Mantle geochemistry: How geochemists see the deep Earth

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CIDER - KITP Summer School

Lecture #1, July 2004

Geochemistry 50 years ago dealt with fewer questions and parameters, e.g. Birch (1952)

- How does meteorite chemistry compare with seismic properties of Earth's interior
- Is it Olivine+Pyroxene or other phases ?
- How much Fe in the mantle ?
- How much Al,Ca,Na,K ("sialic components") is in the mantle ?
- 11 elements of interest: O,Mg,Si,Fe,Ni,Al,Ca,S,Na,K,P

What can geochemistry do in 2004?

- The earth is made of 90 or so chemical elements, about 30 w/isotopic variations
- Chemical/isotopic characteristics can be tied to geological processes - *mantle isotopic chemistry is a tracer*
- We can tell where a particular piece of mantle has been in the past and/or what has happened to it
- Radiogenic isotopes provide clocks as well as tracers

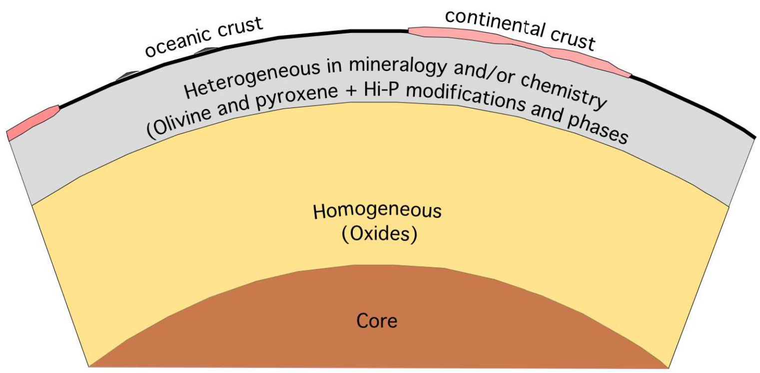
Questions for geochemistry

- How deeply does near surface material circulate into the mantle? On what time scale?
- Does the mantle have large scale chemical structure (layering?)
- Does the core exchange material with the mantle? (Do plumes come from the CMB?)
- What are the characteristics of mantle convection in terms of its ability to stir and homogenize heterogeneous materials?
- What features of mantle seismic heterogeneity are thermal and which are chemical?
- What aspects of mantle structure are congenital?, of recent origin?; steady-state features?

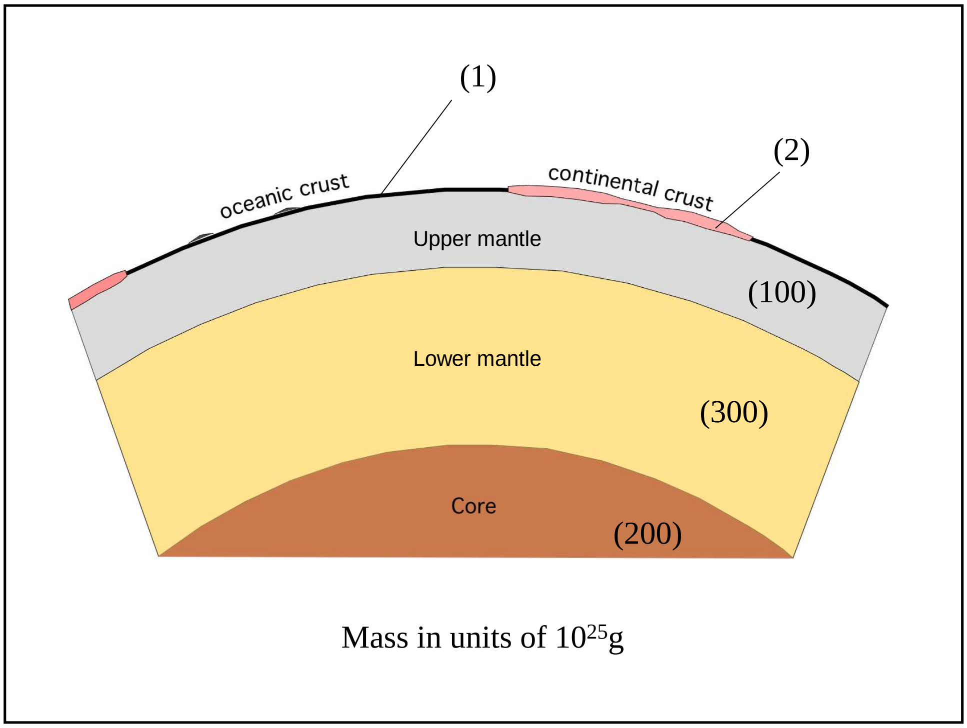
Components of geochemistry

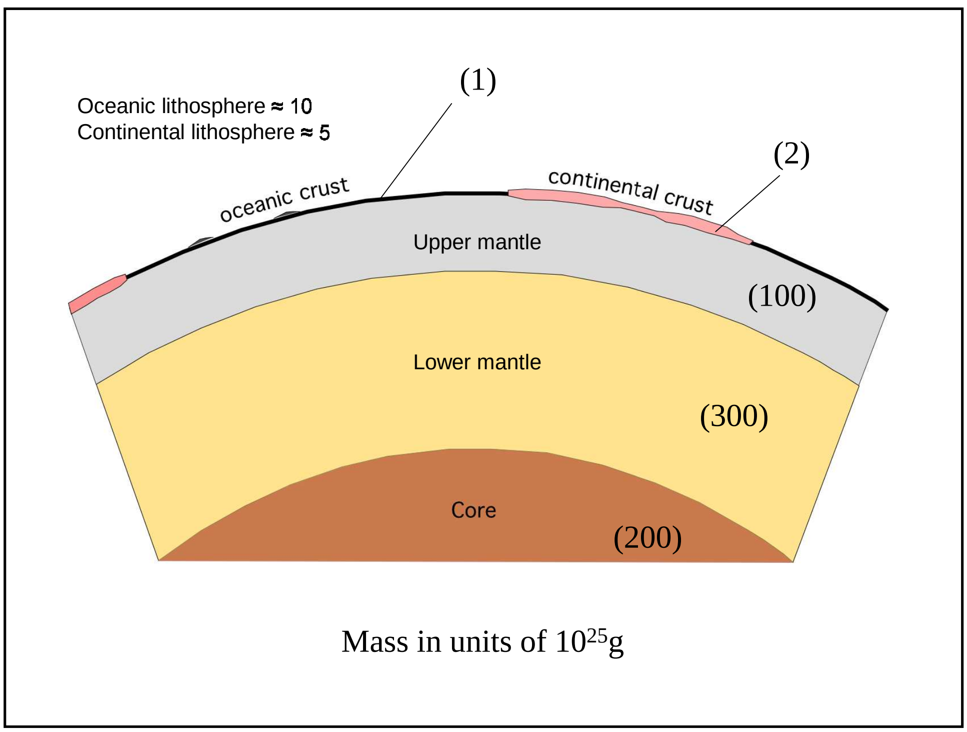
- Petrology of the mantle (proportions of minerals or rock types - e.g. lherzolite, harzburgite, eclogite, pyroxenite)
- Melting of the mantle
- Trace element composition of the mantle (doesn't affect mineralogy, but can be indicative of history)
- Trace element composition II (water and CO_2) - affects melting behavior.
- Isotopic composition of the mantle (from radioactive decay, input from surface reservoirs, input from core?)
- Sampling of the mantle (scale of sampling by magmatism; sampling biases, invisible reservoirs)
- Material balance - the sum of the parts must equal the whole Earth for every element and isotope

The Birch (1952) Mantle

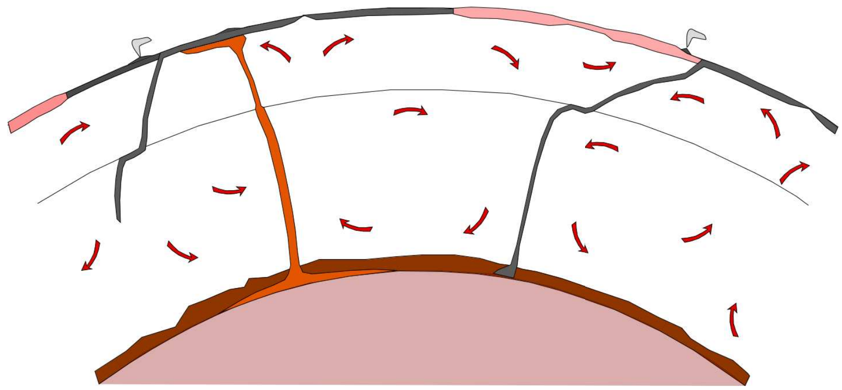


Based primarily on V_p and V_s


(1)
(2)
oceanic crust
continental crust
Upper mantle
(100)
Lower mantle
(300)
Core
(200)
Mass in units of 10^{25}g

