Modeling "Modern" Mantle Composition

- Models for the BSE (bulk silicate Earth) and the "upper" & "lower" mantle
- Uncertainty in models
- model of "lower" mantle composition
- Mass balance and implications for the composition of the BSE

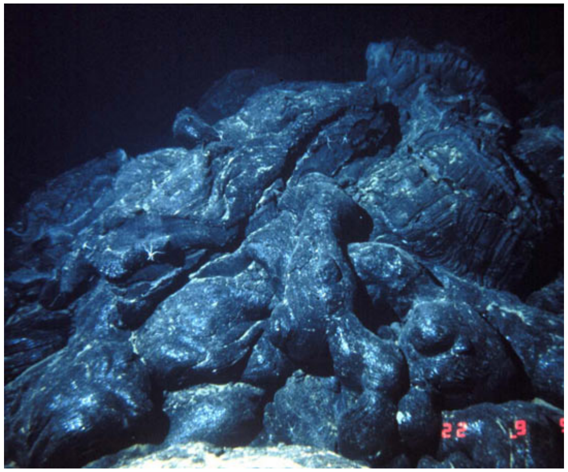
Rick Arevalo (NASA/Goddard)
Bill McDonough (Univ of Maryland)

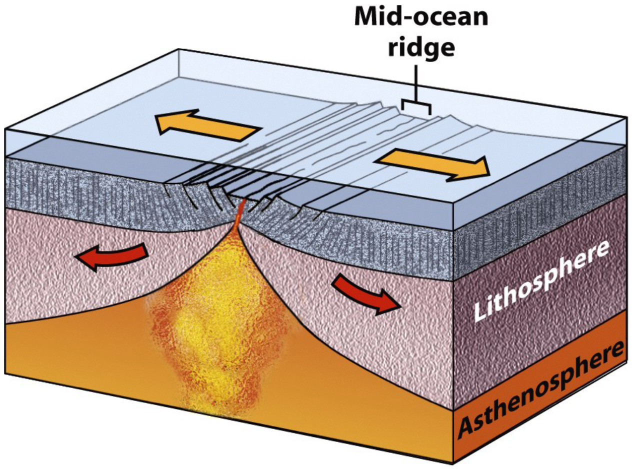
Why study the composition of MORB

- Insights into the composition of the bulk Earth

- Understand differentiation of the BSE
  (BSE : Bulk Silicate Earth = crust + mantle)

- Identify the distribution of elements in the Earth

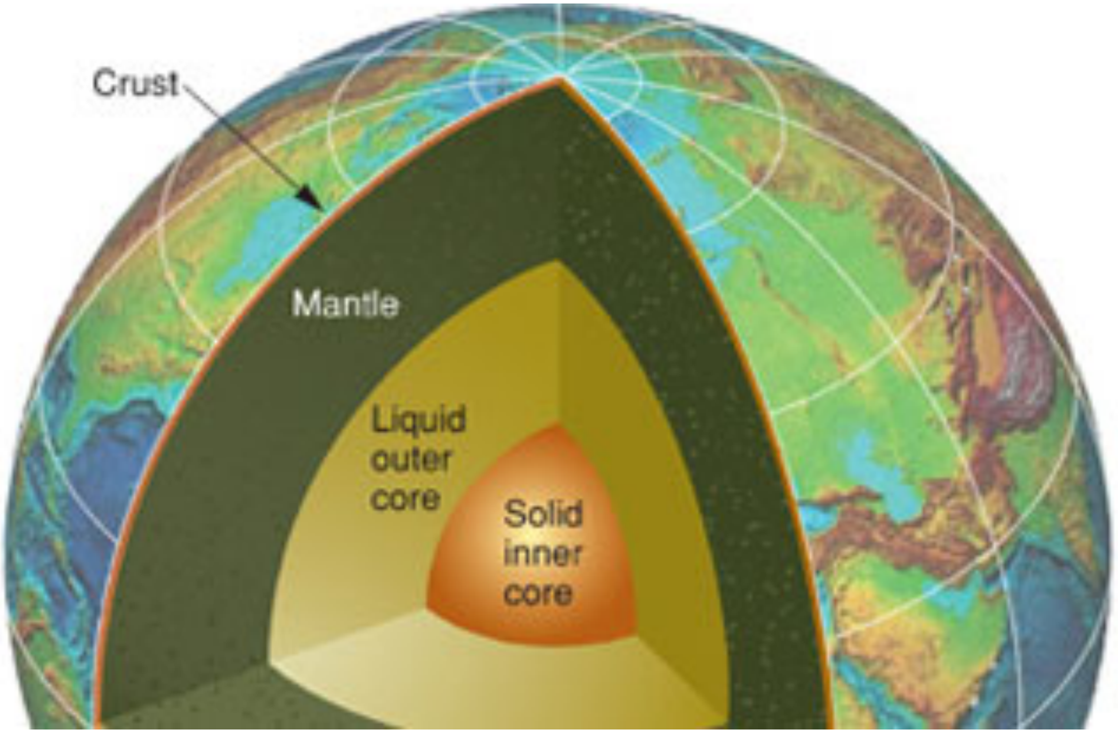




Divergent Plate Boundary

The Mantle: it is the source of basalts

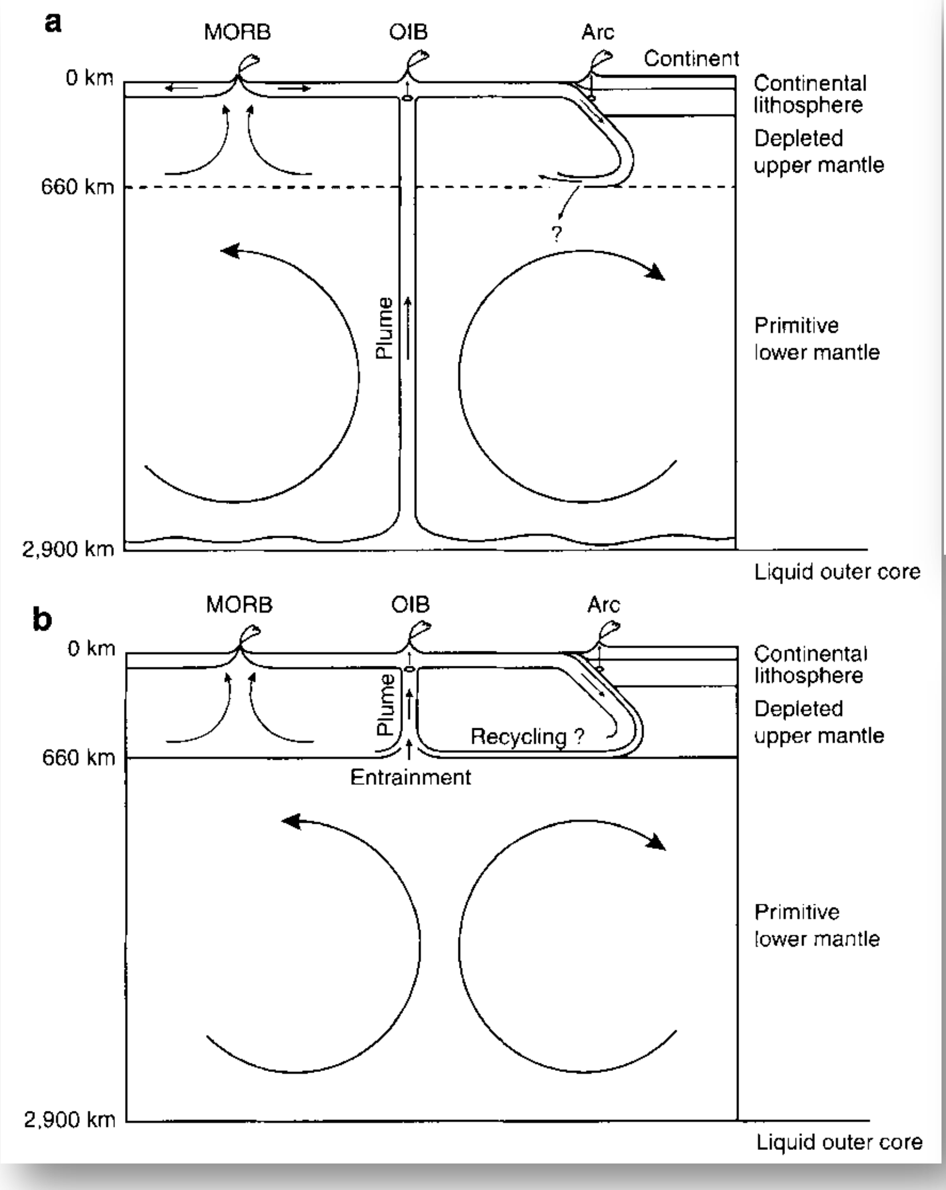
- 2900 km deep
- Surfaced by ~40km Continental or ~7km Oceanic Crust
- Surface potential temperature ~1550 K
- Core-Mantle Boundary (CMB) temperature 4000-5000 K



MORB Mantle

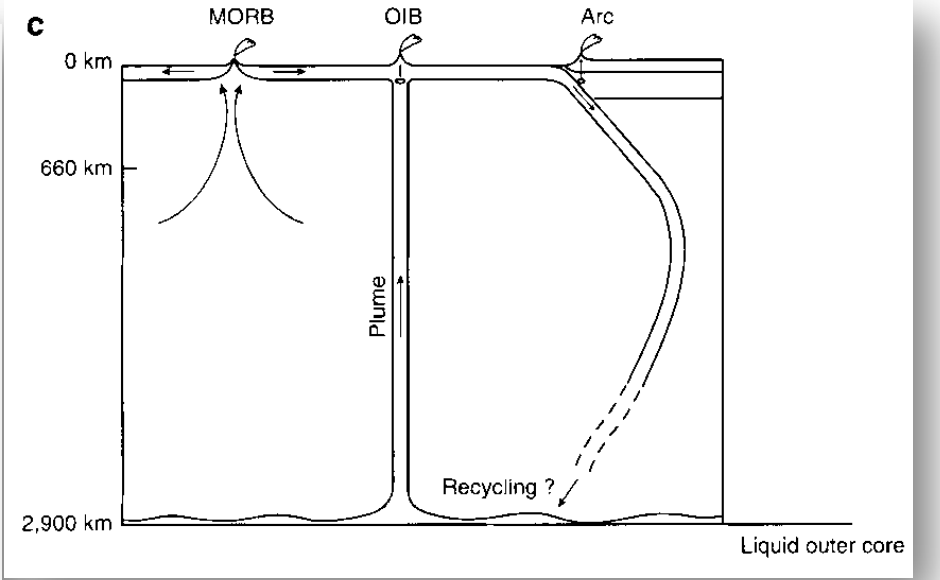
- Depth/Volume ?
- Top of mantle
- Residua from production of Continental Crust
- Recorder of convection efficiency

