The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2047-19

Workshop Towards Neutrino Technologies

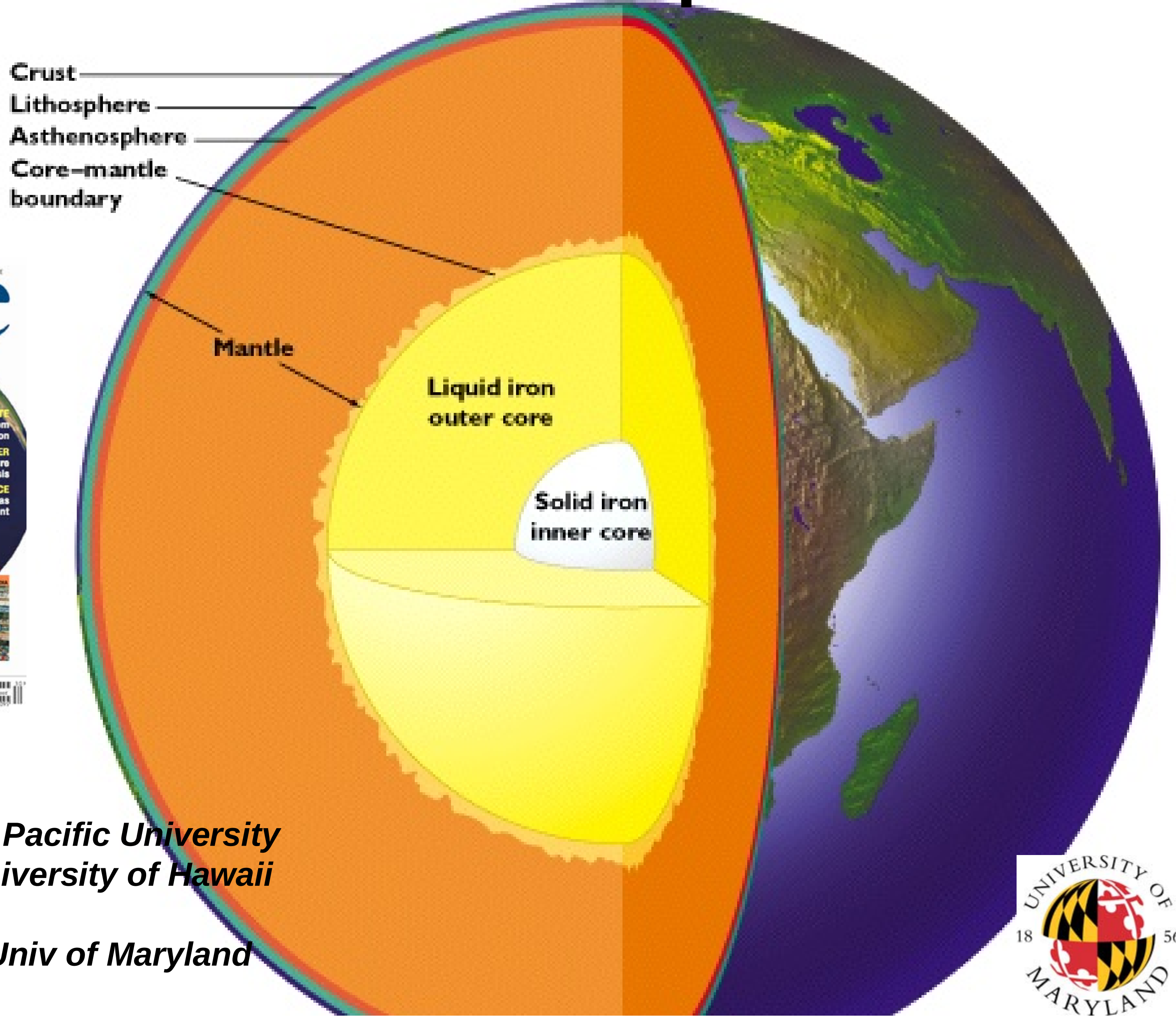
13 - 17 July 2009

Th and U in the Earth

William McDONOUGH

University of Maryland
Department of Geology
College Park, MD 20742, U.S.A.

Th/U in the Earth & heat production



__Collaborators__:

-***Steve Dye: Hawaii Pacific University***

-***John Learned : University of Hawaii***

and

-***Ricardo Arevalo: Univ of Maryland***

5 Big Questions:

- What are earth's K/U & Th/U ratios?

planetary volatility curve

- Radiogenic contribution to heat flow?

secular cooling

- Distribution of reservoirs in mantle?

whole vs layered convection

- Radiogenic elements in the core??

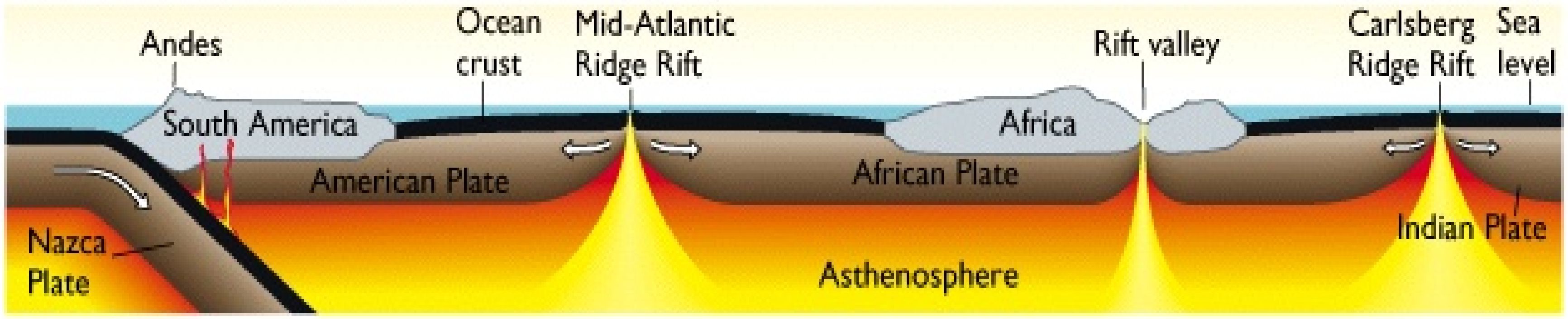
Earth energy budget

- Nature of the Core-Mantle Boundary?

hidden reservoirs

Examples of Plate Boundaries

O-C convergent | O-O divergent | C-C divergent | O-O divergent

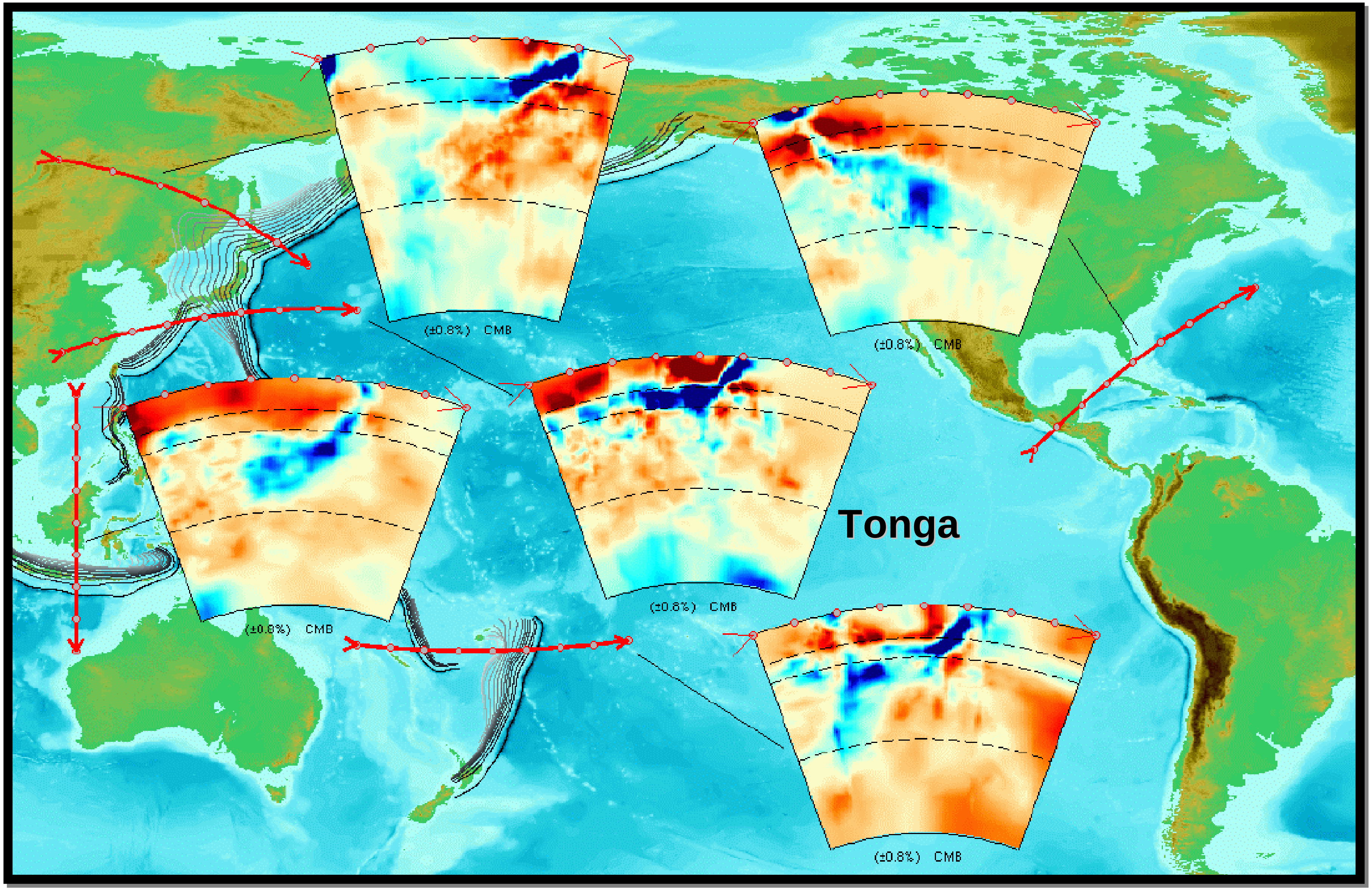


(a)

O-O convergent | O-O divergent | O-C convergent

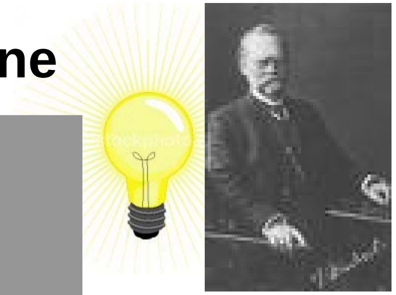
(b)

Seismic Tomography of subducting plates



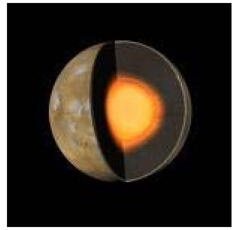
Time Line

1897



Emil Wiechert

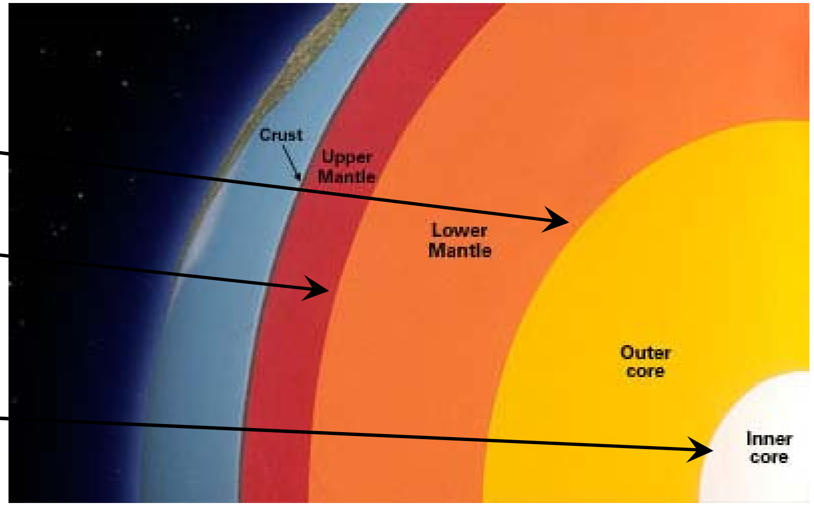
1st order Structure of Earth
Rock surrounding metal