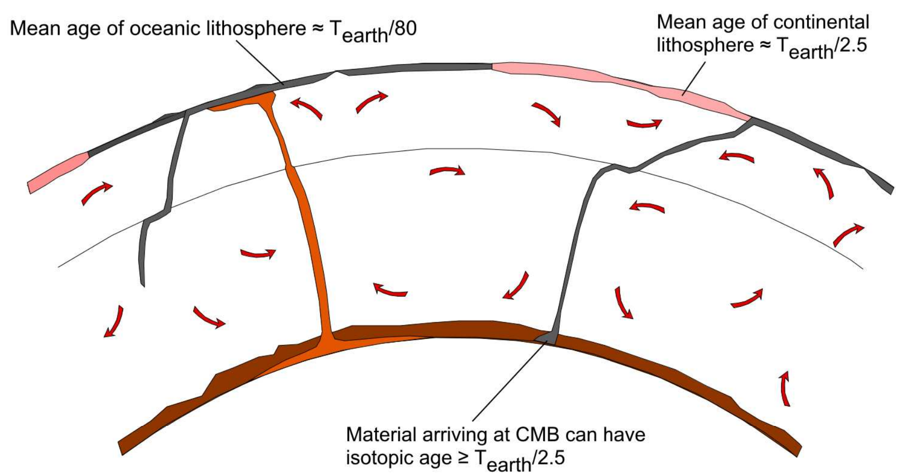

Oceanic lithosphere ≈ 10
Continental lithosphere ≈ 5
(1)
(2)
oceanic crust
continental crust
Upper mantle
(100)
Lower mantle
(300)
Core
(200)
Mass in units of 10^{25}g

Modern picture of the mantle is dynamic



The law of impermanence

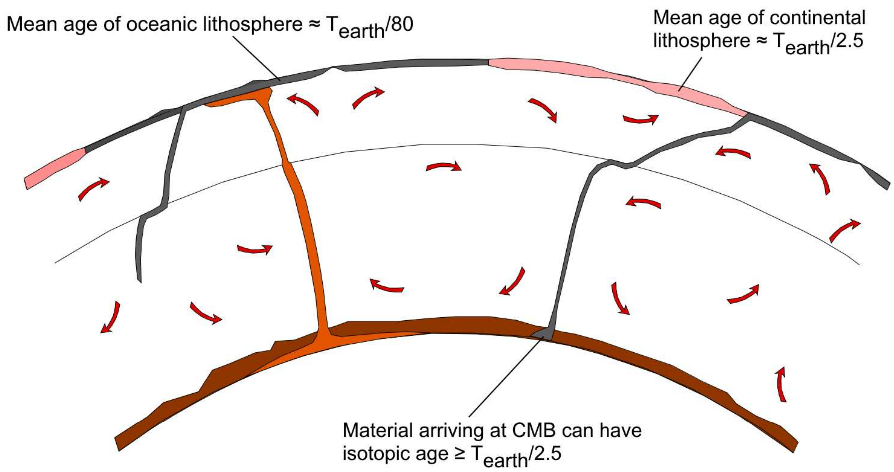
Everything that forms at or near the surface gets reinjected into the deep mantle
(Yes, even the oceans)



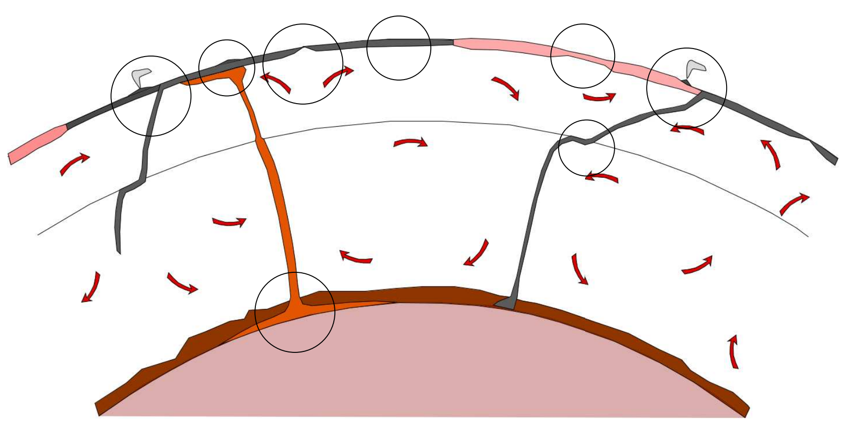
Consider this:

(1) "Heterogeneities" are introduced from the top and the bottom

(2) Magmatism samples only the top and the bottom

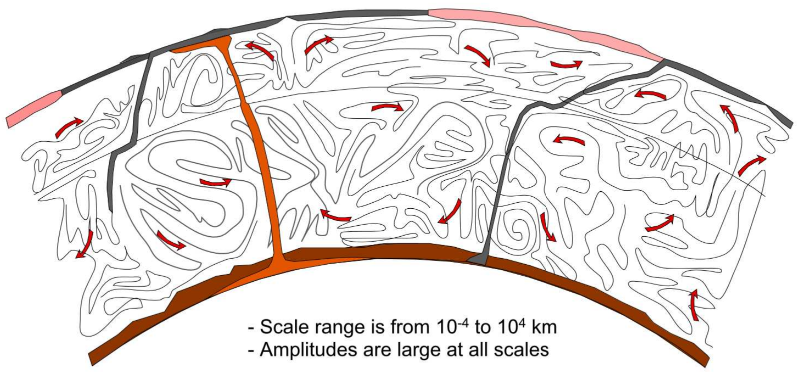


There are key elements of the system where chemistry is done. (Most of what we infer about the mantle depends on how well we understand the processes.)



Heterogeneities in the mantle

Old heterogeneities never die, they don't even fade away, they just get skinny and difficult to sample individually



Heterogeneities have two ages
- age of injection into mantle
- age of material being injected

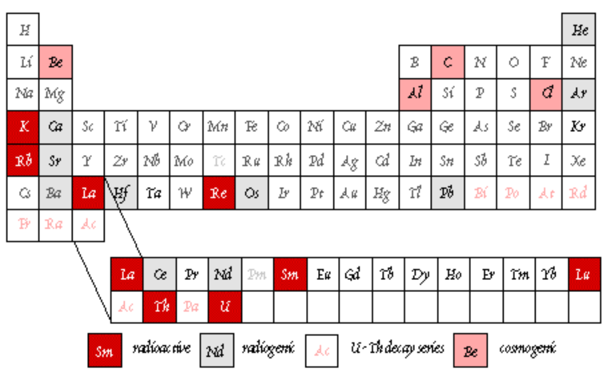
(trap for new players)

Heterogeneities are everywhere
- recycled continental lithosphere/crust
- recycled oceanic lithosphere
  (enriched and depleted)
- plume injections
- discards from the "subduction factory"

Choose one:

There are...
(a) too few
(b) too many
(c) just the right number

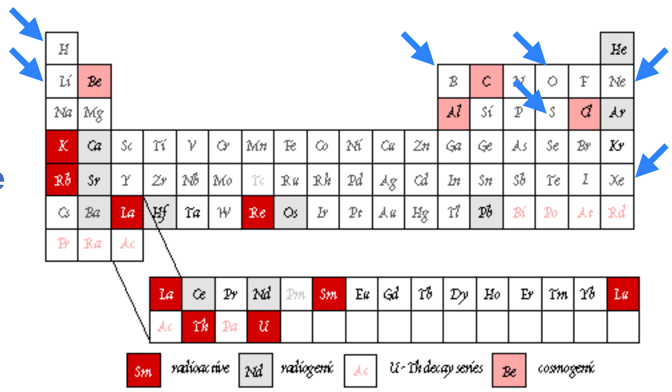
...of isotopic tracers



Parent	Decay Mode	λ	Half-life	Daughter	Ratio
^{40}K	β^+, e.c, β^-	$5.543 \times 10^{-10} y^{-1}$	1.28×10^{9} yr	^{40}Ar, ^{40}Ca	$^{40}Ar/^{36}Ar$
^{87}Rb	β^-	$1.42 \times 10^{-11} y^{-1}$	4.8×10^{10} yr	^{87}Sr	$^{87}Sr/^{86}Sr$
^{138}La	β^-	$2.67 \times 10^{-12} y^{-1}$	2.59×10^{11} yr	^{138}Ce	$^{138}Ce/^{142}Ce$, $^{138}Ce/^{136}Ce$
^{147}Sm	α	$6.54 \times 10^{-12} y^{-1}$	1.06×10^{11} yr	^{143}Nd	$^{143}Nd/^{144}Nd$
^{176}Lu	β^-	$1.94 \times 10^{-11} y^{-1}$	3.6×10^{10} y	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	β^-	$1.64 \times 10^{-11} y^{-1}$	4.23×10^{10} y	^{187}Os	$^{187}Os/^{186}Os$, $^{187}Os/^{188}Os$
^{232}Th	α	$4.948 \times 10^{-11} y^{-1}$	1.4×10^{10} y	^{208}Pb, ^{4}He	$^{208}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{235}U	α	$9.849 \times 10^{-10} y^{-1}$	7.07×10^{8} y	^{207}Pb, ^{4}He	$^{207}Pb/^{204}Pb$, $^{3}He/^{4}He$
^{238}U	α	$1.551 \times 10^{-10} y^{-1}$	4.47×10^{9} y	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

Note: the branching ratio, i.e. ratios of decays to ^{40}Ar to total decays of ^{40}K is 0.117. The production of ^{4}He from ^{147}Sm decay is insignificant compared to that produced by decay of U and Th.

There are stable isotopes too !



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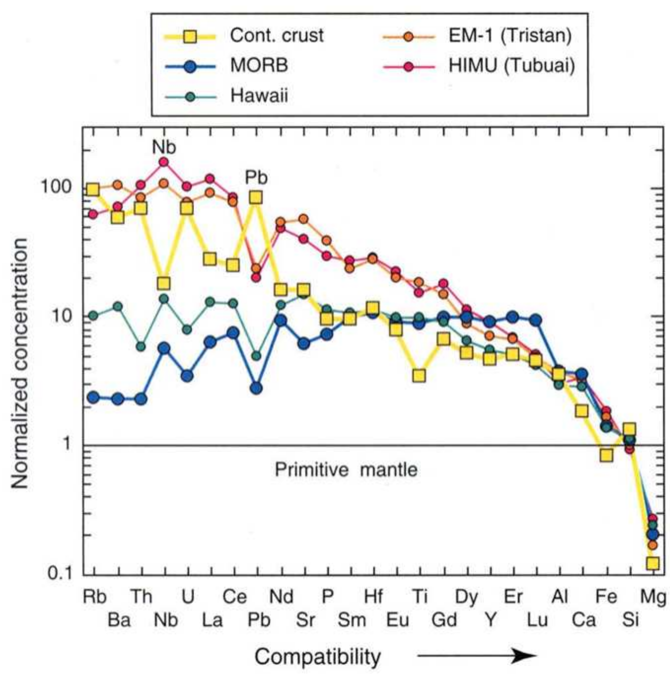
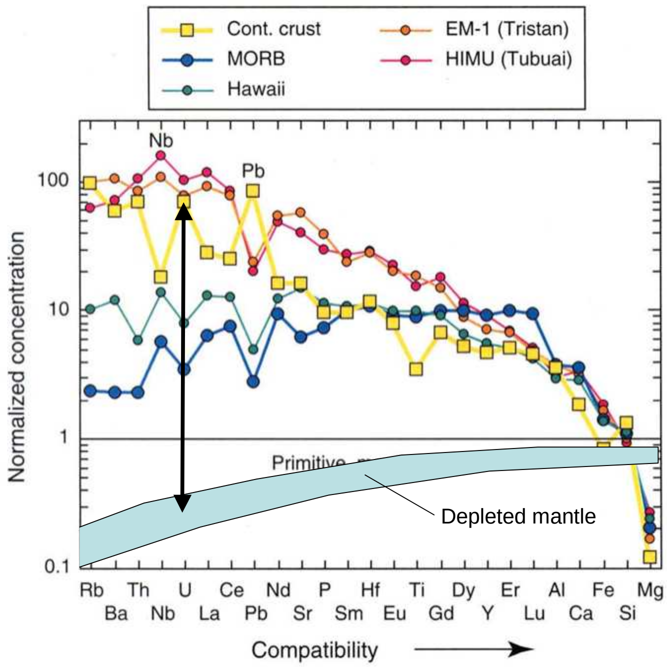
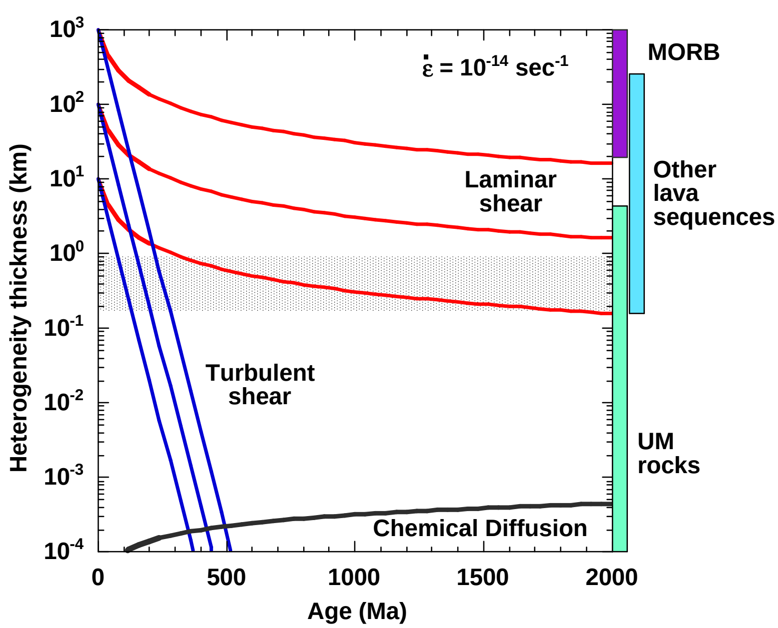
Why the crustal reservoirs matter...

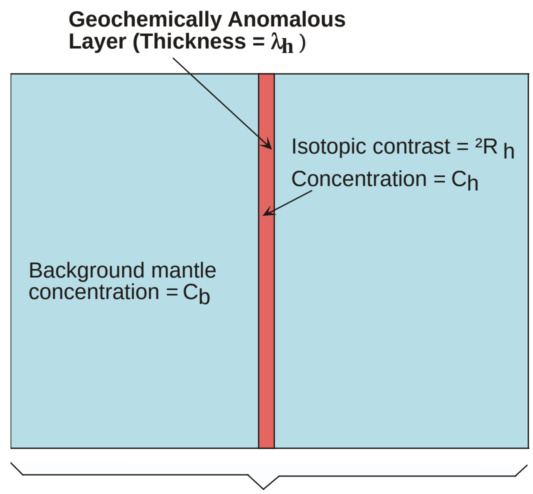


Why the crustal reservoirs matter...





