Major element composition of the mantle and its variability

Cin-Ty A. Lee

Lecture notes on estimating Bulk Silicate Earth composition
http://www.ruf.rice.edu/~ctlee/Chapter2.pdf

Some notes on differentiation, melting
http://www.ruf.rice.edu/~ctlee/Chapter3.pdf

Lecture notes on trace-element geochemistry
http://www.ruf.rice.edu/~ctlee/Chapter7A.pdf

Composition of crust, mantle, earth (easy access)
http://www.ruf.rice.edu/~ctlee/rockcompositions.xls

CHECK OUT THE GERM WEBSITE

Some gods/goddesses……

Allegre, Anders, Hart, Jagoutz, Hofmann, McDonough, McLennan, O'Neill, Palme, Taylor, Ringwood, Rudnick, Sun, Wanke, Wasserburg, Urey, Zindler

Bulk Silicate Earth major element composition

- How well is it known?

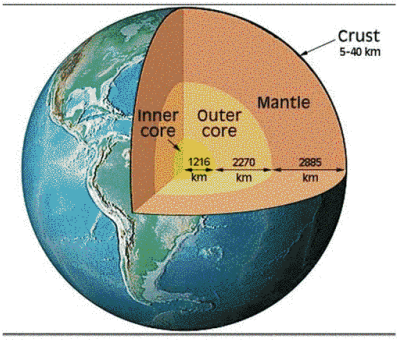
Major-element heterogeneity of mantle

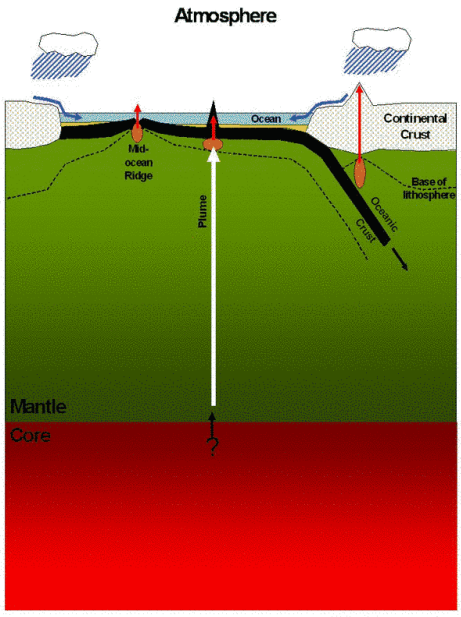
- How does it originate?
- What are the mass proportions of "reservoirs"?
- What is the spatial distribution of heterogeneities?
- Is the mantle stratified?

What are the geodynamic and geophysical implications of major elements and their variation in the Earth?

Density
Velocity
Viscosity

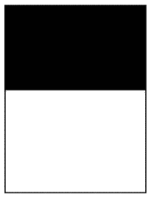
How do we estimate Bulk Silicate Earth composition from a heterogeneous planet?

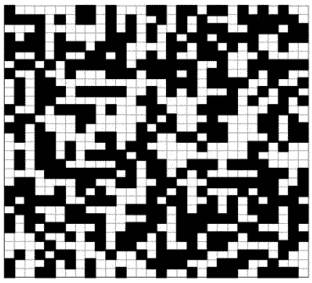




Not to scale

Let's first define heterogeneity

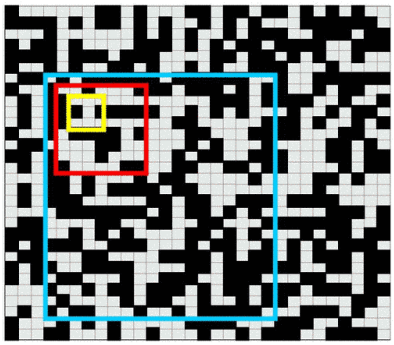


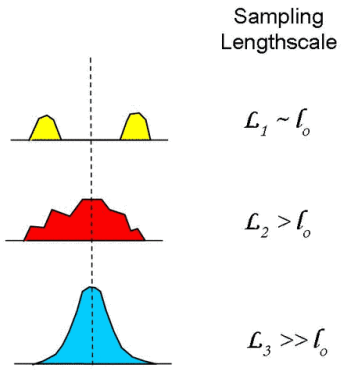


Heterogeneity: a qualitative term describing how "well-mixed" a system is

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

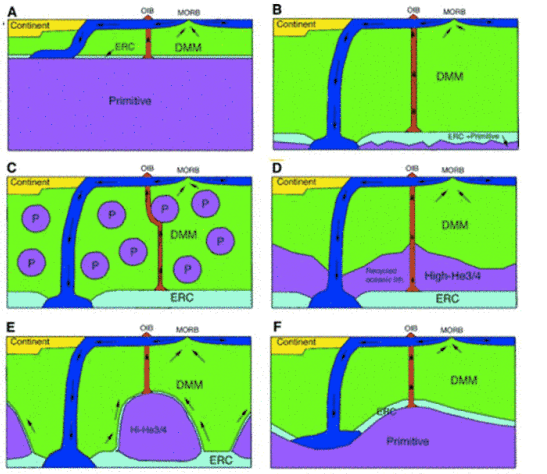
At what point do we consider a heterogeneity a reservoir?