1915 — CORE-MANTLE

1925 — UPPER-LOWER MANTLE

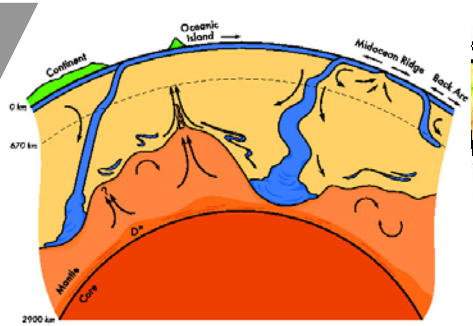
1935 — INNER-OUTER CORE

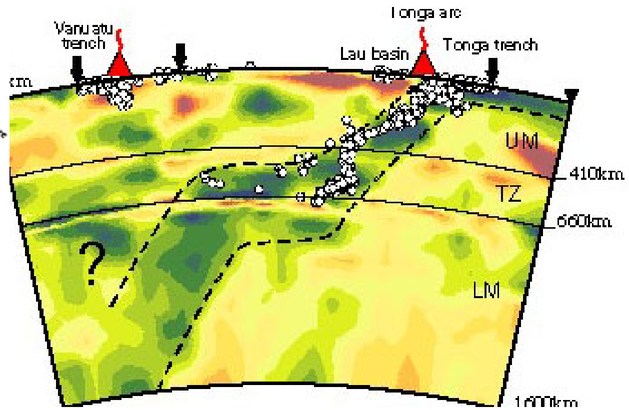


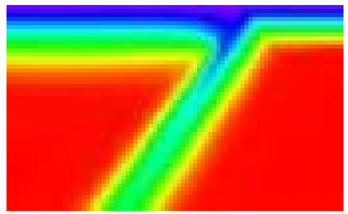
1970

PLATE TECTONICS

1995







Chondrite: mix of chondrules, matrix, and CAI

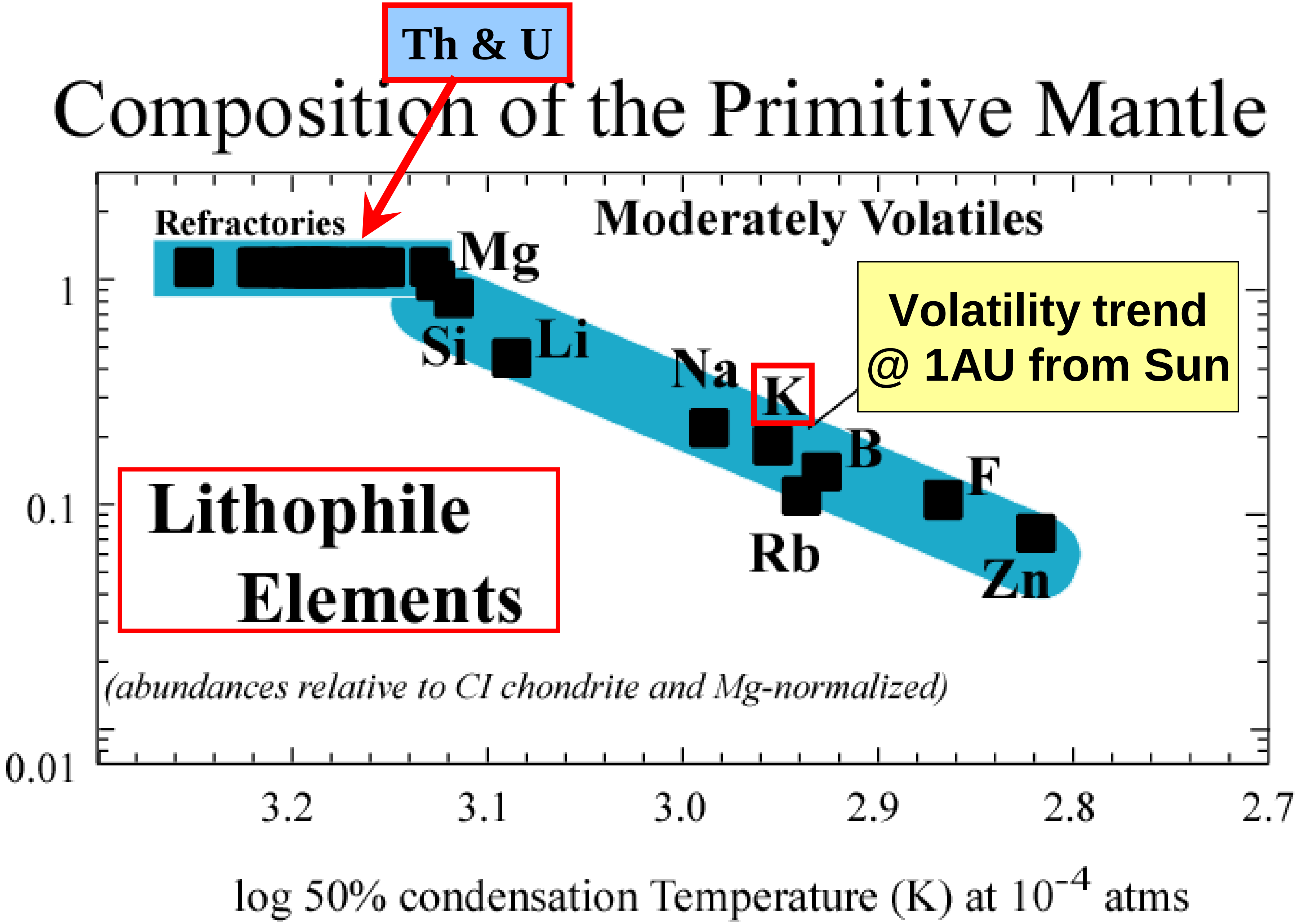
Heterogeneous mixtures of components with different formation temperatures and conditions

Planet:
mix of metal, silicate, volatiles

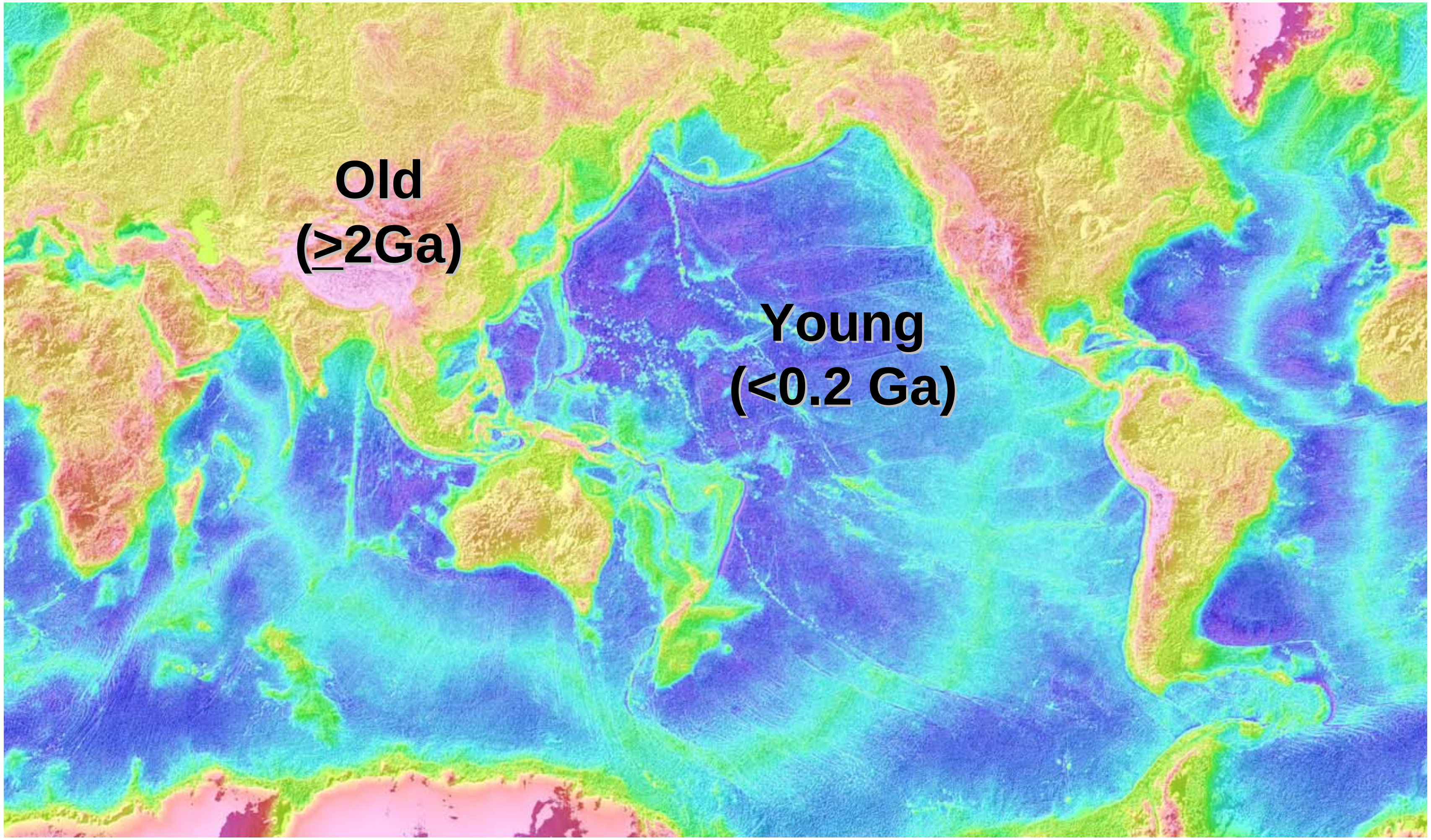
"Standard" Planetary Model

- Chondrites, primitive meteorites, are key
- So too, the composition of the solar photosphere
- Refractory elements (**RE**) in chondritic proportions
- Absolute abundances of **RE** – model dependent
- **Mg, Fe & Si** are non-refractory elements
- Chemical gradient in solar system →
- Non-refractory elements – model dependent
- U & Th are **RE**, whereas K is moderately volatile