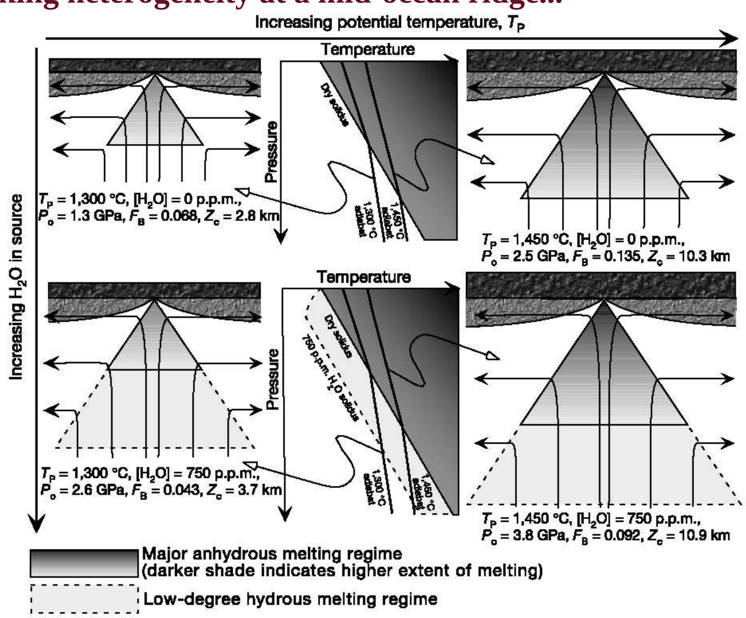
Thickness of geochemical anomalies

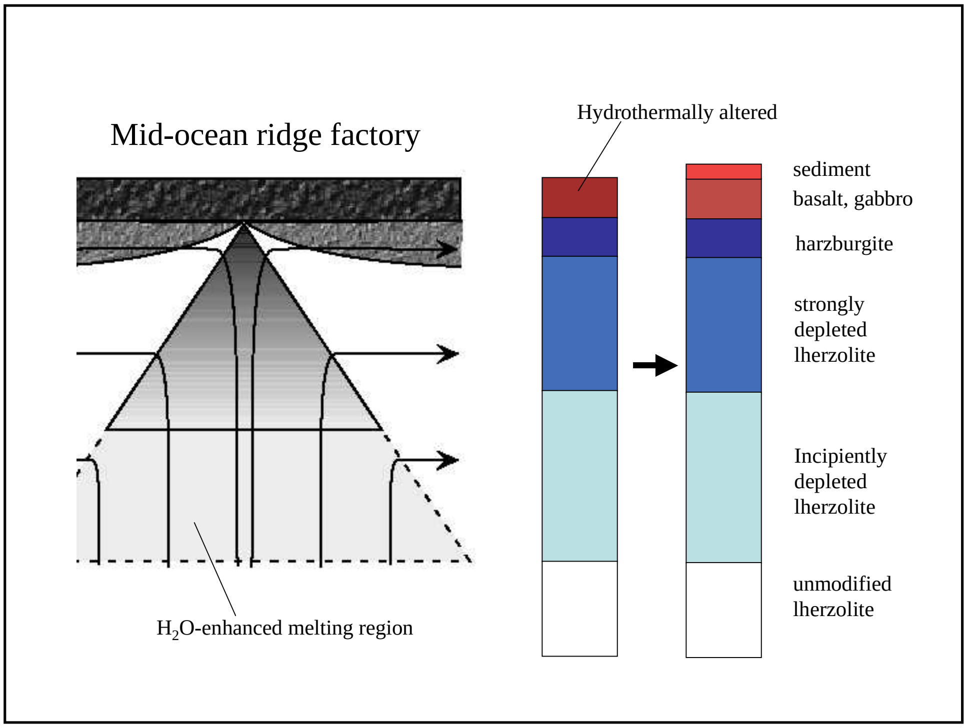


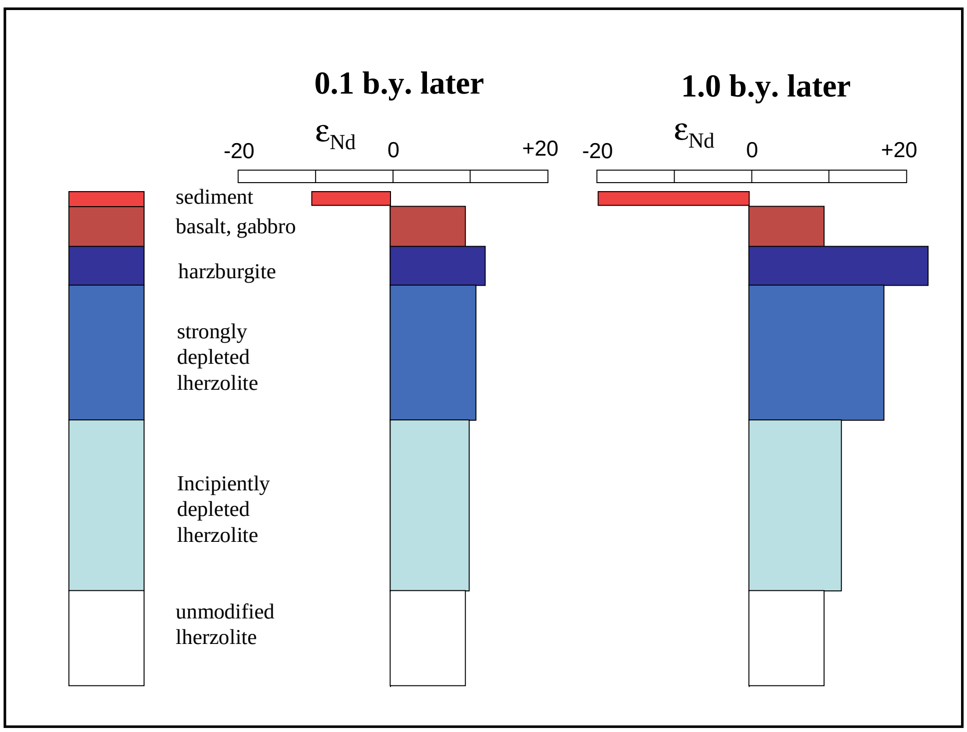
Background mantle that must be averaged with anomalous material (effective anomaly thickness):

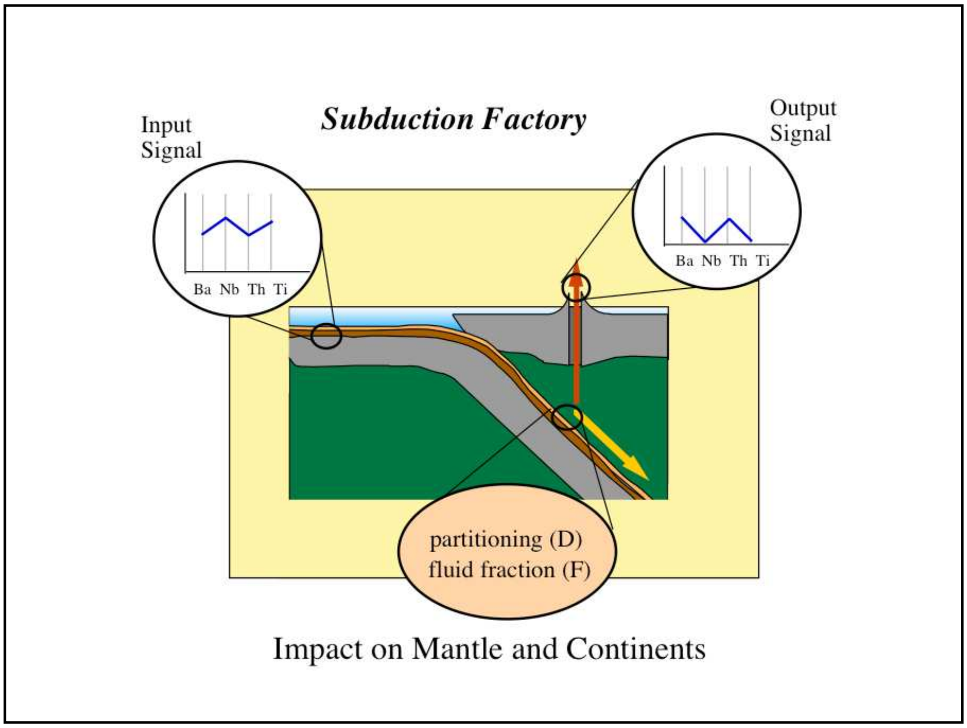
$$\lambda_b = \lambda_h \frac{C_h \, {}^2R_h}{C_b \, {}^2R_a}$$

