CIDER 2018: Geochemistry Lecture #3 - Part #1, Fundamentals

Radiogenic Isotope and Deep Mantle Heterogeneity

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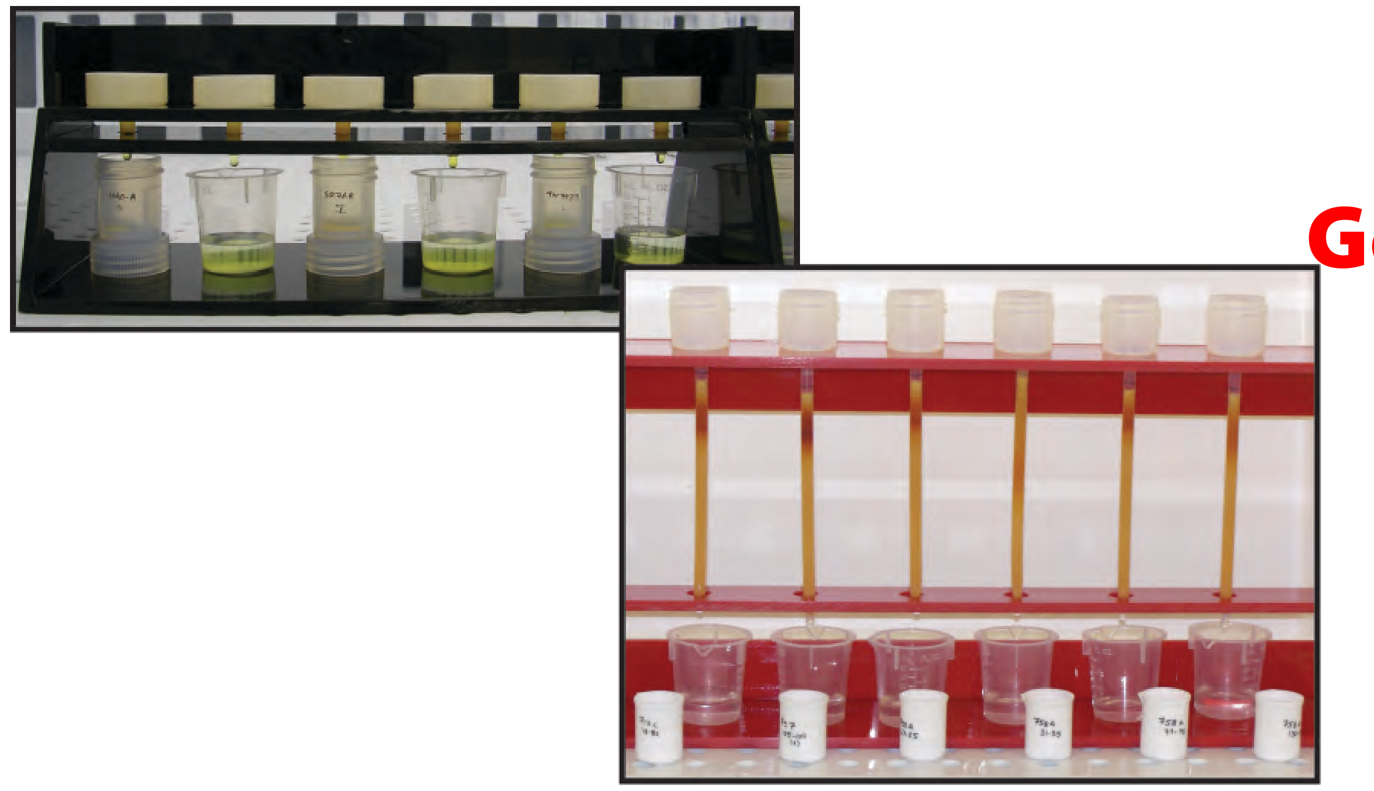
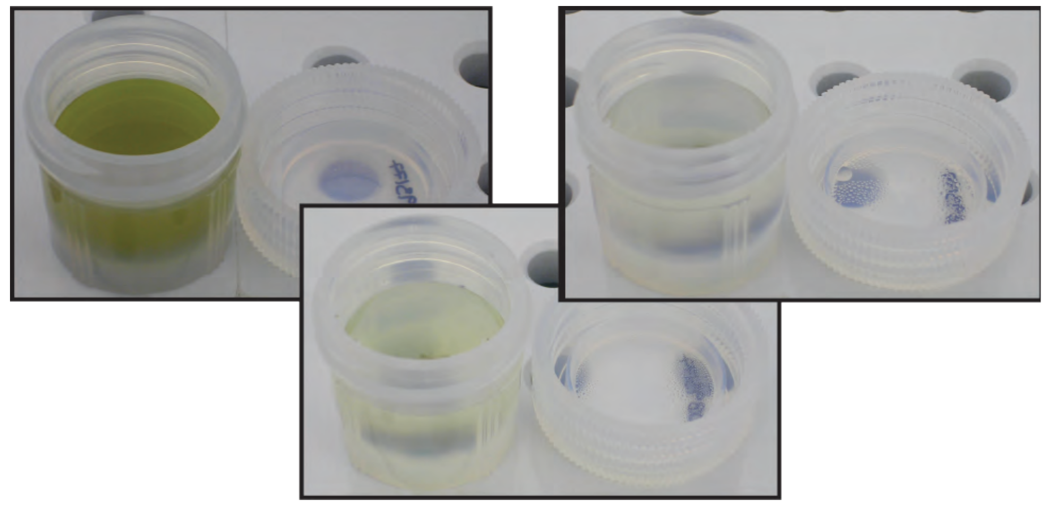
Reading materials:

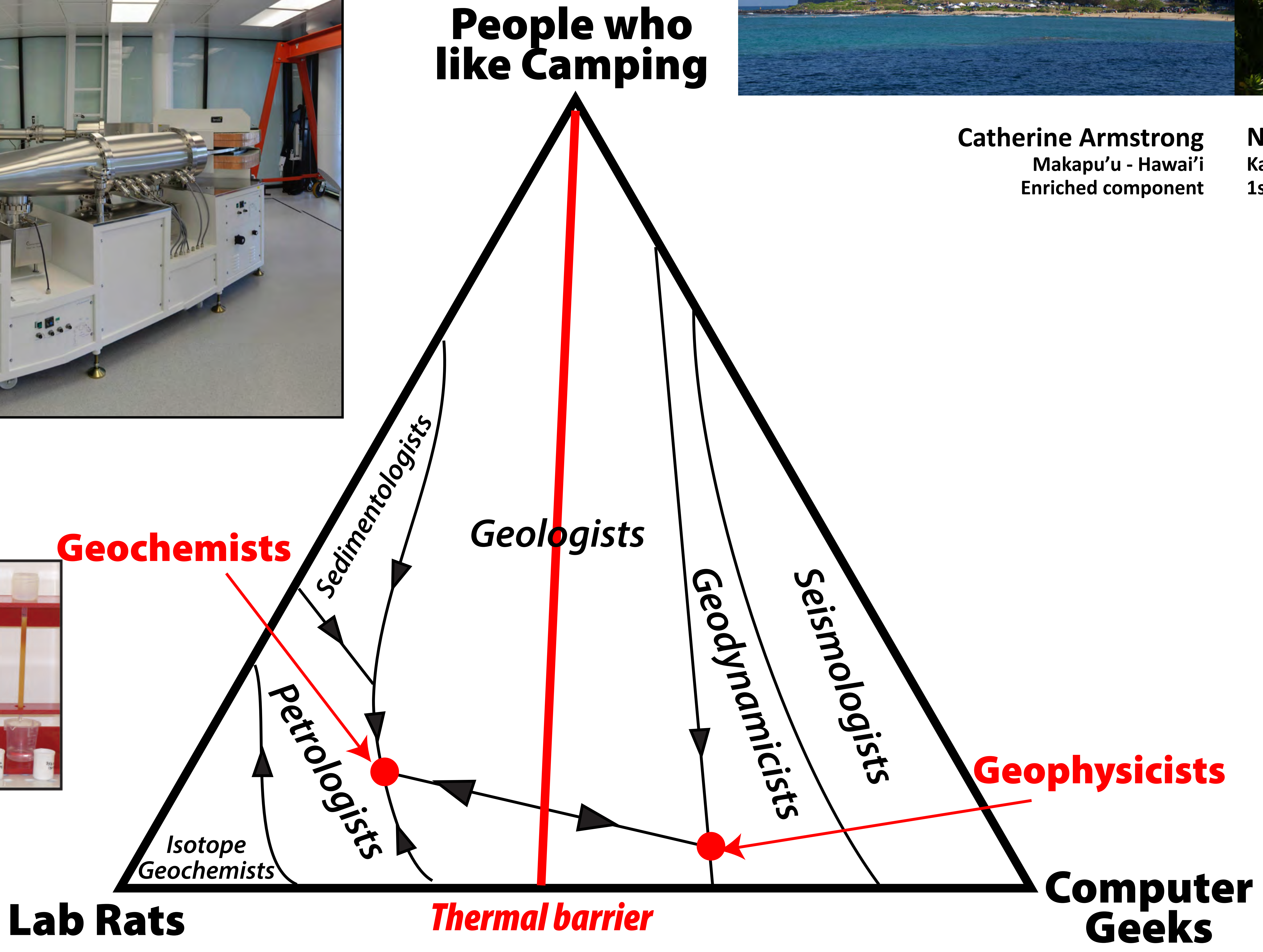
Hofmann A., ToG, Chapter 2.03 (2003): Sampling Mantle Heterogeneity through Oceanic Basalts: Isotopes and Trace Elements
White, W. (2015). Probing the Earth's Deep Interior Through Geochemistry. *Geochemical Perspectives*, 95–251. http://doi.org/10.7185/geochempersp.4.2