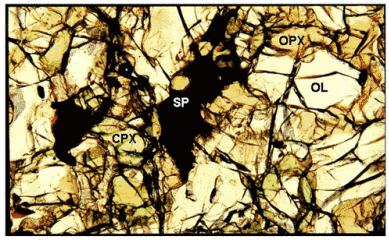




Tell me what lengthscale you're interested in…

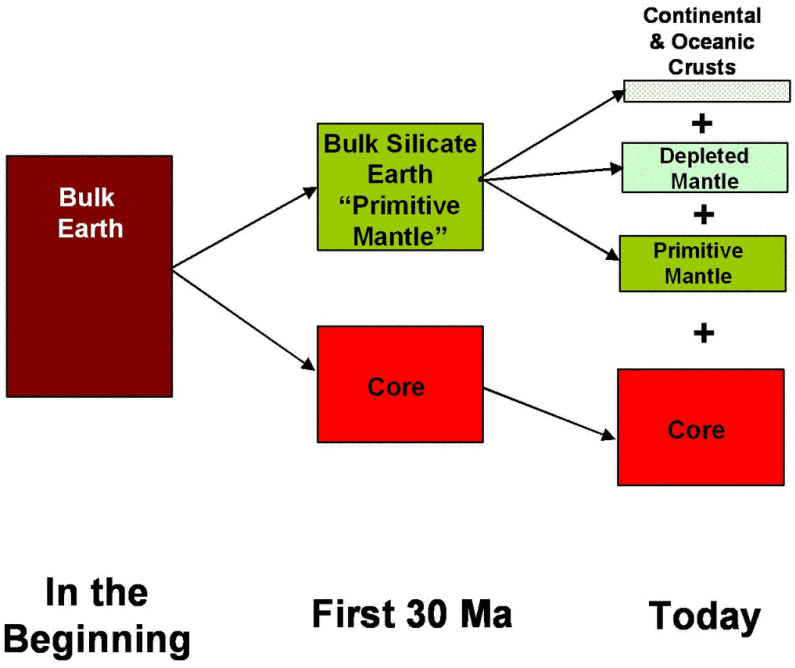
300 km

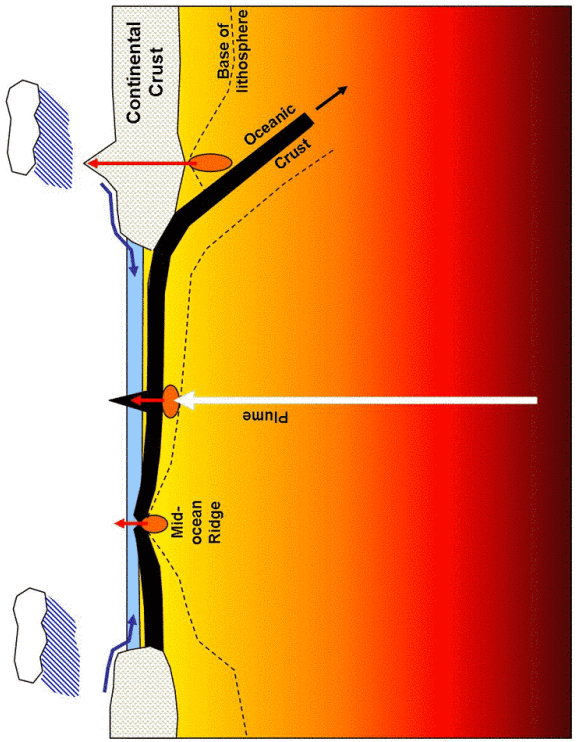




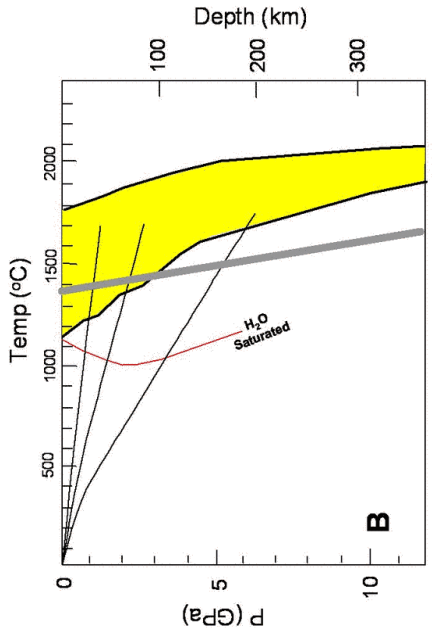
1 cm

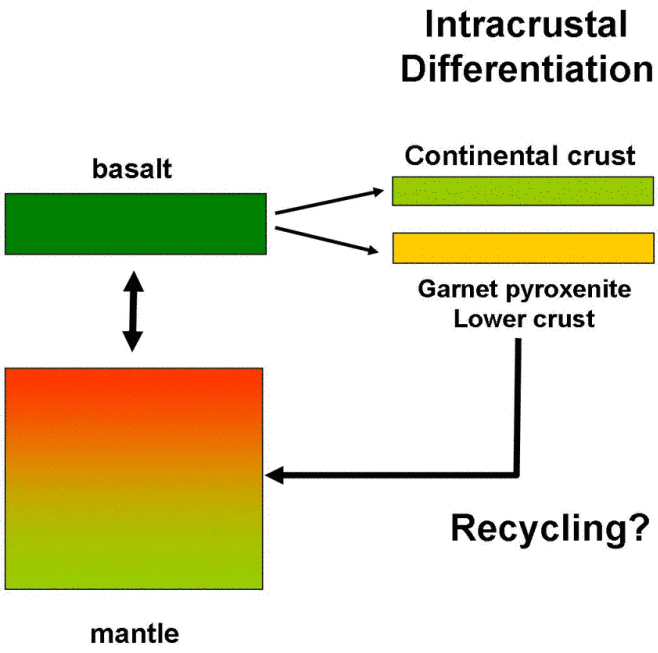
Tackley, 2000



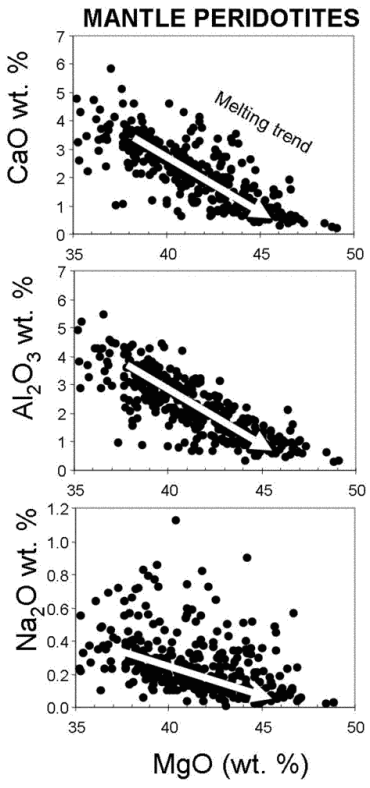


How the mantle partially melts

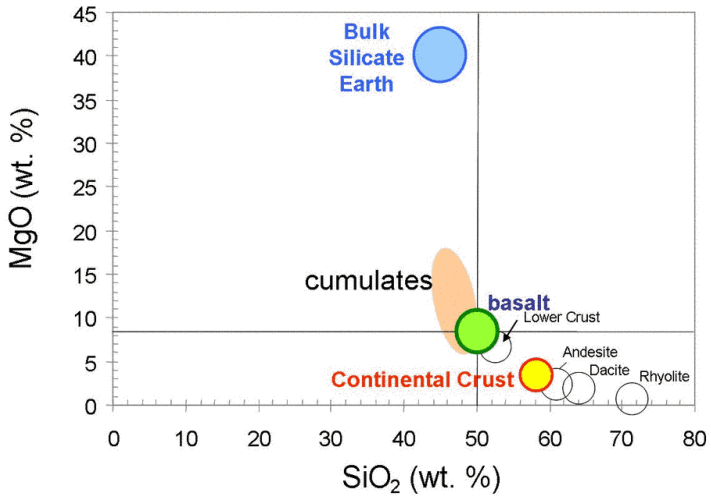




Effects of melt extraction



The whole gamut of silicate differentiation products summarized below

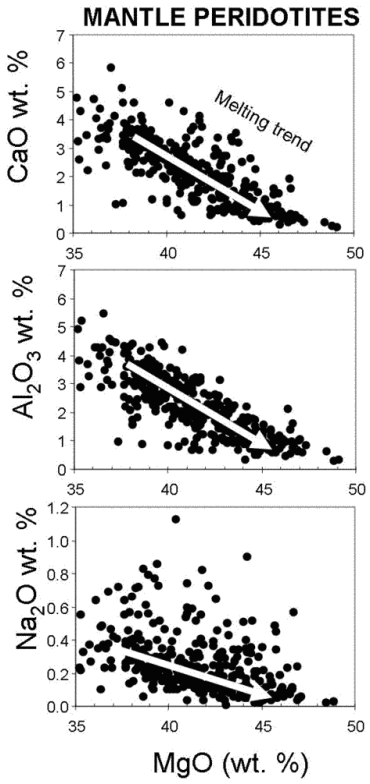


How do we estimate bulk silicate Earth?

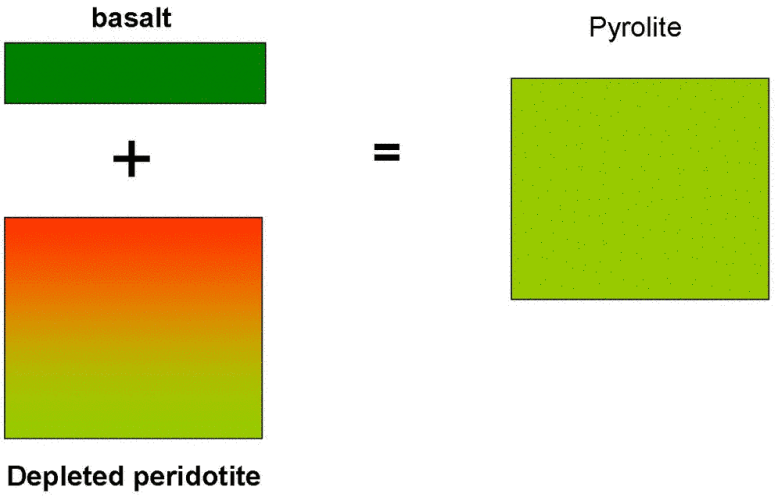
- Find a peridotite that has never been melted
- Reconstruct the composition of the primitive mantle: Pyrolite
- Assume Earth is like a chondrite
- Chondrite-Melt residue approach

➢Find a peridotite that has never been melted

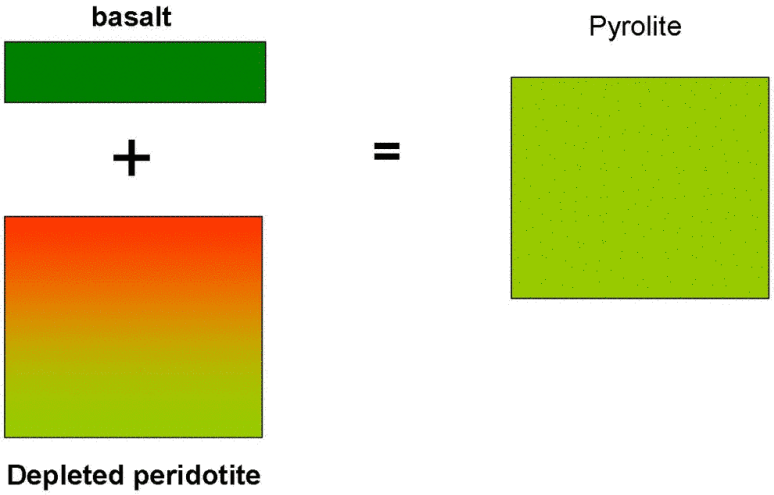
Problem: how can we tell a peridotite has never melted?