Convectional perspective

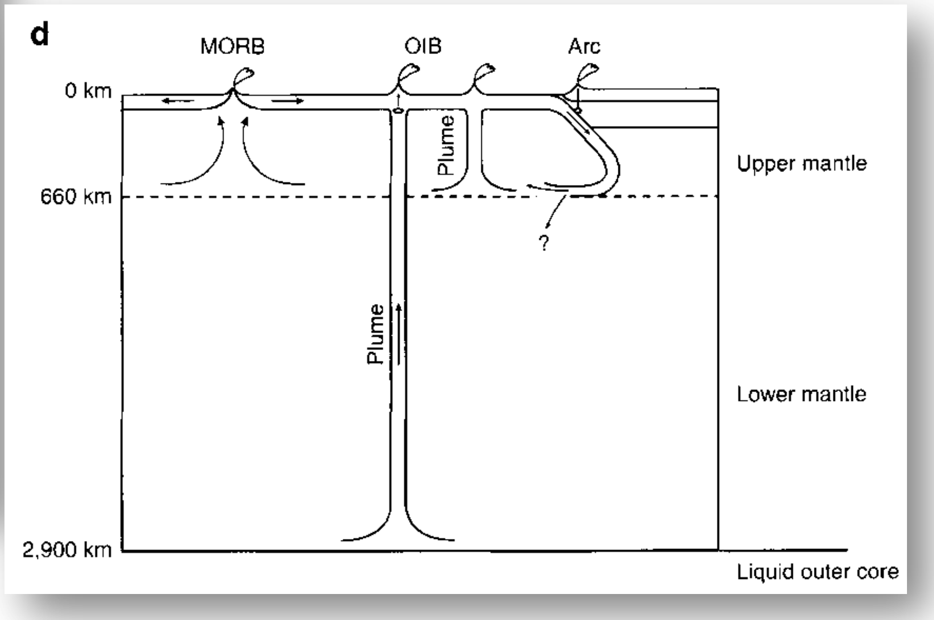


Hofmann 1997 Nature

Non-layered model

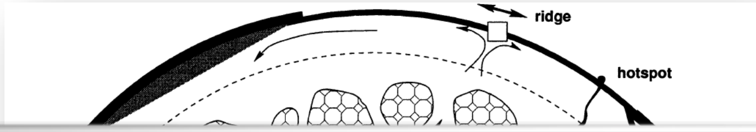


Non-layered model

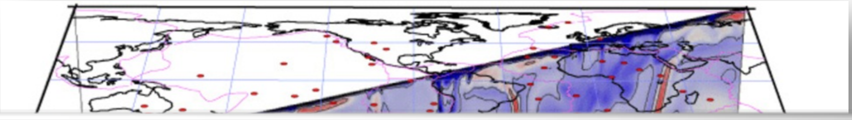


The simplest mantle models assume two distinct reservoirs: “upper” and “lower” mantle source regions.

Becker et al. (1999) EPSL



McNamara and Zhong (2005) Nat

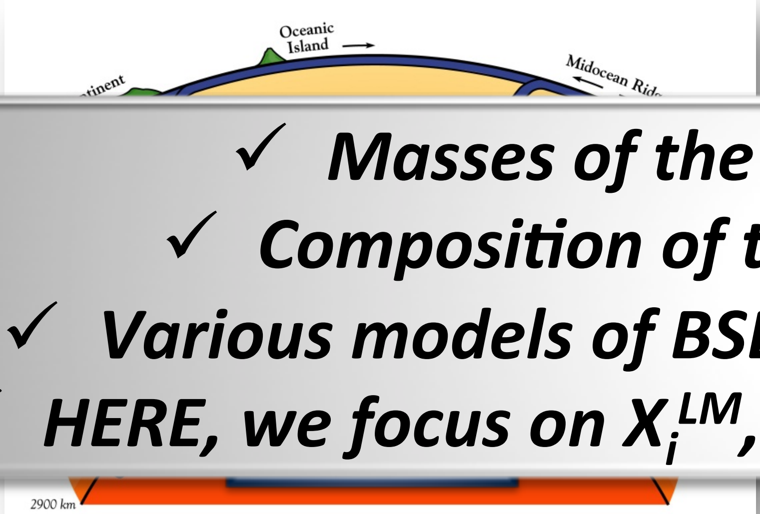


Assuming a two-component mantle:

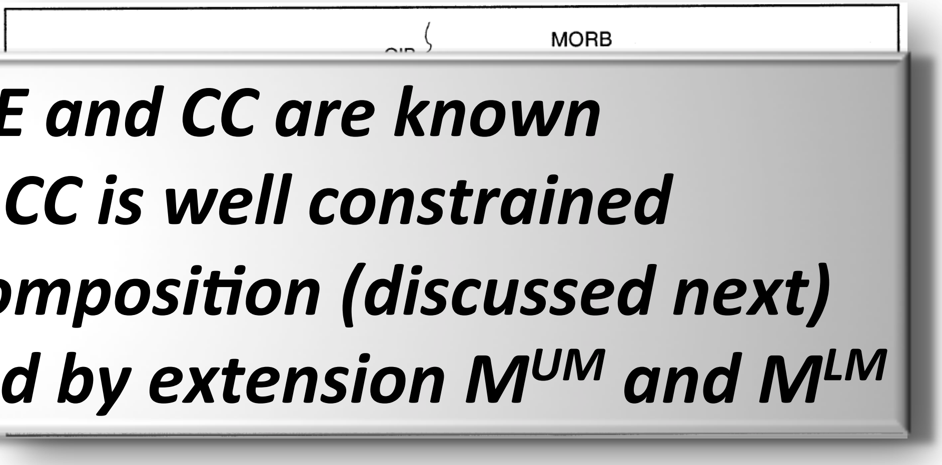
$$M^{BSE}\cdot X_i^{BSE} = M^{CC}\cdot X_i^{CC} + M^{UM}\cdot X_i^{UM} + M^{LM}\cdot X_i^{UM} \quad \text{or,}$$

Atoms of element i in BSE = Atoms i in CC + UM + LM

Kellogg et al. (1999) Sci



Morgan and Morgan (1999) EPSL



- ✓ **Masses of the BSE and CC are known**
- ✓ **Composition of the CC is well constrained**
- ✓ **Various models of BSE composition (discussed next)**
- ✓ **HERE, we focus on X_i^{LM}, and by extension M^{UM} and M^{LM}**

U content of BSE models

- Nucelosynthesis: U/Si and Th/Si production probability
- Solar photosphere: matches C1 carbonaceous chondrites
- Estimate from Chondrites: ~11ppb planet (16 ppb in BSE)
- Heat flow: secular cooling vs radiogenic contribution… ?
- Modeling composition: which chondrite should we use?

<u>A brief (albeit biased) history of U estimates in BSE:</u>

•Urey (56) 16 ppb

•Wasserburg et al (63) **33** ppb

•Ganapathy & Anders (74) 18 ppb

•Ringwood (75) 20 ppb

•Jagoutz et al (79) 26 ppb

•Schubert et al (80) **31** ppb

•Davies (80) 12-23 ppb

•Wanke (81) 21 ppb

Turcotte & Schubert (82; 03) **31** ppb

Hart & Zindler (86) 20.8 ppb

McDonough & Sun (95) 20 ppb ± 20%

Allegre et al (95) 21 ppb

Palme & O’Neill (03) 22 ppb ± 15%

Lyubetskaya & Korenaga (05) 17 ppb ± 17%

O’Neill & Palme (08) **10** ppb

Javoy et al (10) **12** ppb

Disagreement with “chondritic” Earth Models

Murakami et al (May - 2012, *Nature*): “…the lower mantle is enriched in silicon … consistent with the [CI] **chondritic Earth model**.”

Campbell and O’Neill (March - 2012, *Nature*): “Evidence **against a chondritic Earth**”

Zhang et al (March - 2012, *Nature Geoscience*): The Ti isotopic composition of the **Earth and Moon overlaps that of enstatite chondrites**.

