Composition of the Earth and its reservoirs: Geochemical observables

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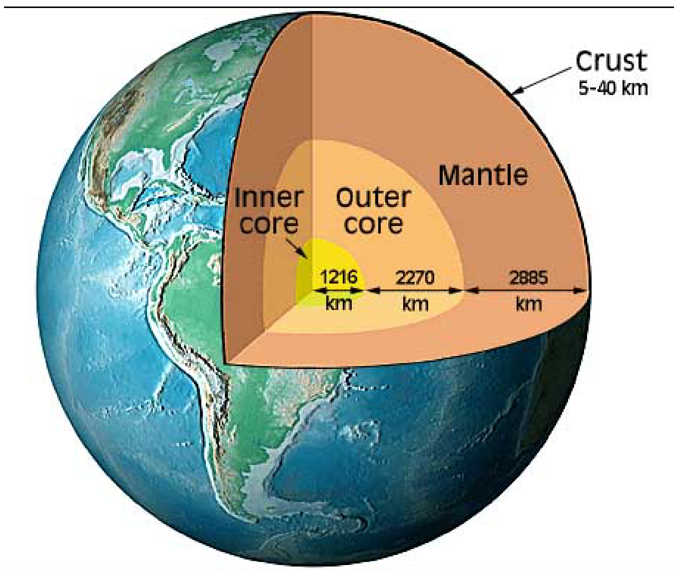
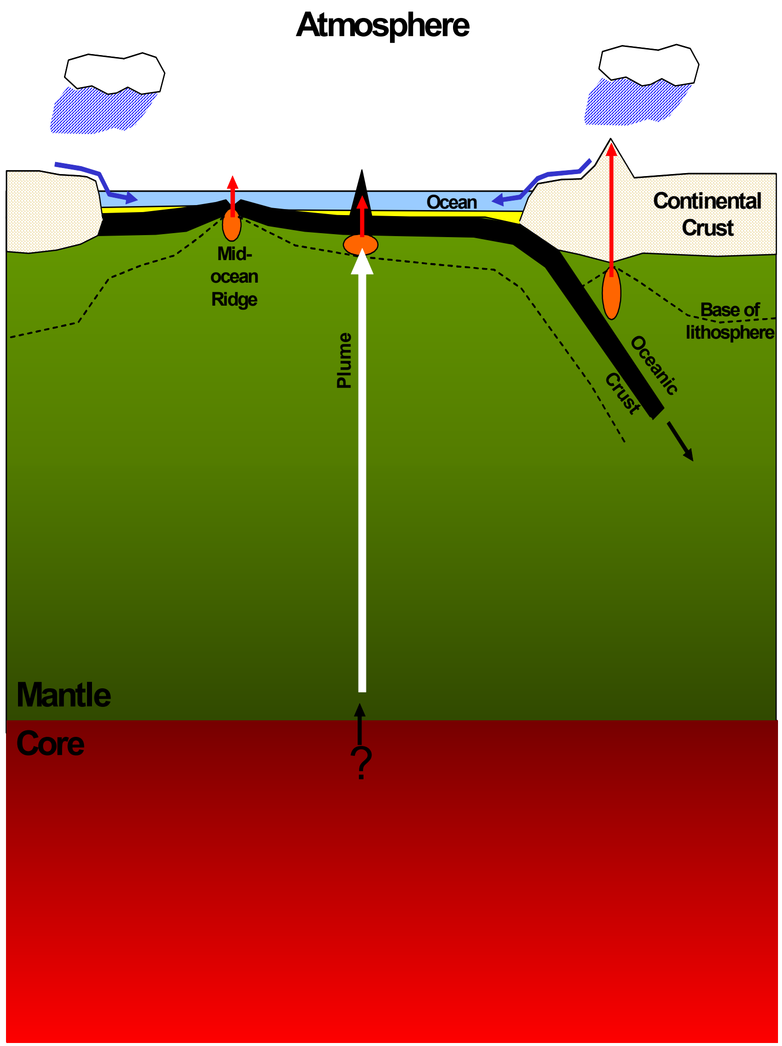
RICE

MYRES-I 2004

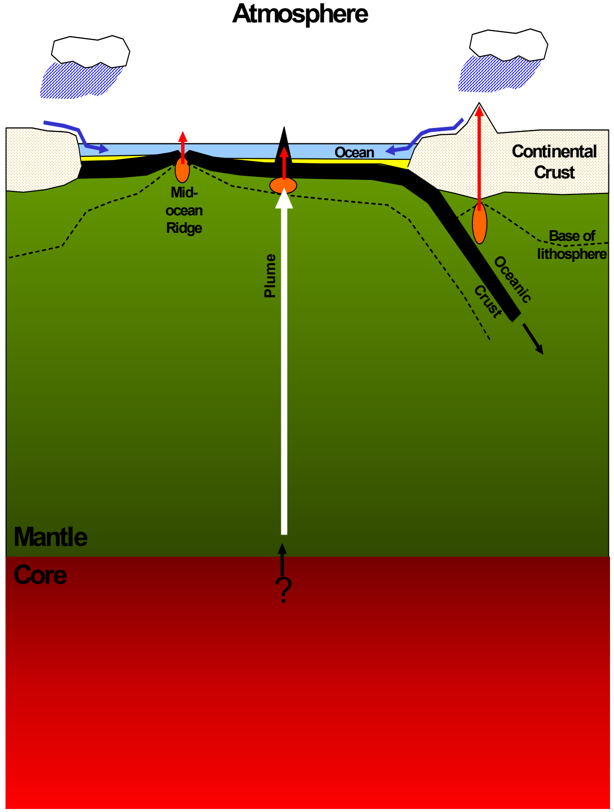
The Earth is dynamic and heterogeneous





Not to scale

The Earth is differentiating:
But are we mixing or unmixing reservoirs?



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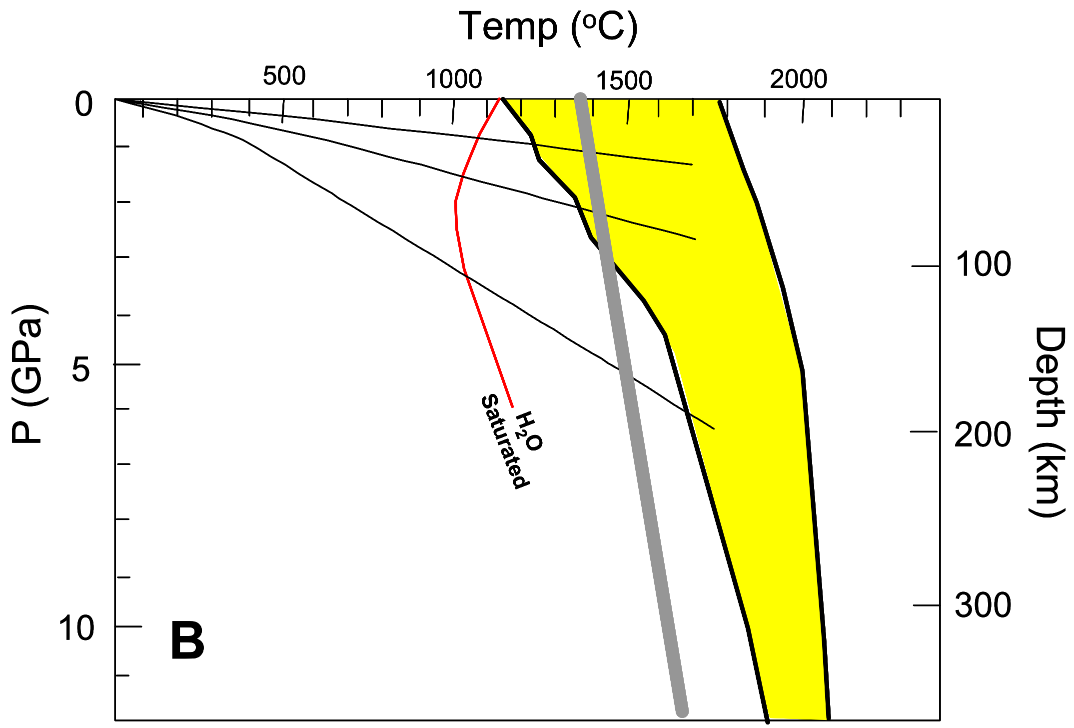
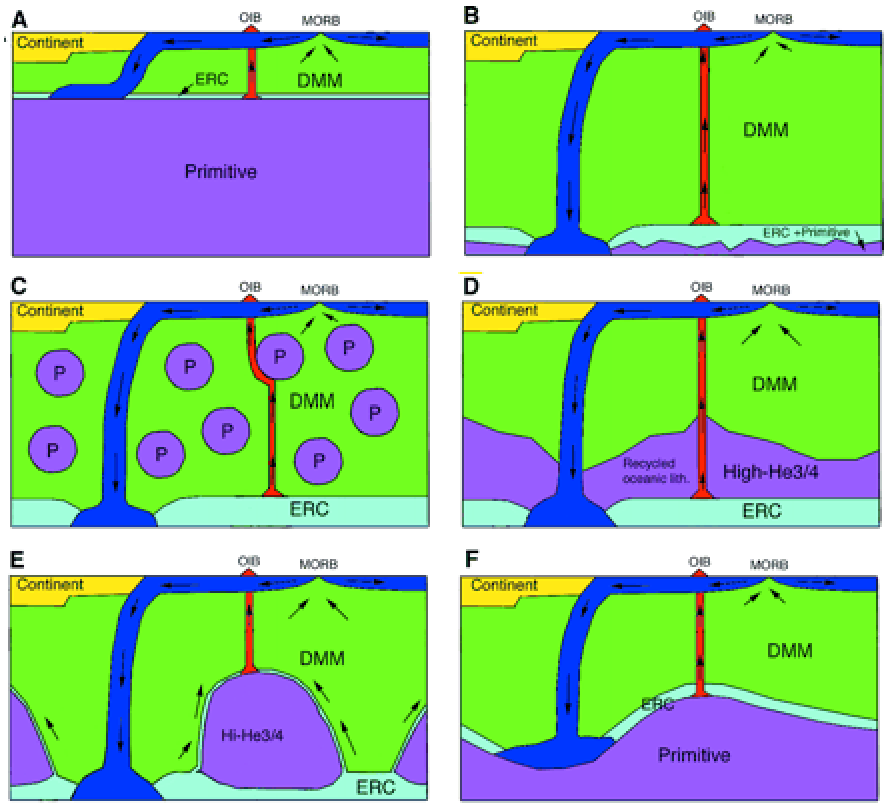
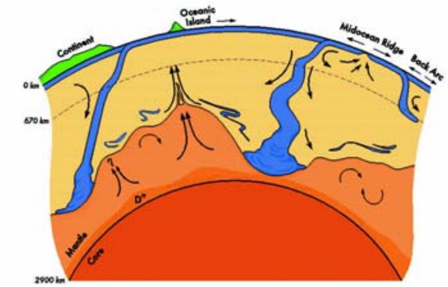