Ocean Entry: Oct 2002

How to Move Forward?
Need to Break some Boundaries …



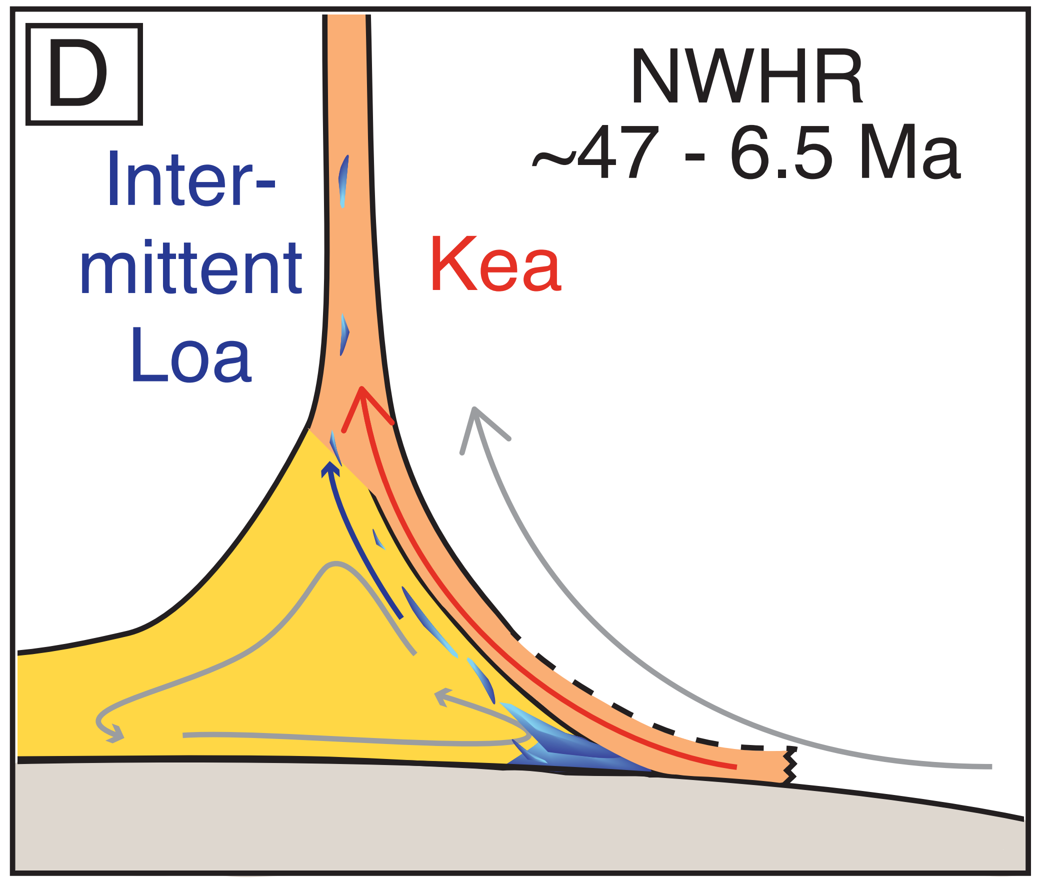




Experiments at 1 atm, 298 K

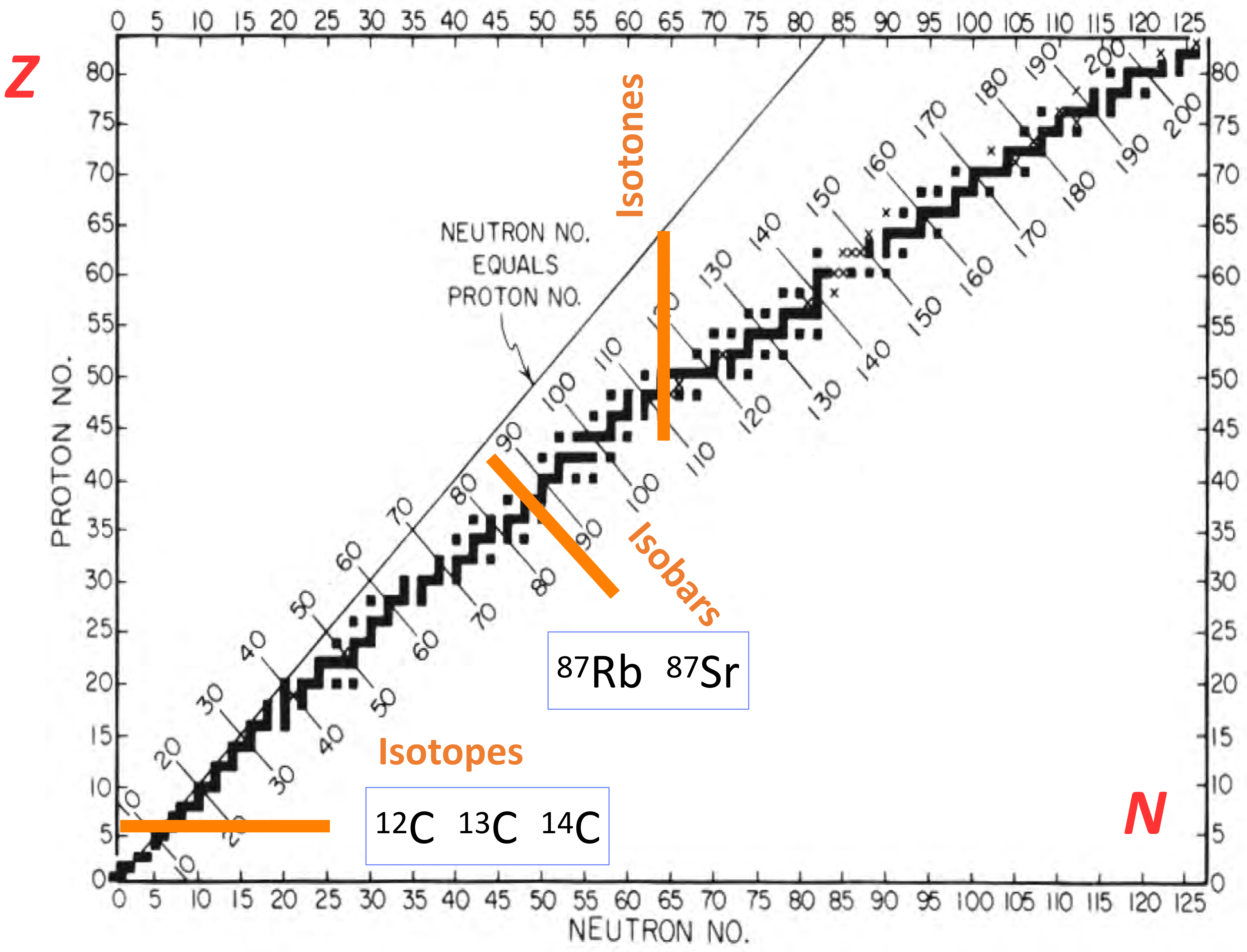
Catherine Armstrong
Makapu'u - Hawai'i
Enriched component

