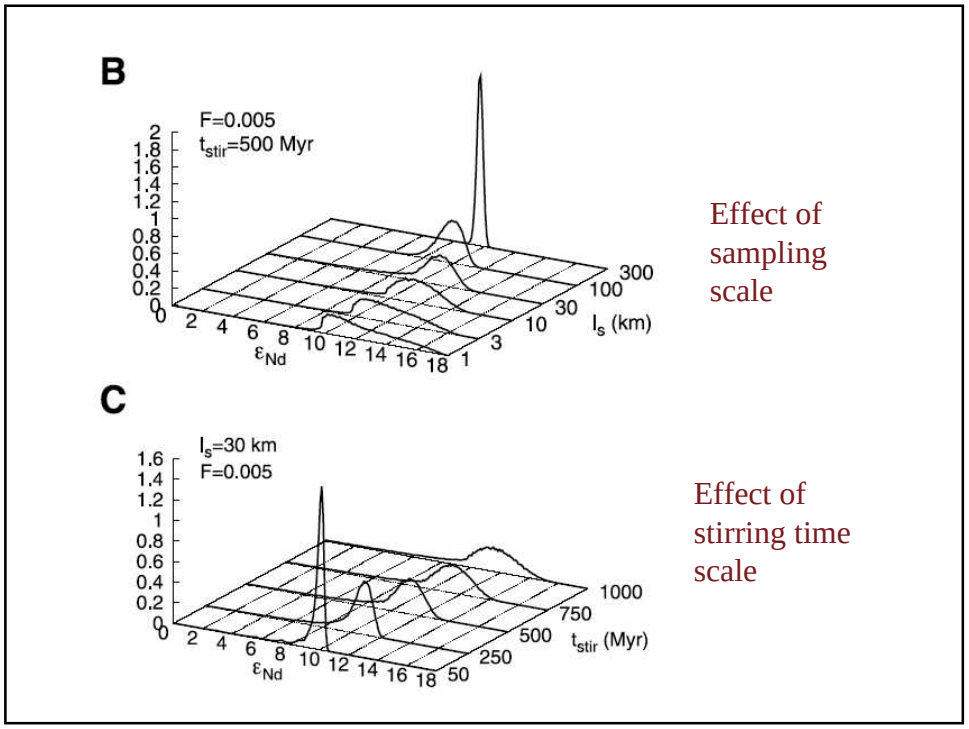
$$l_{h2.i} = l^o_{hjk} e^{(-t-t^o_{2.i})/\tau_{stir}}$$

(turbulent)

$$l_{h2.i} = l^o_{hjk} \frac{1}{\sqrt{1+[\dot{\varepsilon}(t-t^o_{2.i})]^2}}$$

(laminar)





Effect of sampling scale

Effect of stirring time scale

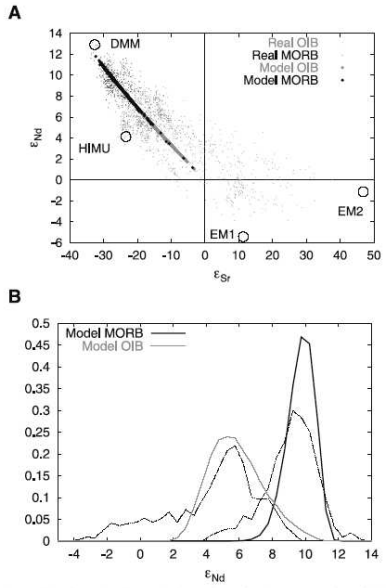


Fig. 11. (A) Model MORB and OIB data plotted on real data. By increasing the source region available to the OIBs, we shift the distribution towards the undepleted composition. These calculations employ the time-dependent mass transport history with continental recycling and assume a 100 km sampling length scale. (B) Histograms of the model data shown above. The light, dotted curves represent the real histograms, as previously shown in Fig. 1A. In both cases we fail to reproduce some of the less depleted or more enriched material observed in the real data.