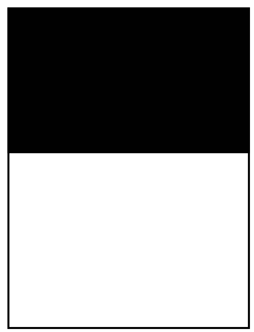
GASTRONOMY

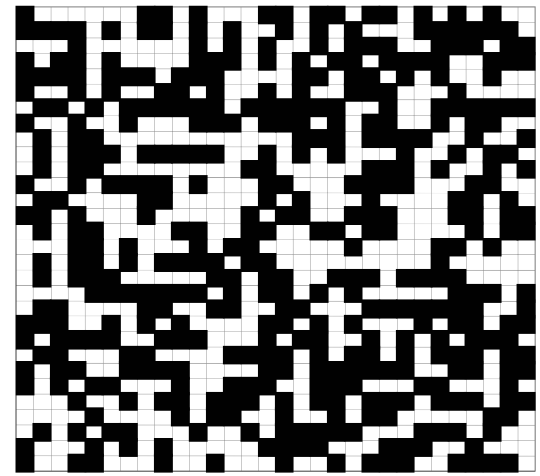


Tackley, 2000



Definition of heterogeneity

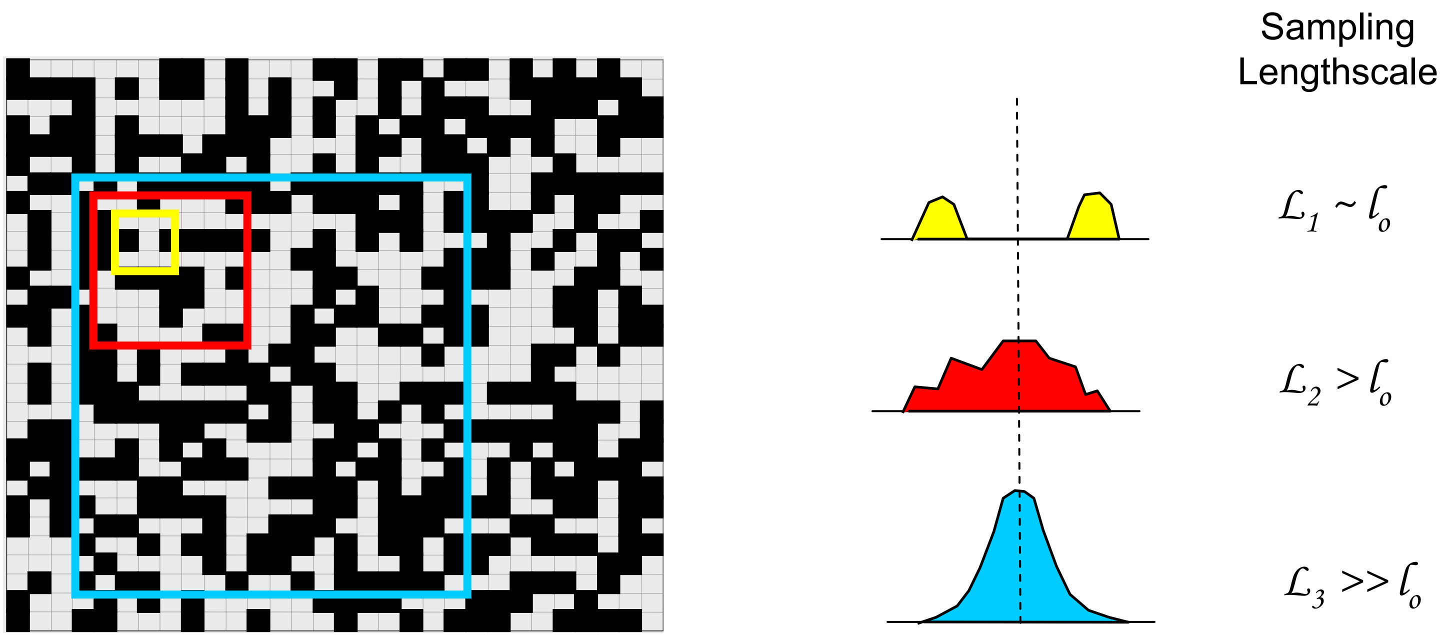




Heterogeneity: a qualitative term describing how “well-mixed” a system is

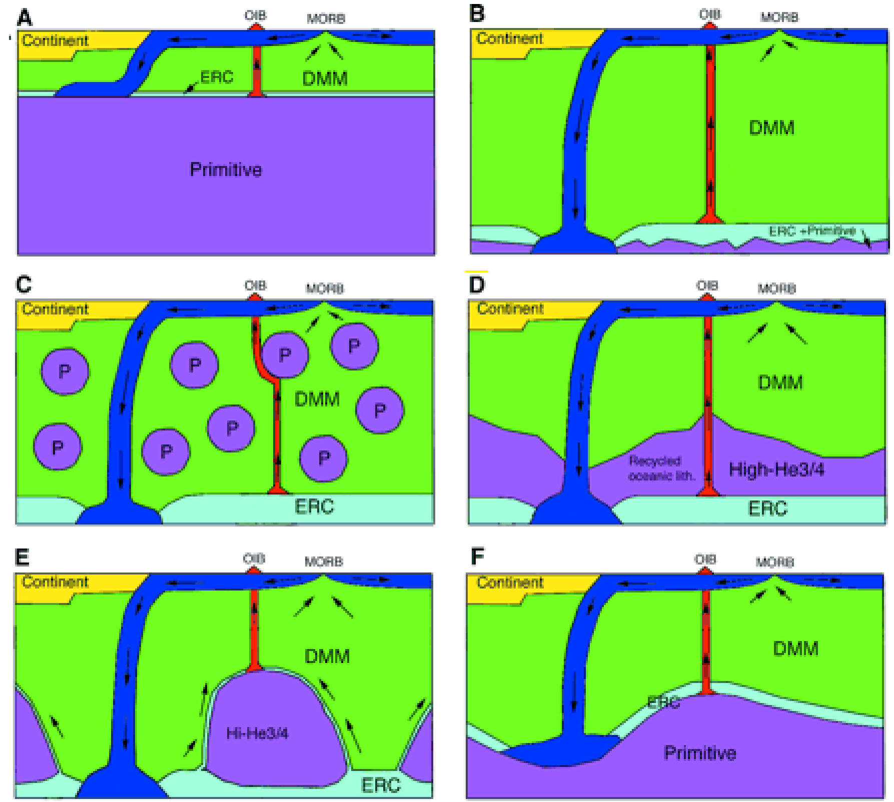
Reservoirs: chemically distinct regions in a system that have physically defined boundaries

At what point do we consider a heterogeneity a reservoir?

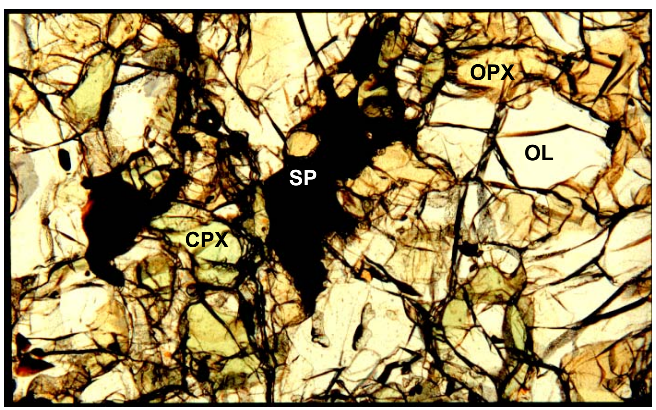


Tell me what lengthscale you're interested in…

3000 km



Tackley, 2000



1 cm

Forms of compositional heterogeneities

Major - wt. %

Minor - ~0.1 wt. %

Trace - <100 ppm

Isotopic

What types of compositional heterogeneities lead to variations in physical parameters?