Nicole Williamson
Kaua'i
1st island, 5 Ma and when many things change



Lauren Harrison
NWHR: Modeling, Mantle Geodynamics

Chart of the Nuclides: ^{A}X or $_{Z}X_{N}$



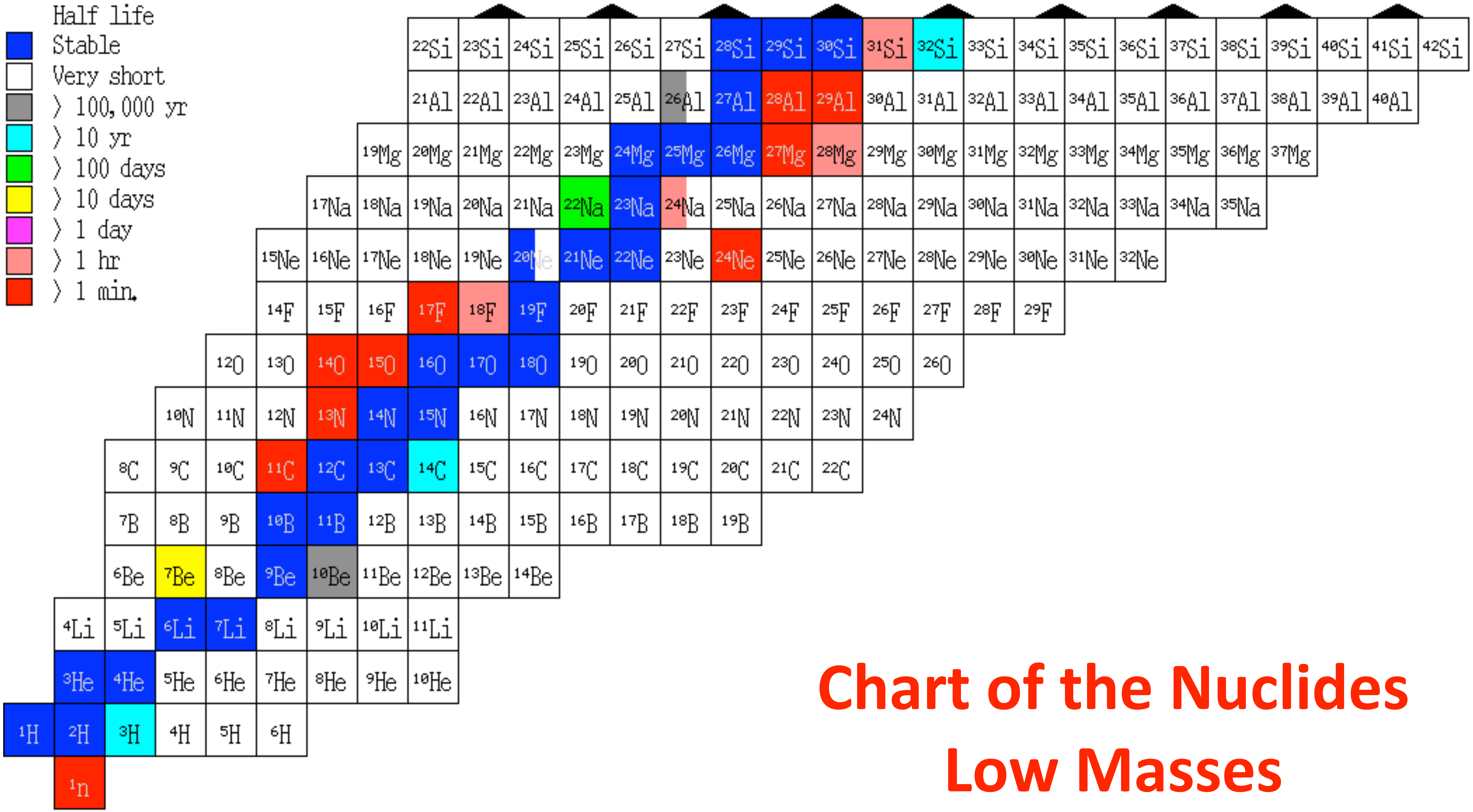
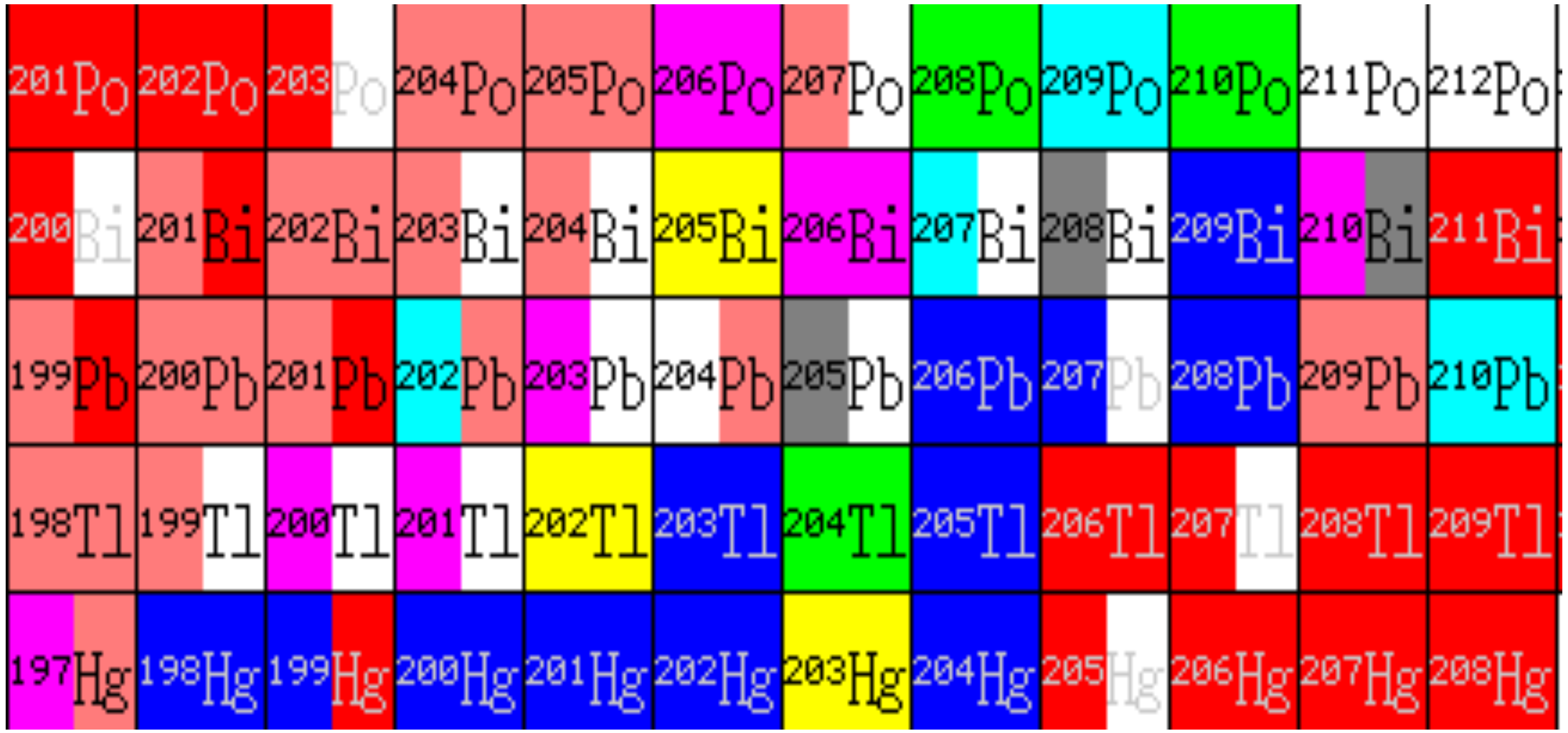


Chart of the Nuclides
Low Masses

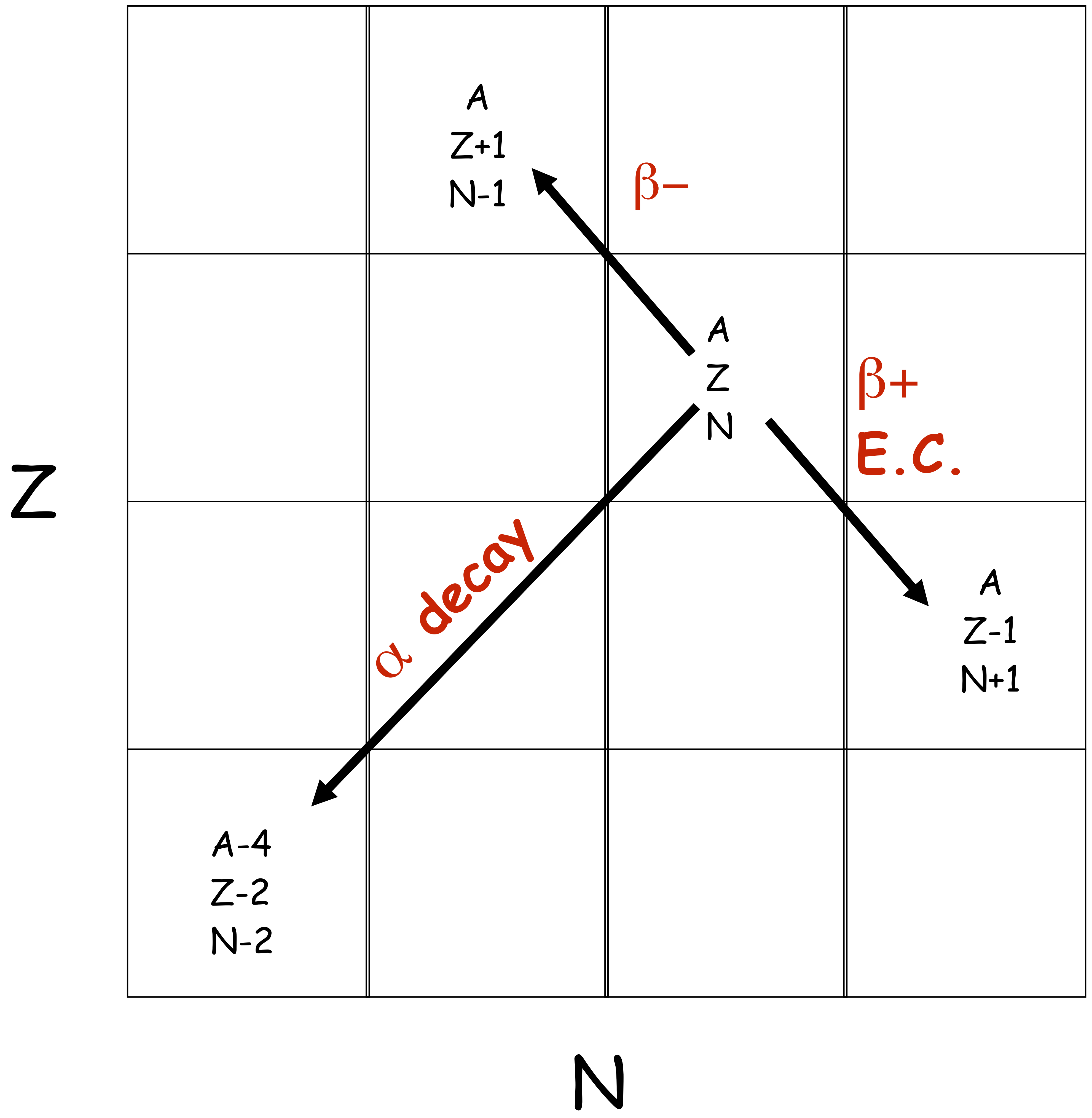
Chart of the Nuclides: Intermediate Masses


Half life
Stable
Very short
> 100,000 yr
> 10 yr
> 100 days
> 10 days
> 1 day
> 1 hr
> 1 min.


201Po 202Po 203Po 204Po 205Po 206Po 207Po 208Po 209Po 210Po 211Po 212Po
200Bi 201Bi 202Bi 203Bi 204Bi 205Bi 206Bi 207Bi 208Bi 209Bi 210Bi 211Bi
199Pb 200Pb 201Pb 202Pb 203Pb 204Pb 205Pb 206Pb 207Pb 208Pb 209Pb 210Pb
198Tl 199Tl 200Tl 201Tl 202Tl 203Tl 204Tl 205Tl 206Tl 207Tl 208Tl 209Tl
197Hg 198Hg 199Hg 200Hg 201Hg 202Hg 203Hg 204Hg 205Hg 206Hg 207Hg 208Hg

High Masses

Radioactive Decay Schemes



Note: important diagram for understanding radioactive decay!