Composition of the Primitive Mantle

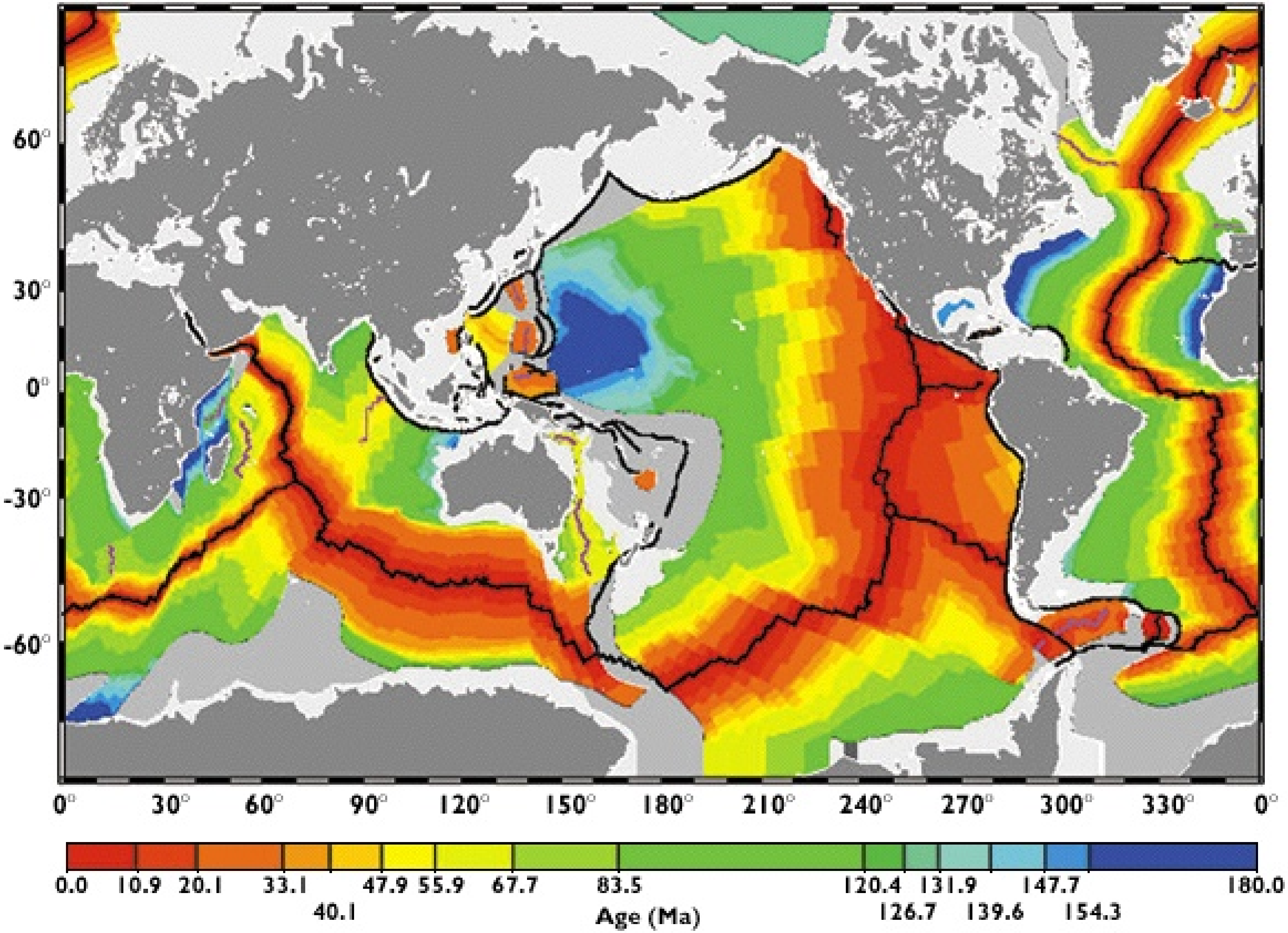


Two types of crust: Oceanic & Continental

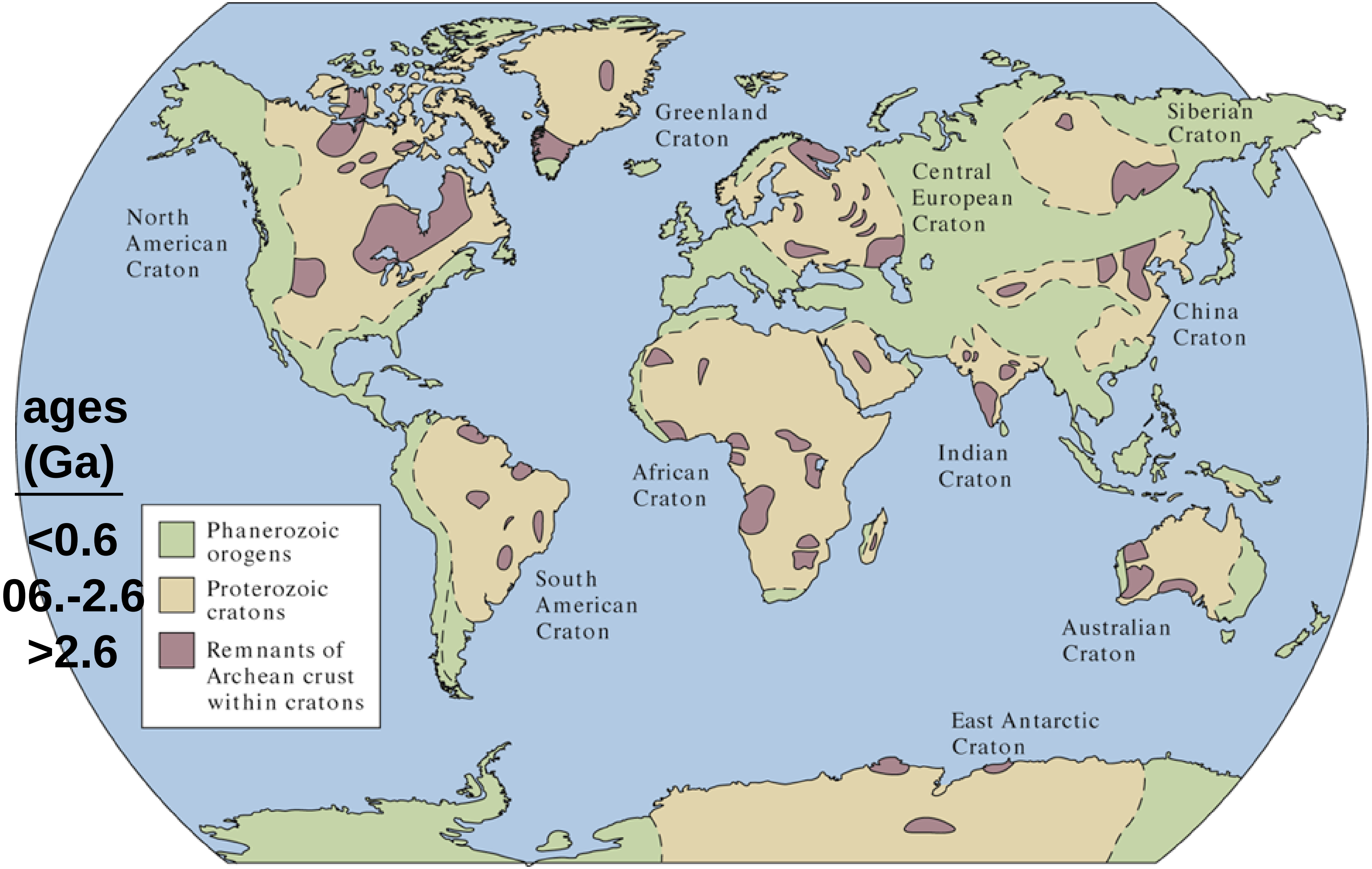


Oceanic crust: single stage melting of the mantle
Continental crust: multi-stage melting processes → Compositionally distinct

Oceanic crust <200 million years old



Continents up to 3500 million years old

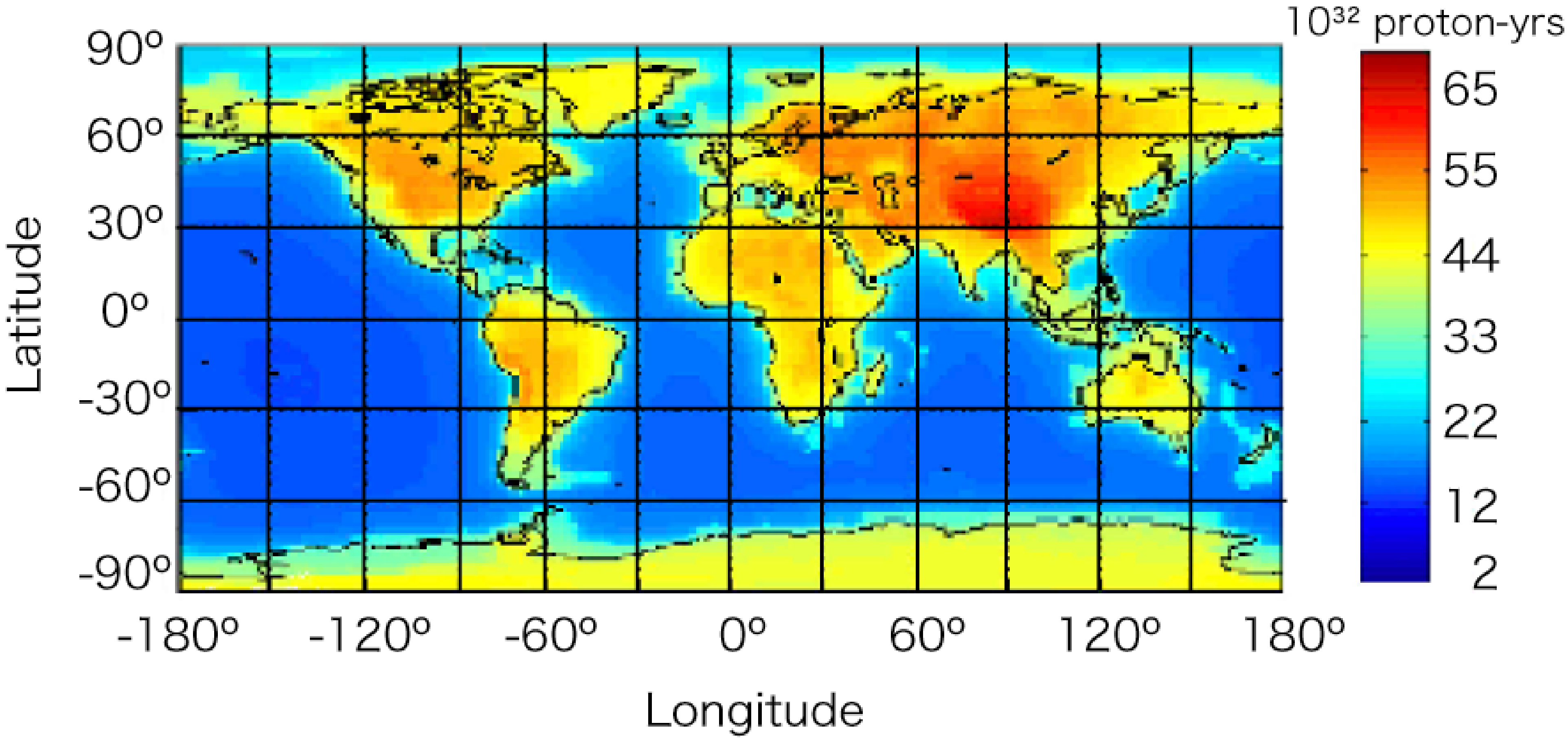


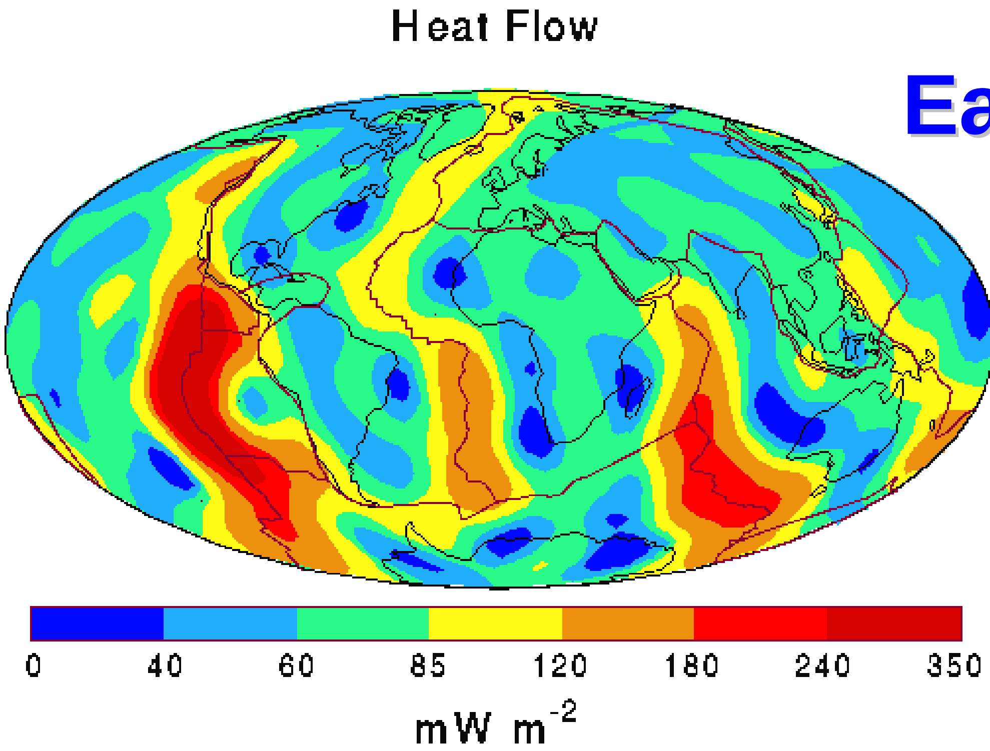
ages (Ga)