Three Steps to Bliss

1. Bulk Earth Composition

↓

2. Composition of reservoirs

↓

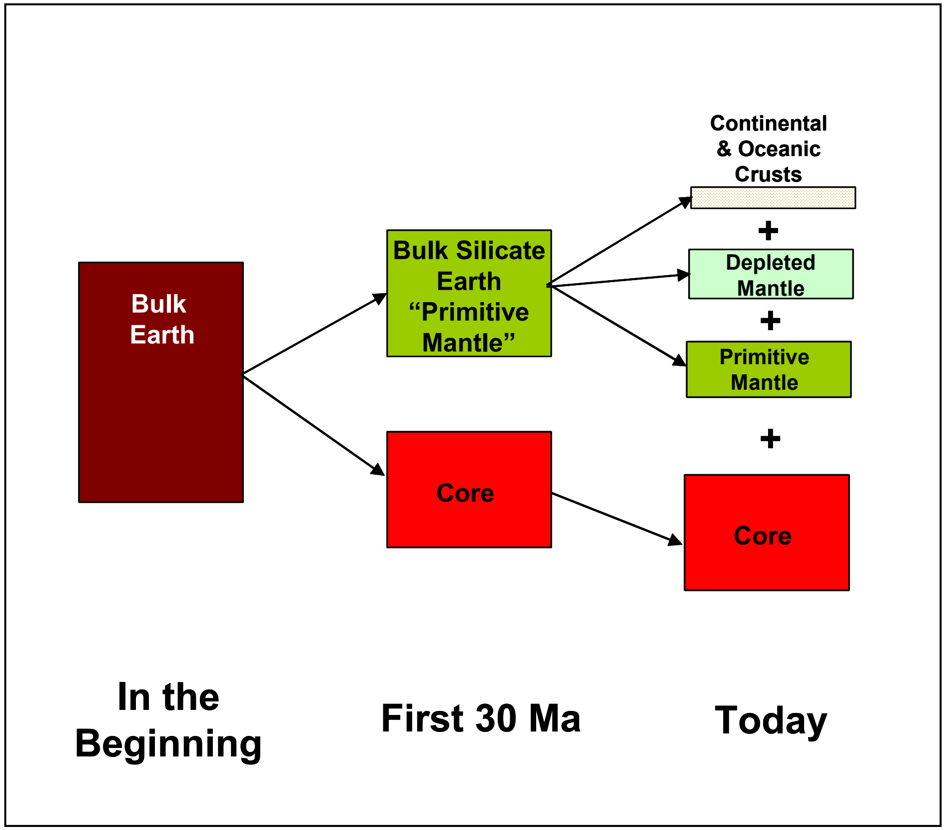
3. Quantifying the size and distribution of reservoirs

STEP 1
Towards a Bulk Earth Composition

Bulk Silicate Earth
(Primitive Mantle)

+

Core



What types of samples can we work with?

Mantle rocks (xenoliths, massifs, ophiolites)

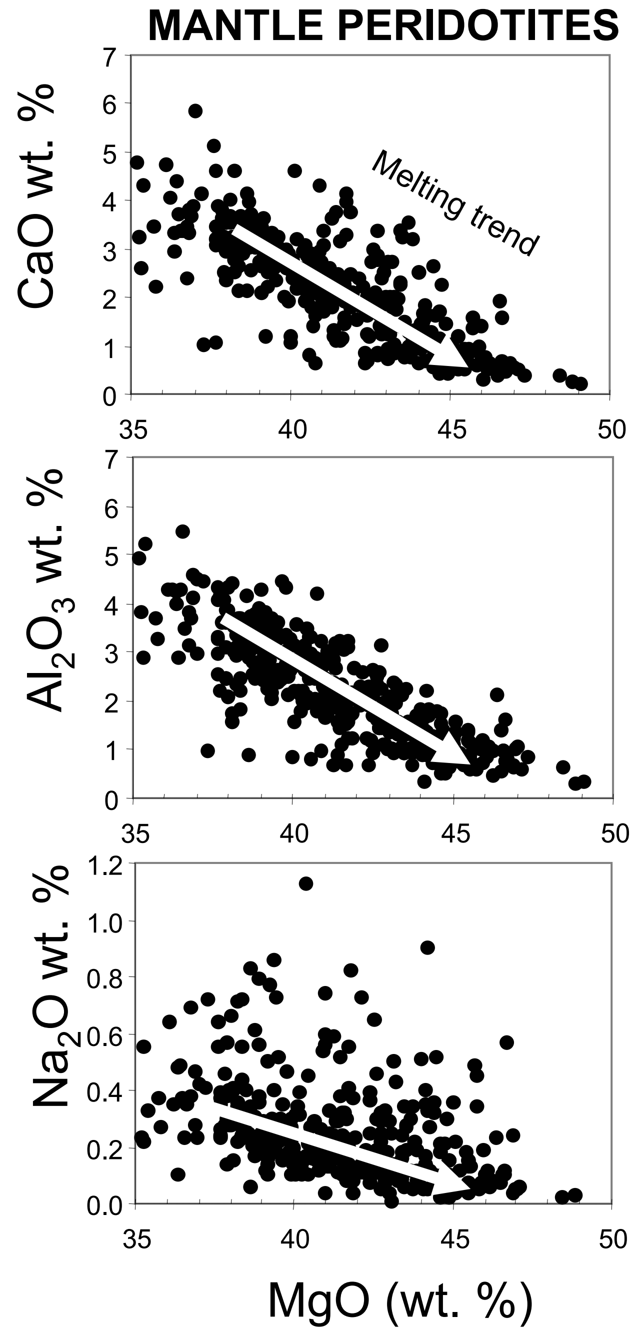
Lavas/Magmas

Sediments

Meteorites?

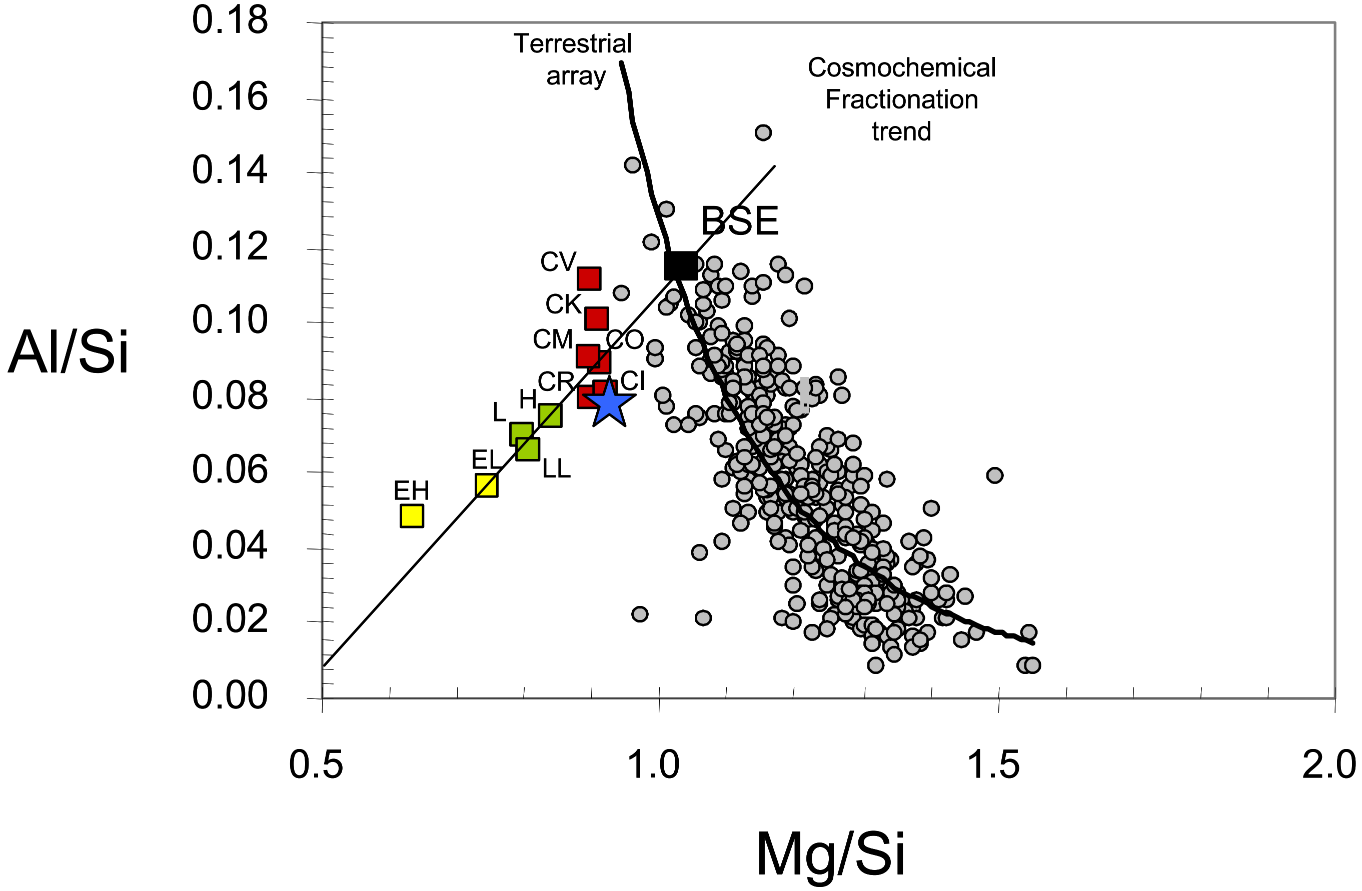
The search for the holy grail

Do samples of “Primitive Mantle” exist?