Radioactive Decay

Law of Radioactive Decay:

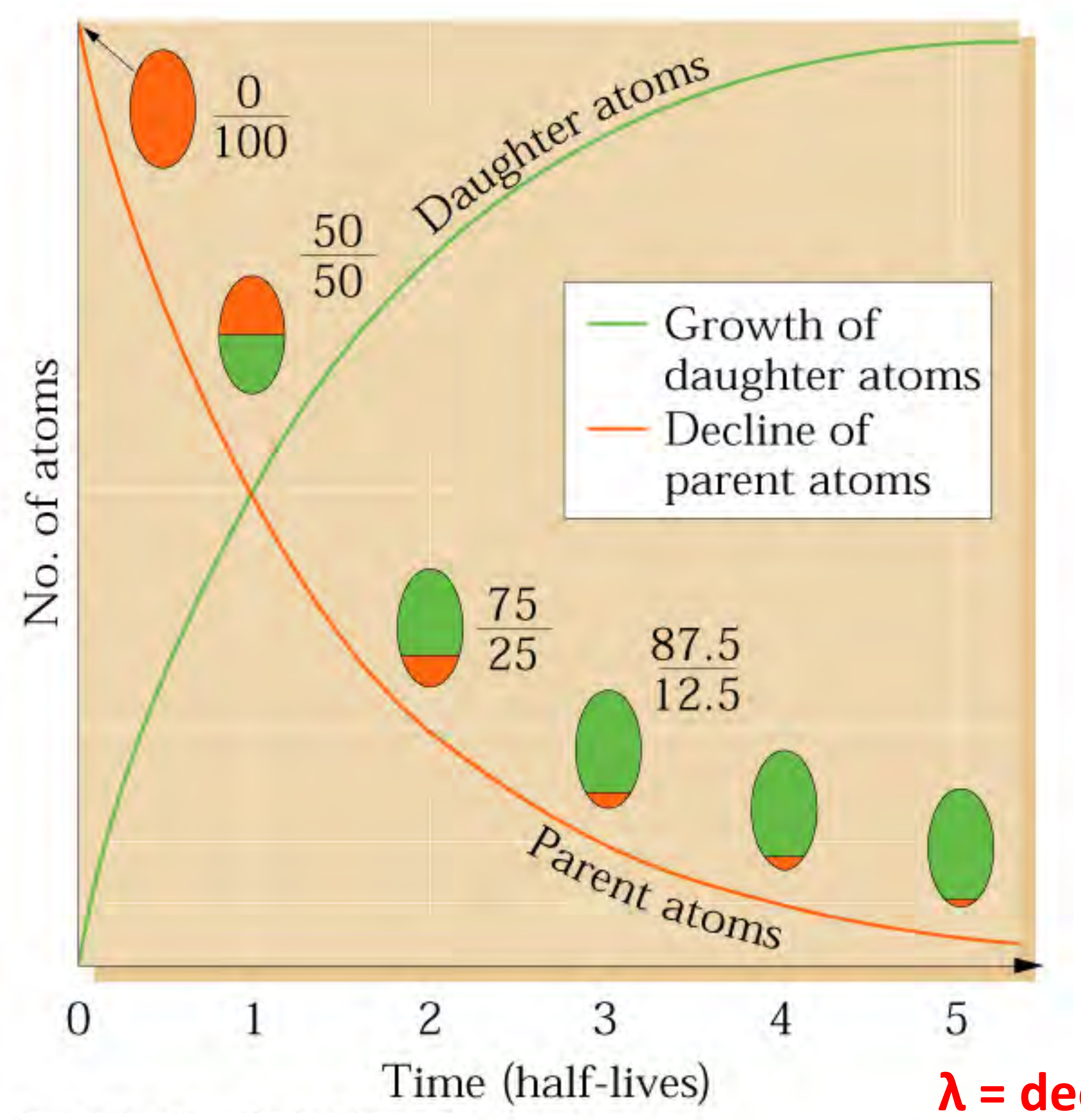
$$-\frac{dN}{dt} \propto N \quad \text{or} \quad -\frac{dN}{dt} = \lambda N$$

The rate of decay of an unstable parent atom (N) at any time (t) is proportional to the number of parent atoms existing at that time.

Rearranging and integrating:

$$\mathbf{N/N_0 = e^{-\lambda t}}$$

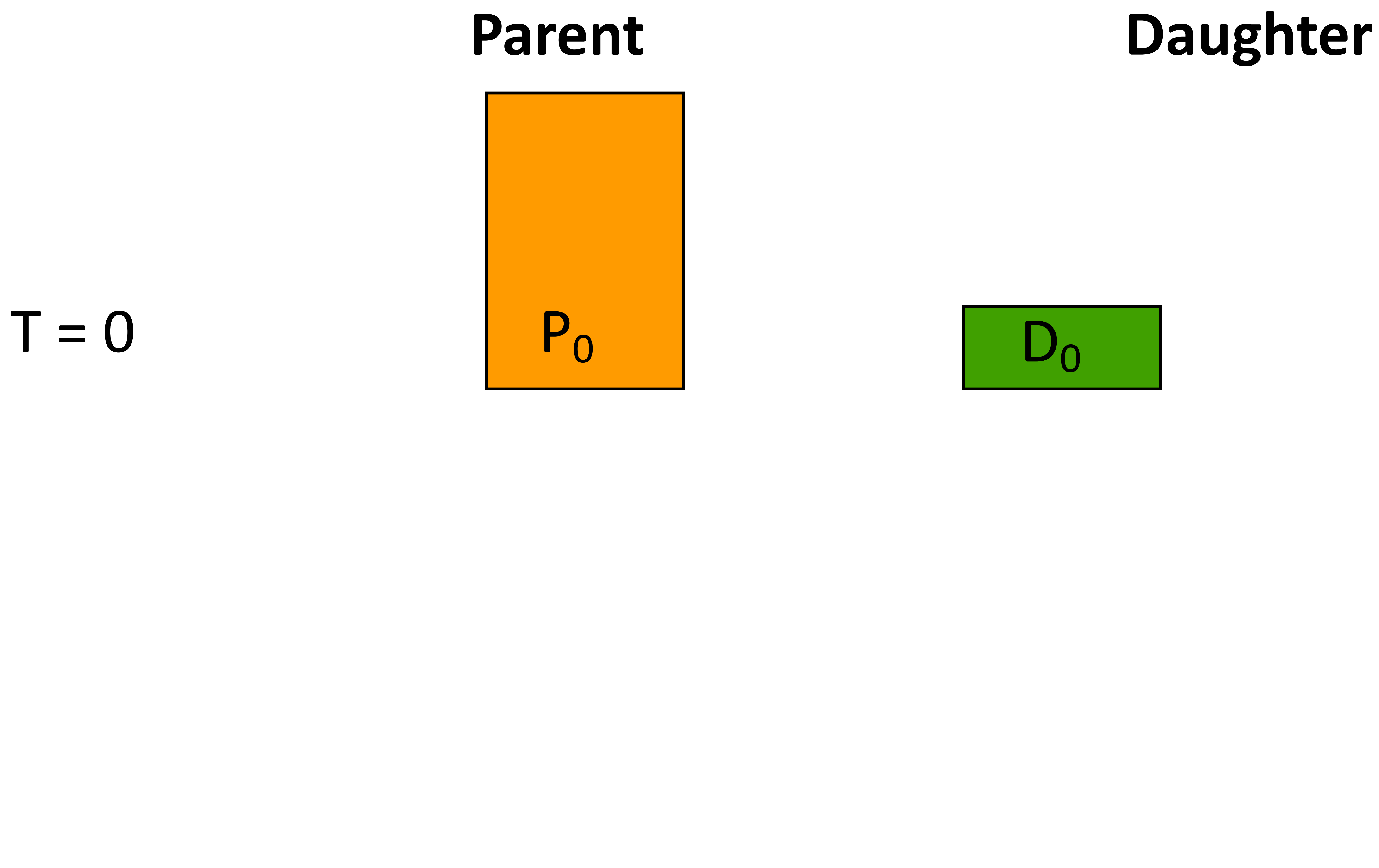
where N_0 is the original number of atoms of the radioactive nuclide, and N is the number after some time (t).