➢Reconstruct the composition of the primitive mantle: Pyrolite

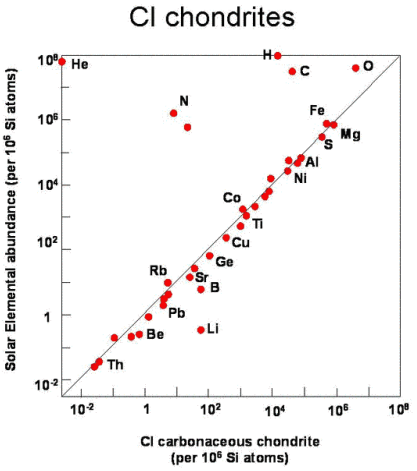


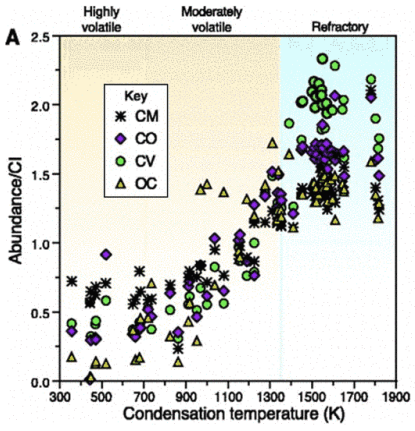
➢Reconstruct the composition of the primitive mantle: Pyrolite



BUT the proportions of basalt and depleted peridotite are somewhat arbitrary

➢Assume Earth is like a chondrite

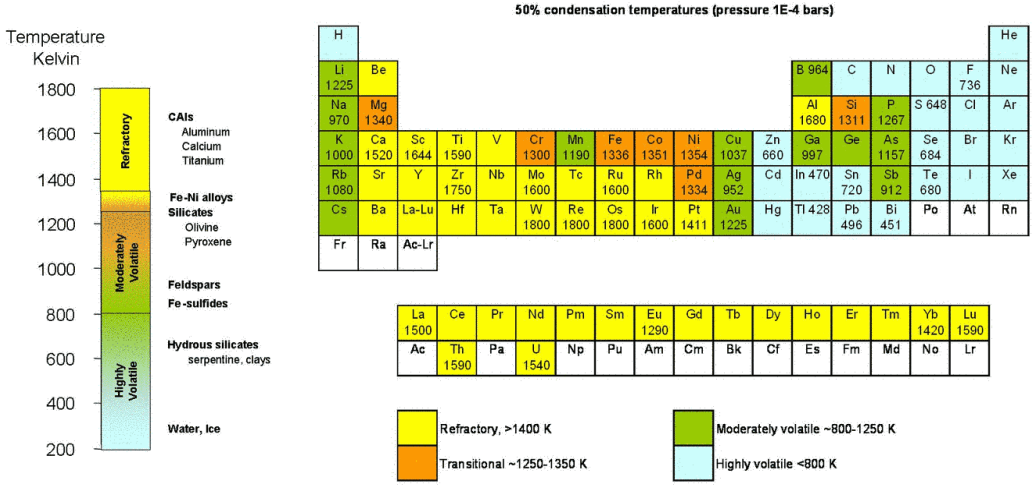




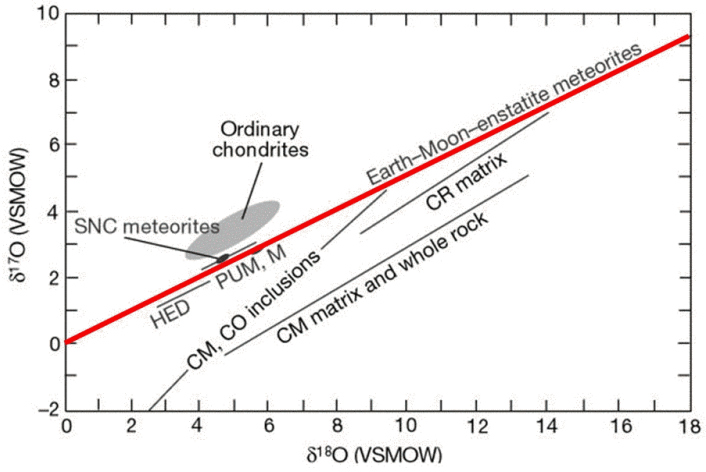
The Early Evolution of the Inner Solar System: A Meteoritic Perspective

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

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



➢Assume Earth is like a chondrite

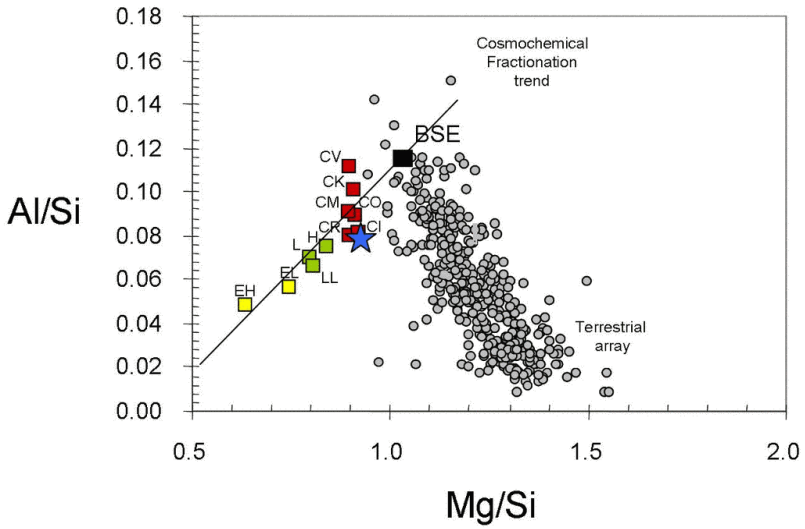


Drake and Righter, 2002; after:

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

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

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



Modified and elaborated from Jagoutz et al. 1979

All planetary bodies or meteorite parent bodies seem to be somewhat unique

Earth made from Earth-like objects

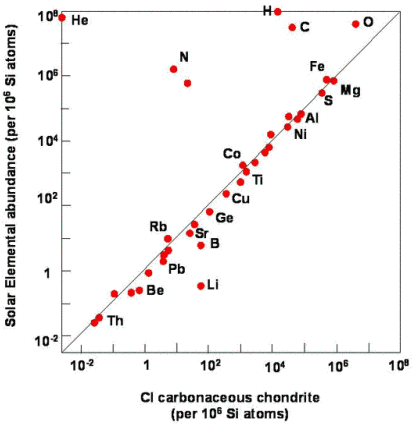
➢Chondrite-Melt residue approach

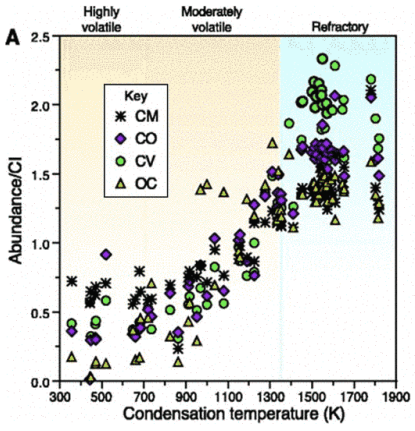
(REMEMBER THIS)

Refractory lithophile element ratios are constant

everything else varies a lot

CI chondrites





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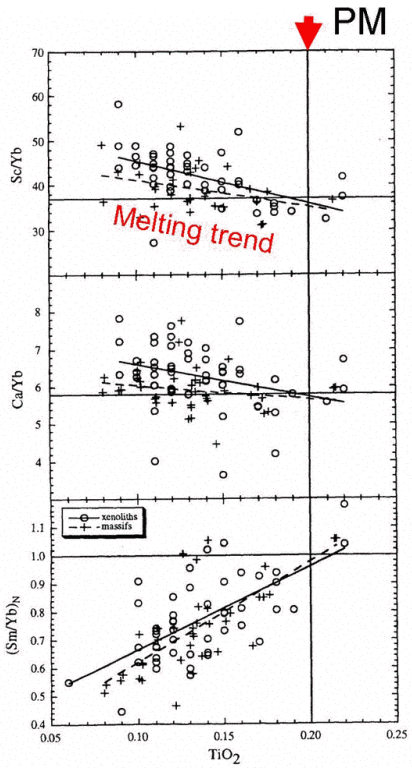
Refractory Lithophile Elements
Ca, Ti, REE, Al, Sc, Y, Mg, U