<0.6
06.-2.6
>2.6

Geoneutrino flux model for the Earth

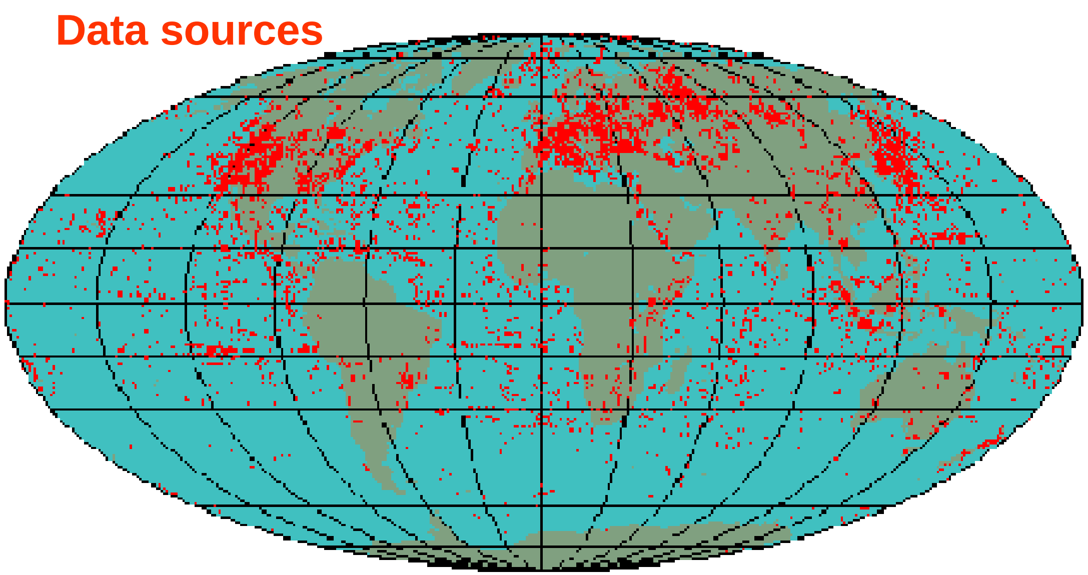
Using crust & mantle composition with PREM & crustal-thickness





Earth's Total Heat Flow

- Conductive heat flow measured from bore-hole temperature gradient and conductivity



Total heat flow

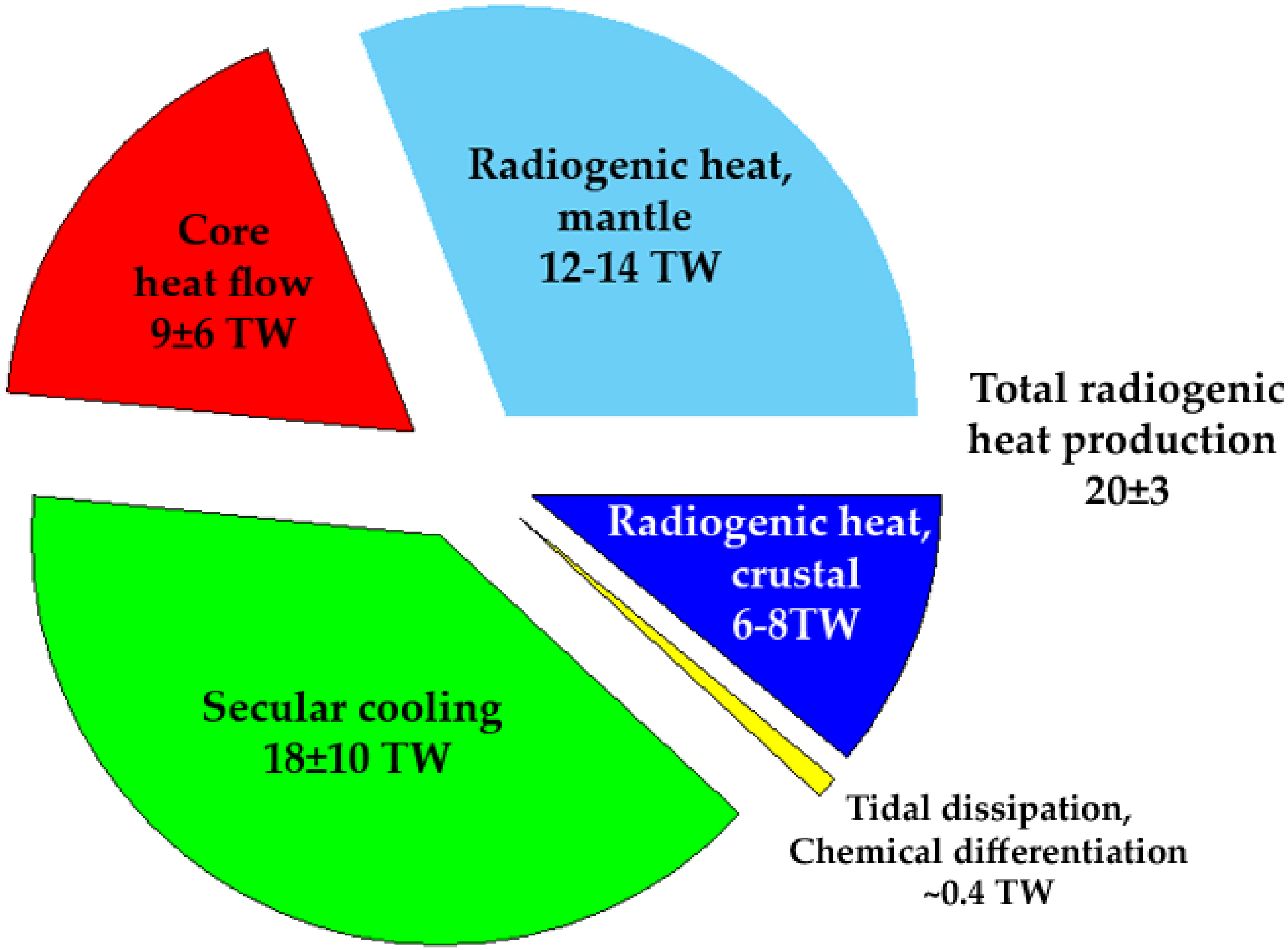
<u>Conventional view</u>

46±3 TW

<u>Challenged recently</u>

31±1 TW

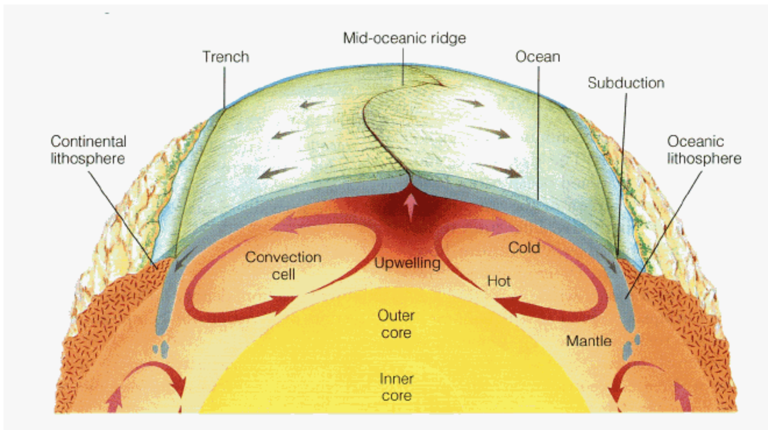
Earth's surface heat flow (total 46 ±3)



Urey Ratio and Mantle Convection Models

$$\text{Urey ratio} = \frac{\textbf{radioactive heat production}}{\textbf{heat loss}}$$

- Mantle convection models typically assume:
  mantle Urey ratio: 0.4 to 1.0, generally ~0.7
- Geochemical models predict
  mantle Urey ratio 0.3 to 0.5



Parameterized Convection Models

Thermal evolution of the mantle

$$Q \propto Ra^{\beta},$$

Q: heat flux, Ra: Rayleigh number,

β: an amplifer - balance between viscosity and heat dissipation

- **Models with Ur $\geq$ 0.65**

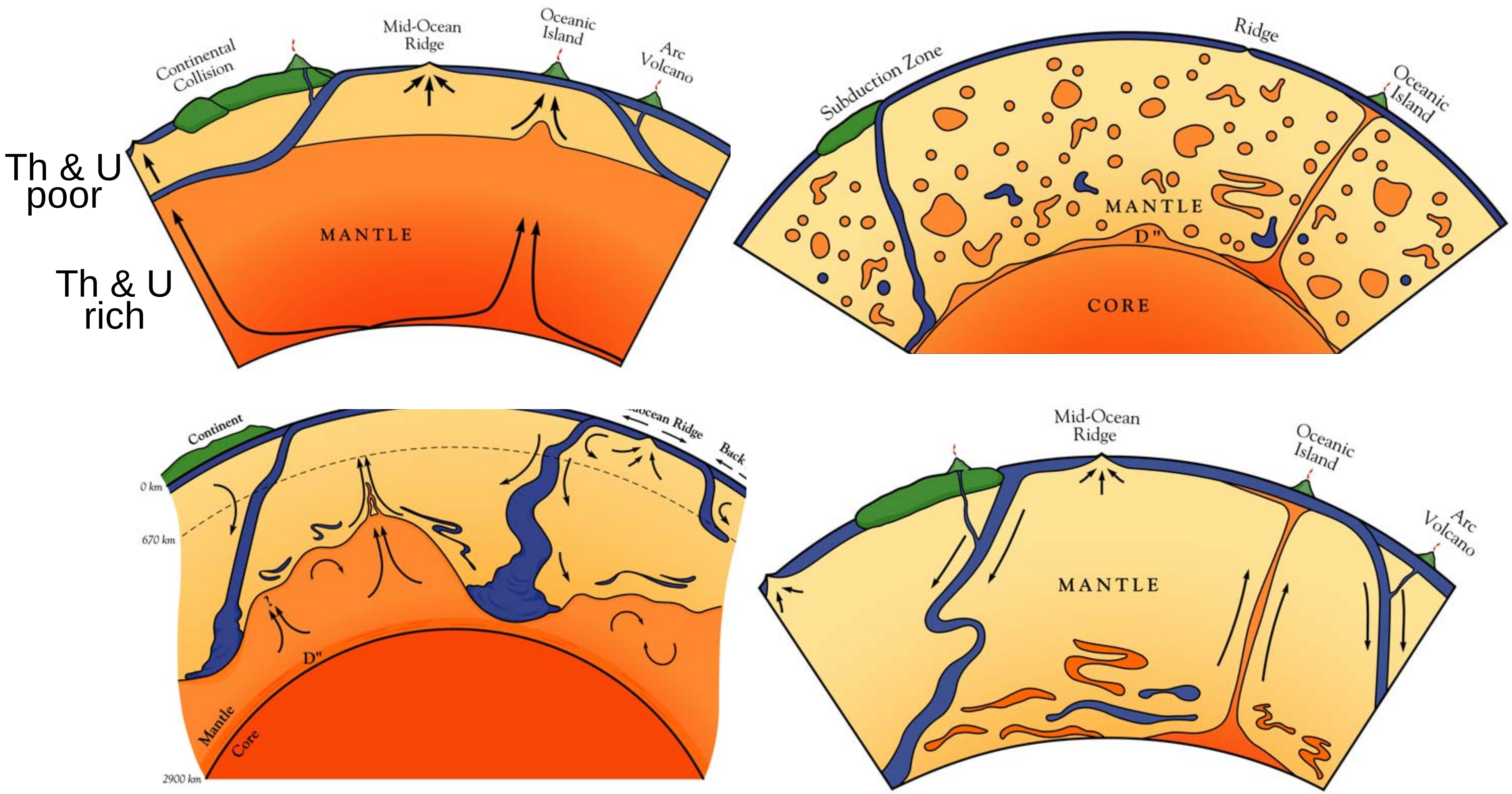
  Schubert et al '80; Davies '80; Turcotte et al '01