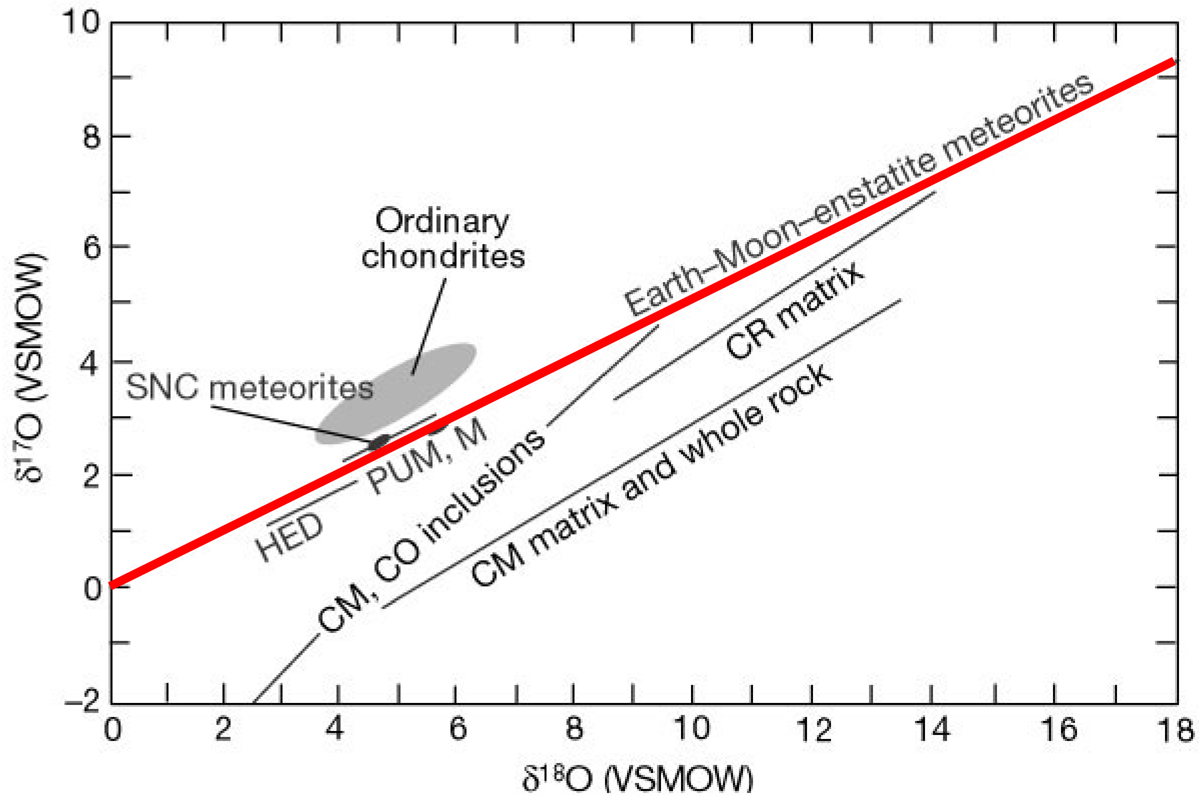


Can we use “primitive” meteorites, e.g. undifferentiated meteorites as a proxy for the undifferentiated Earth?

Yes and No



Al/Si
Mg/Si
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
1.5
2.0
Terrestrial array
Cosmochemical Fractionation trend
BSE
CV
CK
CM
CO
CR
CI
H
L
LL
EL
EH



Drake and Righter, 2002; after:

40. Clayton, R. N. & Mayeda, T. K. Oxygen isotope studies in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **63**, 2089-2104 (1999).

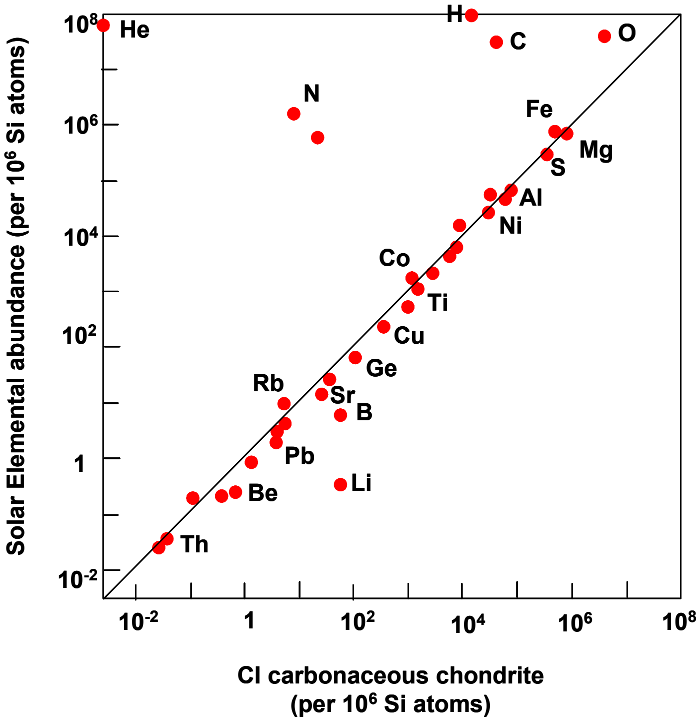
41. Clayton, R. N. Oxygen isotopes in meteorites. *Annu. Rev. Earth Planet. Sci.* **21**, 115-149 (1993).

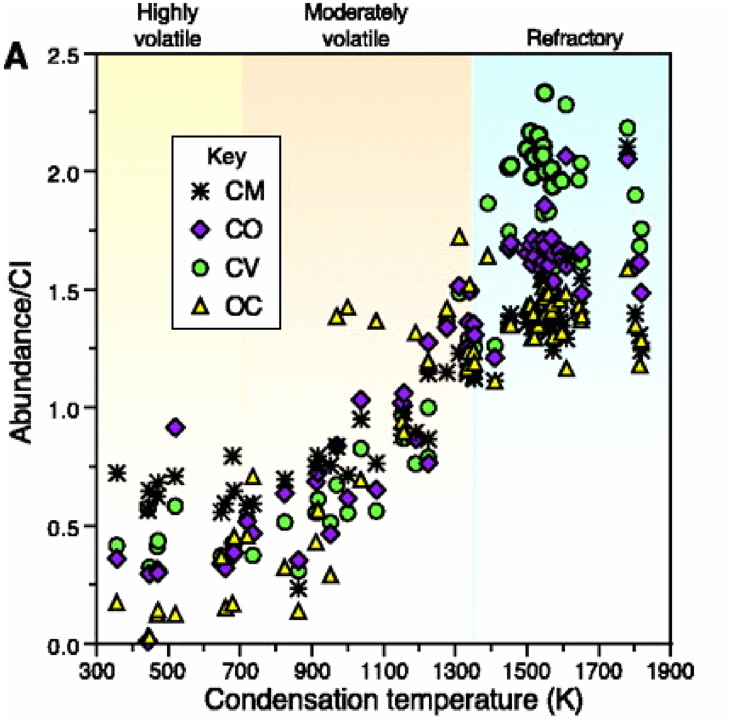
42. Clayton, R. N., Mayeda, T. K., Goswami, J. N. & Olsen, E. J. Oxygen isotope studies in ordinary chondrites. *Geochim. Cosmochim. Acta* **55**, 2317-2337 (1991).

It is safe to say that Earth is derived from Earth-like materials

. . . but all is not lost

CI chondrites





The Early Evolution of the Inner Solar System: A Meteoritic Perspective

C. M. O'D. Alexander, A. P. Boss, R. W. Carlson

SCIENCE, Volume 293, Number 5527, pp. 64-68

50% condensation temperatures (pressure 1E-4 bars)

H																	He
Li 1225	Be											B 964	C	N	O	F 736	Ne
Na 970	Mg 1340											Al 1680	Si 1311	P 1267	S 648	Cl	Ar
K 1000	Ca 1520	Sc 1644	Ti 1590	V	Cr 1300	Mn 1190	Fe 1336	Co 1351	Ni 1354	Cu 1037	Zn 660	Ga 997	Ge	As 1157	Se 684	Br	Kr
Rb 1080	Sr	Y	Zr 1750	Nb	Mo 1600	Tc	Ru 1600	Rh	Pd 1334	Ag 952	Cd	In 470	Sn 720	Sb 912	Te 680	I	Xe
Cs	Ba	La-Lu	Hf	Ta	W 1800	Re 1800	Os 1800	Ir 1600	Pt 1411	Au 1225	Hg	Tl 428	Pb 496	Bi 451	Po	At	Rn
Fr	Ra	Ac-Lr															

La 1500	Ce	Pr	Nd	Pm	Sm	Eu 1290	Gd	Tb	Dy	Ho	Er	Tm	Yb 1420	Lu 1590
Ac	Th 1590	Pa	U 1540	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

- Refractory, >1400 K
- Transitional ~1250-1350 K
- Moderately volatile ~800-1250 K
- Highly volatile <800 K

Nebular differentiation

Refractory

Moderately volatile

Volatile

Planetary differentiation

Lithophile – silicate loving

Siderophile – Fe loving

Atmophile - atmosphere

Establish concentrations in "Primitive Mantle" using refractory lithophile element ratios for chondrites