Stay away from volatile, siderophile or chalcophile elements
volatile = atmosphere
siderophile = Fe-core
chalcophile = sulphides, which go to core

Establish concentrations in "Primitive Mantle" by coupling refractory lithophile element ratios for chondrites with melting trends in peridotites

This gives TiO_2 of BSE



McDonough & Sun (1995)

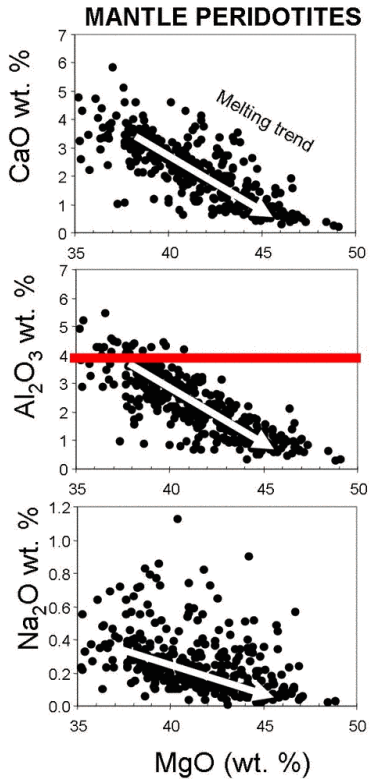
This gives Ti and Al concentration of bulk silicate Earth

↓

To get other refractory LITHOPHILE elements…

$Al_{BSE} * (U/Al)_{chondrite} = U_{BSE}$

Use melt depletion trends in peridotites to infer concentrations of BSE for other elements, e.g. Mg, Si, etc.



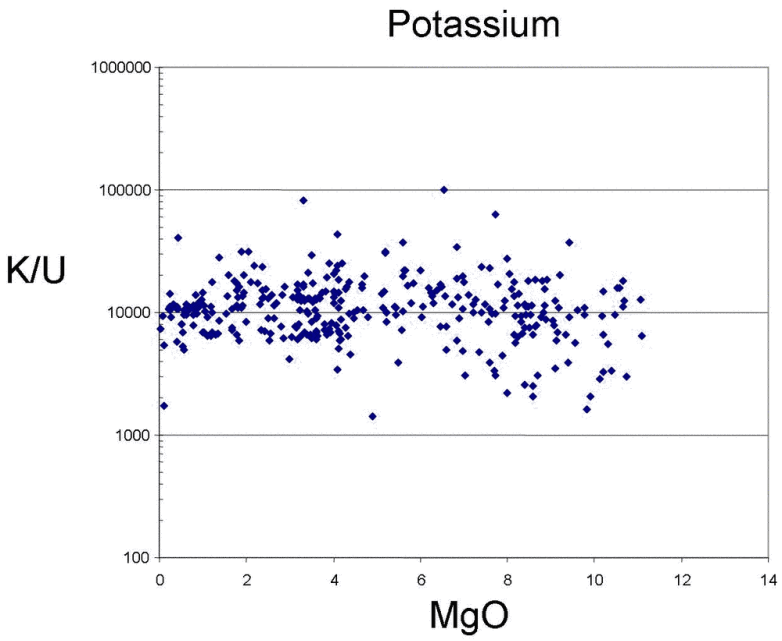


Table 2.3. CI chondrite and model primitive mantle compositions

		CI chondrite[1]	Primitive Mantle[2]			CI chondrite	Primitive Mantle
Li	ppm	1.5	1.6	Pd	ppb	560	3.9
Be	ppm	0.025	0.068	Ag	ppb	199	8
B	ppm	0.87	0.3	Cd	ppb	686	40
C	%	3.45	0.012	In	ppb	80	11
N	ppm	3180	2	Sn	ppb	1720	130
F	ppm	60.7	25	Sb	ppb	142	5.5
Na	ppm	5000	2670	Te	ppb	2320	12
Mg	%	9.89	22.8	I	ppb	433	10
Al	%	0.868	2.35	Cs	ppb	187	21
Si	%	10.64	21	Ba	ppb	2340	6600
P	ppm	1220	90	La	ppb	234.7	648
S	ppm	62500	250	Ce	ppb	603.2	1675
Cl	ppm	704	17	Pr	ppb	89.1	254
K	ppm	558	240	Nd	ppb	452.4	1250
Ca	%	0.928	2.53	Sm	ppb	147.1	406
Sc	ppm	5.82	16.2	Eu	ppb	56	154
Ti	ppm	436	1205	Gd	ppb	196.6	544
V	ppm	56.5	82	Tb	ppb	36.3	99
Cr	ppm	2660	2625	Dy	ppb	242.7	674
Mn	ppm	1990	1045	Ho	ppb	55.6	149
Fe	%	19.04	6.26	Er	ppb	158.9	438
Co	ppm	502	105	Tm	ppb	24.2	68
Ni	ppm	11000	1960	Yb	ppb	162.5	441
Cu	ppm	126	30	Lu	ppb	24.3	67.5
Zn	ppm	312	55	Hf	ppb	104	283
Ga	ppm	10.0	4	Ta	ppb	14.2	37
Ge	ppm	32.7	1.1	W	ppb	92.6	29
As	ppm	1.86	0.05	Re	ppb	36.5	0.28
Se	ppm	18.6	0.075	Os	ppb	486	3.4
Br	ppm	3.57	0.05	Ir	ppb	481	3.2
Rb	ppm	2.3	0.6	Pt	ppb	990	7.1
Sr	ppm	7.8	19.9	Au	ppb	140	1
Y	ppm	1.56	4.3	Hg	ppb	258	10
Zr	ppm	3.94	10.5	Tl	ppb	142	3.5
Nb	ppb	246	658	Pb	ppb	2470	150
Mo	ppb	928	50	Bi	ppb	114	2.5
Ru	ppb	712	5	Th	ppb	29.4	79.5
Rh	ppb	134	0.9	U	ppb	8.1	20.3

[1][*Anders and Grevesse*, 1989]
[2][*McDonough and Sun*, 1995]

Table 2.1. Different models for the major-element composition of the bulk silicate Earth (primitive Mantle)

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
MgO	38.1	38.1	38.3	36.8	35.5	37.8	37.8	36.3
Al_2O_3	4.6	3.3	4.0	4.1	4.8	4.1	4.4	4.7
SiO_2	45.1	45.1	45.1	45.6	46.2	46	45	45.6
CaO	3.1	3.1	3.5	3.5	4.4	3.2	3.5	3.8
FeO	7.9	8	7.8	7.5	7.7	7.5	8.1	8.2
Total	98.8	97.6	98.7	97.5	98.6	98.6	98.8	98.5
Mg#	0.896	0.895	0.897	0.897	0.891	0.899	0.893	0.888

Mg# = Mg/(Mg+Fe)

1. [*Ringwood*, 1975]
2. [*Ringwood*, 1979]
3. [*Jagoutz et al.*, 1979]
4. [*Wänke et al.*, 1984]
5. [*Palme and Nickel*, 1985]
6. [*Hart and Zindler*, 1986]
7. [*O'Neill and Palme*, 1998]

Table 1.2. Comparative chemistries of different Earth reservoirs

	Bulk Silicate Earth[1]	Continental Crust[2]	Oceanic crust	
			Most primitive basaltic glass[3]	Calculated primary composition[4]
MgO (wt. %)	36.33	4.4	10.1	17.81
Al_2O_3 (wt. %)	4.73	15.8	16.4	12.08
SiO_2 (wt. %)	45.56	59.1	49.7	47.85
CaO (wt. %)	3.75	6.4	13.0	11.22
FeO^T (wt. %)	8.17	6.6	7.9	8.98
Mg#	0.888	0.543	0.695	0.780