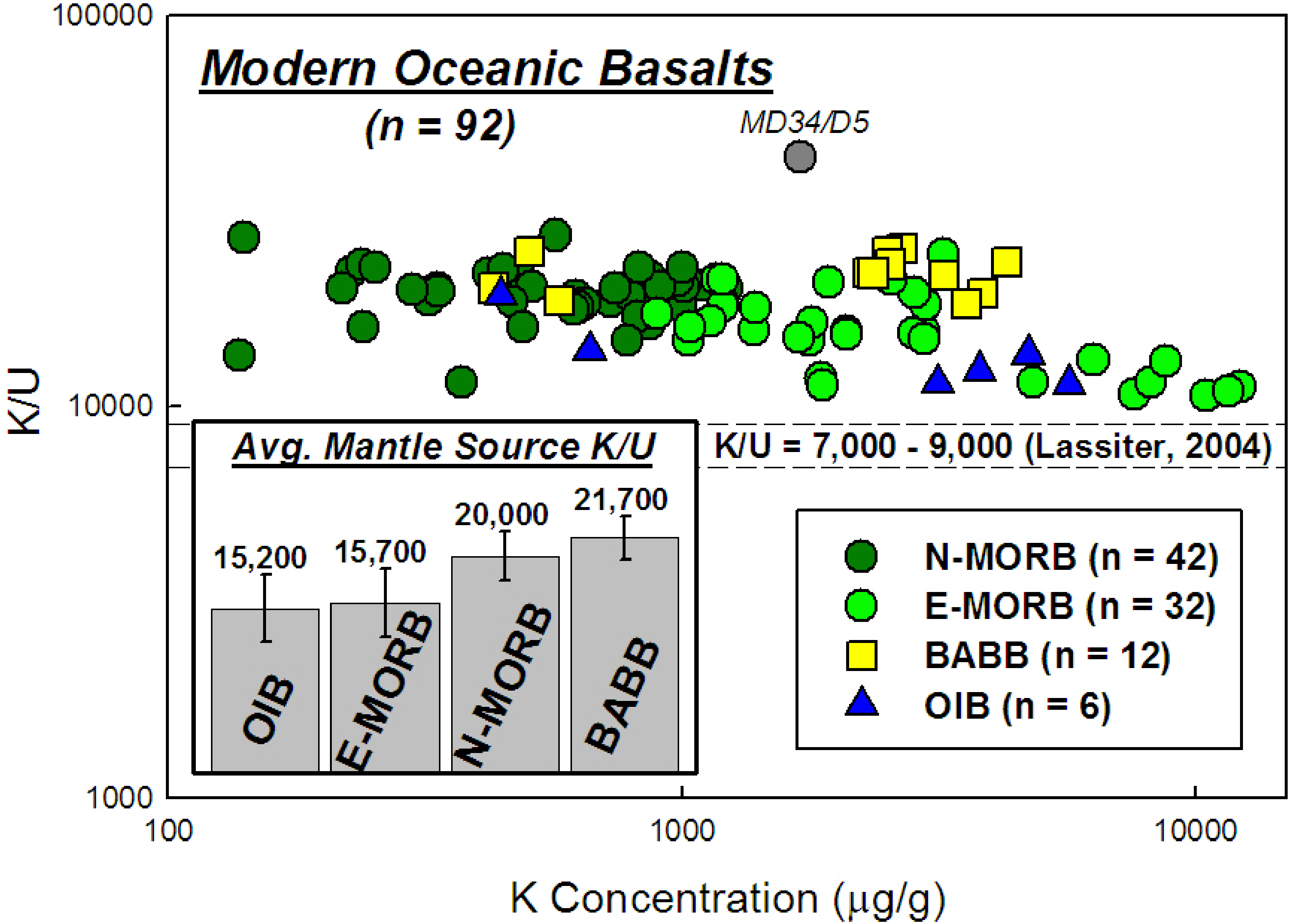
- **Models with Ur $\leq$ 0.5**

  Jaupart et al '08; Korenaga '06; Grigne et al '05,'07

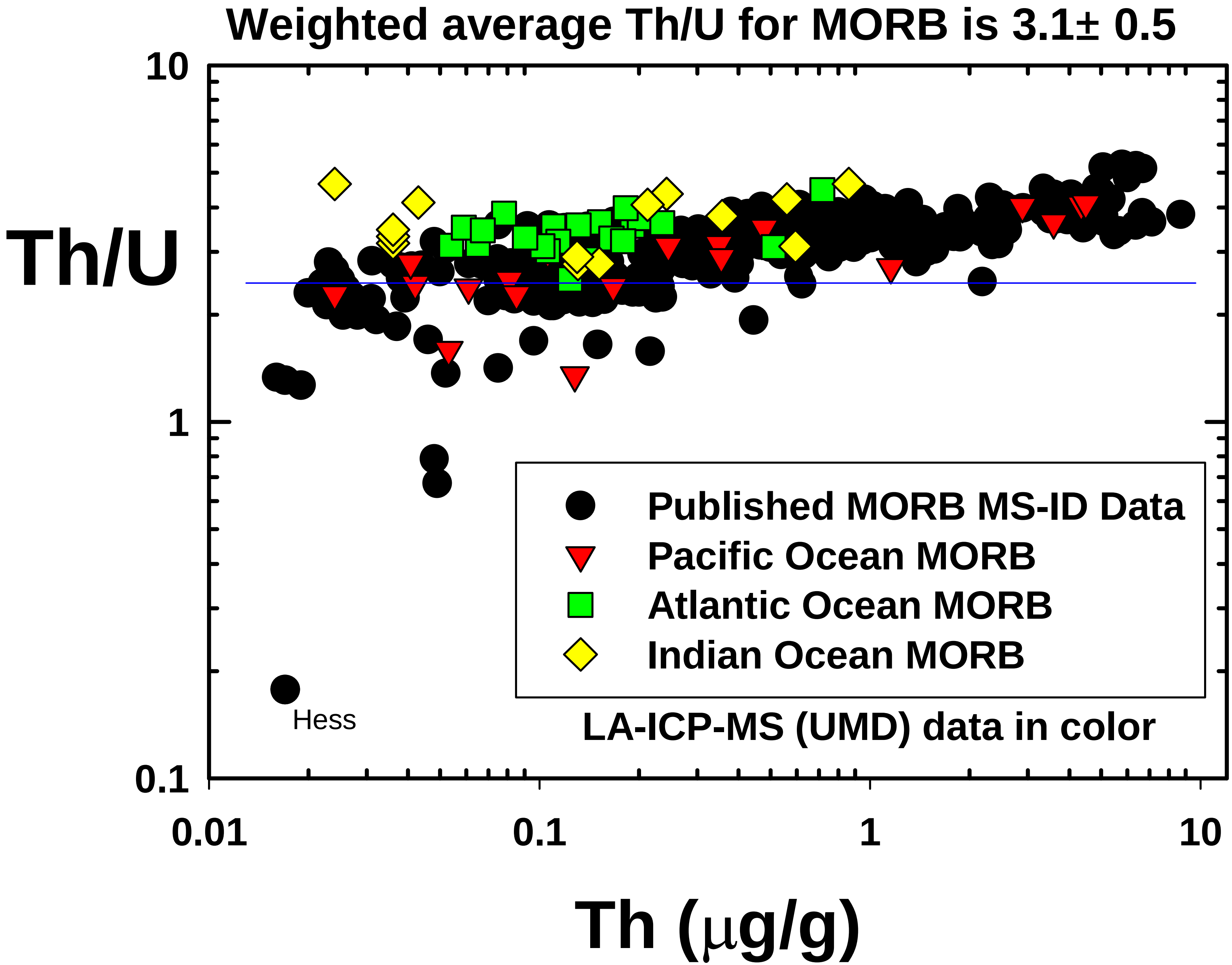
Mantle is depleted in some elements (e.g., Th & U) that are enriched in the continents.

-- models of mantle convection and element distribution





Modern Oceanic Basalts
(n = 92)
MD34/D5
K/U
K Concentration (µg/g)
100000
10000
1000
100
1000
10000
Avg. Mantle Source K/U
15,200
15,700
20,000
21,700
OIB
E-MORB
N-MORB
BABB
K/U = 7,000 - 9,000 (Lassiter, 2004)
N-MORB (n = 42)
E-MORB (n = 32)
BABB (n = 12)
OIB (n = 6)



Weighted average Th/U for MORB is 3.1± 0.5
Th/U
10
1
0.1
0.01
0.1
1
10
Th (μg/g)
Published MORB MS-ID Data
Pacific Ocean MORB
Atlantic Ocean MORB
Indian Ocean MORB
Hess
LA-ICP-MS (UMD) data in color

Pb isotopes

mid-ocean ridge basalts
"MORB"

Direct samples of the present-day mantle

Composition relates to time-integrated

- U/Pb

- Th/Pb

QuickTime™ and a
decompressor
are needed to see this picture.

Th/U and Pb isotopes

- Th/U and $^{208}Pb/^{206}Pb$ composition of MORBs
- At secular equilibrium (activity of $^{230}Th \sim {}^{238}U$) and ($^{232}Th/^{230}Th$) activity is Th/U ratio of the source:

$$\frac{Th}{U} \approx \frac{^{232}Th}{^{238}U} = \frac{\lambda_{238}}{\lambda_{232}} \frac{\left(^{232}Th\right)}{\left(^{238}U\right)} \xrightarrow{se} \frac{\lambda_{238}}{\lambda_{232}} \frac{\left(^{232}Th\right)}{\left(^{230}Th\right)} \equiv \kappa_{Th}$$

- For MORB $Th/U_{source} = Th/U_{lava}$
  - Mid-Atlantic Ridge $\kappa_{Th} = 2.5 \pm 0.1$
  - East Pacific Rise $\kappa_{Th} = 2.5 \pm 0.2$
  - Hawaii and Iceland $\kappa_{Th} = 3.0 \pm 0.2$

Th/U and Pb isotopes

- Time integrated Th/U mantle as determined from the Pb isotopes (where *T* is the age of the Earth):

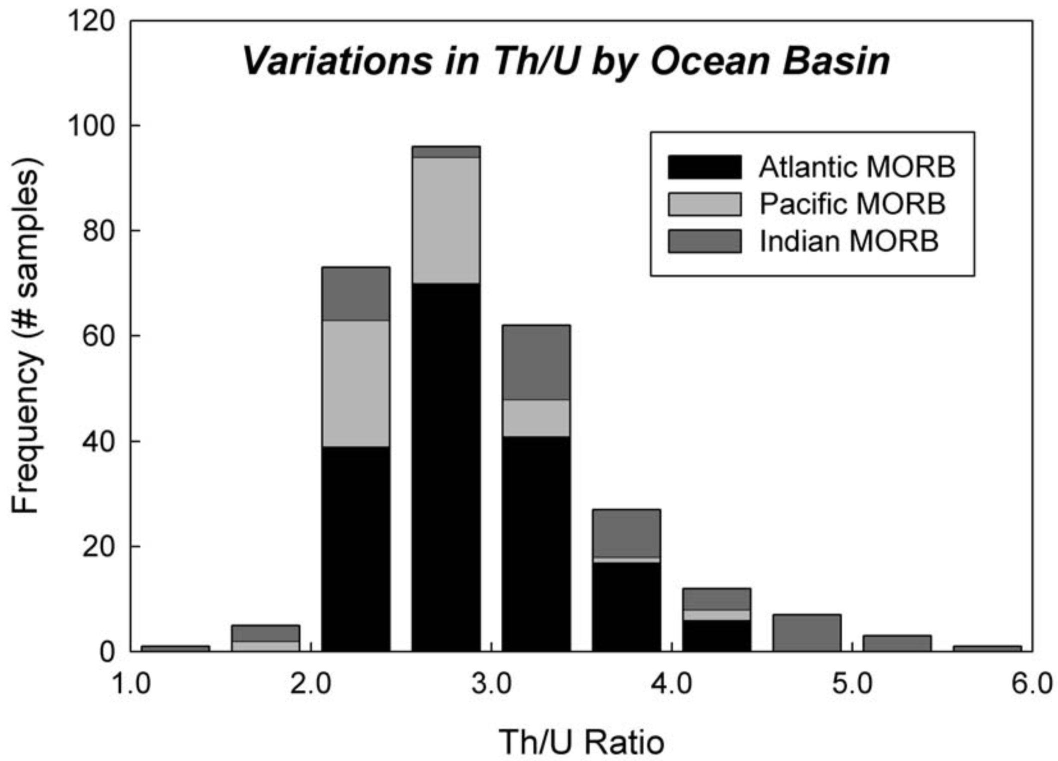
$$\frac{Th}{U} \approx \frac{^{232}Th}{^{238}U} = \frac{^{208}Pb*}{^{206}Pb*}\frac{\left(e^{\lambda_{238}T}-1\right)}{\left(e^{\lambda_{232}T}-1\right)} \equiv \kappa_{Pb}$$

- Data:
  - Mid-Atlantic Ridge κ_{Pb}= 3.8±0.1
  - East Pacific Rise κ_{Pb} = 3.7±0.1
  - Indian Ridges κ_{Pb} = 3.9±0.1
  - Hawaii and Iceland κ_{Pb} = 3.8±0.1

Th/U in the Earth

Th/U$_{chonrites}$ 3.9±0.4

QuickTime™ and a decompressor are needed to see this picture.