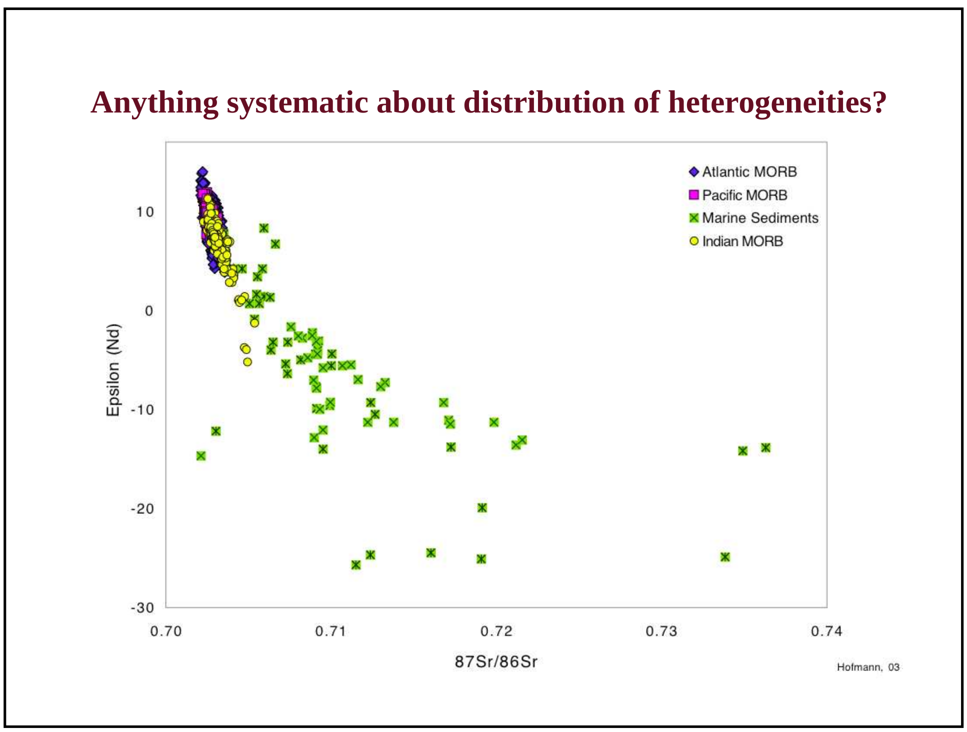
Making heterogeneity at a mid-ocean ridge...



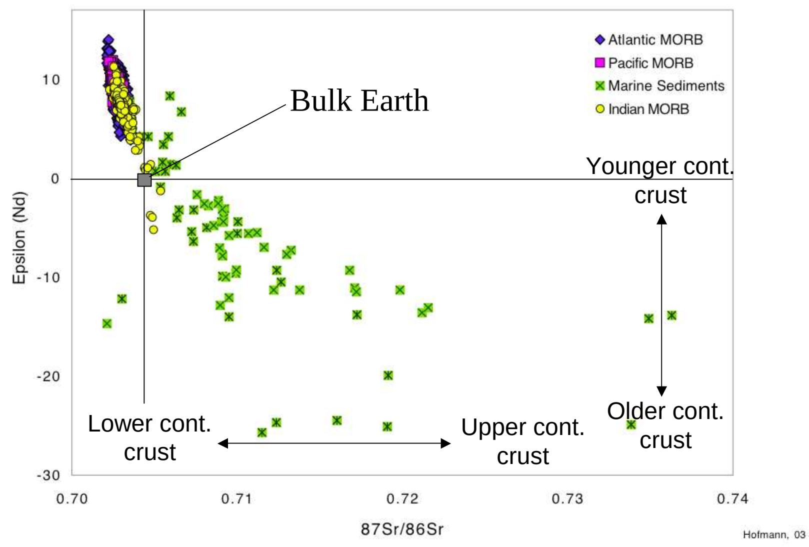

Mid-ocean ridge factory
Hydrothermally altered
sediment
basalt, gabbro
harzburgite
strongly depleted lherzolite
Incipiently depleted lherzolite
unmodified lherzolite
H_2O-enhanced melting region


0.1 b.y. later
1.0 b.y. later
ε_{Nd}
-20
0
+20
sediment
basalt, gabbro
harzburgite
strongly depleted lherzolite
Incipiently depleted lherzolite
unmodified lherzolite

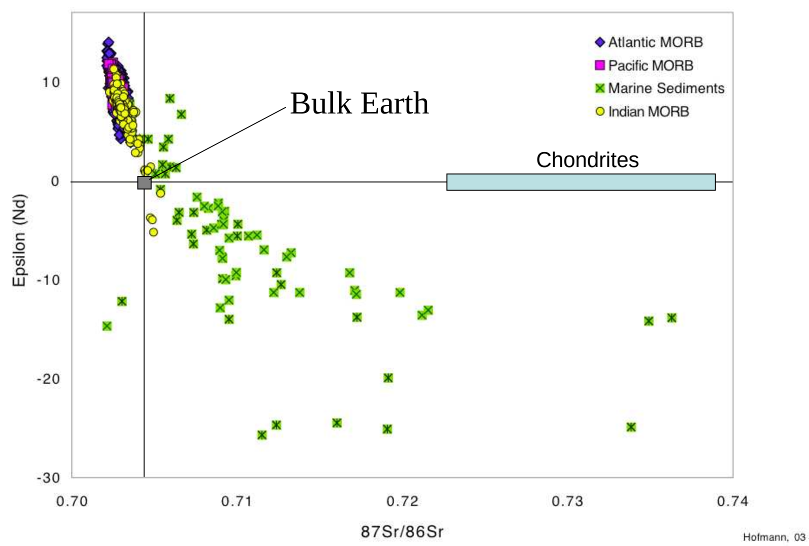

Subduction Factory
Input Signal
Output Signal
Ba Nb Th Ti
Ba Nb Th Ti
partitioning (D)
fluid fraction (F)
Impact on Mantle and Continents

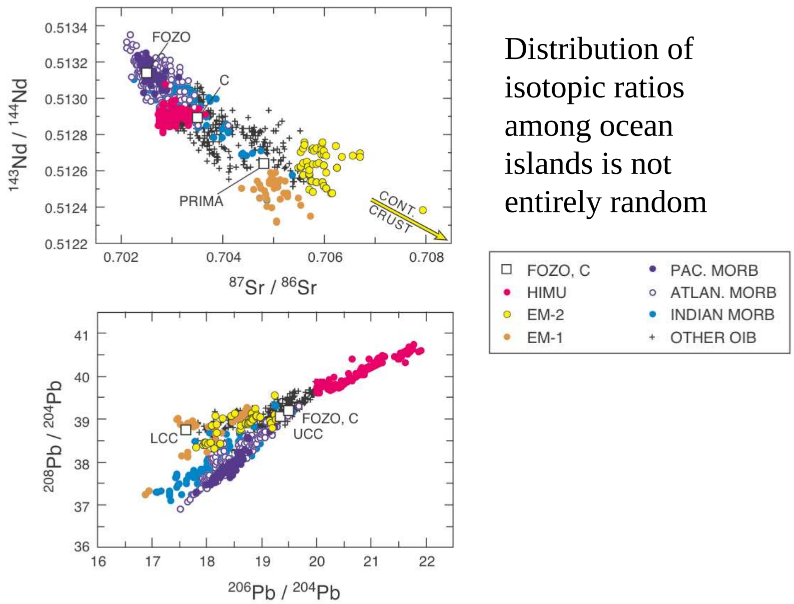

Anything systematic about distribution of heterogeneities?
Atlantic MORB
Pacific MORB
Marine Sediments
Indian MORB
Epsilon (Nd)
10
0
-10
-20
-30
0.70
0.71
0.72
0.73
0.74
87Sr/86Sr
Hofmann, 03

Anything systematic about distribution of heterogeneities?



Anything systematic about distribution of heterogeneities?