[1][*O'Neill and Palme*, 1998]
[2][*Rudnick*, 1995]
[3][*Frey et al.*, 1974]
[4][*Elthon*, 1979]
Mg# = molar Mg/(Mg+Fe); FeO^T is total Fe^{2+} and Fe^{3+}

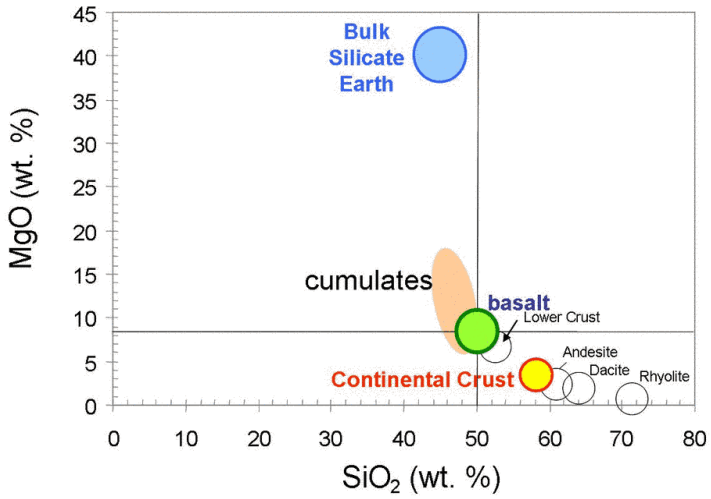
Bulk Silicate Earth major element composition

- How well is it known?

Major-element heterogeneity of mantle

- How does it originate?
- What are the mass proportions of "reservoirs"?
- What is the spatial distribution of heterogeneities?
- Is the mantle stratified?

The whole gamut of silicate differentiation products summarized below



How much basaltic oceanic crust down there?

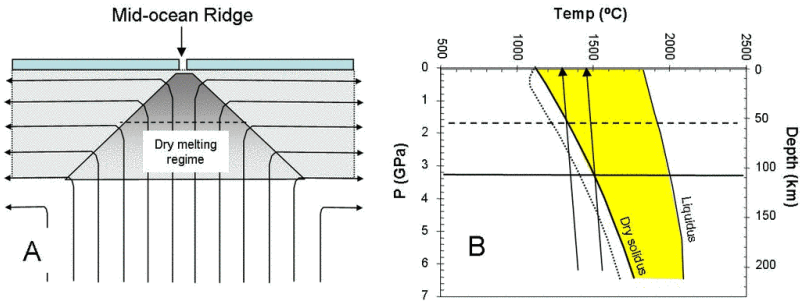
How much delaminated material?

How much harzburgite?

Table 1.1. Some physical properties of the Earth

Mean radius (km)	6371.01		
Total surface area (km^2)	5.10×10^8		
Oceanic surface area (km^2)	3.62×10^8		
Volume (km^3)	1.08×10^{12}		
Mass (kg)	5.97×10^{24}		
Mean density (g/cm^3)	5.52		
Core radius (km)	3485		
	Mass (kg)	% of Whole Earth	% of Bulk Silicate Earth
Total atmosphere	5.14×10^{18}	8.65×10^{-5}	
Hydrosphere	1.66×10^{21}	0.0279	0.0413
Total Crust	2.37×10^{22}	0.3951	0.585
Continental crust	1.52×10^{22}	0.25	0.38
Oceanic crust	8.45×10^{21}	0.14	0.21
Mantle	4.01×10^{24}	67.08	99.37
Bulk Silicate Earth	4.03×10^{24}	67.51	
Core	1.94×10^{24}	32.5	

Data are from [*Lodders and Fegley*, 1998]

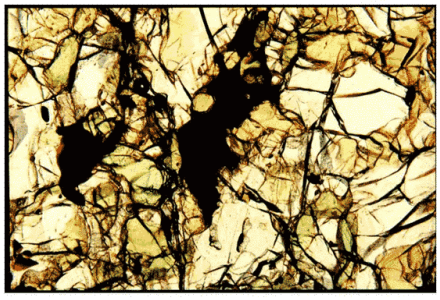


Inspired by Hirth and Kohlstedt 1996

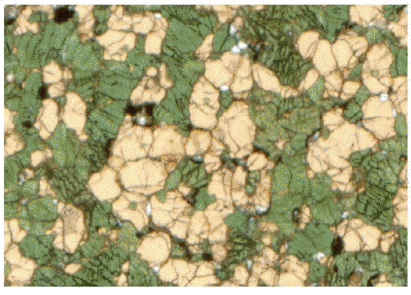
Can we detect any of these heterogeneities?

Compositional effects on seismic velocities

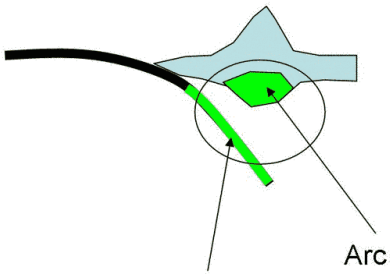
PERIDOTITES

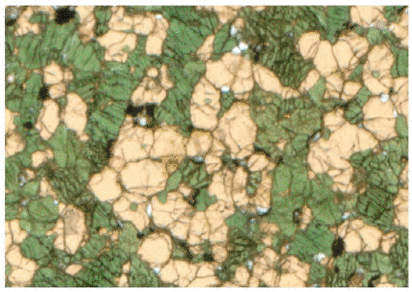


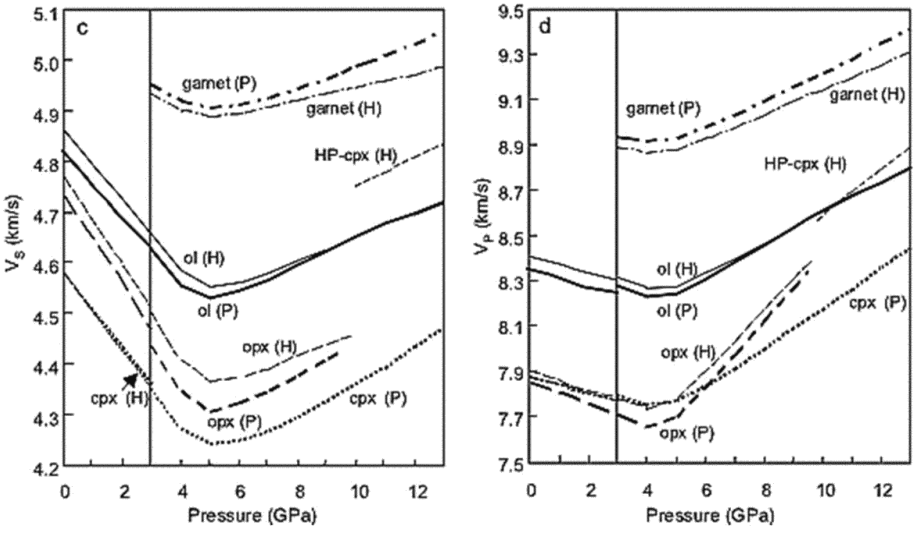
“ECLOGITES”



"ECLOGITES"



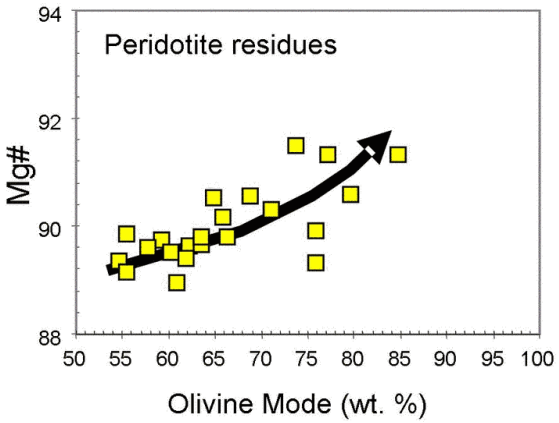




Matsukage, Nishihara, Karato (JGR, 2005)

What are some useful scalings for PERIDOTITES?

Petrogenetic or geodynamic significance



Mg#
High values = melt depleted
High values = lower Fe, lower density

$$Mg\# = \frac{Mg}{Mg+Fe} \times 100$$

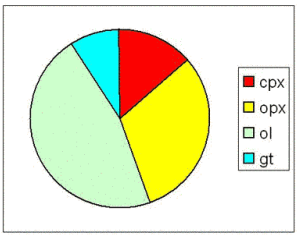
*Mg and Fe in moles

How does seismic velocity vary with Mg#?