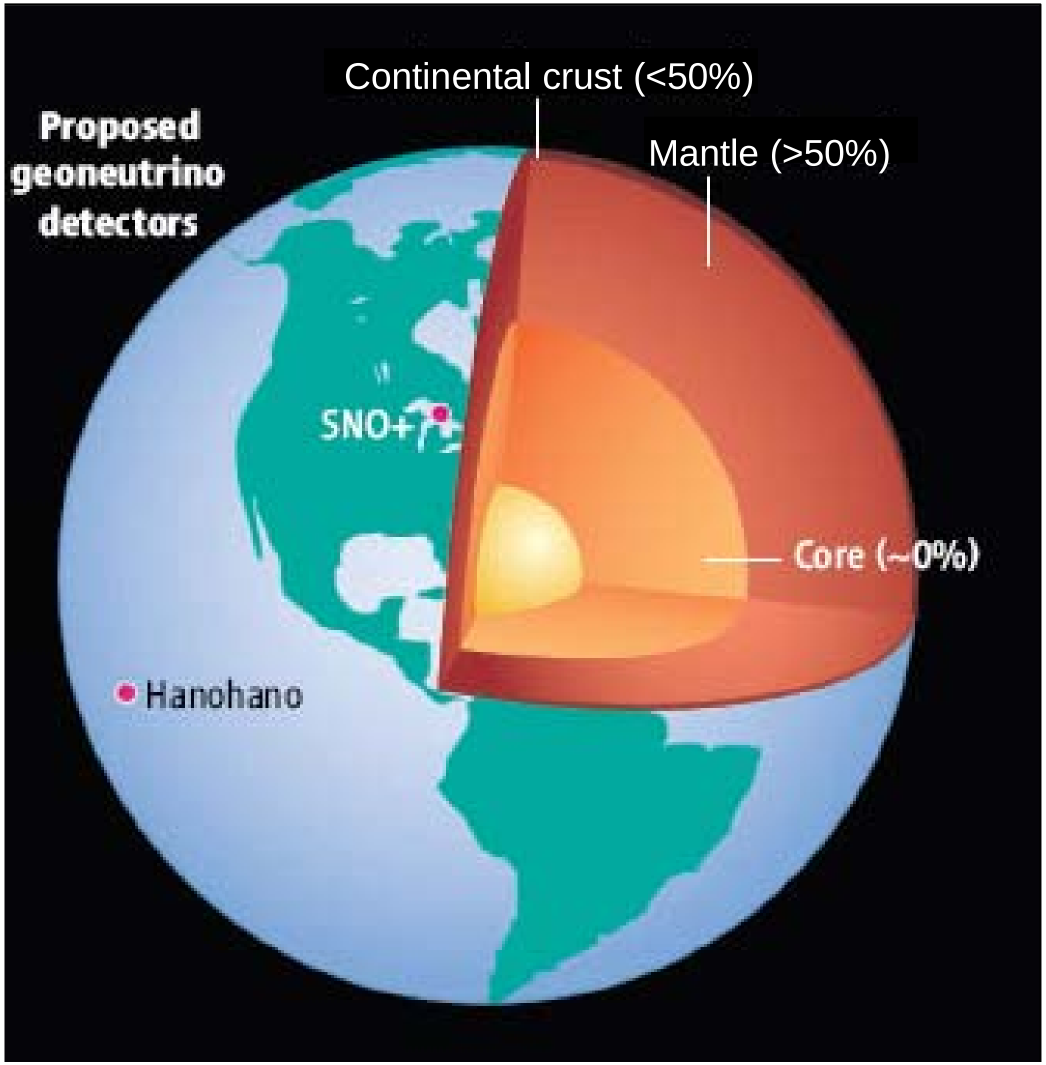


Th/U$_{continental\ crust}$ ~4.5

Th/U$_{mantle}$ ~ 3

U in the Earth:

"Differentiation"



~13 ng/g U in the Earth

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

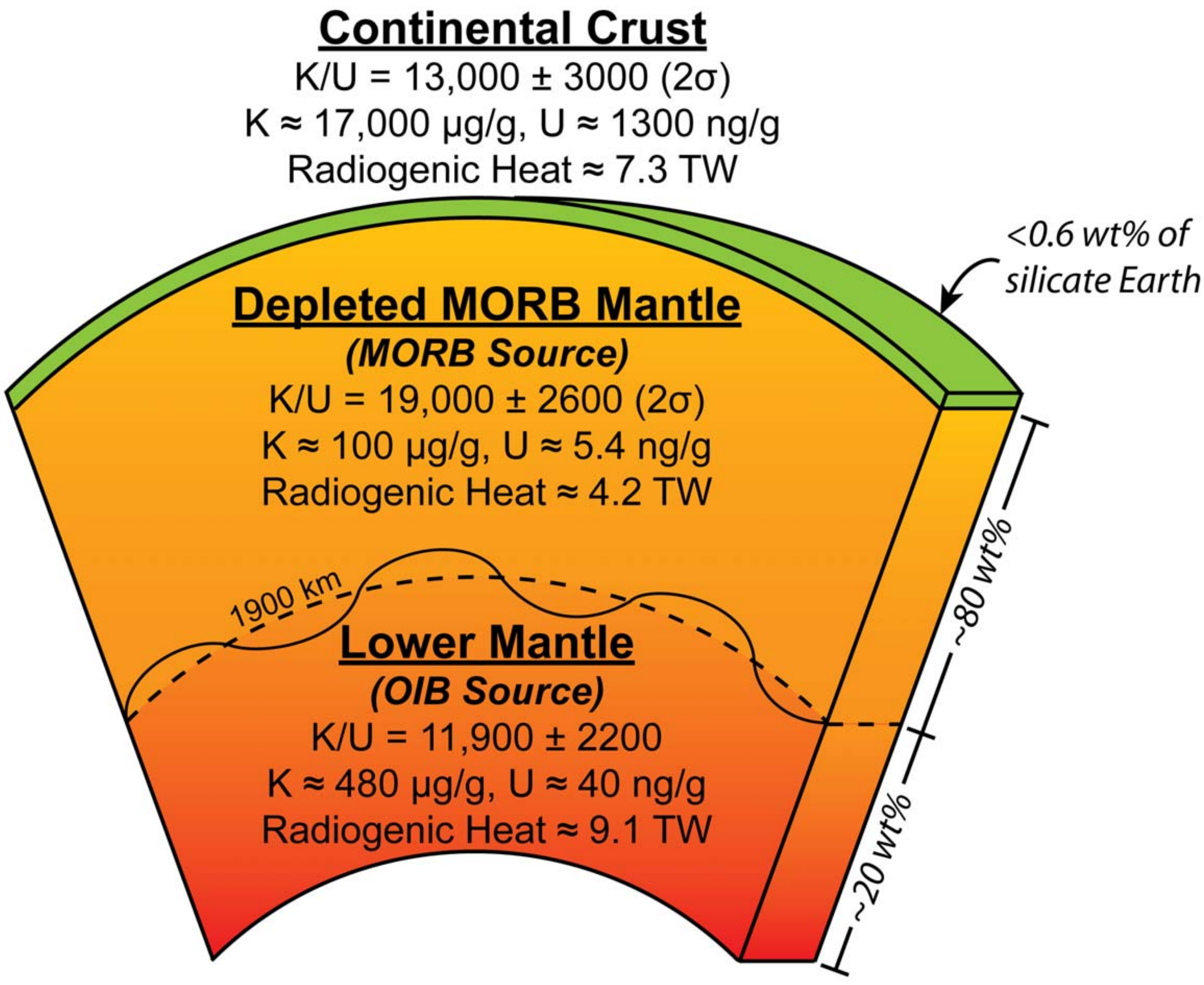
Silicate sphere
20 ng/g U

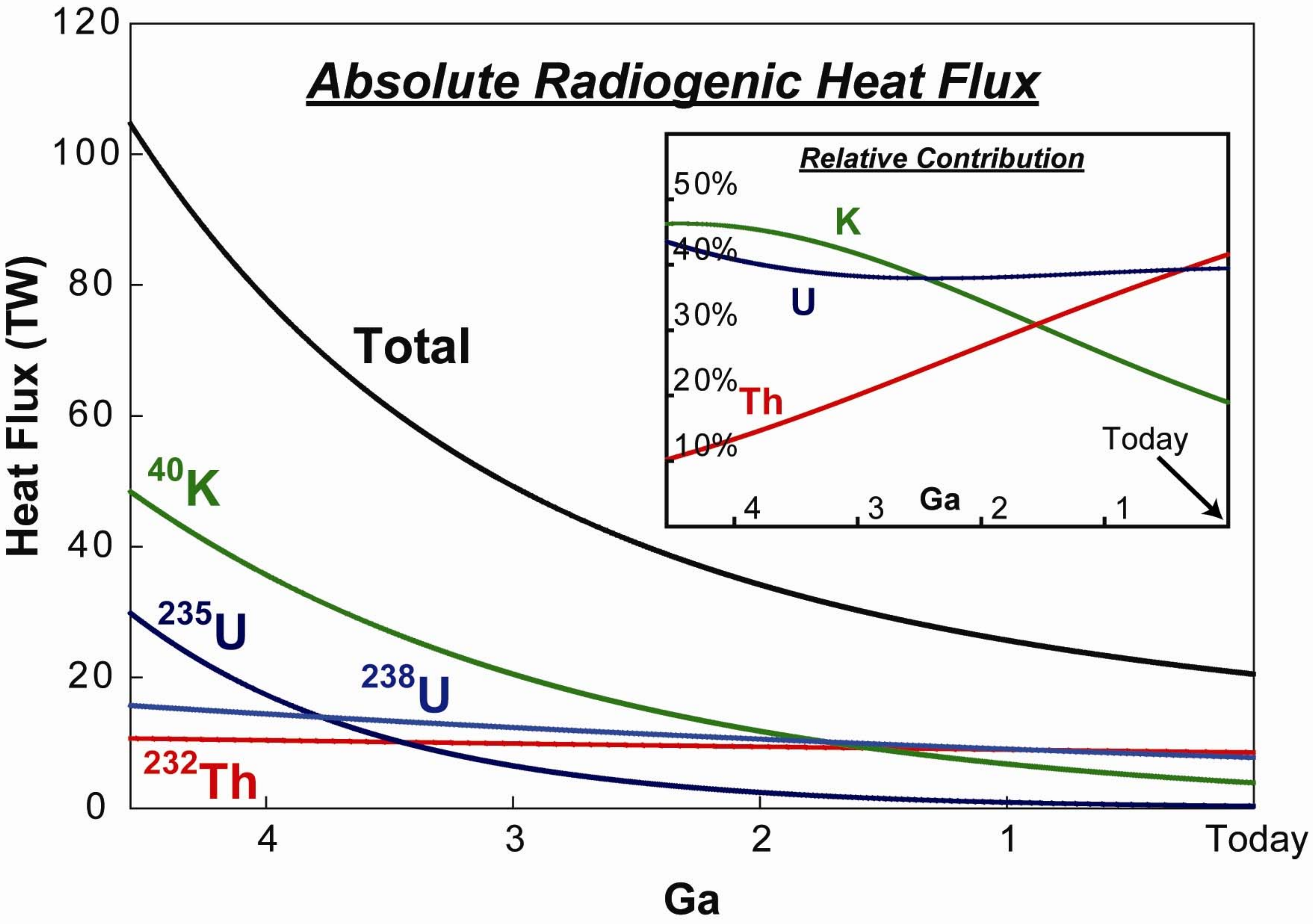
Continental Crust
1000 ng/g U

Mantle
10 ng/g U

Chromatographic separation
Mantle melting & crust formation

Earth's budget of heat producing elements





Absolute Radiogenic Heat Flux
Heat Flux (TW)
120
100
80
60
40
20
0
4
3
2
1
Today
Ga
Total
40K
235U
238U
232Th
Relative Contribution
50%
40%
30%
20%
10%
K
U
Th
Today
4
3
Ga
2
1

Conclusions

1) K/U 13,800 + 2,600 (2σ)

2) Ur for mantle convection ~0.34

3) Cooling rate 70-120 $kGyr^{-1}$

4) There is a fundamental need for constraints from geodynamics

Paramount Request

Detecting Potassium (K) $\bar{\nu}_e$

(1) Significant for the Planetary budget of volatile element
-- What did we inherit from our accretion disk?