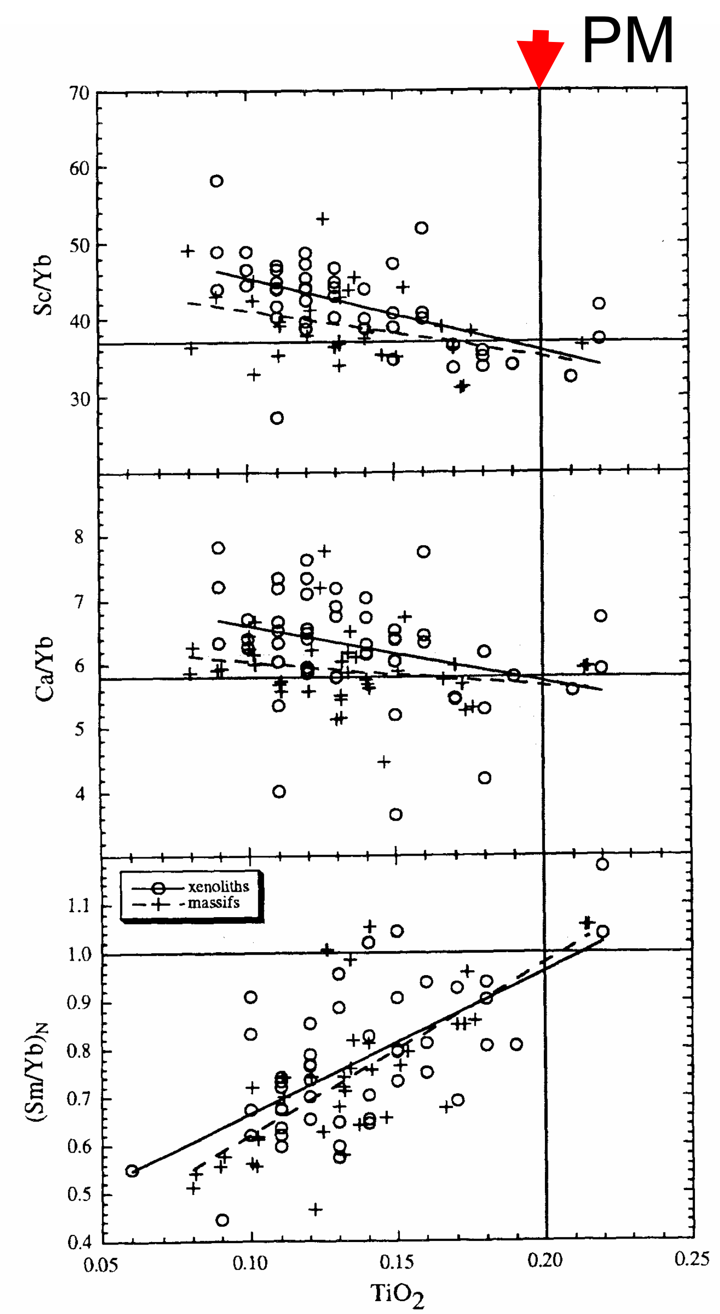
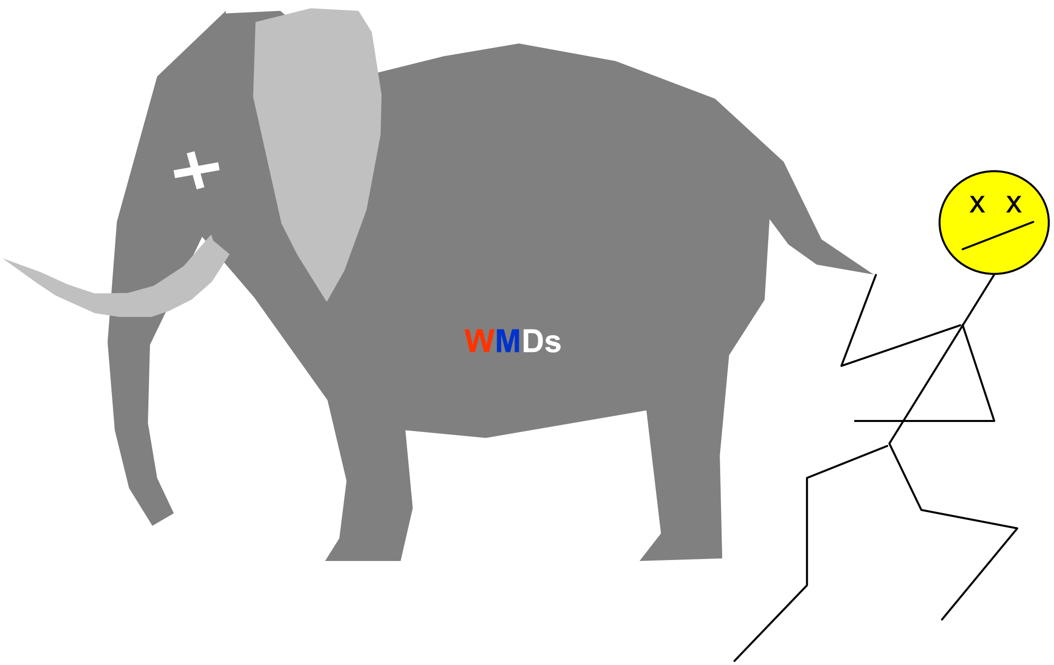
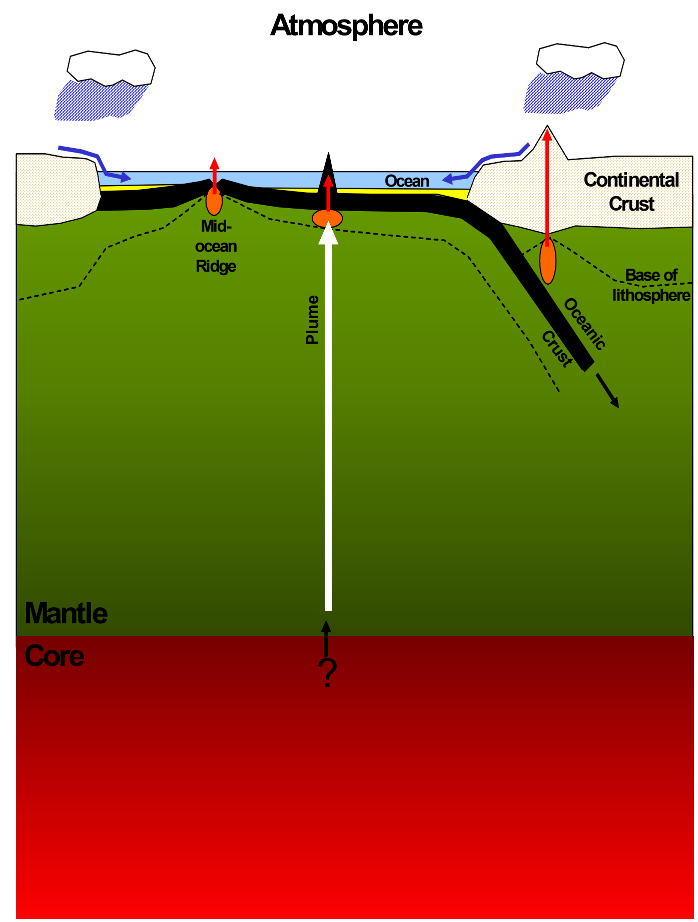


Fig. 6 from
McDonough & Sun (1995)