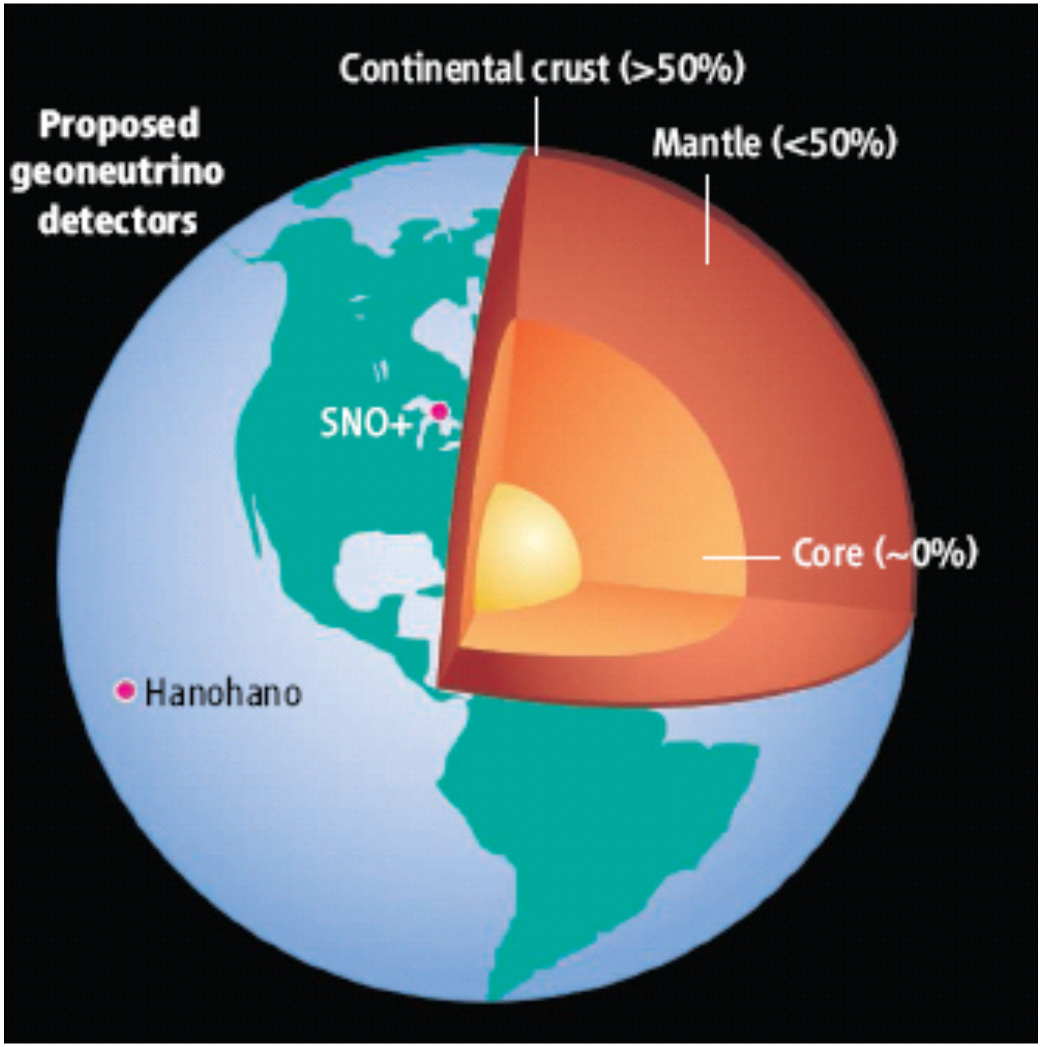
Fitoussi and Bourdon (March - 2012, *Science*): “Si isotopes support the conclusion that **Earth was not built solely from enstatite chondrites**.”

Warren (Nov - 2011, *EPSL*): “Among known chondrite groups, **EH yields a relatively close fit to the stable-isotopic composition of Earth**.”

- Compositional models differ widely, implying a **factor of three difference** in the U & Th abundances of the Earth

U in the Earth:

“Differentiation”



~13 ng/g U in the Earth

Metallic sphere (core)
<<<1 ng/g U

Silicate sphere
20* ng/g U

**O’Neill & Palme (2008) 10 ng/g*

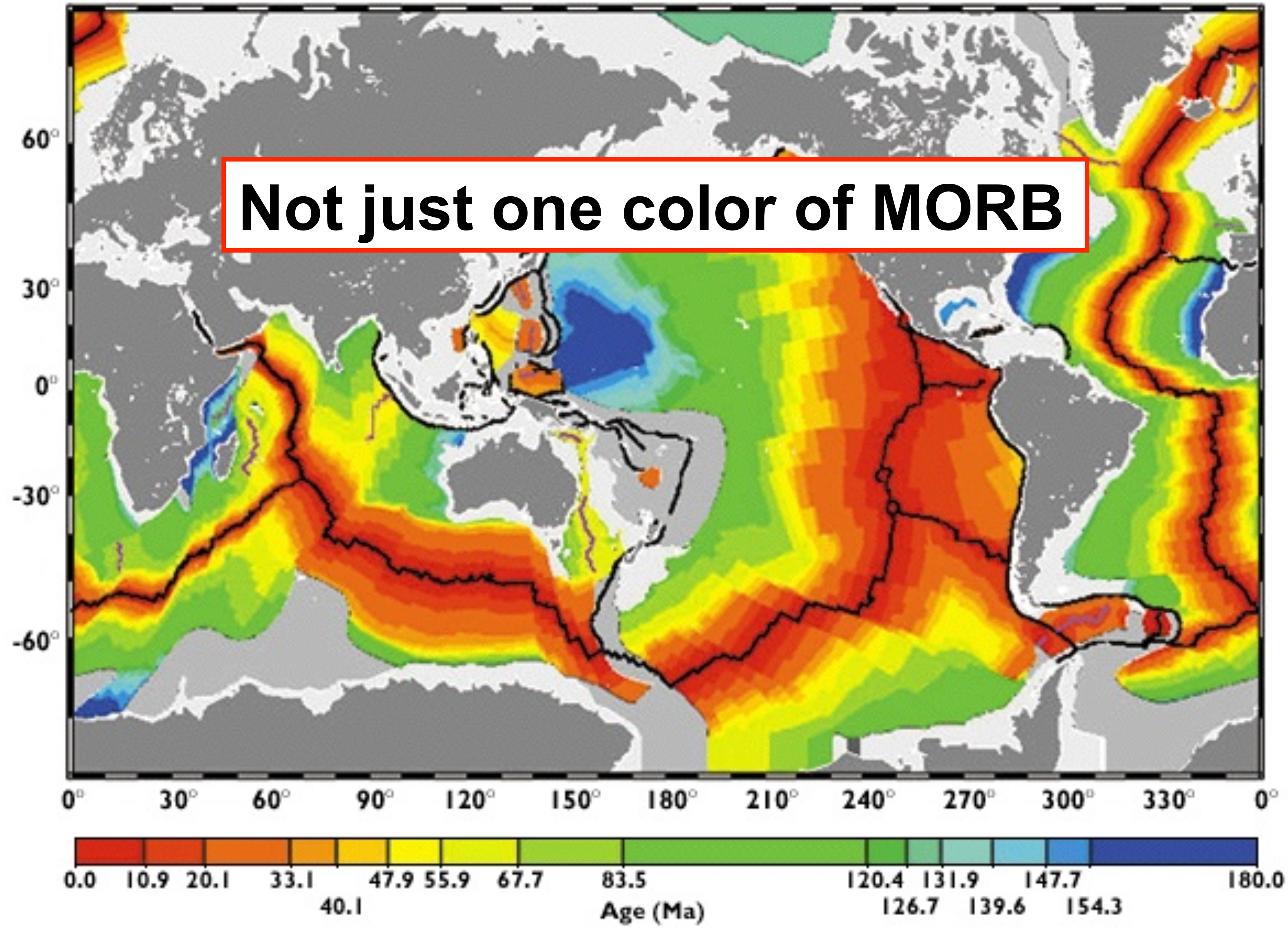
**Turcotte & Schubert (2002) 31 ng/g*

Continental Crust
1300 ng/g U

Mantle
~12 ng/g U

Chromatographic separation
Mantle melting & crust formation

MORB: Distribution of ages at ridges



Not just one color of MORB

Spreading rate and structure

Fast *East Pacific Rise*

- Thermal structure - warmer
- Crust is **thicker**, lithosphere is thinner
- Higher degrees of melting
- Sustained magma chambers and volcanism
- LESS COMPOSITIONAL DIVERSITY

Slow *Mid-Atlantic Ridge*

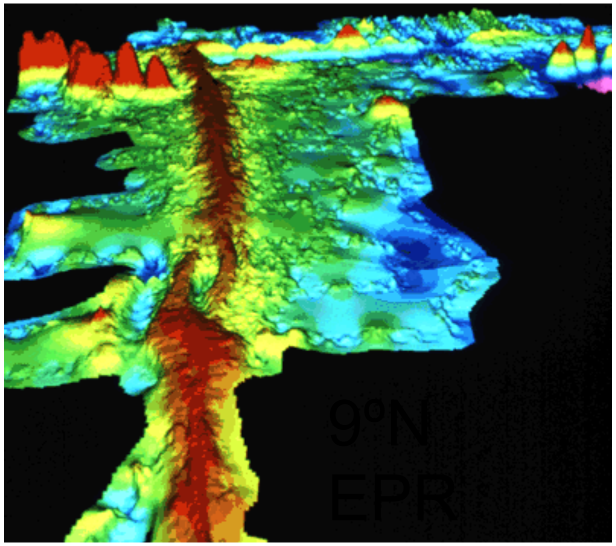
- Thermal structure - cooler
- Crust is thinner, lithosphere is **thicker**
- lower degrees of melting
- Episodic volcanism
- GREATER COMPOSITIONAL DIVERSITY