The information we need is:

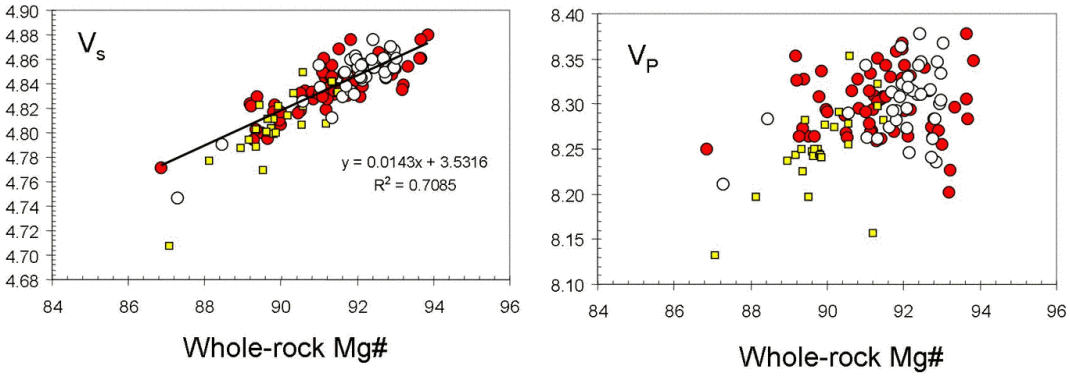
mineralogic proportions

mineral chemistries



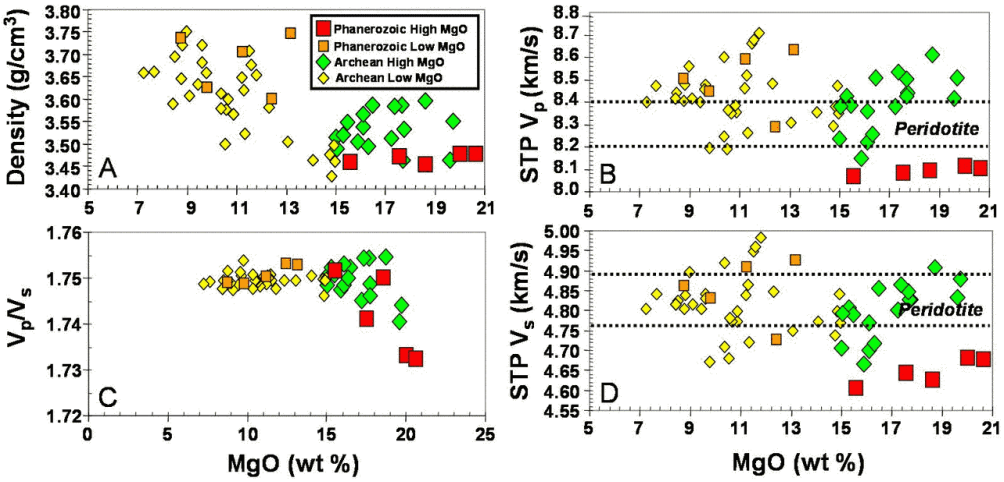
We will assume perfect elasticity
(e.g., anelastic effects ignored; okay for subsolidus)

STP velocities in NATURAL PERIDOTITES

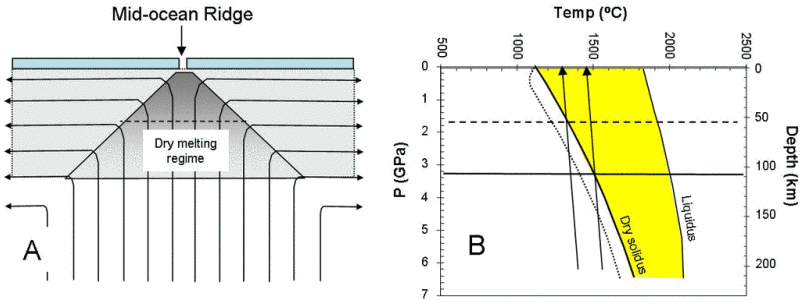


Lee 2003; JGR

ECLOGITES



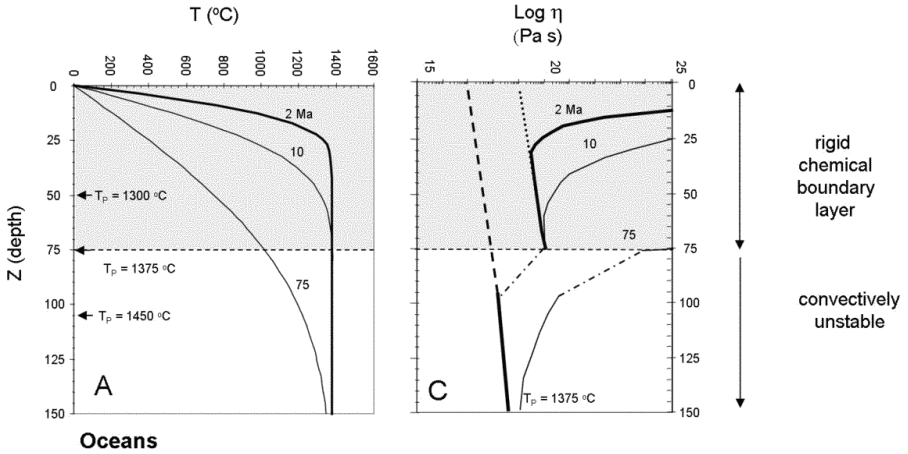
Horodyskyj & Lee



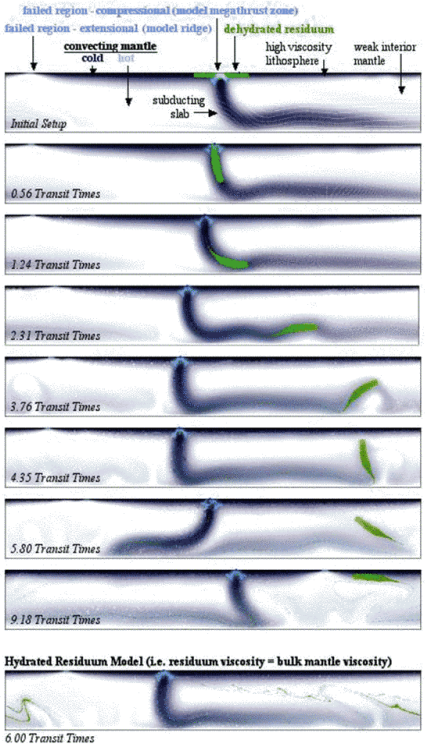
Inspired by Hirth and Kohlstedt 1996

Implications of dehydration for the oceanic lithospheric mantle:

A "rigid" chemical boundary layer is formed



Lee, Lenardic, Cooper, Niu, Levander 2004



Geochemical observations = coherent segments of oceanic lithospheric mantle must be preserved

Preservation possible only if viscosity of lithospheric mantle is high; dehydrated!

Adrian Lenardic
From Lee, Li, Lenardic (2004)

IS THE EARTH'S MANTLE COMPOSITIONALLY STRATIFIED?