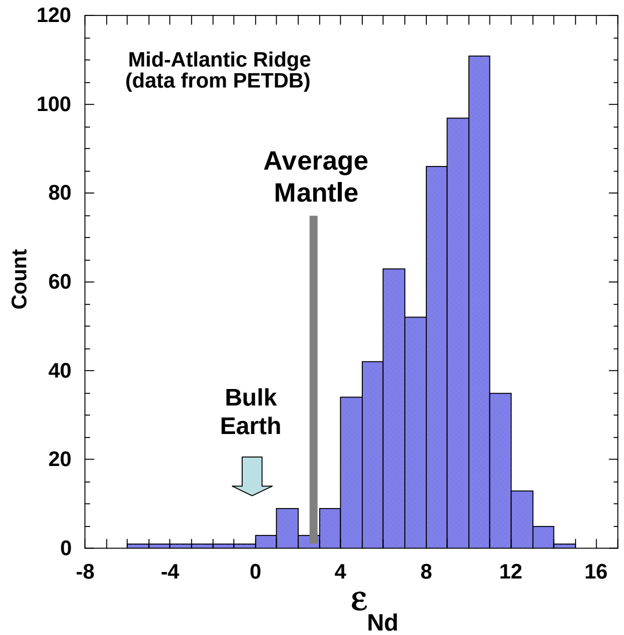


Distribution of isotopic ratios among ocean islands is not entirely random

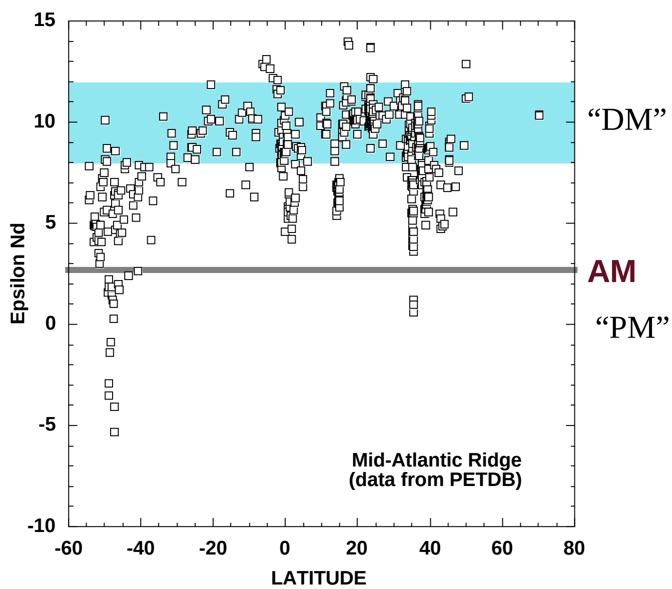
Recycled Reservoir	Subduction Flux km^3/yr	Predicted Fingerprint
Lithospheric mantle	200	High ε(Nd, Hf), low $^{206}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$
Depleted Oceanic crust	20	Slightly lower ε(Nd, Hf), maybe Iceland, Hawaii
Oceanic crust modified by Pb and Rb loss		High $^{206}Pb/^{204}Pb$, low $^{87}Sr/^{86}Sr$ = "HIMU"
Oceanic islands & plateaus	1	Main correlations in Sr, Nd, Hf, Pb space
Altered crust	<10	Changes in K, Rb, Pb, U etc. Extreme isotopic compositions not observed in OIB
Sediment, terrigenous	<1	Highest $^{87}Sr/^{86}Sr$, low ε(Nd, Hf), high Pb, low Nb Concentrations. = "EM-2"
Sediment, pelagic	<1	High $^{87}Sr/^{86}Sr$, lowest ε(Nd), higher ε(Hf) Very low $^{206}Pb/^{204}Pb$, higher $^{208}Pb/^{204}Pb$ = "EM-1"
Delaminated subcontinental lithosphere	??	Alternative origin of "EM-1" OIBs

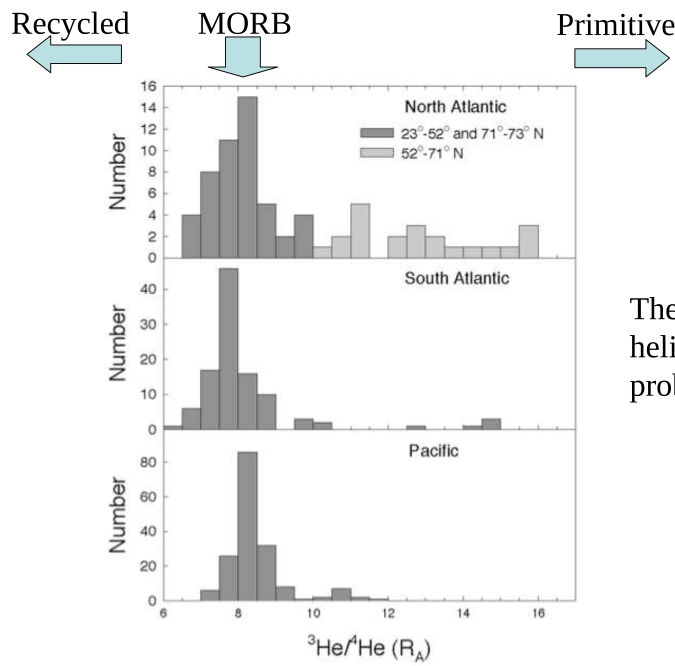
Al Hofmann's analysis, 2003

Material balance for Sm-Nd...



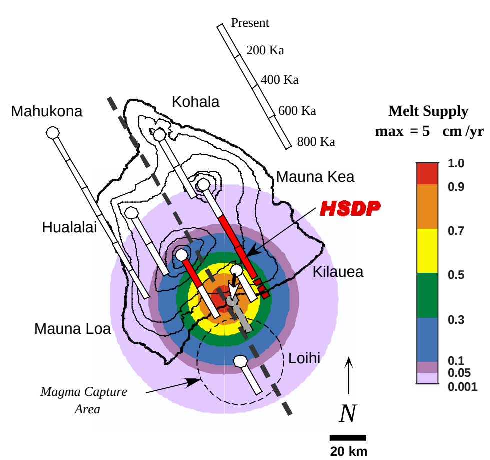
An example of heterogeneity on various scales - Nd isotopes in MAR basalts. 5 to 10 units of variation can be found over 10km or 10,000km along the ridge. The entire range of values observed worldwide (in all types of oceanic basalts) is found along the ridge