(2) Fundamental to unraveling Mantle structure
-- ^{40}K controls mantle Ar inventory $^{40}K \rightarrow {}^{40}Ar$ (EC)

(3) Geophysics want K in core to power the Geodynamo?
-- We don’t understand the energy source…

naturenews

Published online 15 May 2008 | Nature | doi:10.1038/news.2008.822

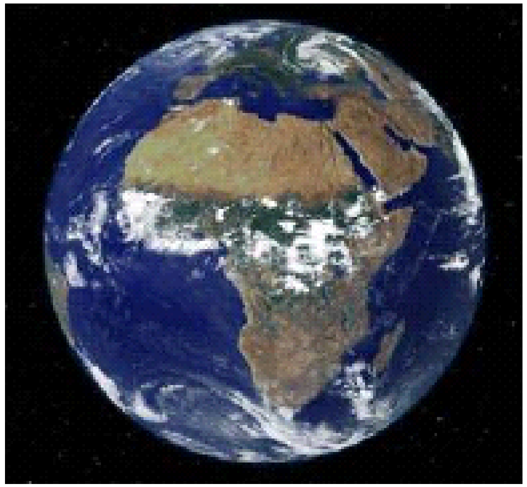
News

Are there nuclear reactors at Earth's core?

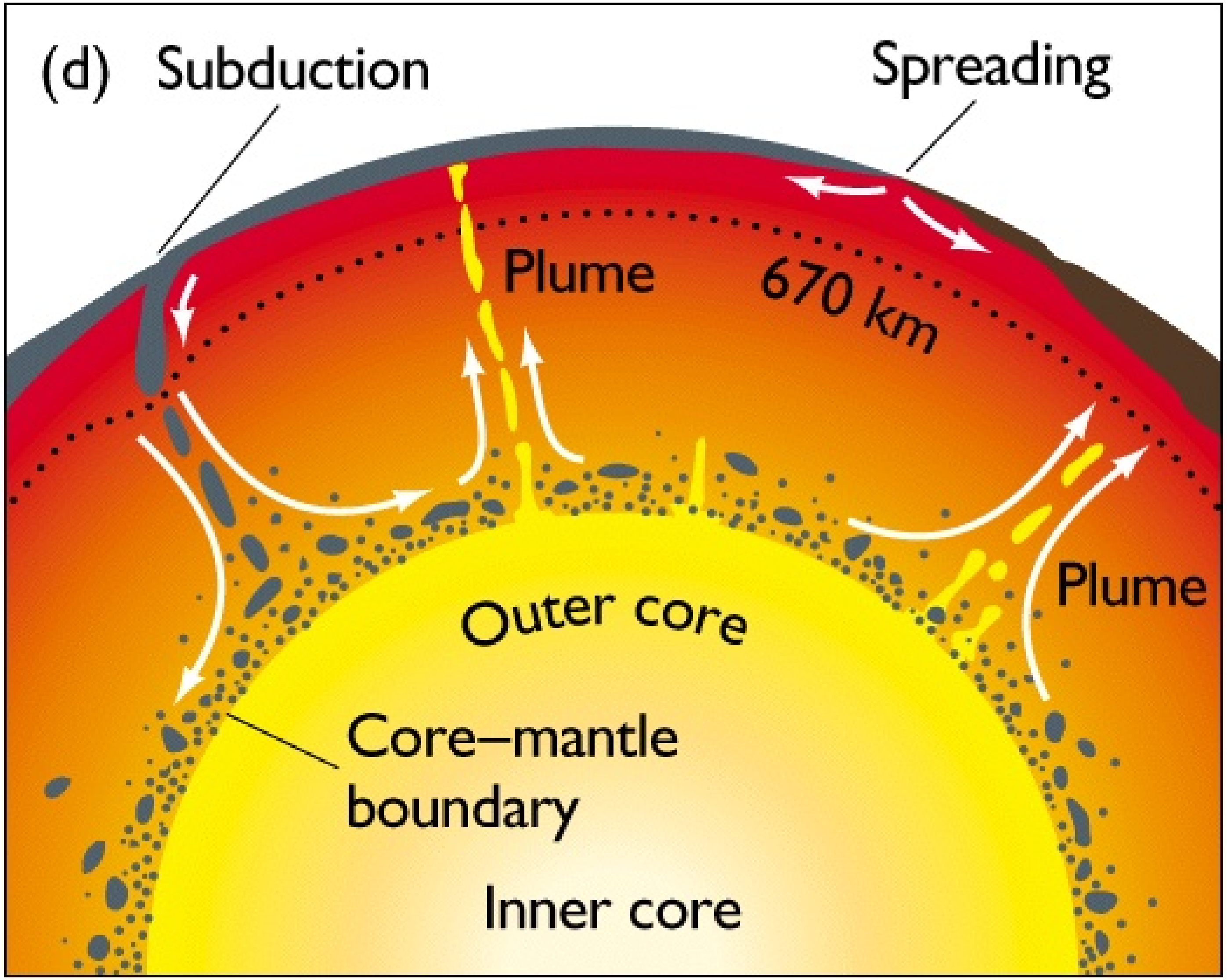
Fission reactors may have been burning for billions of years.

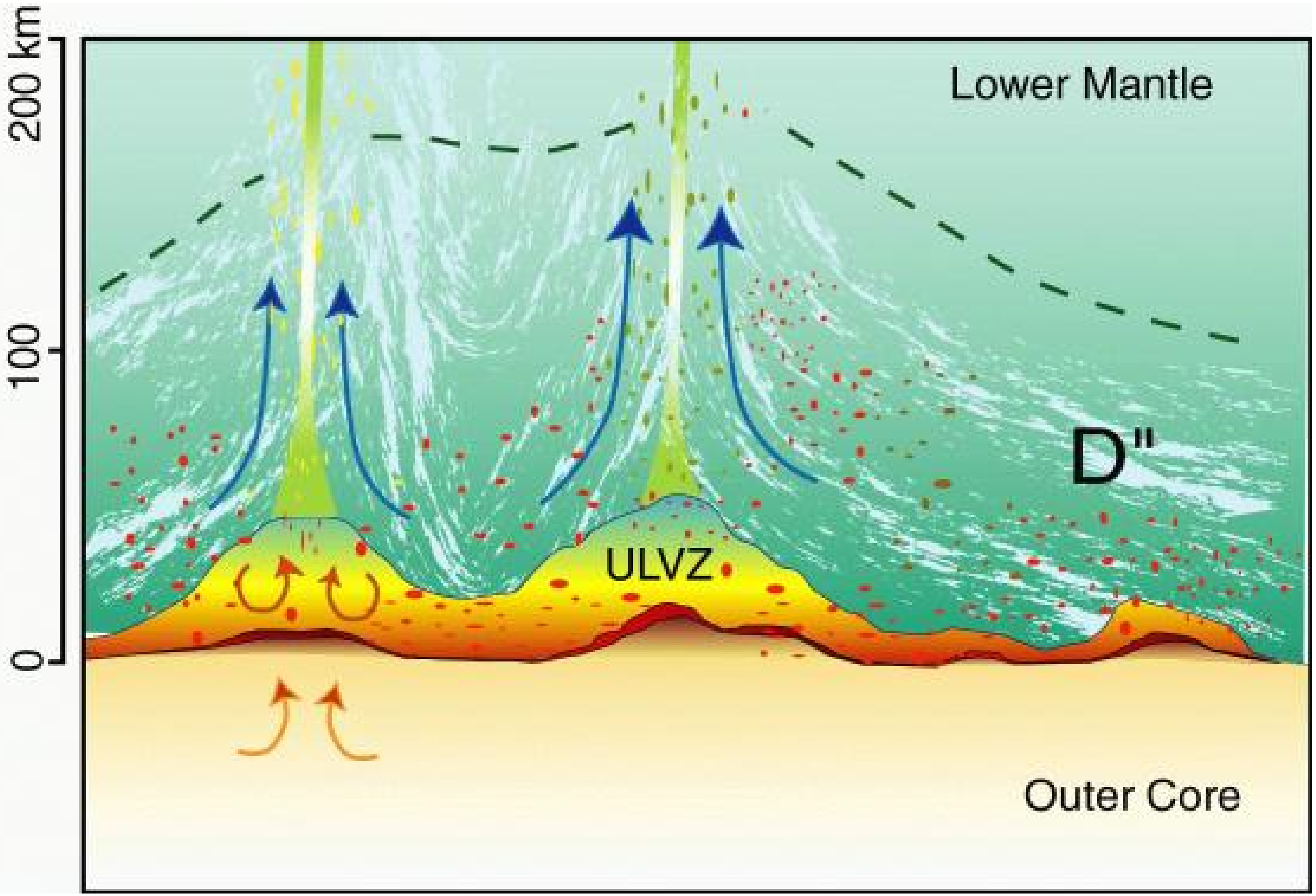
Published May 2008

Based on: R. de Meijer & W. van Westrenen
South African Journal of Science (2008)



Could this be home to
buried nuclear infernos?


(d)
Subduction
Spreading
Plume
670 km
Plume
Outer core
Core–mantle
boundary
Inner core


200 km
100
0
Lower Mantle
D"
ULVZ
Outer Core

hmmmmmm

^{142}Nd is the daughter of ^{146}Sm, an extinct parent.