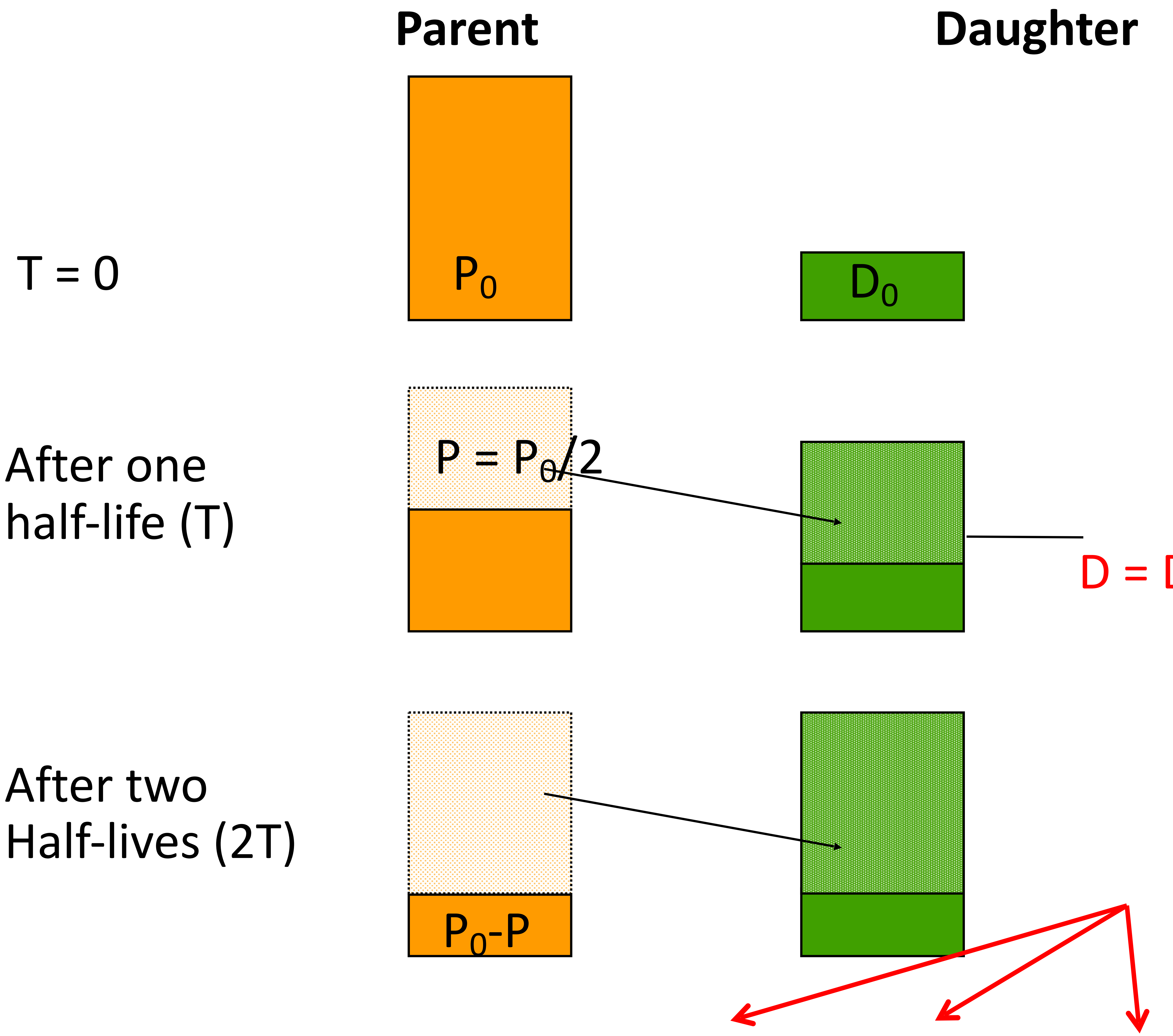


λ = decay constant

Half-life ($T_{1/2}$) = the time required for half of the unstable atoms to decay

$$\mathbf{T_{1/2} = \ln 2/\lambda = 0.693/\lambda}$$


Parent
Daughter
T = 0
P_0
D_0



$D = D_0 + P\,(e^{\lambda T} - 1)$

<u>Why Ratios?</u> *A mass spec measures isotopic ratios rather than absolute abundances*

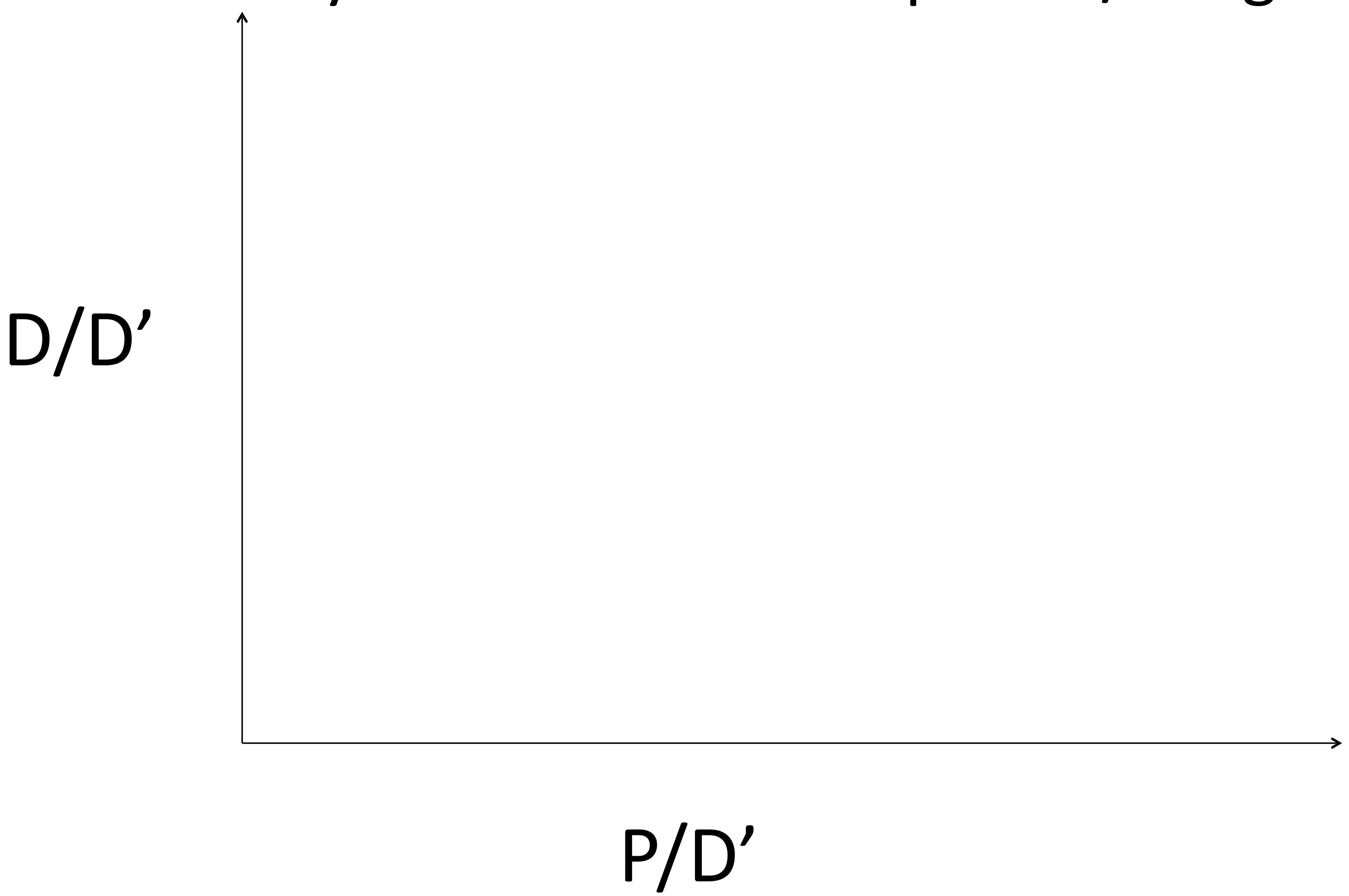
General equation: $(D/D')_t = (D/D')_0 + (P/D')\,(e^{\lambda t} - 1)$

The Isochron Equation

The equation $(D/D')_t = (D/D')_0 + (P/D')\,(e^{\lambda t}-1)$ is the **isochron equation**.

In a plot of $X = P/D'$ and $Y = D/D'$, a set of geologic materials of the same age T and the same initial isotope ratio $(D/D')_0$ will lie on a straight line of slope $e^{\lambda t}-1$.

The P/D' ratio is usually referred to as the parent/daughter ratio.



This type of plot is called an _Isochron plot!_

The Isochron Equation: Rb-Sr

Example: in the Rb-Sr system, where P = ^{87}Rb and D = ^{87}Sr, and D' = ^{86}Sr

$$(^{87}Sr / ^{86}Sr)_t = (^{87}Sr / ^{86}Sr)_0 + (^{87}Rb / ^{86}Sr)_t \, (e^{\lambda 87Rbt}-1)$$

$$y \quad = \quad y_0 \quad + \quad x \quad\quad m$$

This is the equation of a straight line, where:

$X = (^{87}Rb / ^{86}Sr)_t$

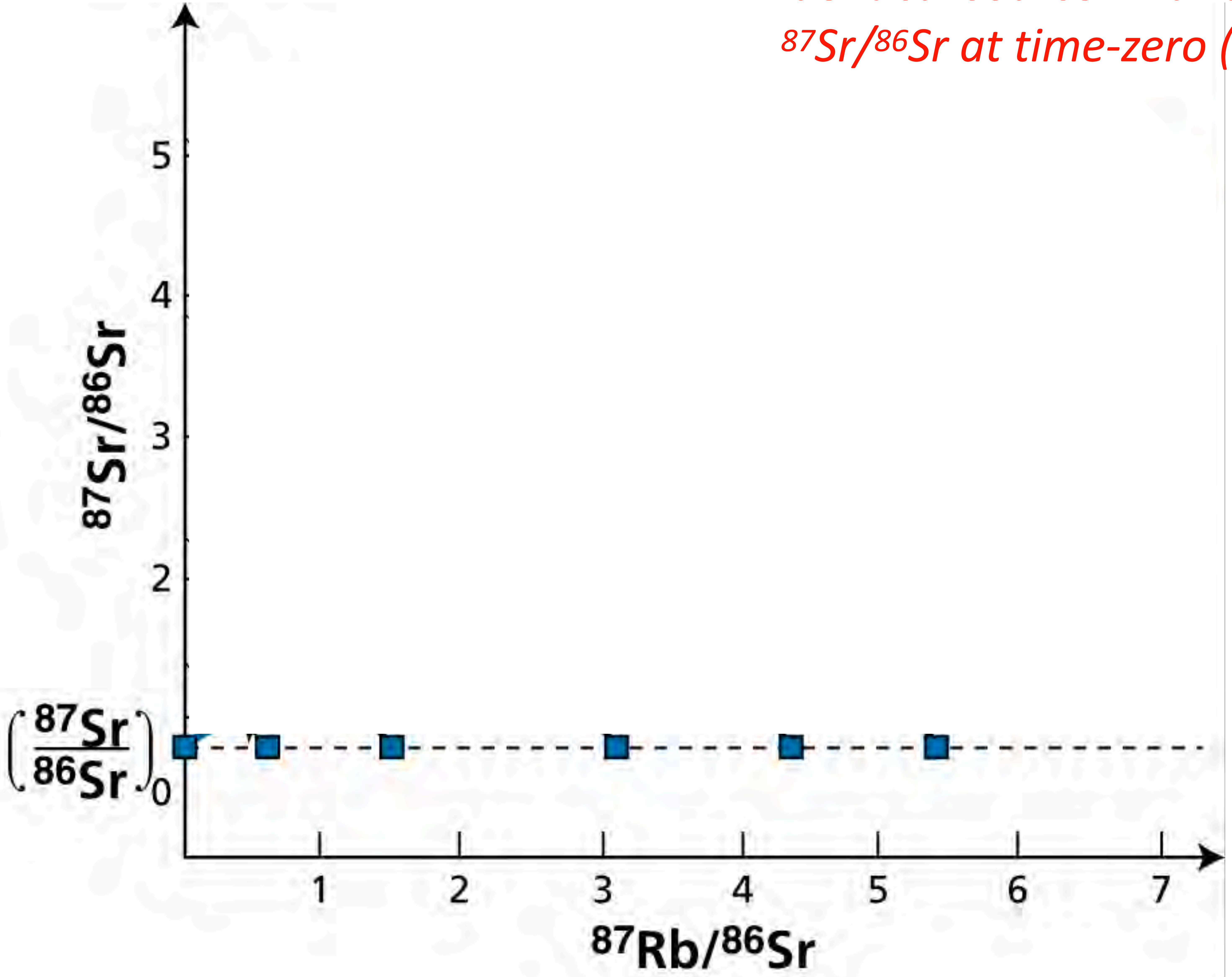
$Y = (^{87}Sr / ^{86}Sr)_t$

Slope $m = (e^{\lambda 87Rbt}-1)$

intercept $y_0 = (^{87}Sr / ^{86}Sr)_t$

Rb-Sr Isochron

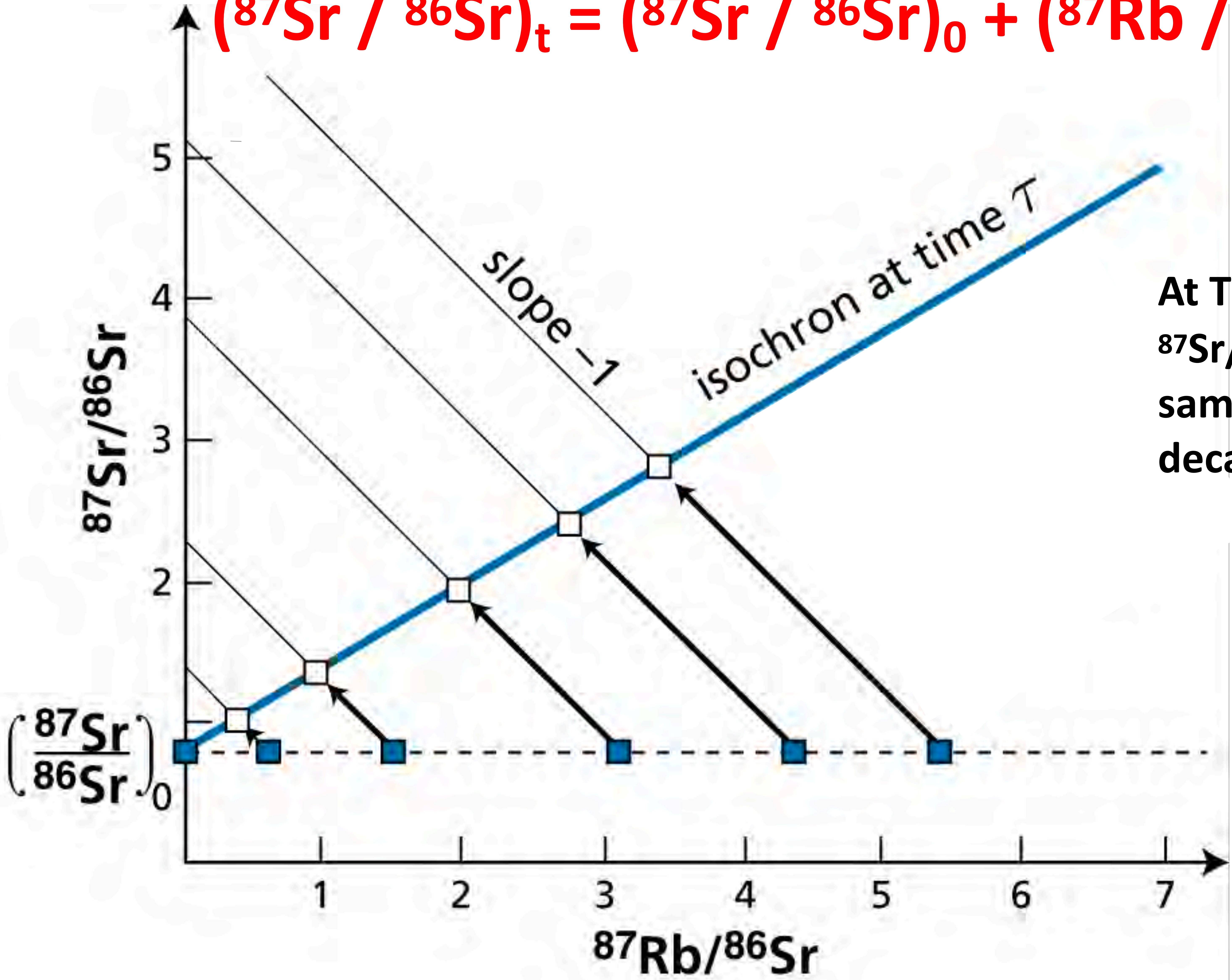
***Plotted:** the isotopic compositions of 6 samples with variable Rb/Sr that formed from the same identical source – variable Rb/Sr, but constant $^{87}Sr/^{86}Sr$ at time-zero (before radioactive decay).*



At T=0
Homogeneous source
i.e. initial ratio

Rb-Sr Isochron

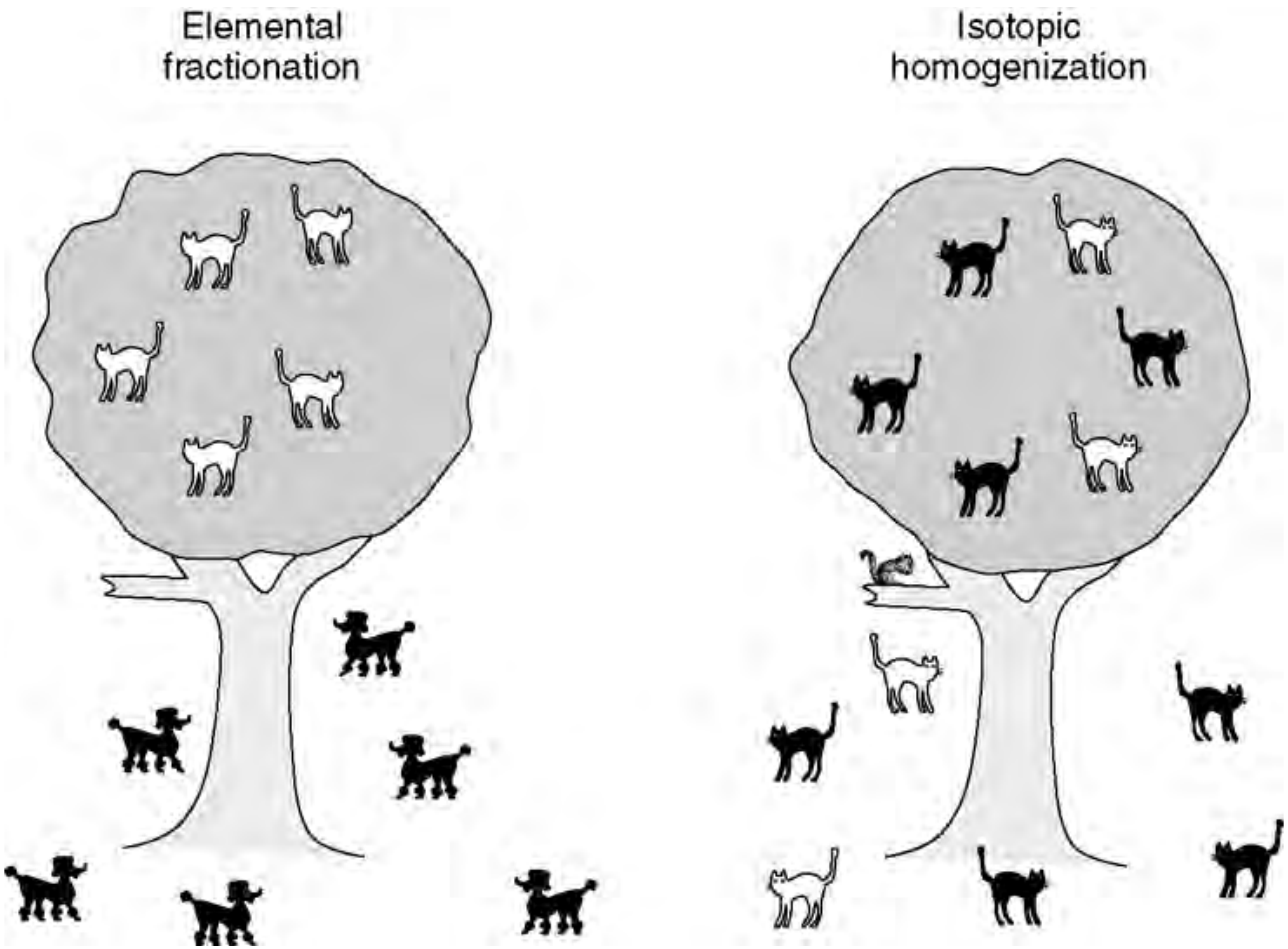
$$(^{87}Sr / ^{86}Sr)_t = (^{87}Sr / ^{86}Sr)_0 + (^{87}Rb / ^{86}Sr)_t\,(e^{\lambda 87Rb t}-1)$$



At T=τ

$^{87}Sr/^{86}Sr$ ratios of the samples have grown by decay of ^{87}Rb into ^{87}Sr

Initial Ratio - Isotopic Homogenization



Albarède, fig. 3.1

Left Diagram: cats and dogs interact vigorously affecting site occupation (tree or yard). Just like two elements with different chemical properties, they arrange themselves so as to achieve the most stable configuration (e.g. Sr partitions strongly into feldspar relative to silicate melt).
Right Diagram: white cats and black cats have very similar properties and like isotopes of the same element are arranged randomly among the available sites. The most likely arrangement is an identical proportion of isotopes in each site (e.g. the initial ratio of ^{87}Sr to ^{86}Sr is the same in a feldspar and in the silicate magma from which it crystallizes, irrespective of concentration differences).