Figures from WHOI : Deeper Discovery News

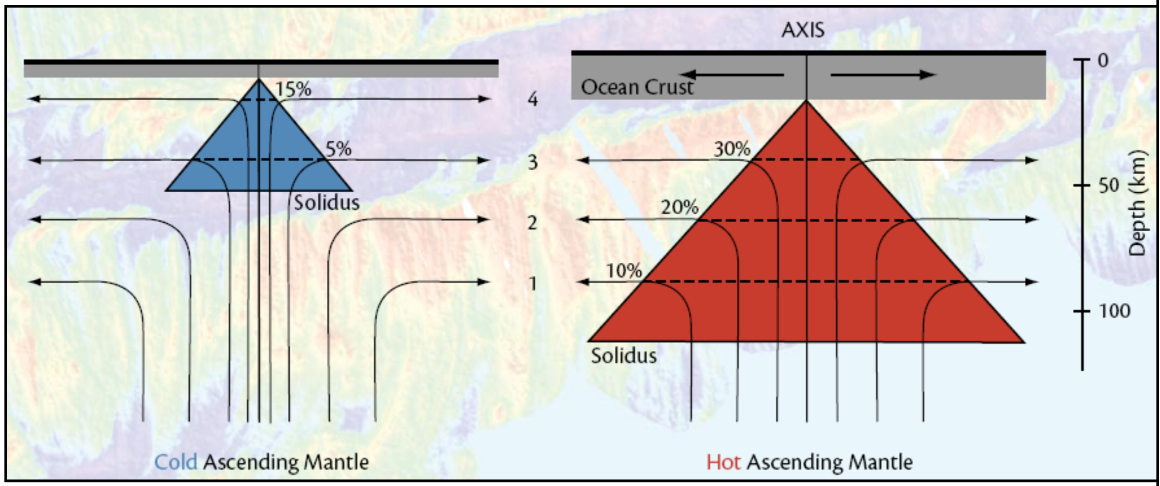
Highly incompatible elements in MORB

- MORB : active melting of the upper mantle
- production 20-25 km^3·yr^{-1} (Crisp, 1984)
  - ¾ of all magma are intruded sills
- Negligible (crustal) contamination

pubs.usgs.gov

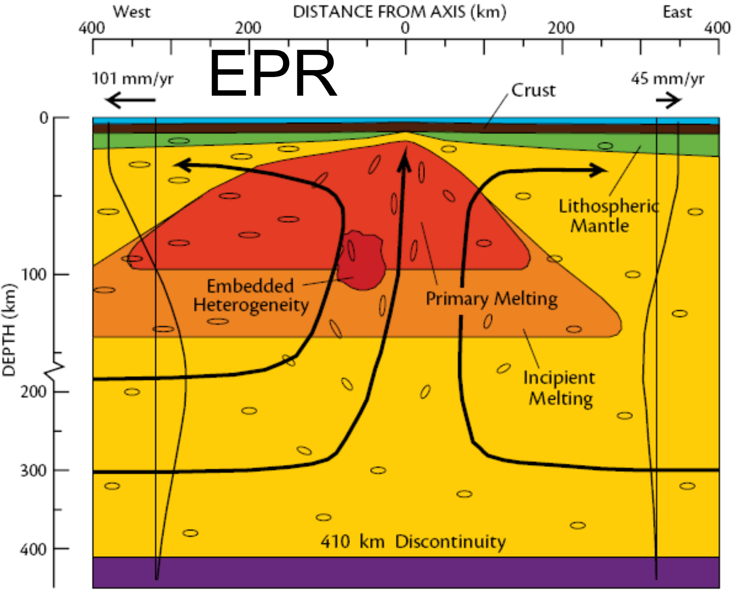


Cold upwelling **Hot** upwelling



Langmuir & Forsyth (2007)

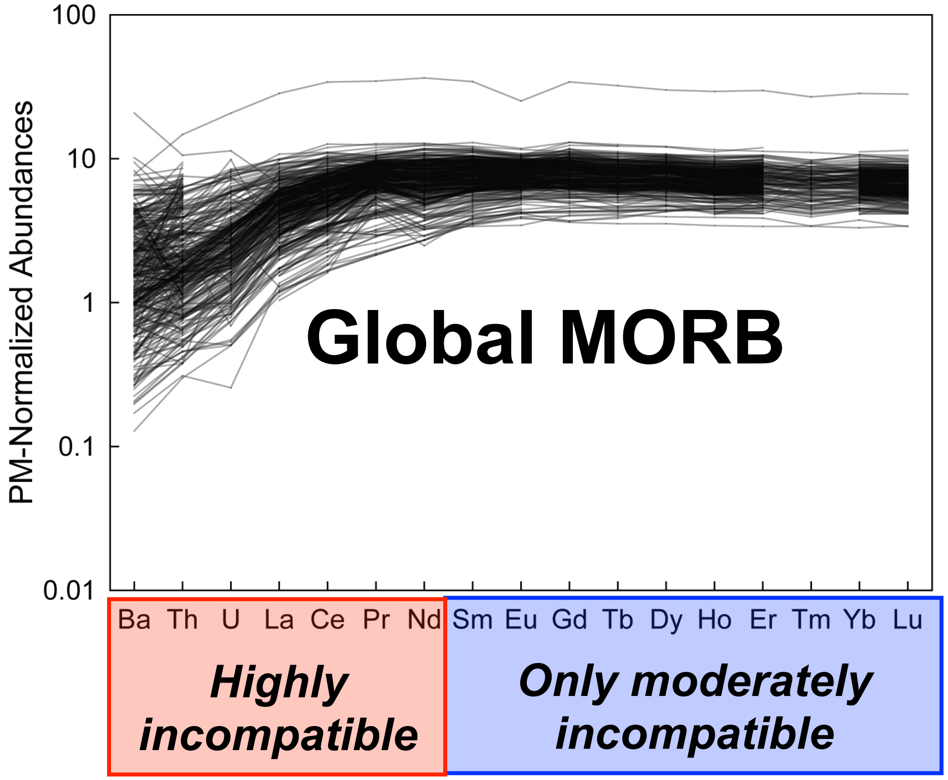
MELT seismic experiment



Highly incompatible elements

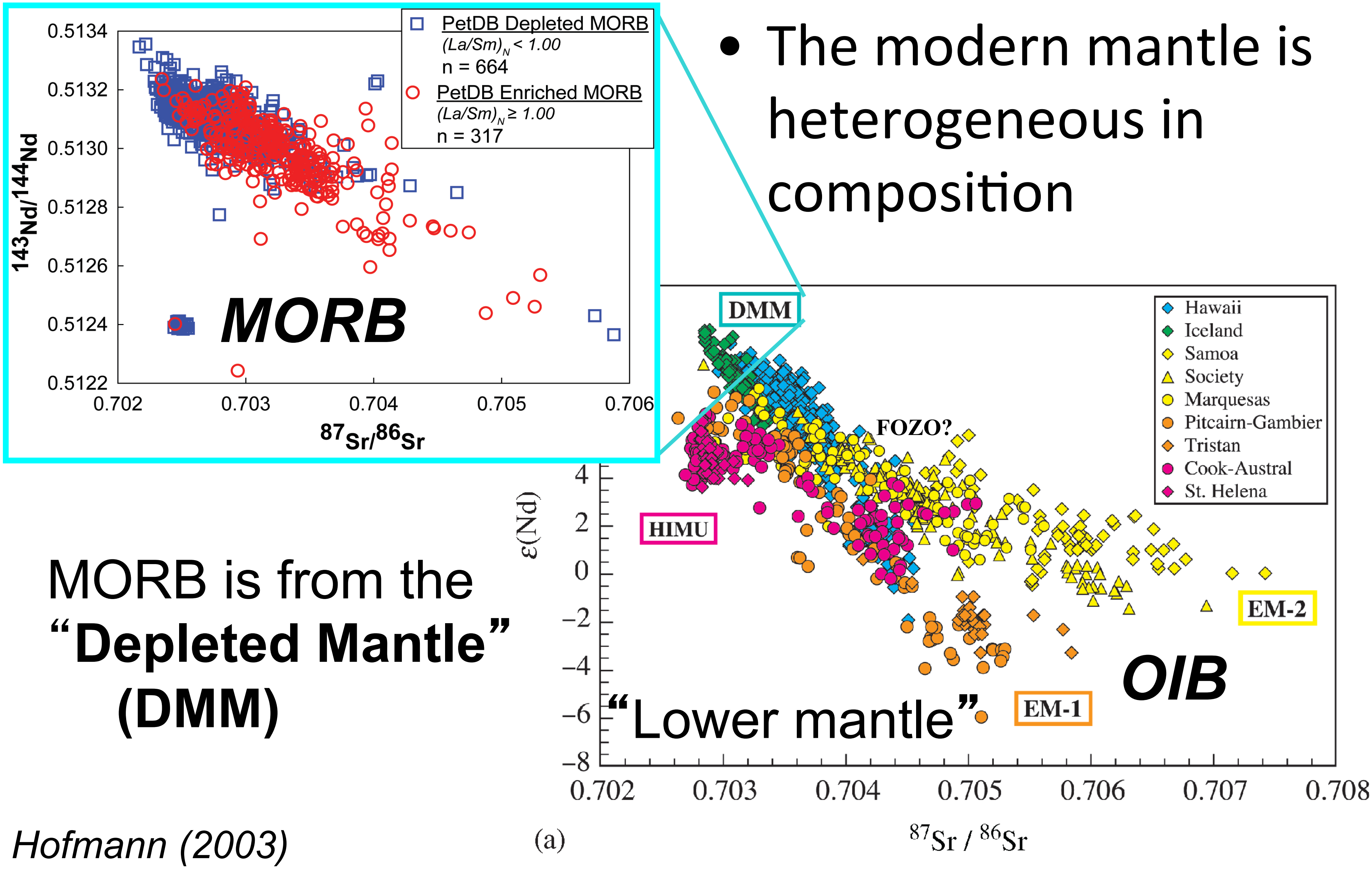
- Highly incompatible elements provide particularly sensitive tracers
  - Effectively removed from mantle sources at only minor degrees of partial melting
  - “See through” melting and crystallization
  - E.g., high-field strength elements (HFSE) and large-ion lithophile elements (LILE)

Data compilation from Arevalo et al. (2010)