THE MOON PROBABLY IS STRATIFIED

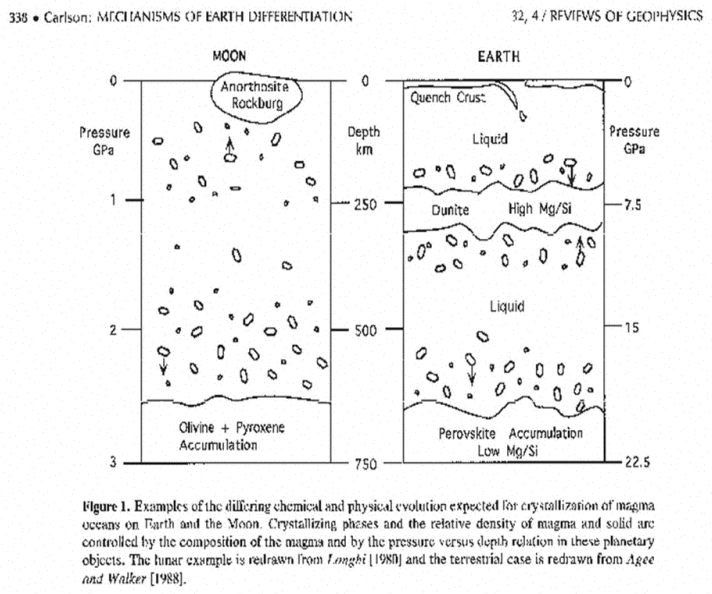
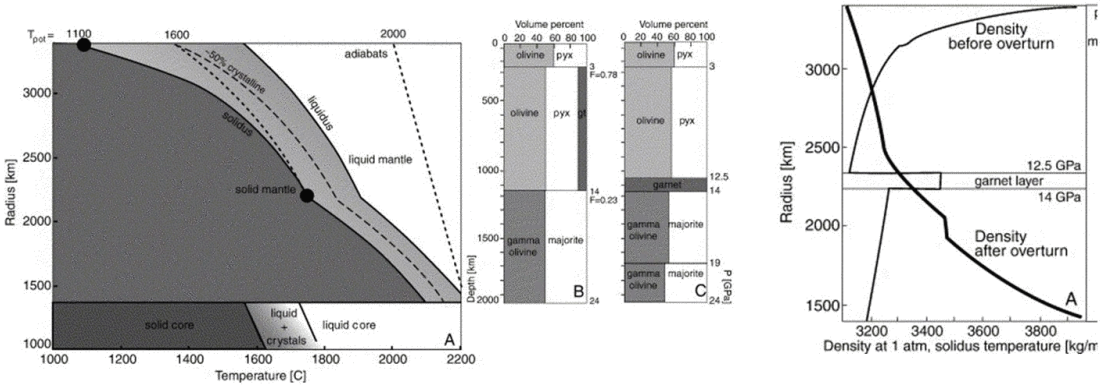


Figure 1. Examples of the differing chemical and physical evolution expected for crystallization of magma oceans on Earth and the Moon. Crystallizing phases and the relative density of magma and solid are controlled by the composition of the magma and by the pressure versus depth relation in these planetary objects. The lunar example is redrawn from *Longhi* [1980] and the terrestrial case is redrawn from *Agee and Walker* [1988].

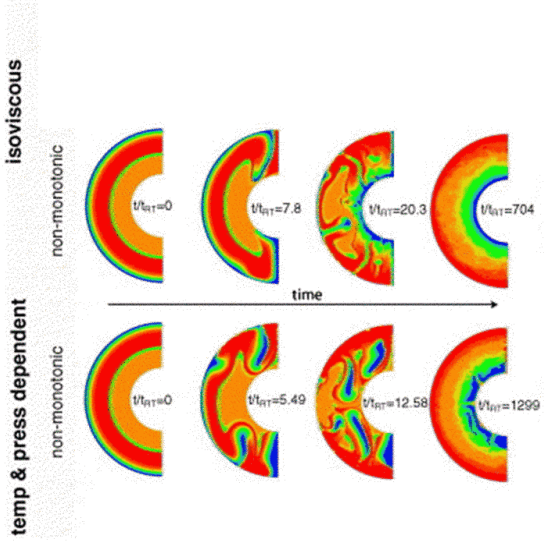
Carlson 1995

MARS MIGHT BE STRATIFIED TOO



Elkins-Tanton, Zaranek, Parmentier, Hess 2005

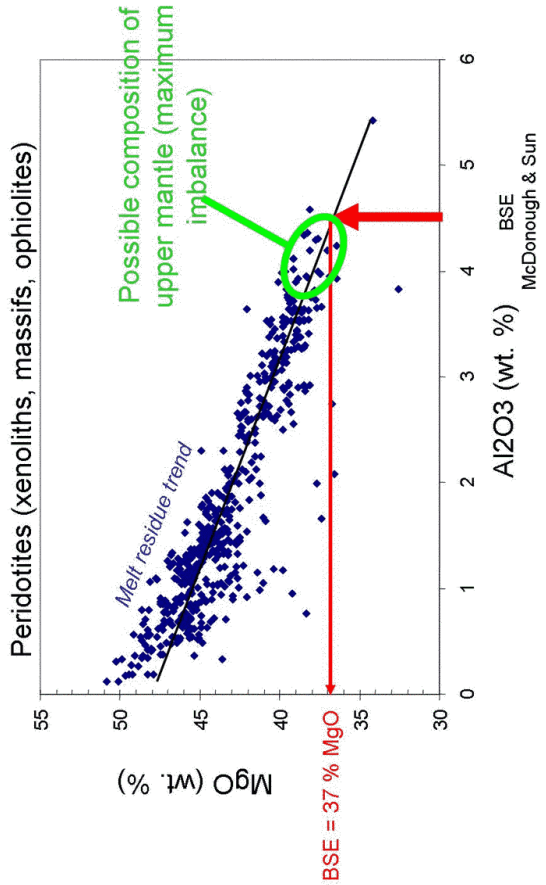
Elkins-Tanton, Zaranek, Parmentier, Hess 2005

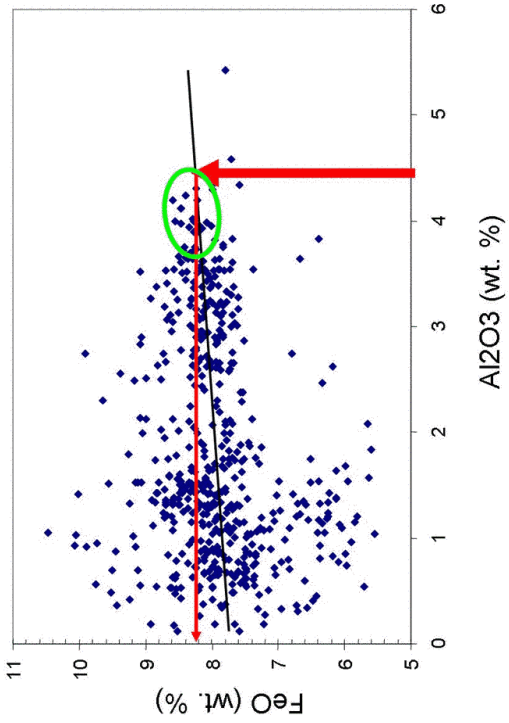


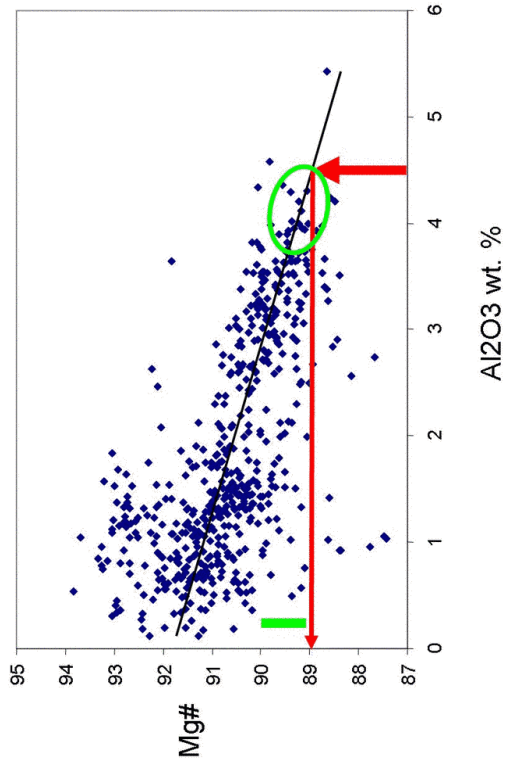
A STRATIFIED EARTH???
(digging up old ghosts)