The MORB distribution is recovered, but there needs to be some cheating to get an OIB distribution

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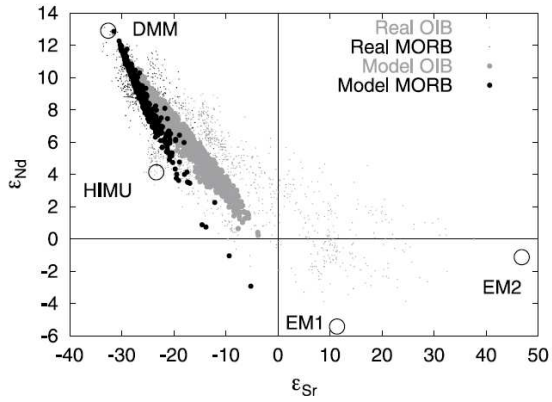


Fig. 12. Synthetic data from our preferred model. All parameters identical to those in Fig. 11 but recycled continental material is enriched in Sm, Nd, and Rb, and depleted in Sr relative to the bulk continental crust.

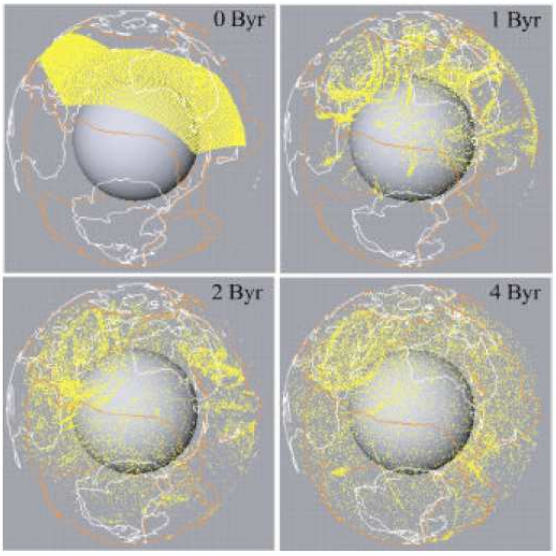
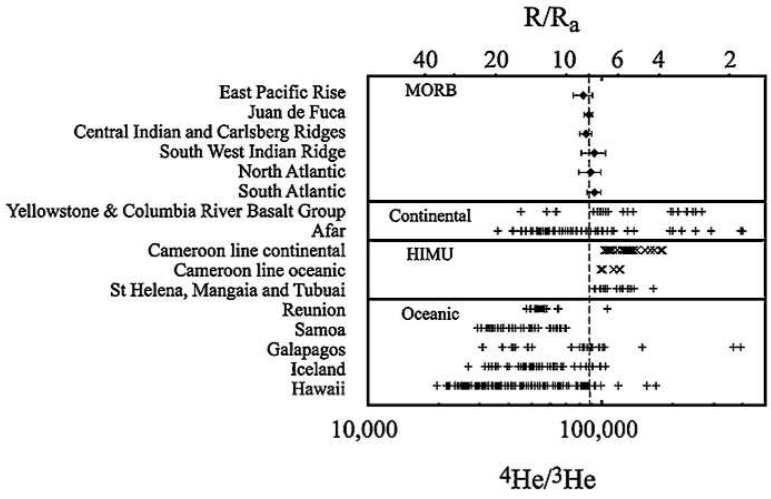
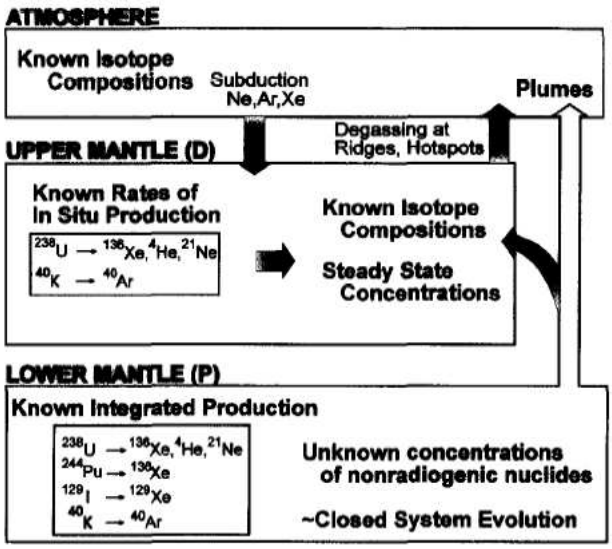


Figure 11 Evolution of the Australian-Indian plate in the steady state mixing model of Van Keken & Zhong (1999). Snapshots of the particles that composed the plate at time 0 are shown at 1, 2, and 4 Byr.