Mantle heterogeneity

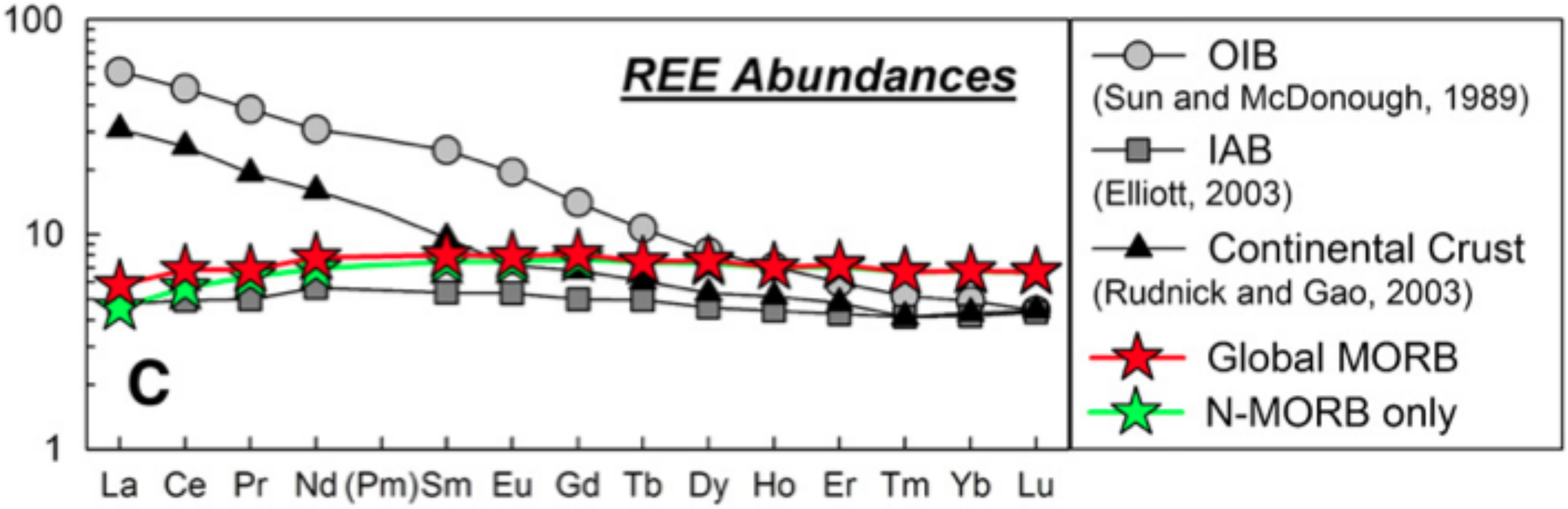
- The modern mantle is heterogeneous in composition



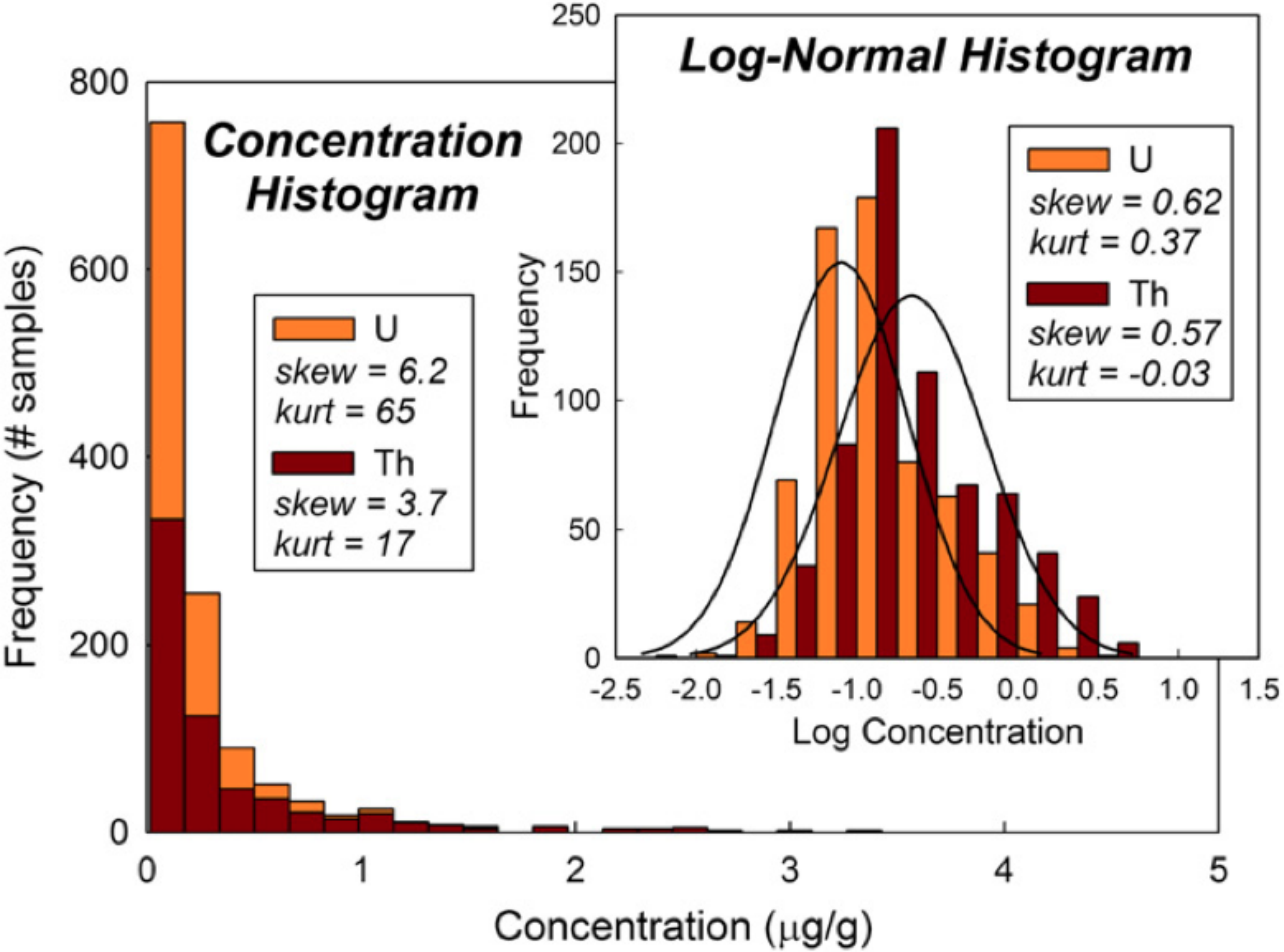
MORB is from the
"Depleted Mantle"
(DMM)

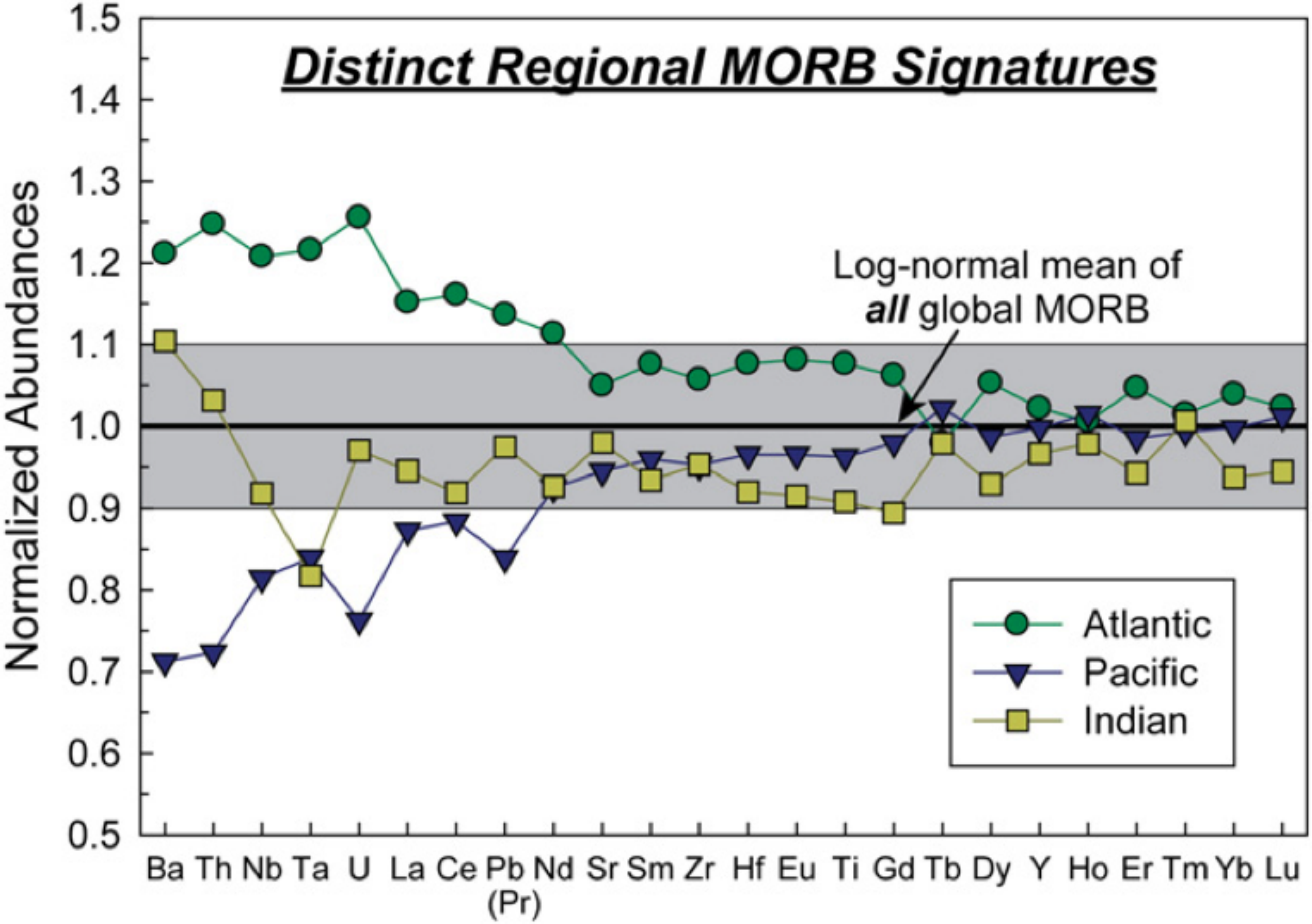
Hofmann (2003)

Complementary compositional nature of Continental Crust and MORB (and OIB)