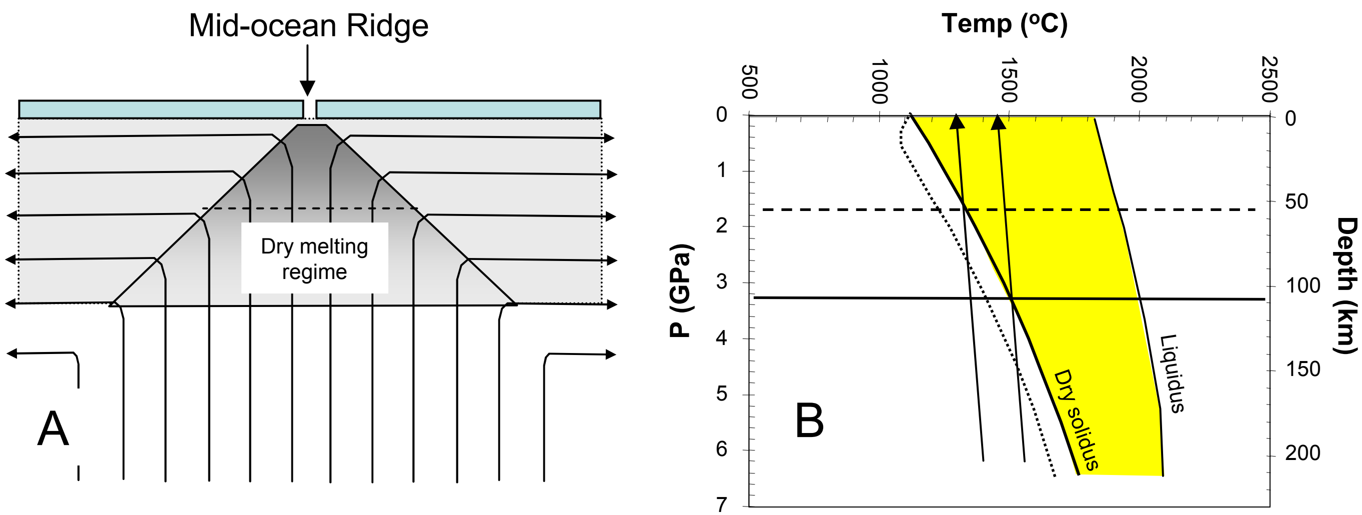
STEP 2. RESERVOIR DOGS



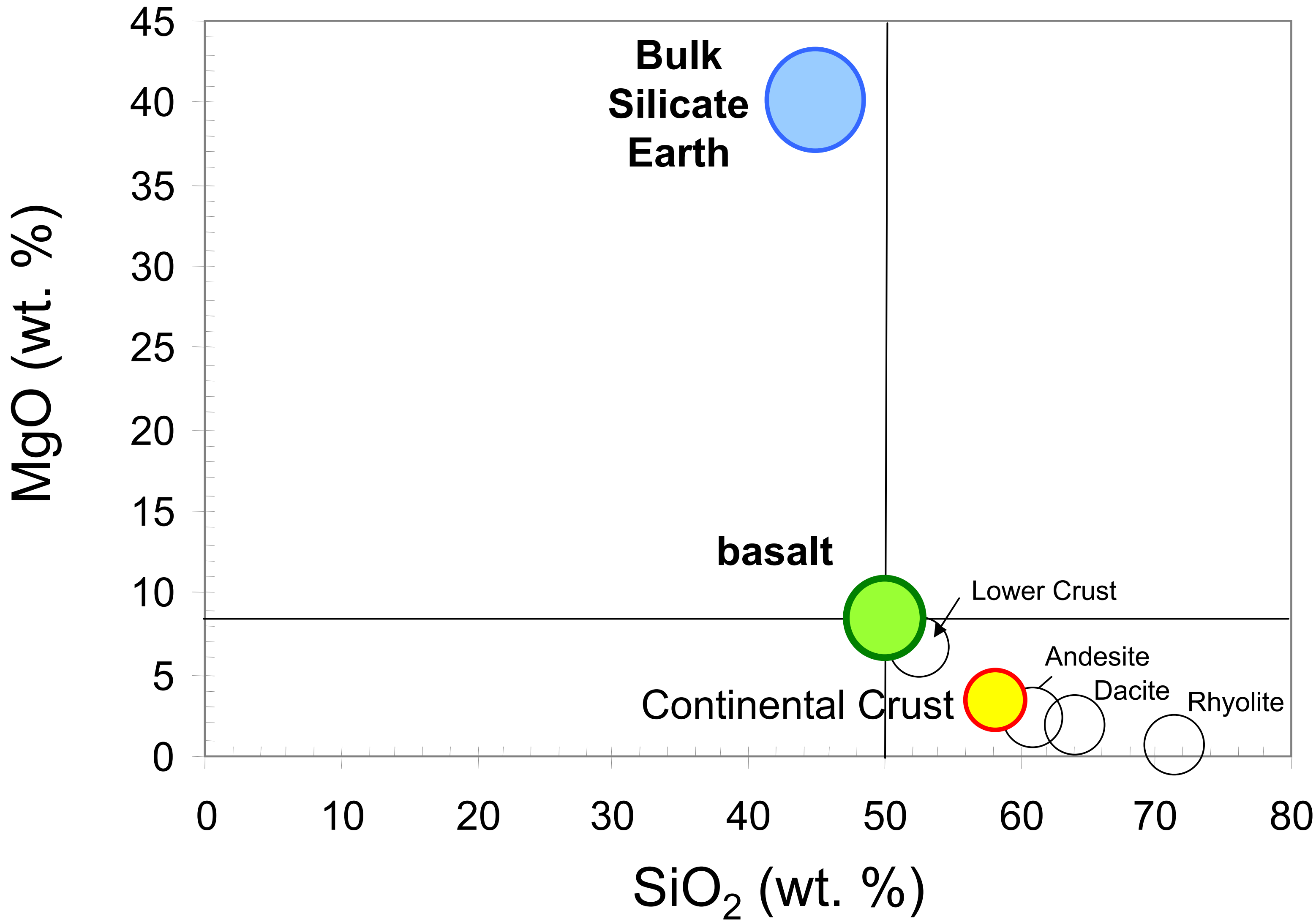


Not to scale

Partial melting as a major differentiation process



Major Element Effects



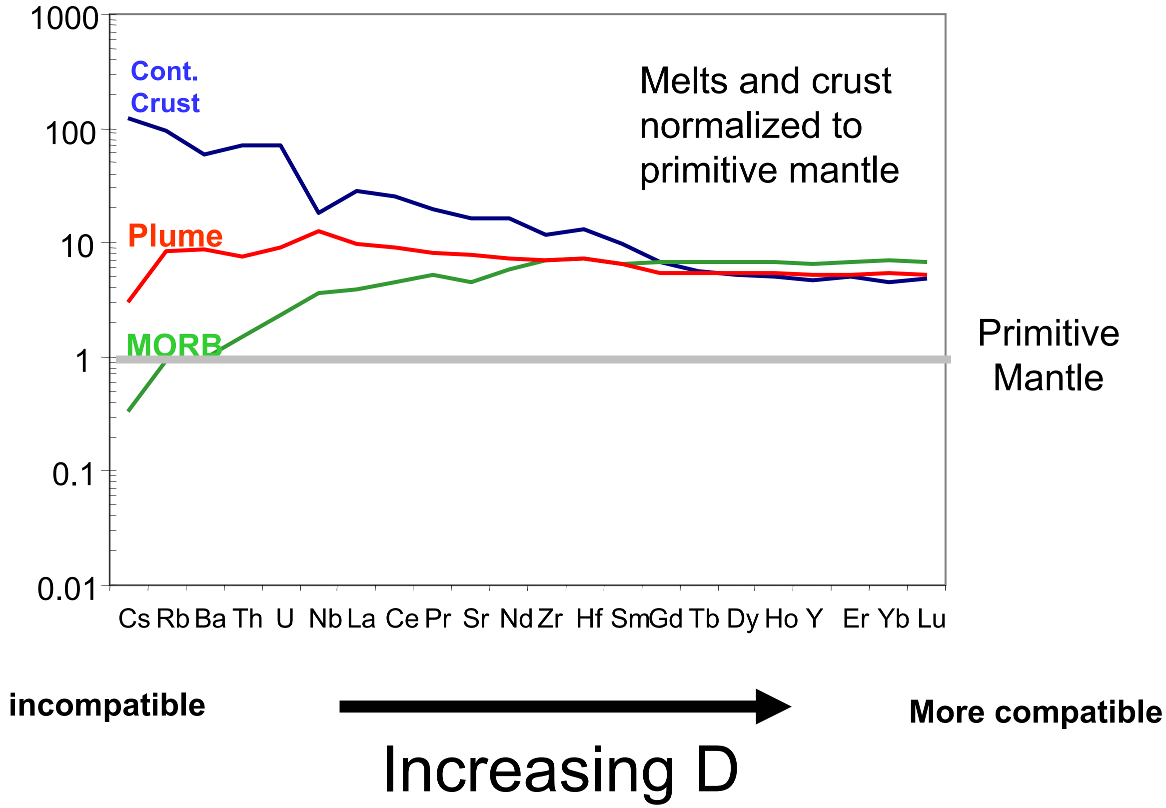
Partition coefficient

$$D = \frac{C_{solid}}{C_{melt}}$$

$D > 1$ compatible in solid

$D < 1$ incompatible in solid

Using magmas as “windows” to the mantle



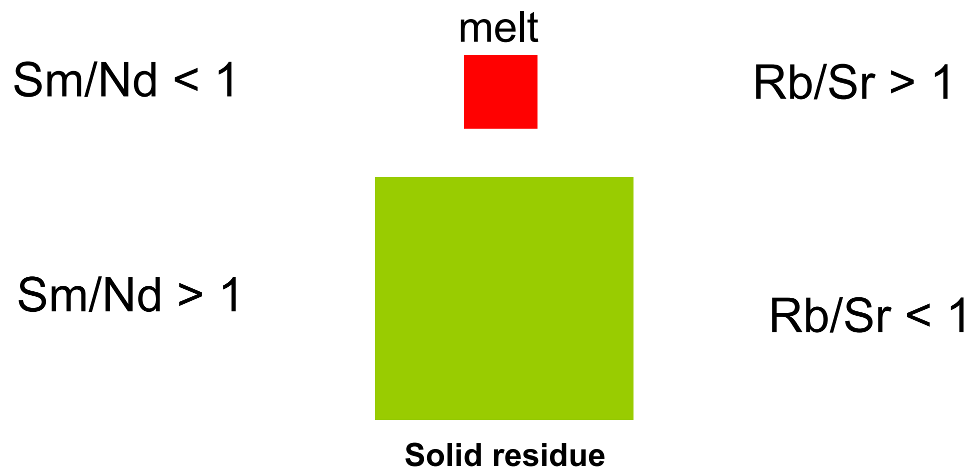
MORB source is depleted in highly incompatible elements (DMM = depleted MORB mantle)

Continental Crust is enriched in highly incompatible elements

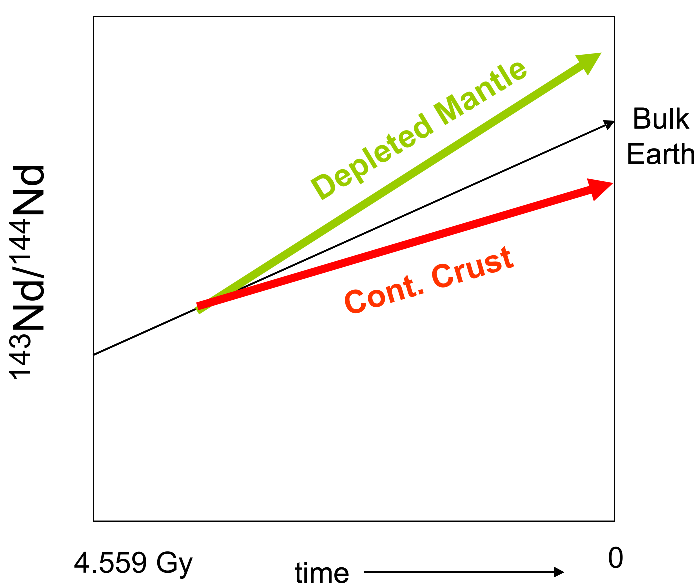
Plume is enriched or more primitive in character

Trace-elements may suffer from fractionation during magmatic processes

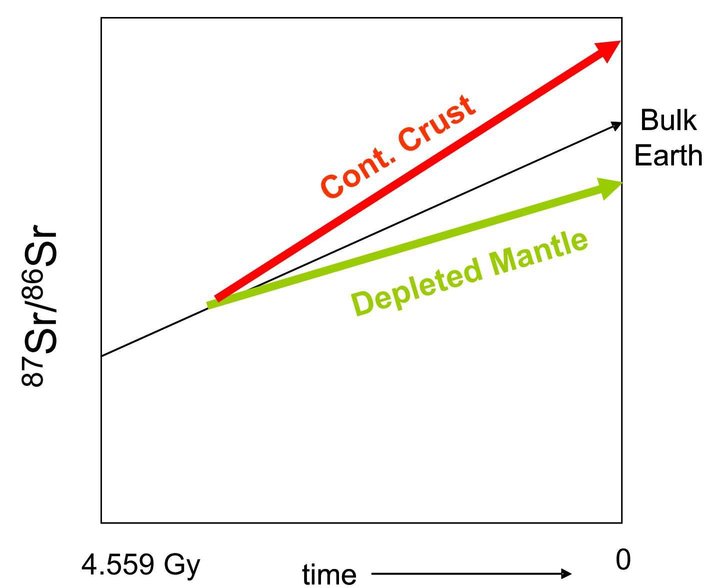
Isotopes in general are NOT fractionated