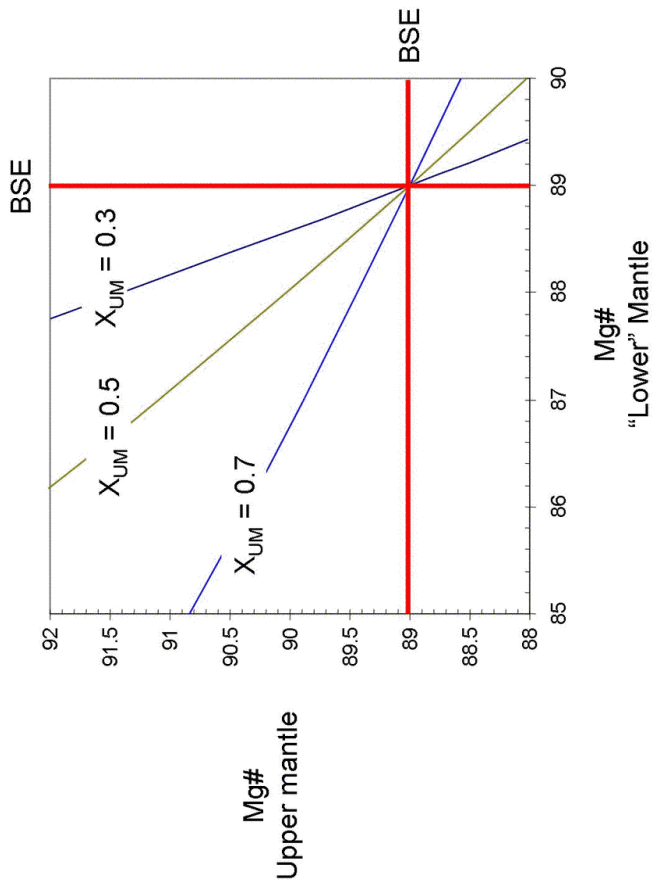
IF WE KNOW BULK SILICATE EARTH COMPOSITION…

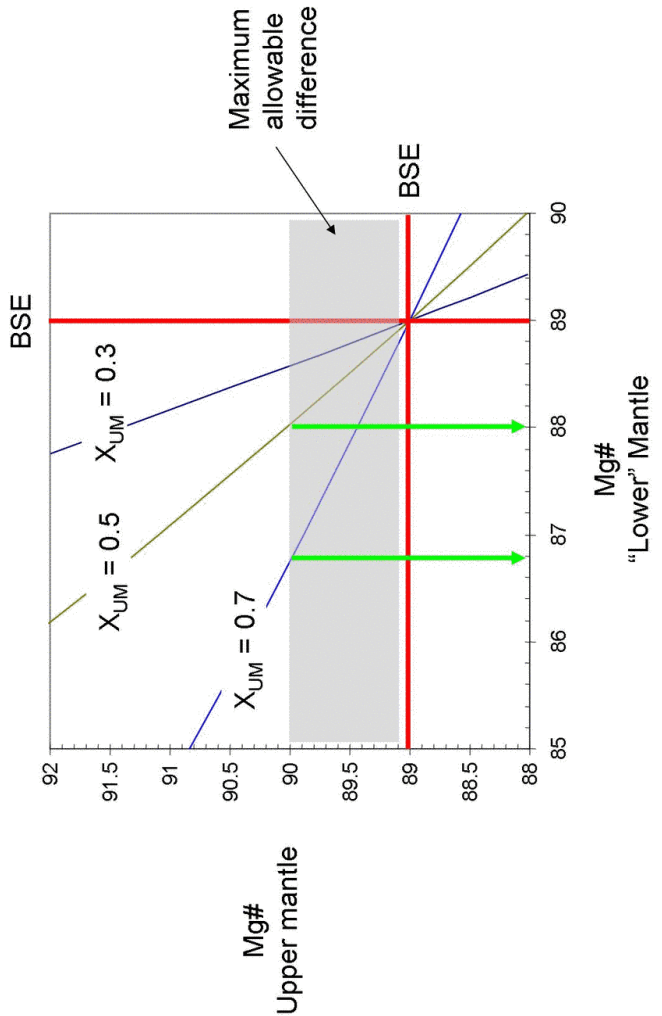
WHAT IS THE COMPOSITION OF THE UPPER (accessible) MANTLE?
In terms of major elements, does it match BSE?

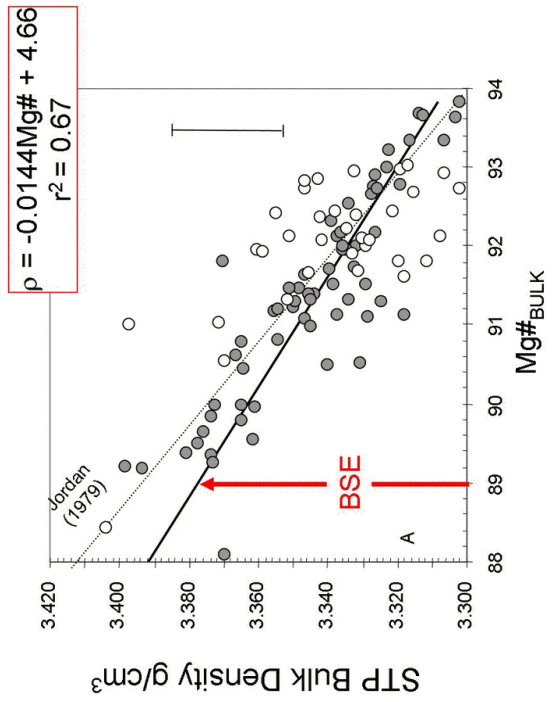

Peridotites (xenoliths, massifs, ophiolites)
Possible composition of upper mantle (maximum imbalance)
Melt residue trend
BSE = 37 % MgO
MgO (wt. %)
55
50
45
40
35
30
Al2O3 (wt. %)
0
1
2
3
4
5
6
BSE
McDonough & Sun


FeO (wt. %)
11
10
9
8
7
6
5
Al2O3 (wt. %)
0
1
2
3
4
5
6


Al2O3 wt. %
Mg#
95
94
93
92
91
90
89
88
87
0
1
2
3
4
5
6

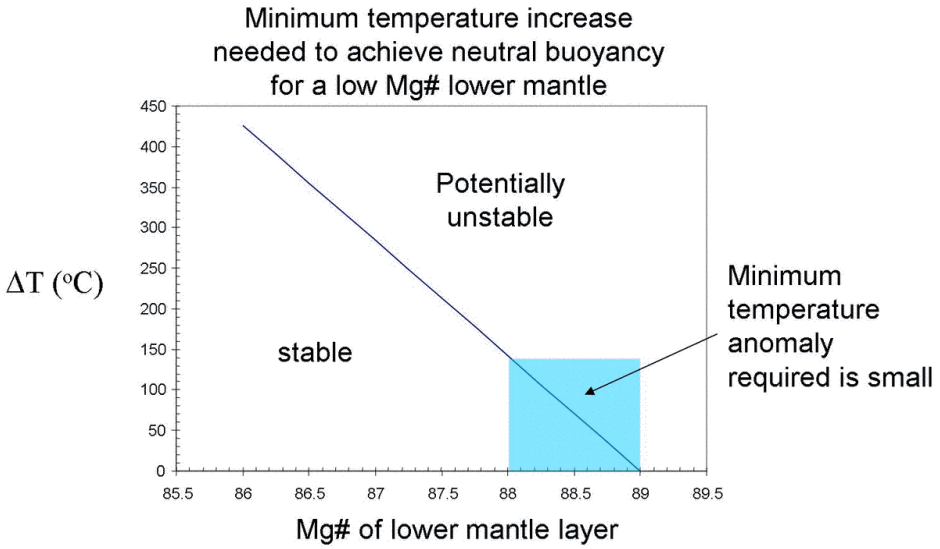

BSE
BSE
X_{UM} = 0.3
X_{UM} = 0.5
X_{UM} = 0.7
Mg#
Upper mantle
Mg#
"Lower" Mantle
92
91.5
91
90.5
90
89.5
89
88.5
88
85
86
87
88
89
90


Maximum allowable difference
BSE
BSE
X_{UM} = 0.3
X_{UM} = 0.5
X_{UM} = 0.7
92
91.5
91
90.5
90
89.5
89
88.5
88
85
86
87
88
89
90
Mg# Upper mantle
Mg# "Lower" Mantle


ρ = -0.0144Mg# + 4.66
r^2 = 0.67
Jordan (1979)
BSE
A
3.420
3.400
3.380
3.360
3.340
3.320
3.300
88
89
90
91
92
93
94
STP Bulk Density g/cm³
$Mg\#_{BULK}$

Lee 2003

$$\frac{\Delta\rho_{th}}{\rho_o} = -\alpha\Delta T \qquad \frac{\Delta\rho_c}{\rho_o} = -\frac{1}{\rho_o}\frac{d\rho}{dMg\#}\Delta Mg\#$$



Bulk Silicate Earth Composition is, for the most part, well-known

Eclogites are seismically detectable
Peridotite variation is difficult to detect seismically
(unless one has Vp/Vs)

The lower mantle today is probably not significantly different in terms of major elements