Proportionally both should be added to make a flat REE pattern for the BSE


Concentration Histogram
Frequency (# samples)
800
600
400
200
0
0
1
2
3
4
5
Concentration (μg/g)
U
skew = 6.2
kurt = 65
Th
skew = 3.7
kurt = 17
Log-Normal Histogram
Frequency
250
200
150
100
50
0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Log Concentration
U
skew = 0.62
kurt = 0.37
Th
skew = 0.57
kurt = -0.03


Distinct Regional MORB Signatures
Normalized Abundances
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
Log-normal mean of
all global MORB
Atlantic
Pacific
Indian
Ba
Th
Nb
Ta
U
La
Ce
Pb (Pr)
Nd
Sr
Sm
Zr
Hf
Eu
Ti
Gd
Tb
Dy
Y
Ho
Er
Tm
Yb
Lu

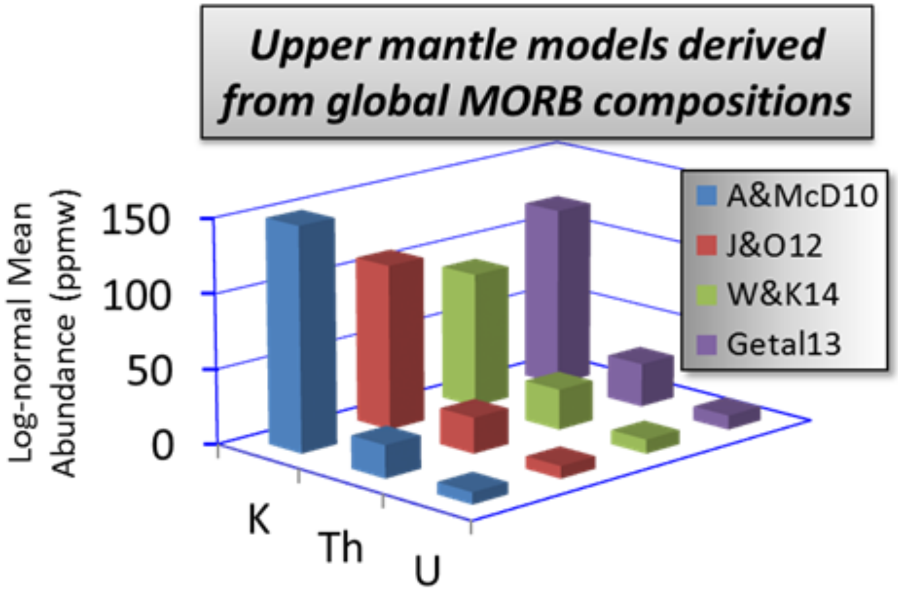
Modeling "Upper" Mantle Composition

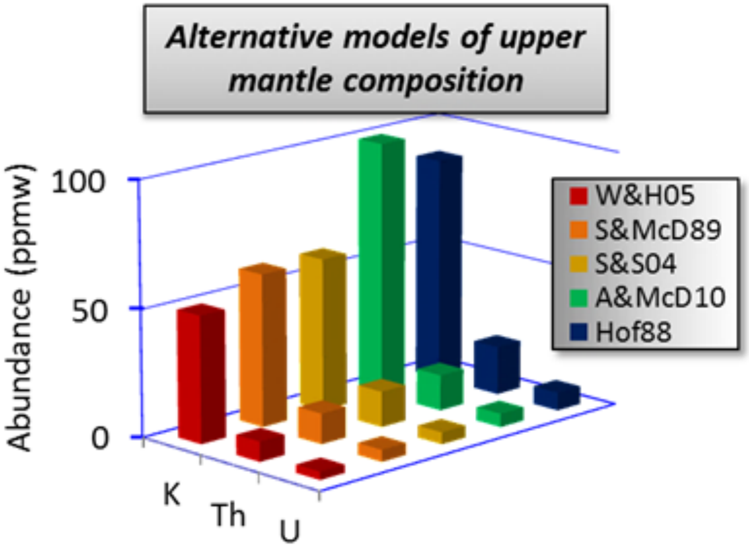
Defining chemical composition for the upper mantle

N-MORB (normal-type): also referred as "depleted" type

Often defined by $(La/Sm)_N \leq 1.00$ or other chemical signature

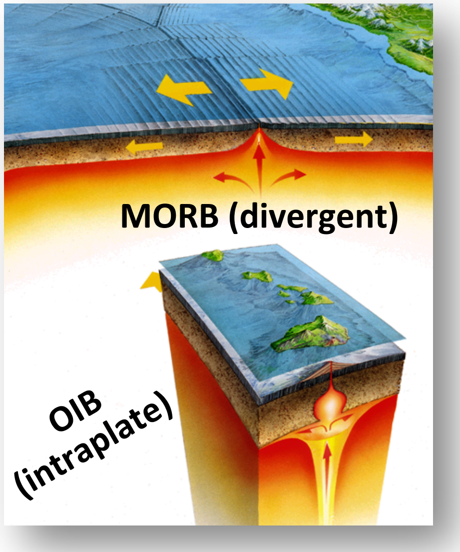
Peridotite-derived models (melt residues)

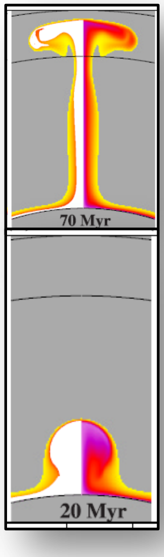

Upper mantle models derived from global MORB compositions


Alternative models of upper mantle composition

Modeling “Lower” Mantle Composition

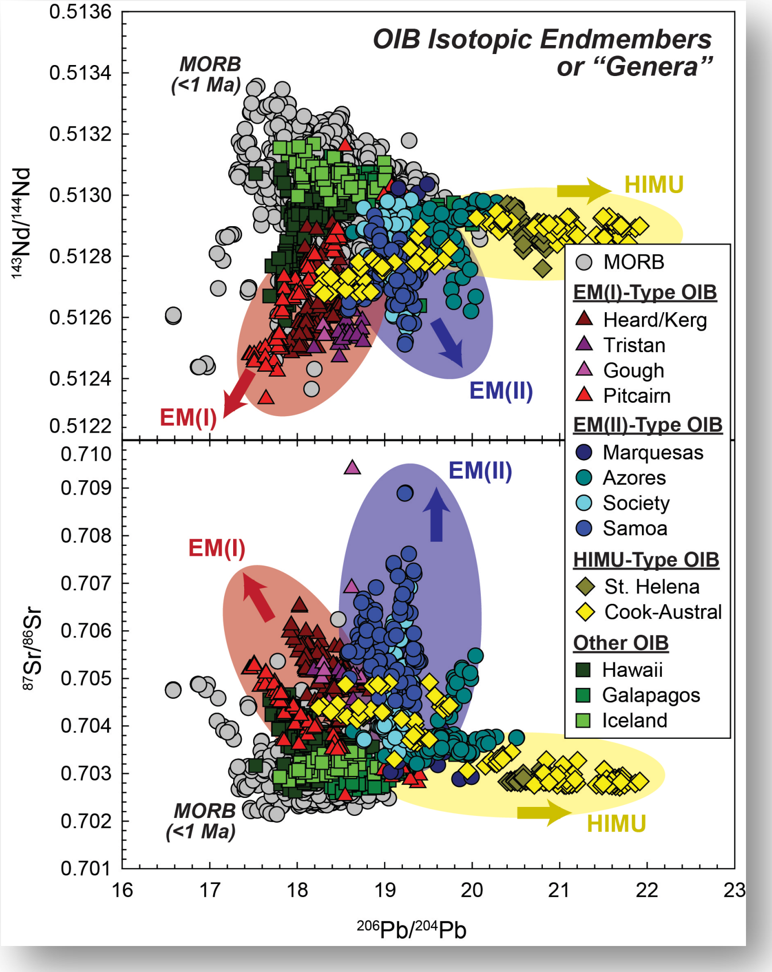
- Ocean Island Basalts (OIBs) represent melting of deeper mantle sources
- Variable compositions reflect long-lived chemical heterogeneities, diverse melting conditions and rates of entrainment
- Enriched relative to MORB based on mass balance of elemental inventories and radiogenic heat production