^{147}Sm – ^{143}Nd



^{87}Rb – ^{87}Sr



Depleted Mantle

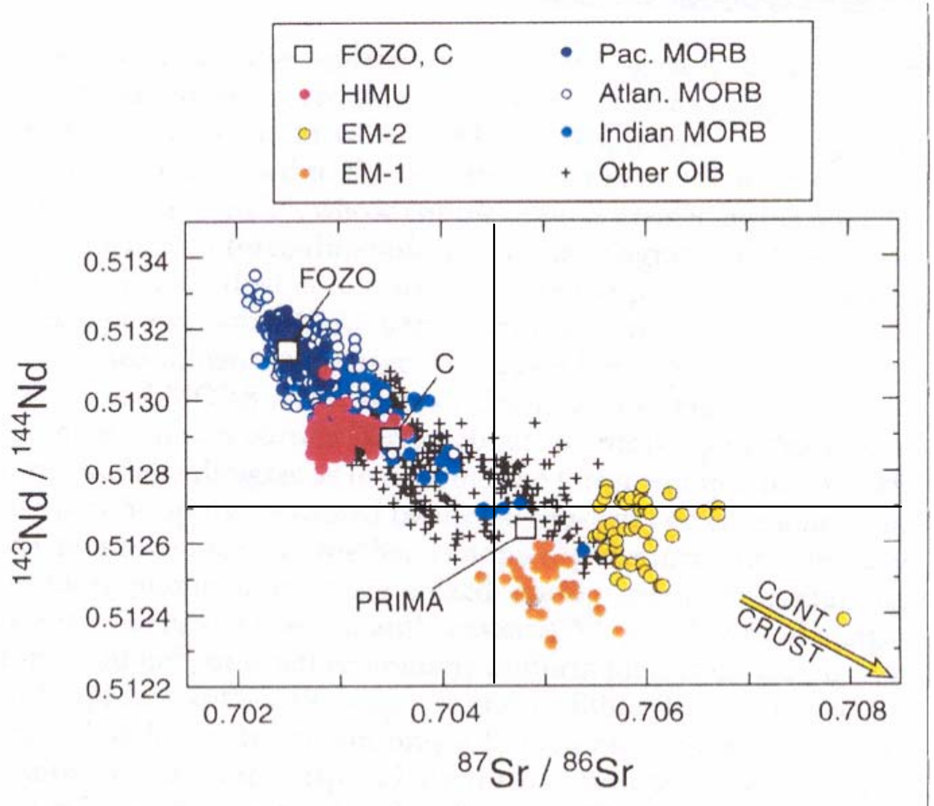
radiogenic Nd

unradiogenic Sr

Continental Crust

unradiogenic Nd

radiogenic Sr



Hofmann, 1997

Nature 385: 219-229

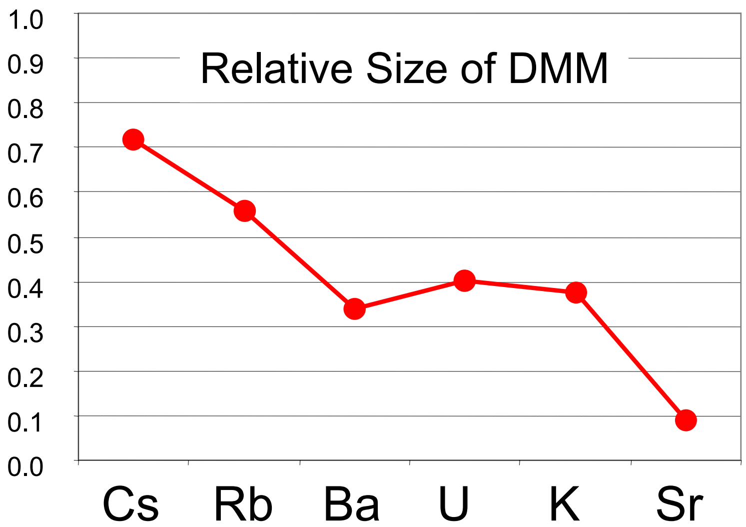
At least the upper part of the Earth's mantle is depleted in highly incompatible elements

This depleted portion appears to be complementary to the continental crust

How much of the mantle is depleted?

Mass Balance Magic

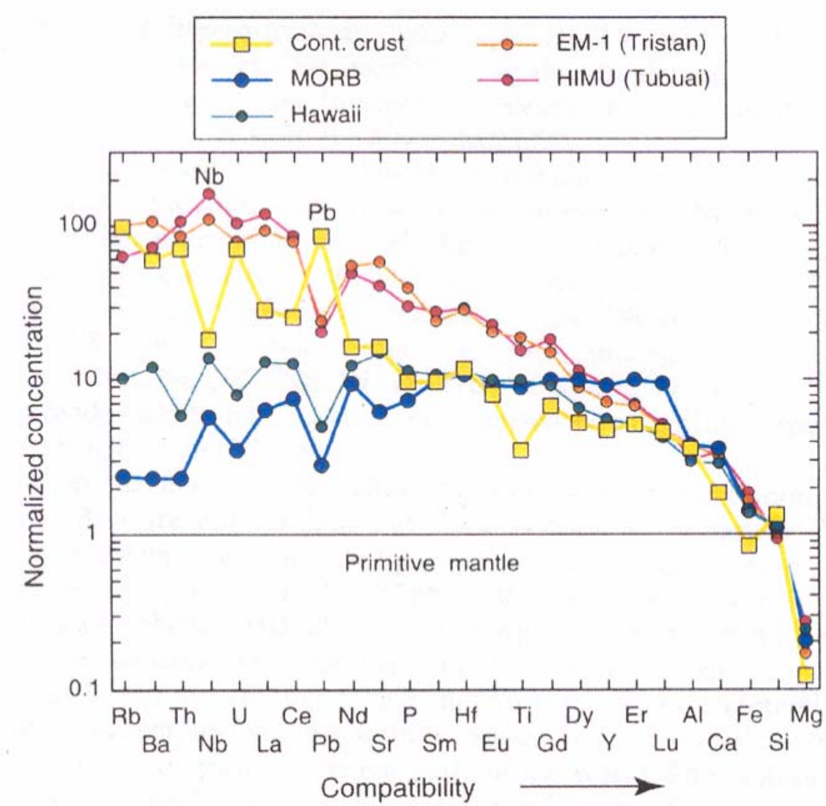
	Concentration (ppm)					
	Cont. Crust	MORB	PM	DMM	DMM/PM	Relative Size of DMM
Cs	2.6	0.007	0.021	0.0007	0.0	0.7
Rb	58	0.56	0.6	0.056	0.1	0.6
Ba	390	6.3	6.6	0.63	0.1	0.3
U	1.42	0.047	0.0203	0.0047	0.2	0.4
K	15606	600	240	60	0.3	0.4
Sr	325	90	19.9	9	0.5	0.1

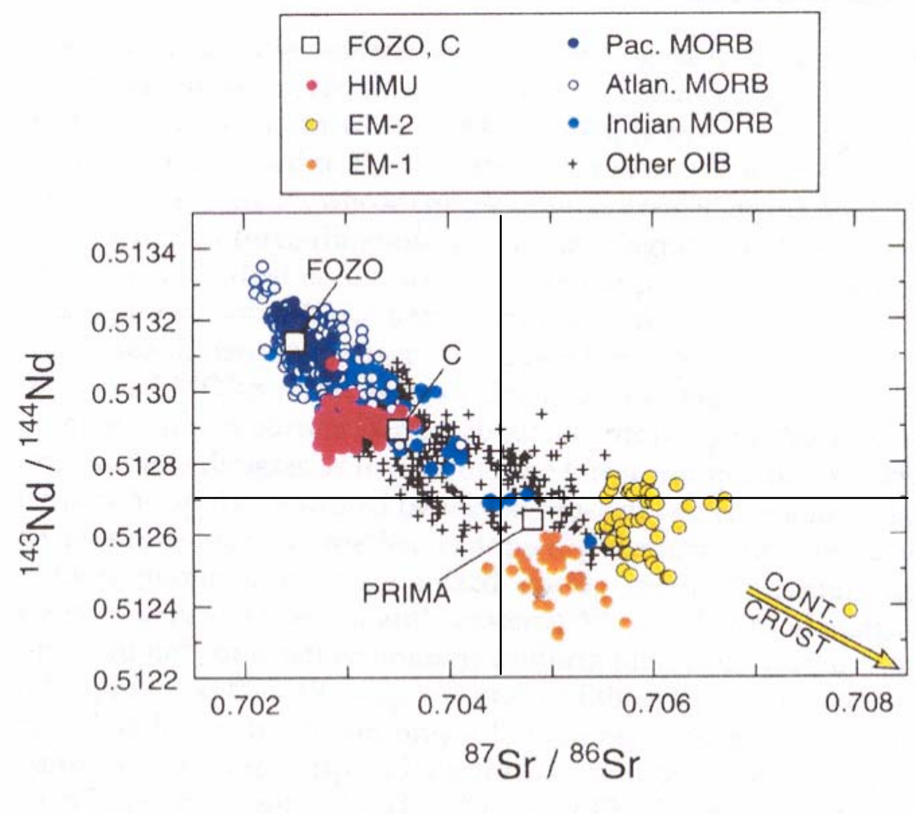


Possibly 30 to 70% of mantle has been processed to make Cont. Crust

Mass Balance Says **NOTHING** about geometry

What do hotspots tell us?
(Ocean Island Basalts – OIB)

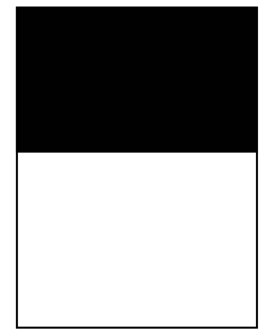




Hofmann, 1997
Nature 385: 219-229

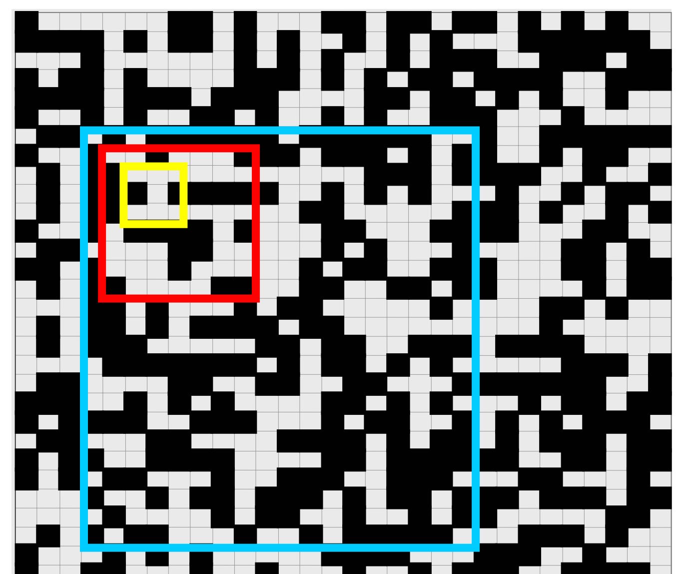
Hotspot magmas appear to be variably enriched in incompatible elements