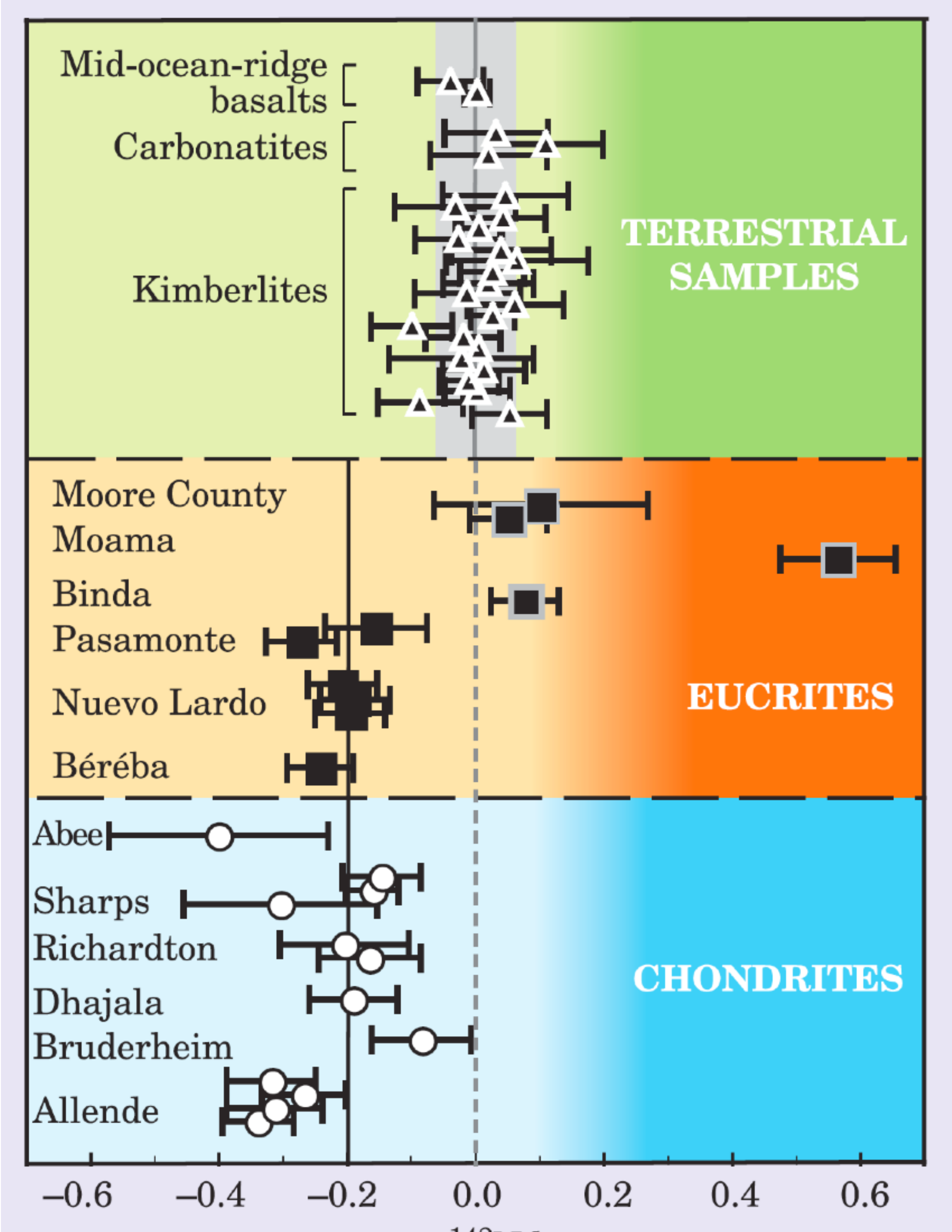
^{142}Nd in the accessible Earth is 20 ppm higher than in chondrites.

Only two simple choices:
- the earth is not chondritic.
- there is a hidden terrestrial low Sm/Nd reservoir we've not yet seen.

All consequences are drastic!

So is the chondritic model for the Earth wrong?

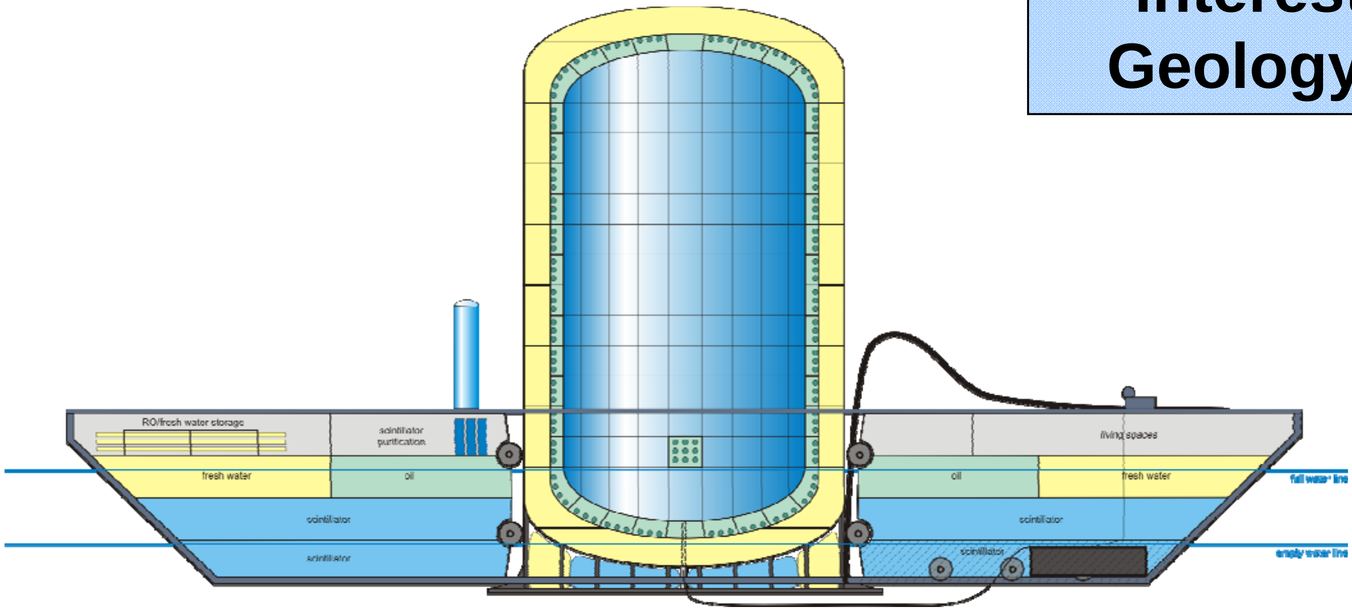
Maybe!



Boyet and Carlson 2006

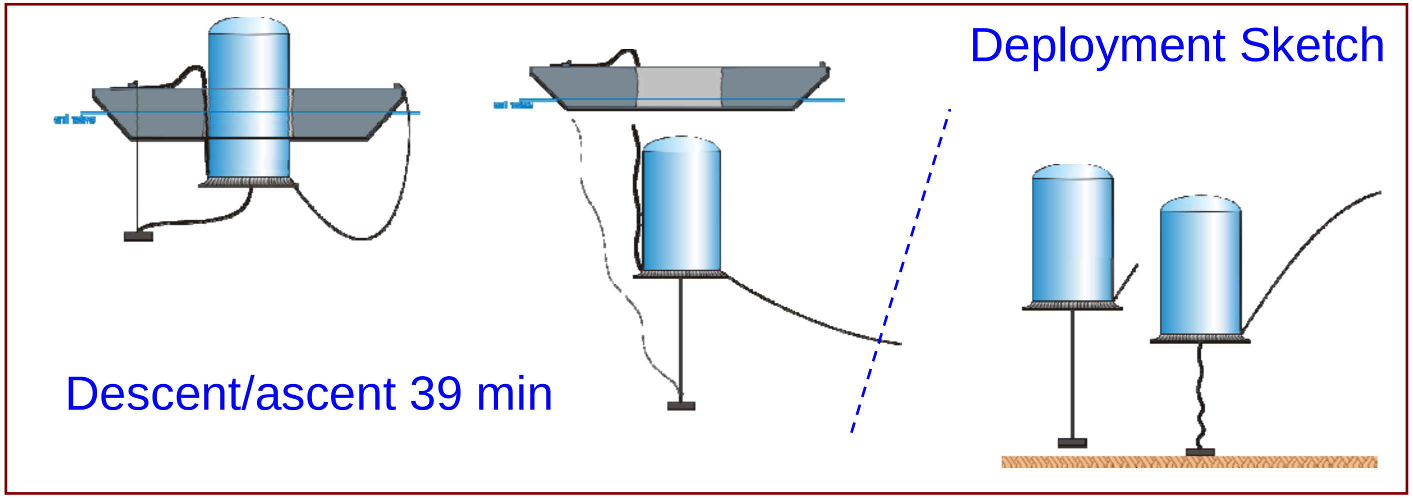
Hanohano

An experiment with joint interests in Physics, Geology, and Security

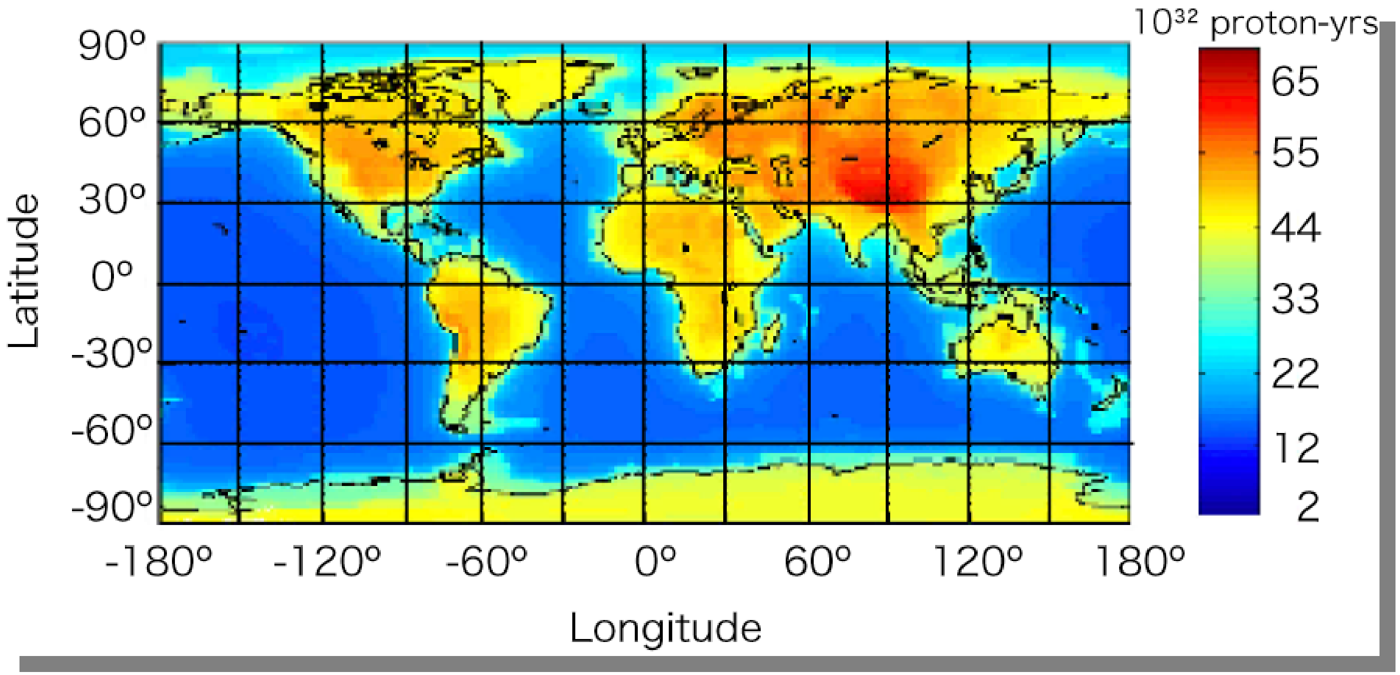


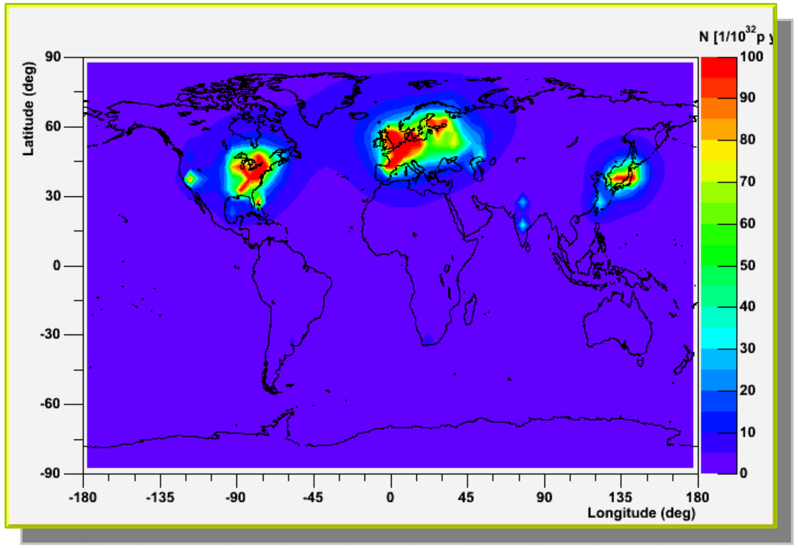
- multiple deployments
- deep water cosmic shield
- control-able L/E detection

A Deep Ocean $\bar{\nu}_e$ Electron Anti-Neutrino Observatory



Predicted Geoneutrino Flux





Reactor Flux -
irreducible background

Geoneutrino flux determinations
-continental (KamLAND, Borexino, SNO+)
-oceanic (Hanohano)

Continental Heat Flow : example from Canadian Shield