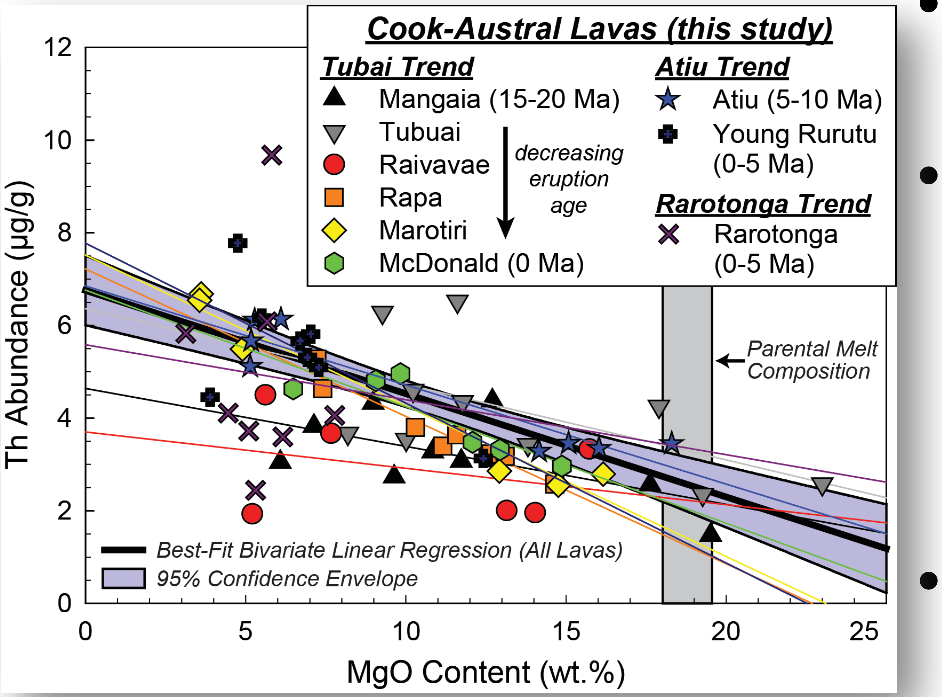


Lin & van Keken (2006) G^3

Data compiled by Stracke et al. (2013) G^3



A Case Study: The Cook-Australs

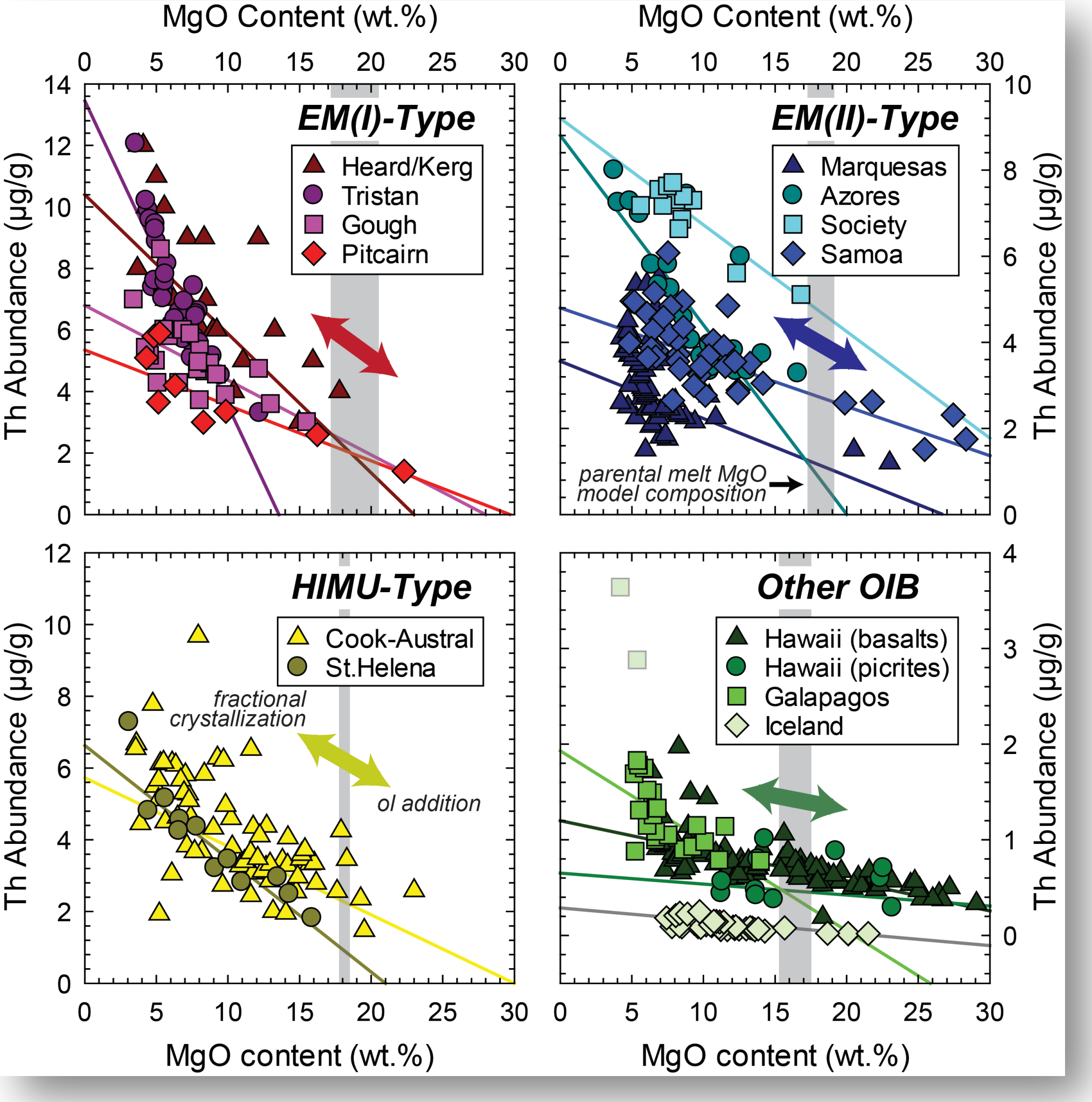


Arevalo et al. (2013) G^3

- Cook-Australs represent archetypal HIMU OIB
- Th is the most incompatible element (peridotite melting) that is neither fluid mobile (e.g., K or Rb) nor redox-sensitive (e.g., W or U)
- MgO maps the evolution of parental melt derivatives

We can calculate the abundance of Th in the near-primary parental melt(s) of the Cook-Australs through linear regression statistics (details forthcoming…).

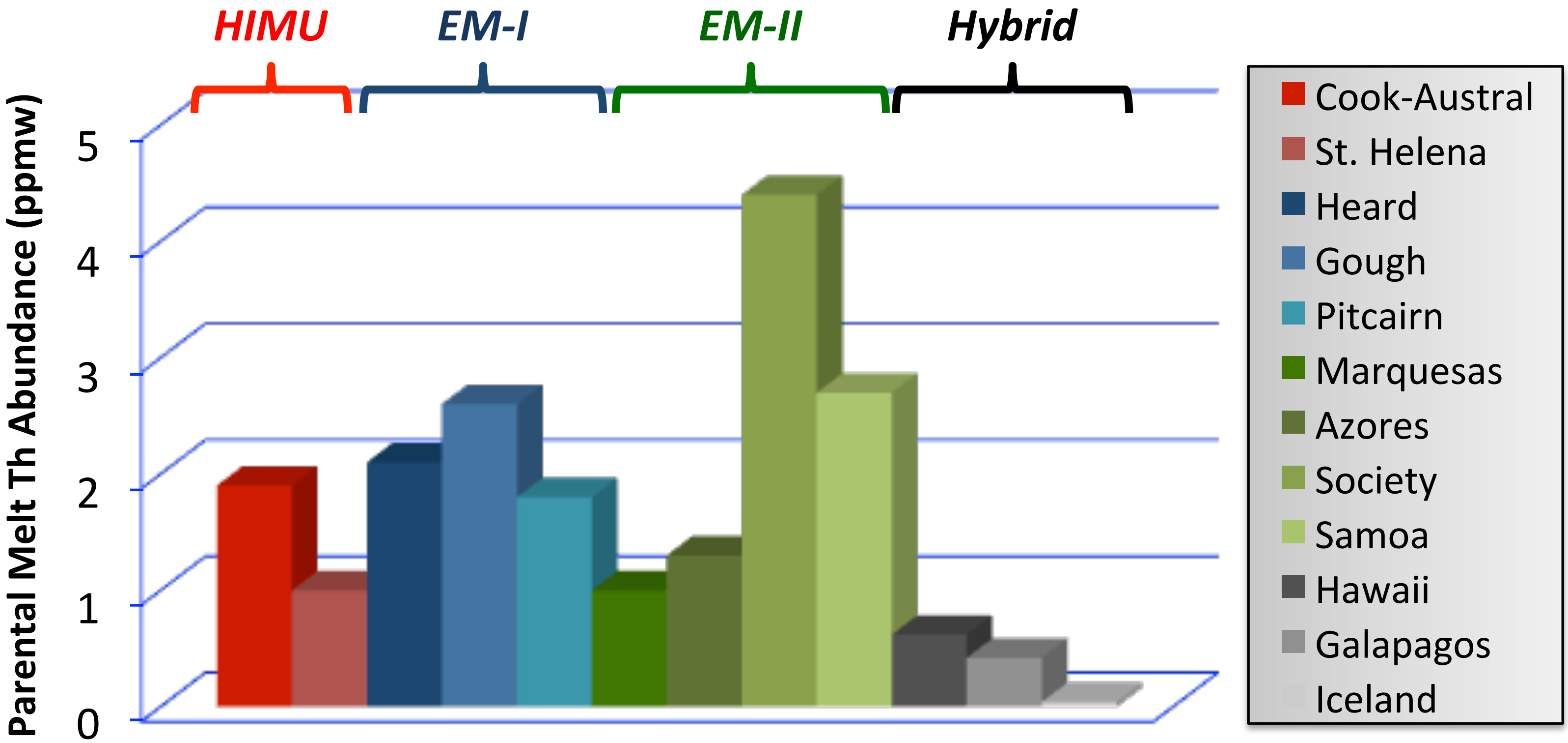
Universal Trends in Th versus MgO



Arevalo et al. (2013) G^3

OIB Parental Melt Composition(s)

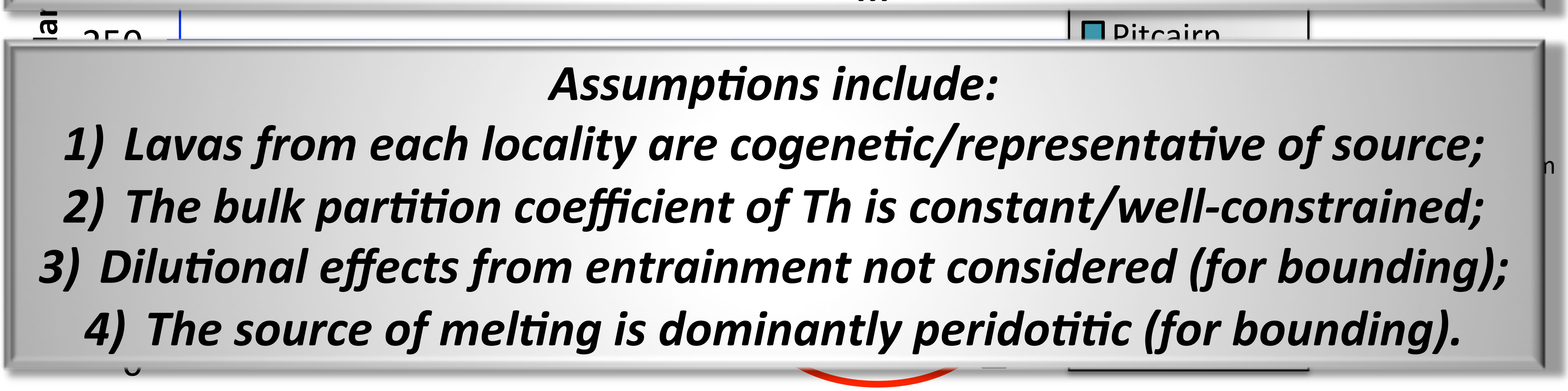
- Near-primary (or parental) melt compositions can be estimated by adding *ol* and *cpx* in constant proportions, dictated by CaO/Al_2O_3 relations, to equilibrate each individual lava with Fo_{90} olivine