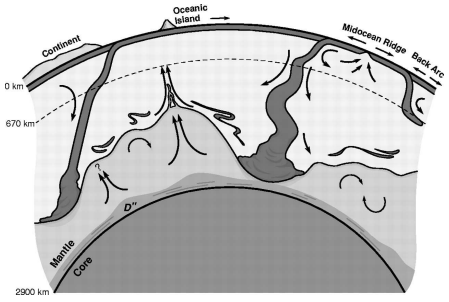
Time evolution: f((U+Th)/He) ⟶

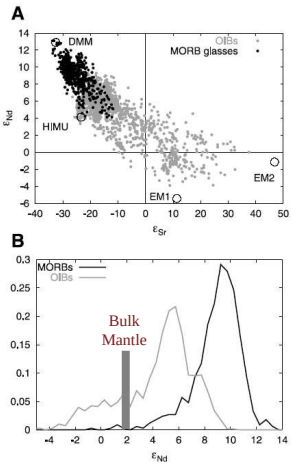


From VanKeken, Hauri, Ballentine, 2002

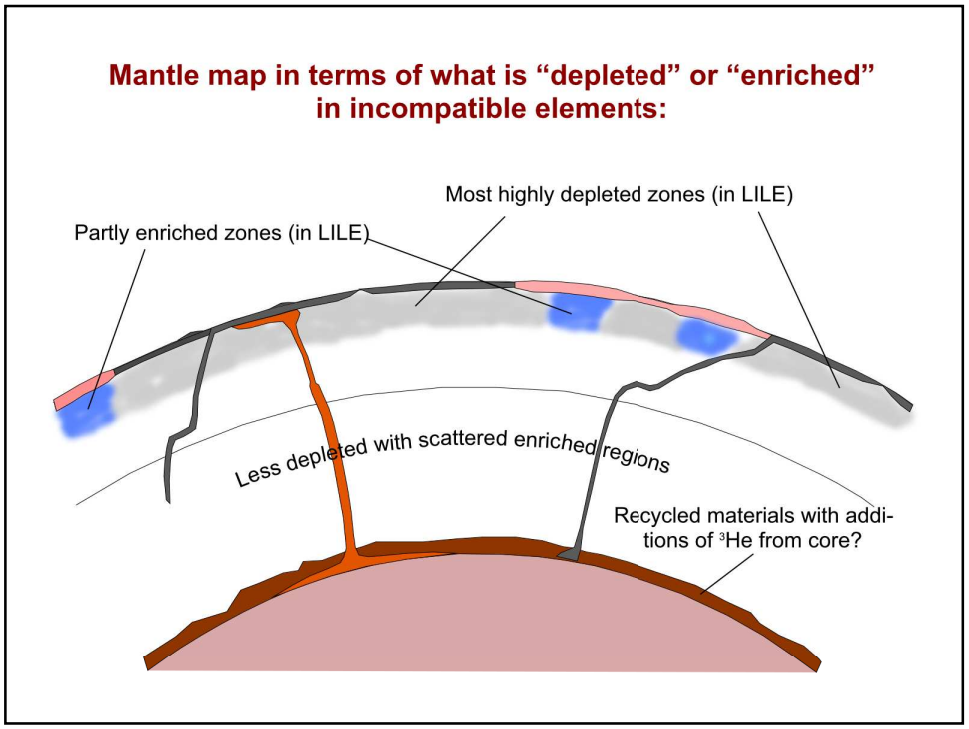


What is wrong with this picture?





$$M_{OIB}C_{OIB}\varepsilon_{OIB} + M_{MORB}C_{MORB}\varepsilon_{MORB} = -M_{CC}C_{CC}\varepsilon_{CC}$$


Mantle map in terms of what is "depleted" or "enriched" in incompatible elements:
Most highly depleted zones (in LILE)
Partly enriched zones (in LILE)
Less depleted with scattered enriched regions
Recycled materials with additions of ^{3}He from core?