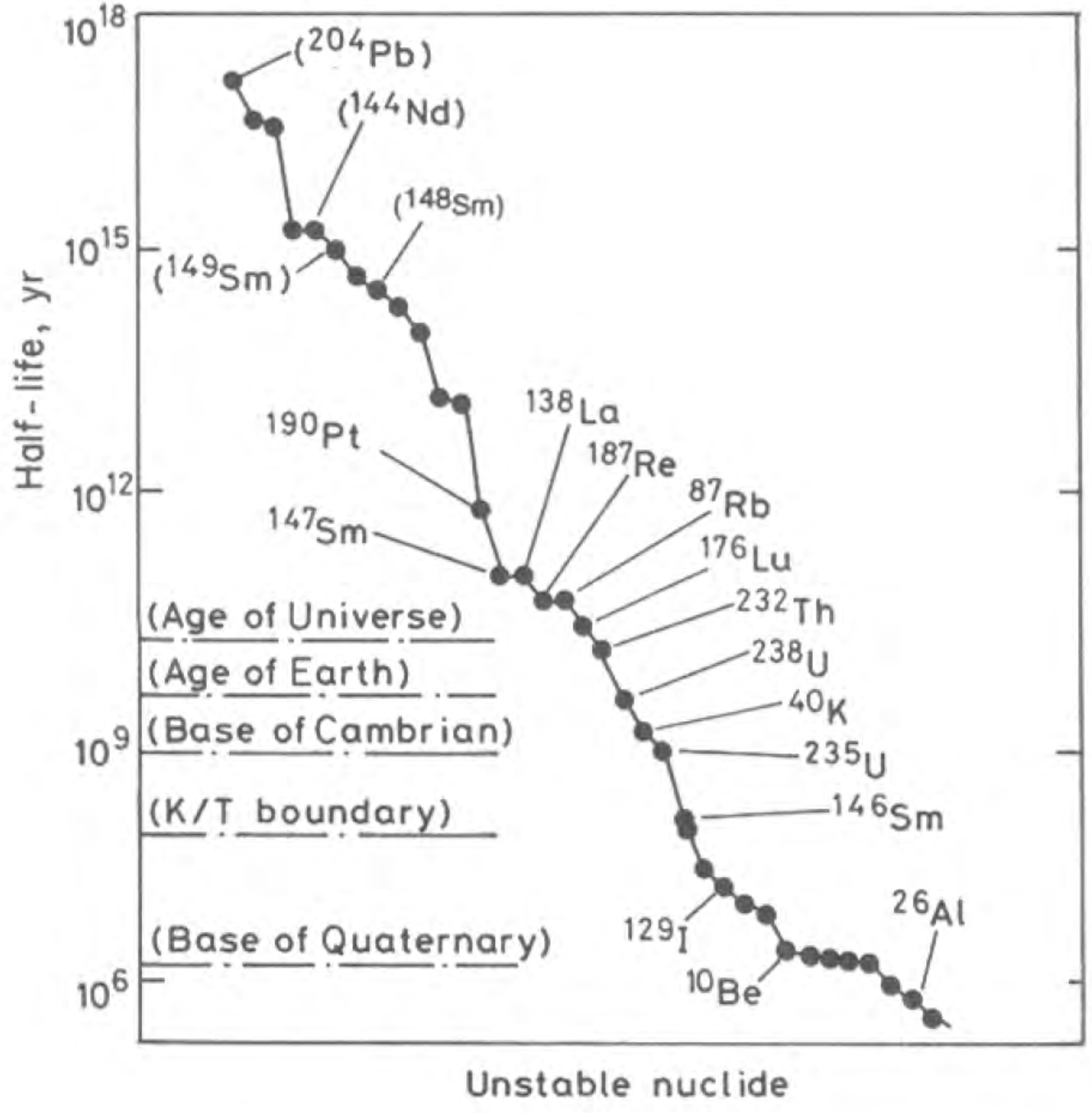


Fig. 1.2. Unstable nuclides with half-lives ($t_{1/2}$) over 0.5 Myr, in order of decreasing stability. Geologically useful parent nuclides are marked. Some very long-lived radionuclides with no geological application are also marked, in brackets.

Unstable Nuclides

Range of measured half-lives ($t_{1/2}$) is 10^{15} to 10^{-12} seconds (range of 10^{35}).

Terminology for Ages:

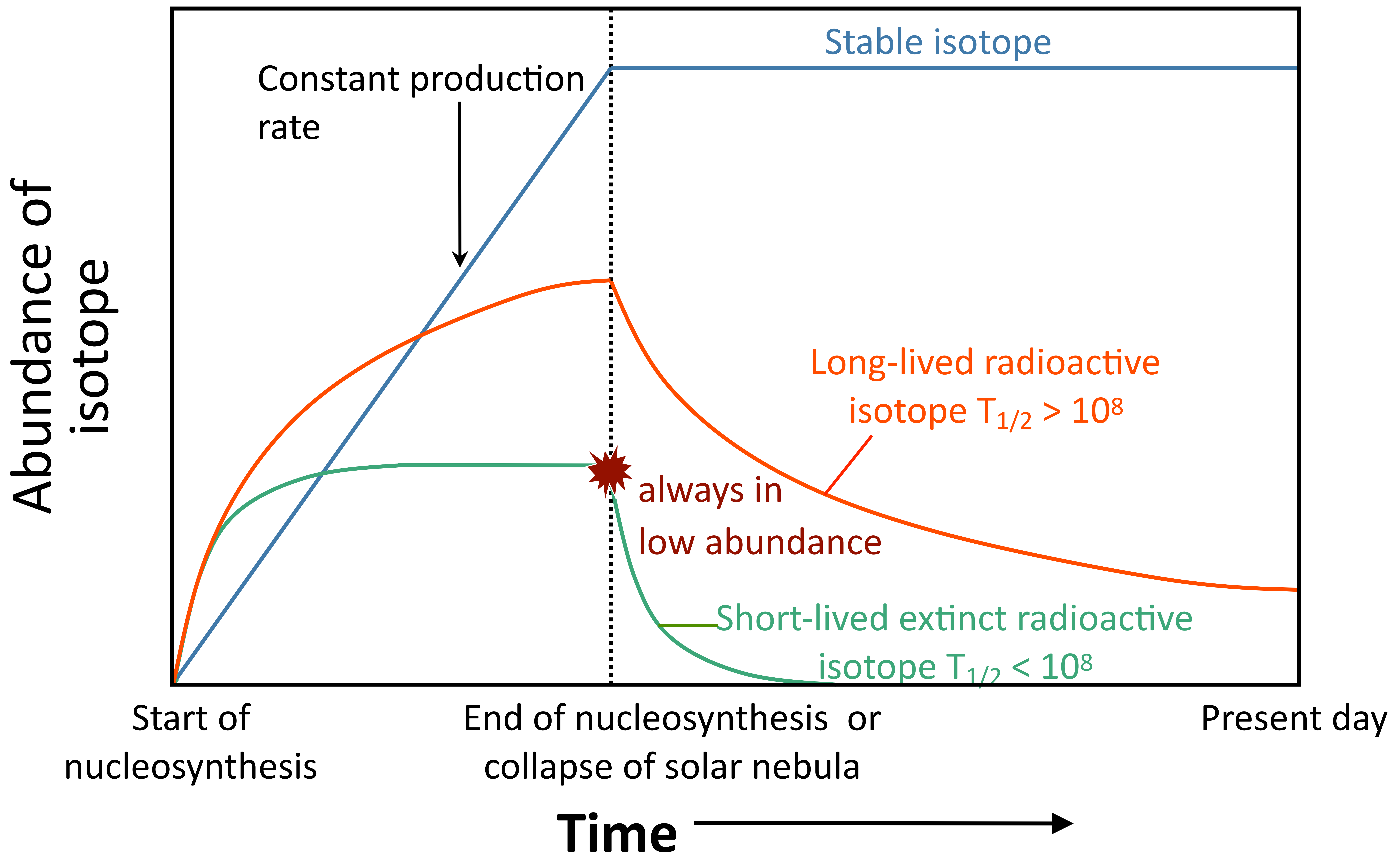
Absolute Age = Ka, Ma, Ga (an event thousands, millions, billions of years ago)

Relative Age = kyr, myr, gyr (an interval of thousands, millions, billions of years)

Radioactive Decay Systems of Geochemical Interest

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^-	$1.93\text{-}1.86 \times 10^{-11}\ y^{-1}$	3.57×10^{10} yr	^{176}Hf	$^{176}Hf/^{177}Hf$
^{187}Re	β^-	$1.64 \times 10^{-11}\ y^{-1}$	4.23×10^{10} yr	^{187}Os	$^{187}Os/^{186}Os$, $^{187}Os/^{188}Os$
^{232}Th	α	$4.948 \times 10^{-11}\ y^{-1}$	1.4×10^{10} yr	^{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} yr	^{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} yr	^{206}Pb, ^{4}He	$^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$