OIB Source Composition(s)

- Assuming 5 – 10% partial melting of the source of the parental melts modeled here, consistent with studies of alkali OIB basalt petrogenesis
  - Corroborated via inverse modeling of Th/Nd and U/Sm
  - For comparison, MORB estimated to represent 8–15% melting

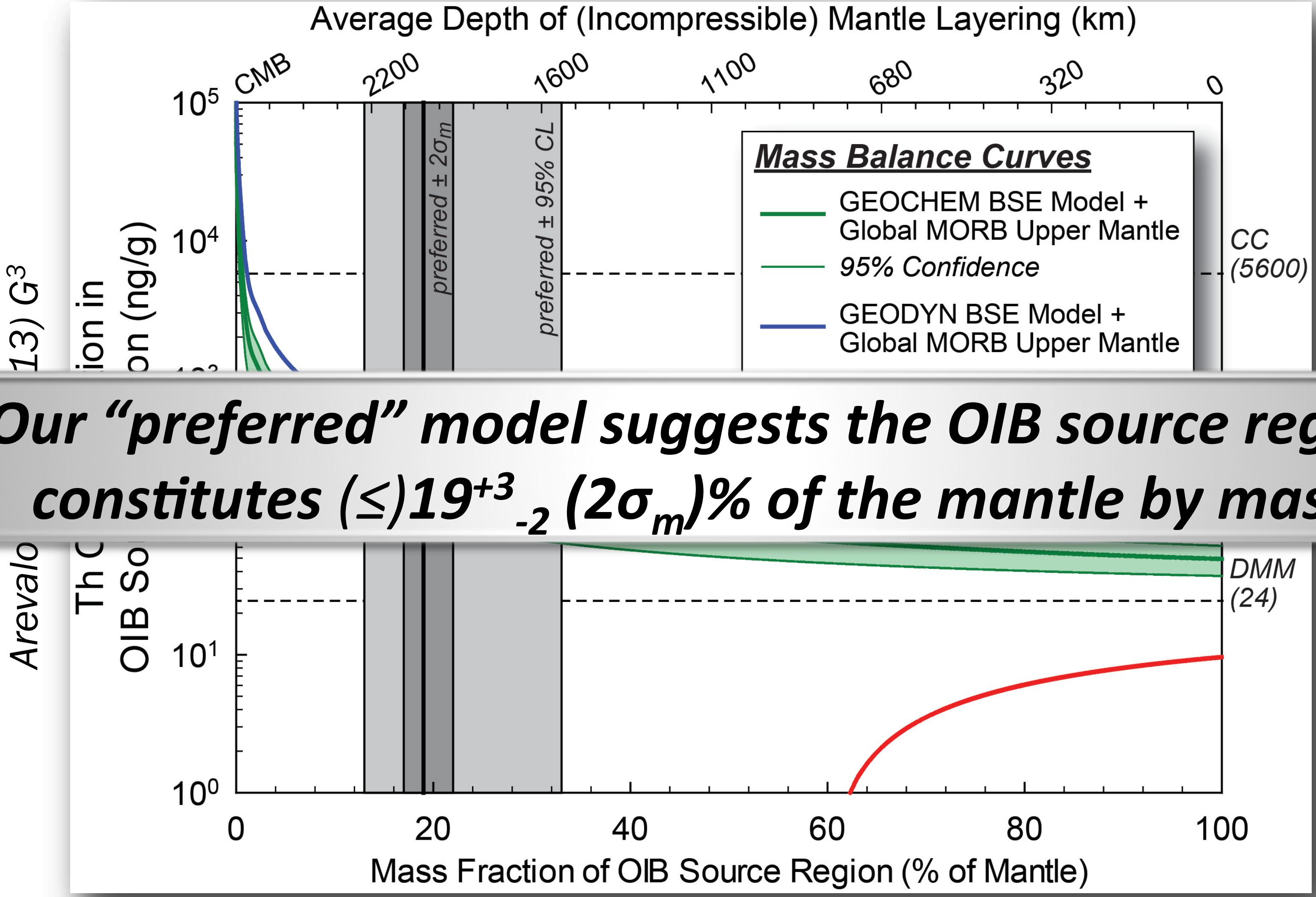
The OIB source region characterized by the samples considered here contains an average of:
(≥) 160 ± 60 (± 20, 2σ_m) ng/g Th.



Assumptions include:

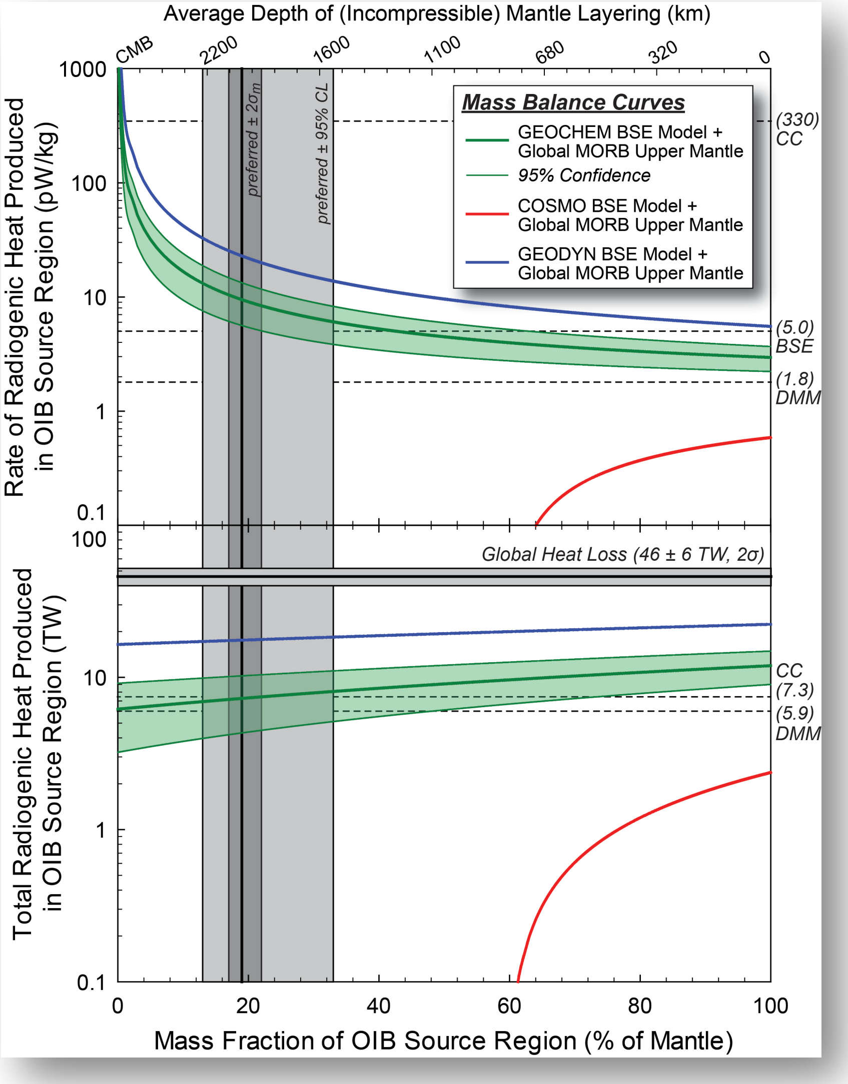
1. ***Lavas from each locality are cogenetic/representative of source;***
2. ***The bulk partition coefficient of Th is constant/well-constrained;***
3. ***Dilutional effects from entrainment not considered (for bounding);***
4. ***The source of melting is dominantly peridotitic (for bounding).***

Size of the OIB Source(s)

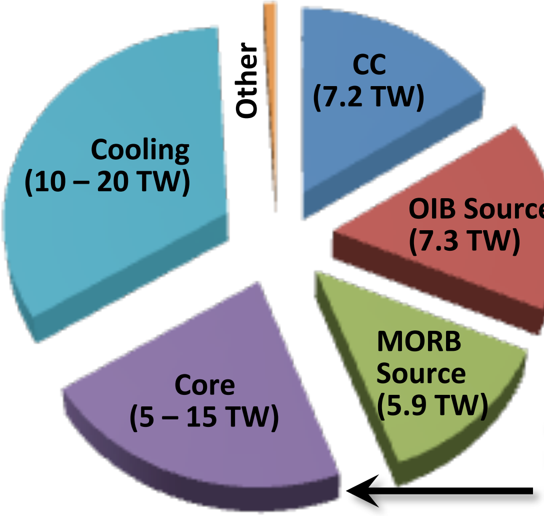


Our "preferred" model suggests the OIB source region constitutes (≤)19^{+3}_{-2} ($2\sigma_m$)% of the mantle by mass.

Radiogenic Heat in the OIB Source(s)



- Our compositional model suggests the OIB source region produces:
  - (≥)9.5 pW/kg rate of heat generation
  - For comparison:
    - MORB source: <2 pW/kg
- The preferred mass balance curve (green) indicates the OIB source contributes:
  - (≤)7.3 TW radiogenic heat



46 ± 3 TW total surface heat flux

Jaupart et al. (2008) *Treatise*

Core heat contributions from Lay et al. (2008) *Nat*

*includes: thermal conduction, geodynamo drivers, etc.