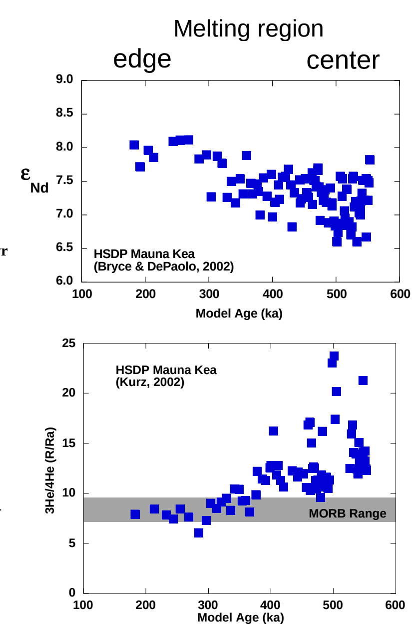


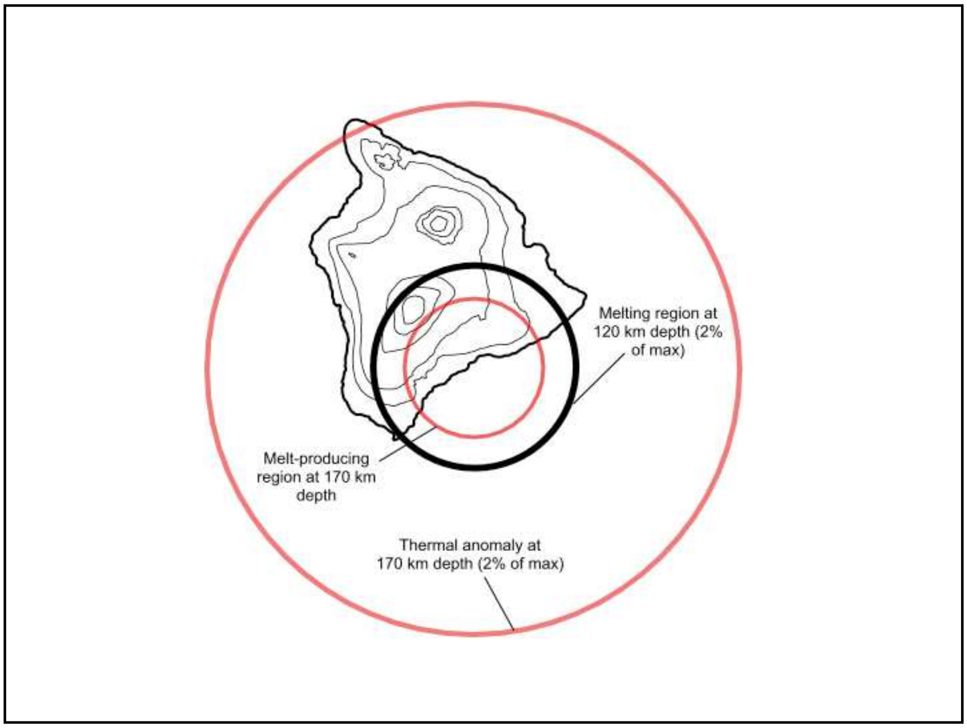


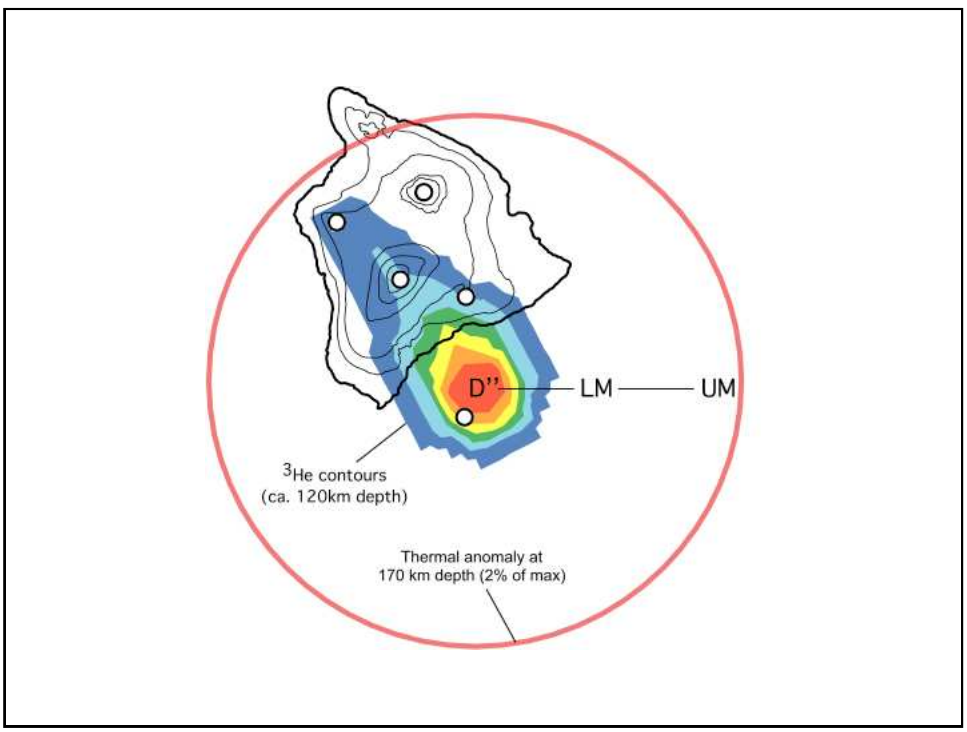
The helium problem

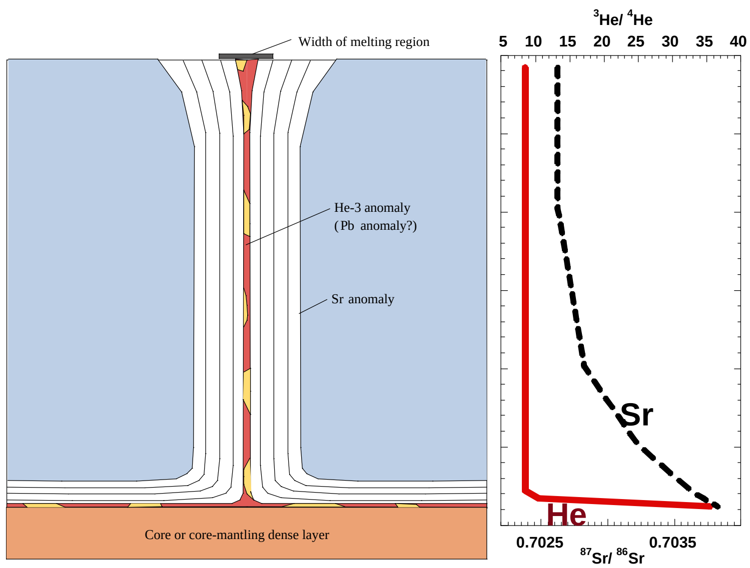
Sampling issues: Pt. 1

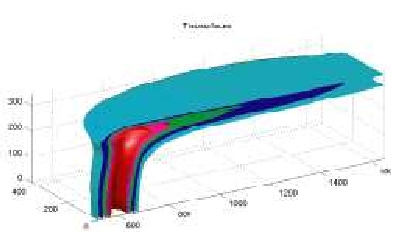


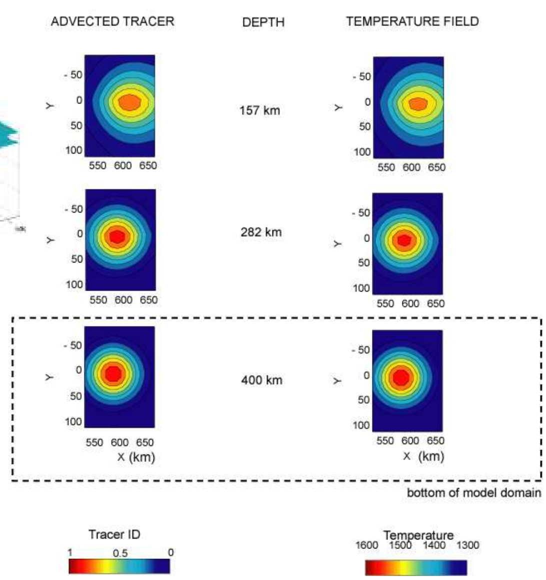



Melting region at 120 km depth (2% of max)
Melt-producing region at 170 km depth
Thermal anomaly at 170 km depth (2% of max)


D''
LM
UM
3He contours (ca. 120km depth)
Thermal anomaly at 170 km depth (2% of max)

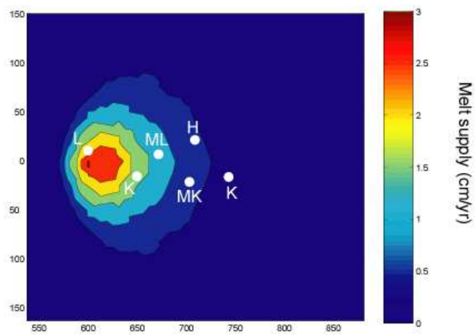


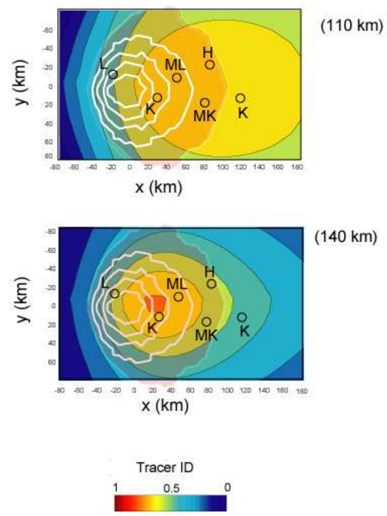




Things may get even more interesting when we model the melting in the context of the flow - (M. Jull, unfinished, 2003)

Melting versus tracers...



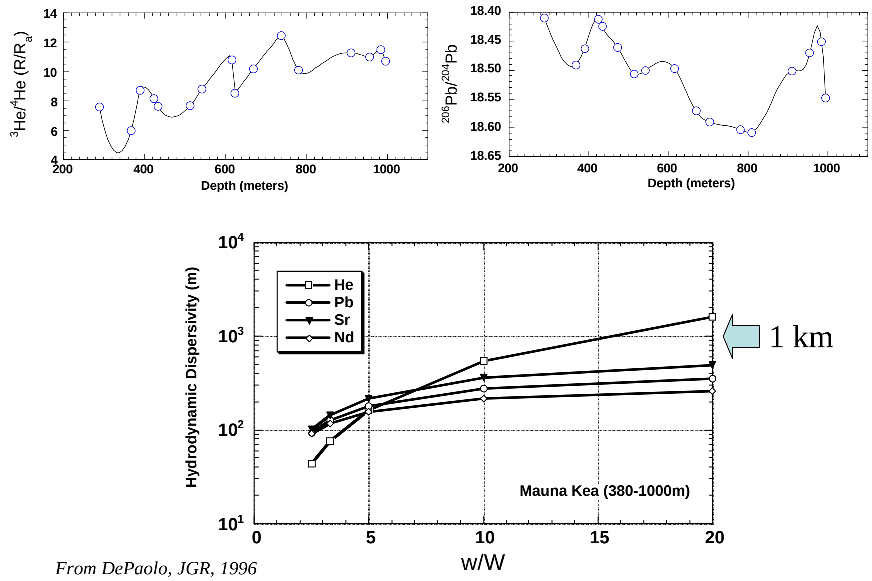


(Modeling from Jull & Ribe, 2002)

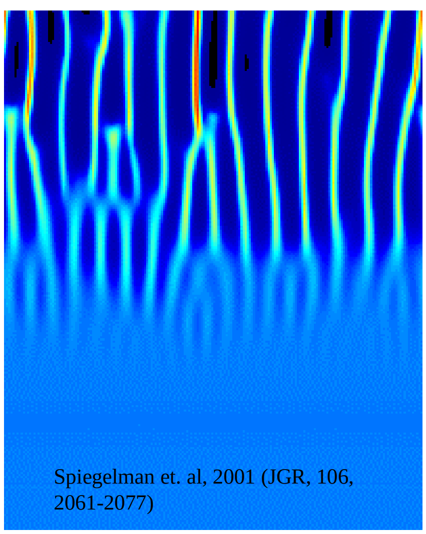
Sampling issues, Pt. 2:
Over what vertical distance are isotopic ratios averaged?