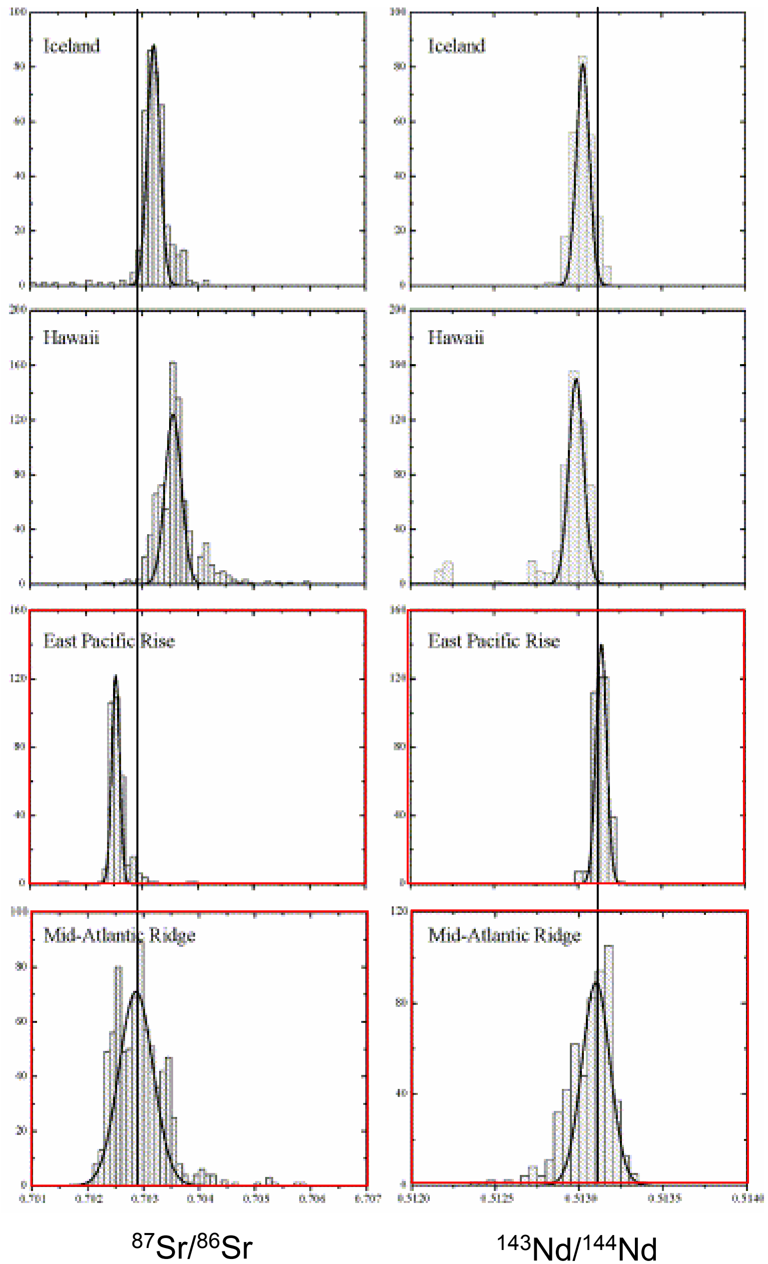
Source feature



Or

Sampling problem?





Meibom & Anderson 2003

Sampling problem is a possibility

BUT average isotopic composition of some OIBs differ from that of MORBs

↓

OIB source must differ slightly in composition from that of MORB source

IF OIBs are associated with plumes +
IF plumes derive from the lower mantle

The lower mantle must be slightly enriched.

Do plumes exist?

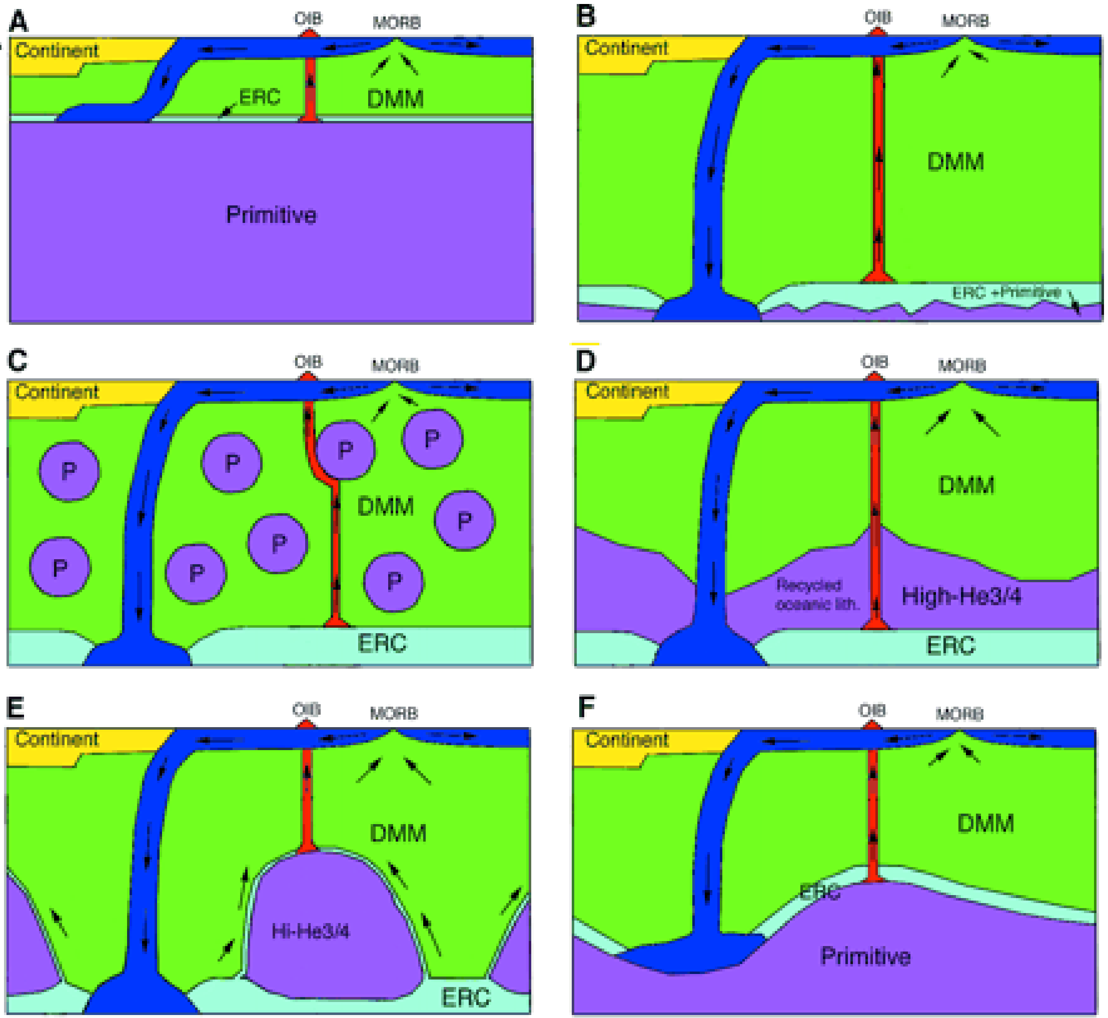
Other Reservoirs in the Silicate Earth

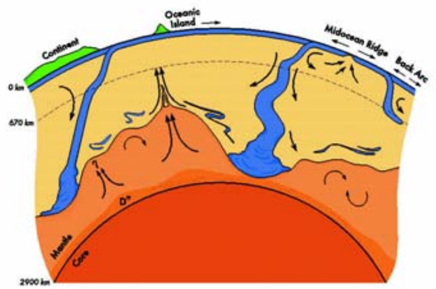
Subducted oceanic crust

SCLM – subcontinental lithospheric mantle

Subducted sediment

Primordial mantle???





Tackley, 2000

Where do we go from here?

More of the same data?

New data?

NEW QUESTIONS?

YOU can be an armchair geochemist

Use compiled datasets

GEOROC

RidgePetDB

GERM

But don't abuse the data sets

New directions → **New data**

DIRECTION 1

Is a homogeneous Bulk Silicate Earth a valid assumption?

Was the primordial mantle stratified? If so, how does this affect geochemical mass balance conditions?

Is the lower part of the mantle Fe-rich?

Can we ignore mass fluxes across the core-mantle boundary?

What data may be able to answer these questions?

Short-lived radionuclides

^{182}Hf-^{182}W, ^{146}Sm-^{142Nd}, ^{107}Pd-^{107}Ag

More precise data on first series transition elements

Fe, Mn, Ni, Co, Cr, V, Sc

Direction 2

Constrain the size and distribution of reservoirs

Geochemistry, Geophysics, Geodynamics, Petrology

G^3P

Do geochemical heterogeneities reflect variations in physical properties that are detectable by geophysical methods?

Clearly, major-element variations affect physical properties of the mantle.

The physical effects of trace-element and isotopic heterogeneities are unclear. However, trace-element and isotopic heterogeneities may be correlated with variations in **oxygen fugacity** and **water content**, both of which may have profound effects on elasticity, conductivity, and viscosity.

$$2FeO + O_2 = Fe_2O_3$$

Future?

- Effects of fO_2 and H_2O on physical properties of peridotite

- Characterizing the variation of fO_2 and H_2O in the mantle and what processes control these parameters

Geochemical research on

partitioning behavior of redox sensitive elements
valence state of redox-sensitive elements
quantification of H_2O content in the mantle

Conclusions

Geochemistry has provided a considerable knowledge base for our understanding of how the Earth works.

Further progress will require interdisciplinary collaboration and the generation of new questions and areas of focus.

More geochemical data will obviously be helpful, but existing databases should be mined to reveal areas that need more refinement.