DePaolo, JGR, 1996

Estimating dispersivity in the Hawaii melting region



From DePaolo, JGR, 1996



Spiegelman et. al, 2001 (JGR, 106, 2061-2077)

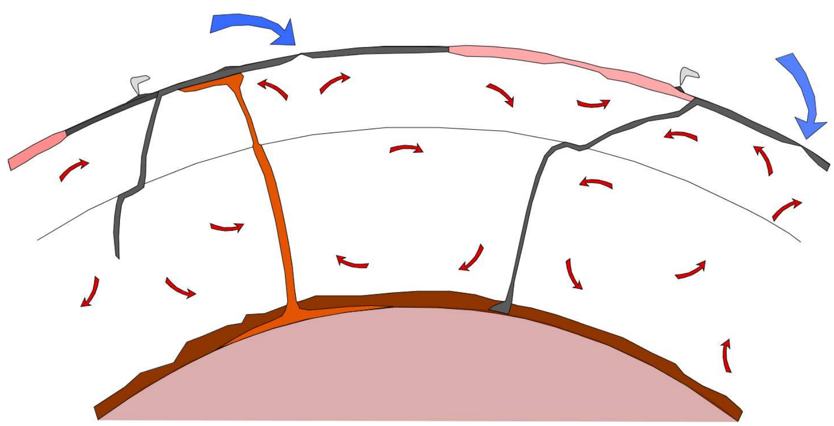
For MOR's the channeling instability may apply; makes for very large vertical dispersion - i.e. lots of averaging. May not be the case for plumes (?)

OK, so what do we think we know......?

Mid-ocean Ridge Basalts.....

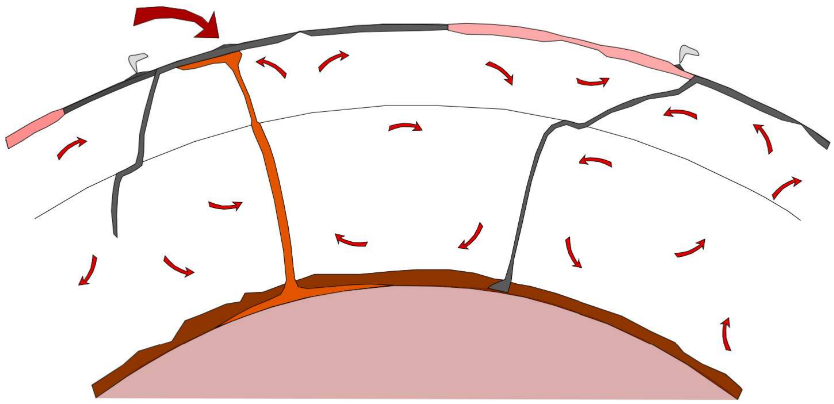
The typical mantle that melts at MOR's...

- 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...

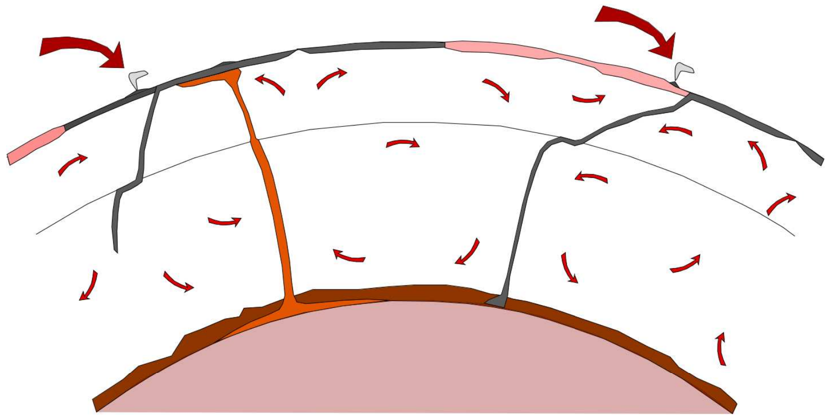
- Exist
- Bring materials up from depth that are different from the ambient upper mantle
- Consist of material that is not primitive (usually "less depleted" than MORB)
- Sometimes contain Helium that looks primitive (but with Nd, Sr, Pb, Hf that does not look primitive)



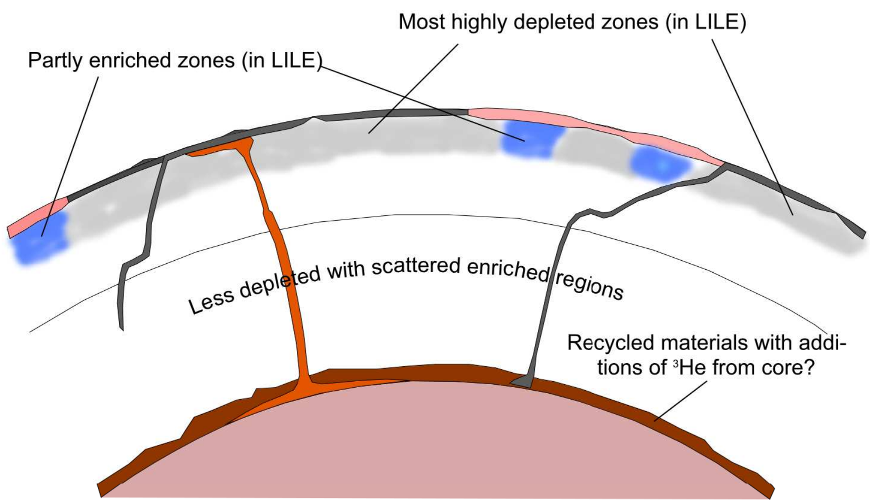
Island Arcs and Backarcs.....

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:



Where we are going in the next 2 weeks....

Lecture 1. Overview: The Geochemists' Earth (reservoirs, budgets and processes). DePaolo.
Lecture 2. *Background A.* Initial Conditions – the early earth and moon, meteorites, extinct radioactivities, terrestrial reservoirs and lithologies. Hart.
Lecture 3. *Background B.* The Tools – Systematics and behavior of trace element and radiogenic isotope tracer systems (diffusion, partitioning, spidergrams, radioactive decay, mixing in open systems). Hart.
Lecture 4. Physics of melting and melt migration: trace element and U-series models. DePaolo.
Lecture 5. Stable isotopes and rare gases: tracers of the shallow earth and tracers of the deep earth? Hart.
Lecture 6. Geochemical evolution and fingerprinting of terrestrial reservoirs: Core, Bulk silicate earth (BSE), Continental crust (CC). DePaolo.
Lecture 7. (continuation of Lecture 6). Geochemical evolution and fingerprinting of terrestrial reservoirs: Primitive upper mantle (PUM), Depleted MORB mantle (DMM) and other mantle domains (HIMU, EM1, EM2, FOZO). Hart.
Lecture 8. Distribution of heat-producing radioactivities (K, U, Th) in the Earth. Hart.
Lecture 9. Terrestrial budgets and evolution modeling. DePaolo.

Geochemistry Tutorials....

Exercises:
a) Nuts and Bolts: chemistry, mass specs, standards and constants, normalization, precision (Hart).
b) Navigating GERM: finding and evaluating geochemical reference data (Hart and DePaolo).
c) GEOROC and PETDB: the world of MORB and OIB data manipulation (Hart).
d) MELTS – understanding differentiation with the MELTS program (Stolper or Asimow).
e) Crust-Mantle Box models; Integrating geochemical reservoir models with tomographic and geodynamic constraints (DePaolo).
f) Melting and melt migration: porous flow and focussed flow models, U-series constraints, spidergram inversions (DePaolo and Hart).