Timescales for Planetary Processes



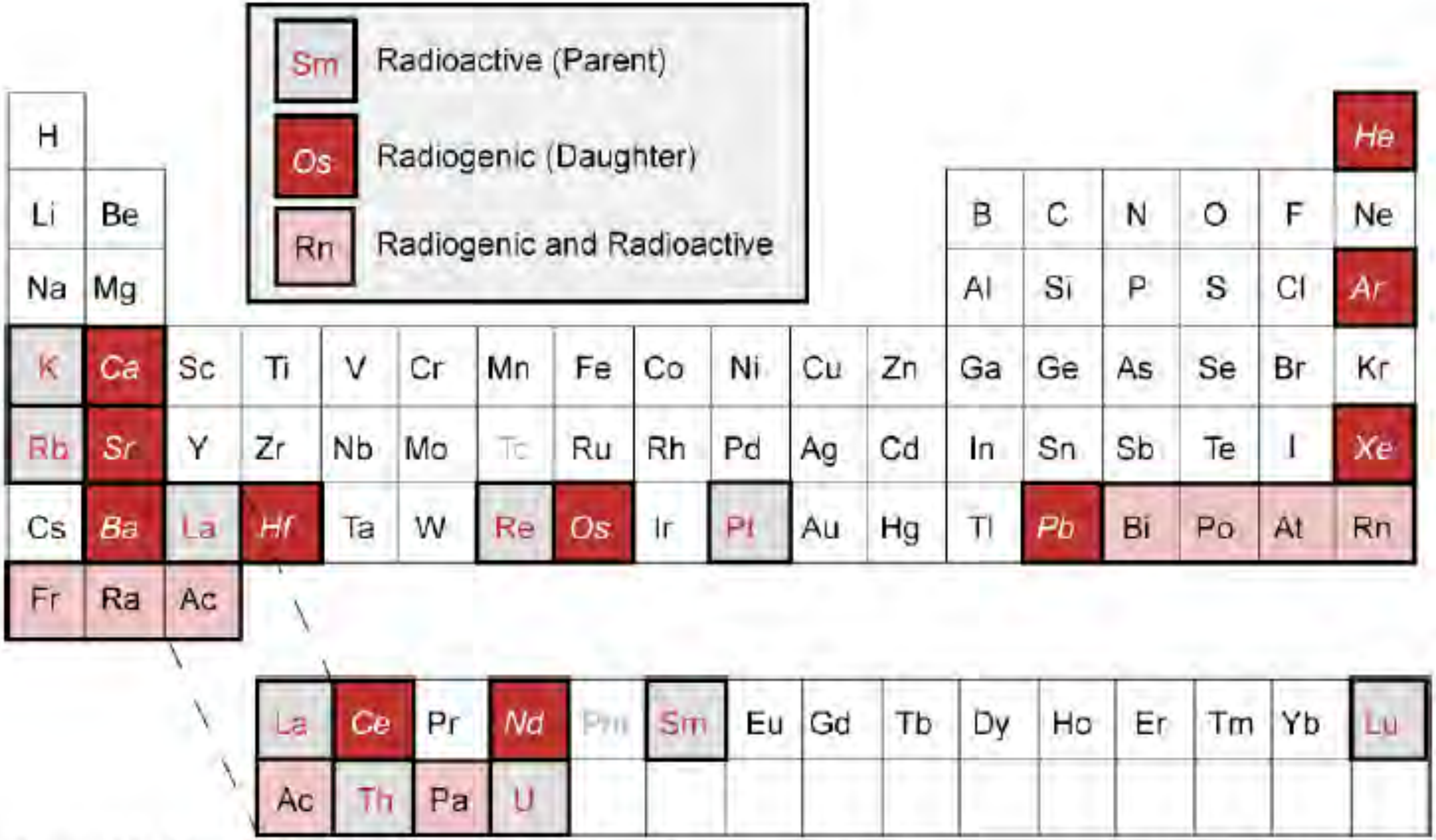
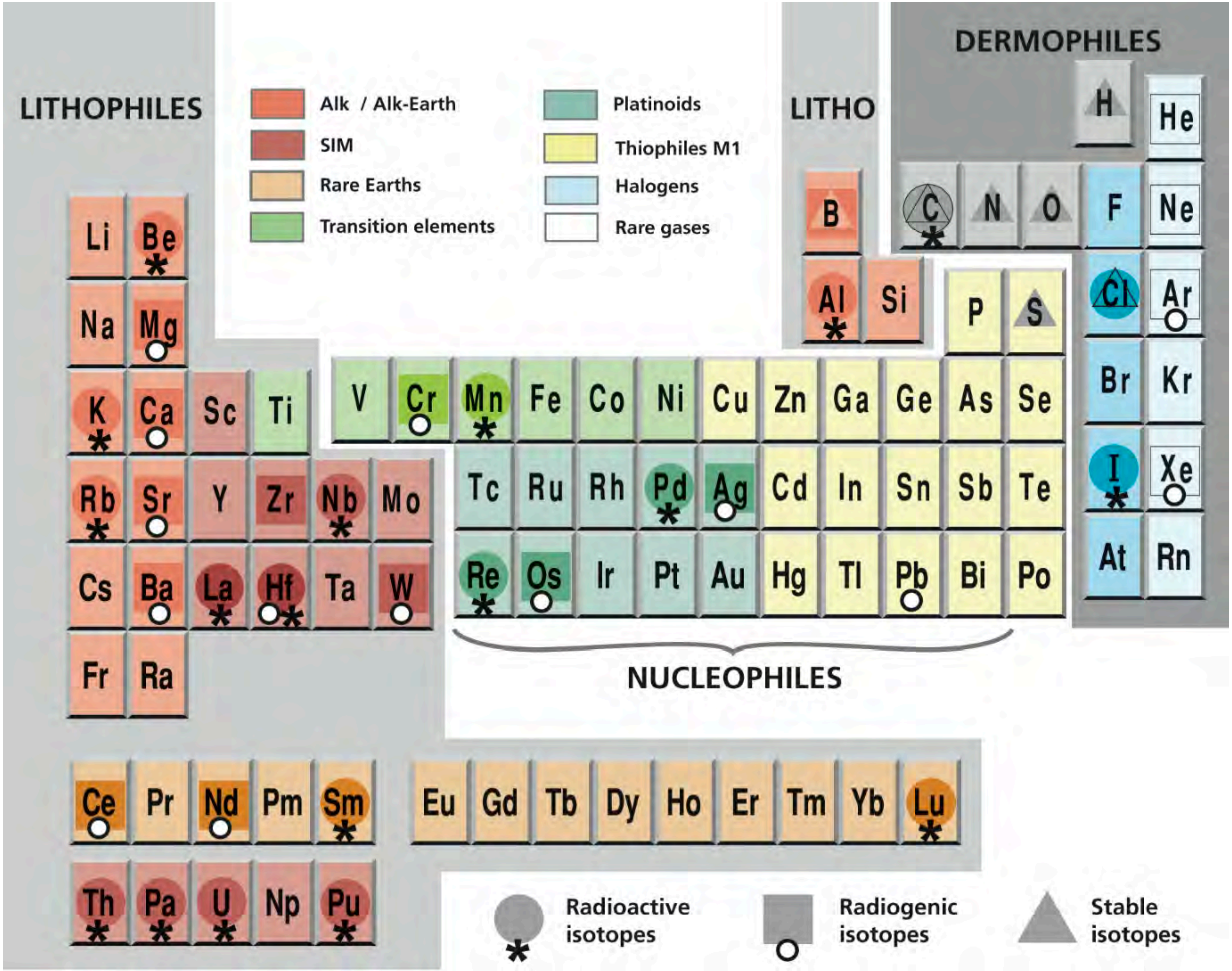


Figure 2.1. Periodic Table showing the elements having naturally occurring radioactive isotopes and the elements produced by their decay.

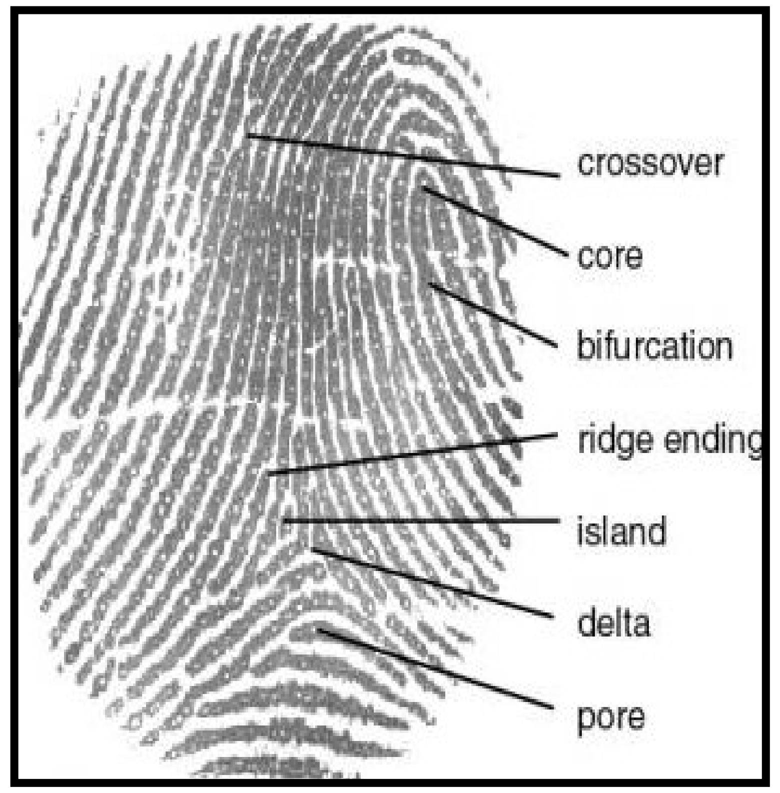
White, fig. 2.1



Allègre, Plate 1

Fingerprinting

Potential use of metal isotopic compositions to trace the source of various materials

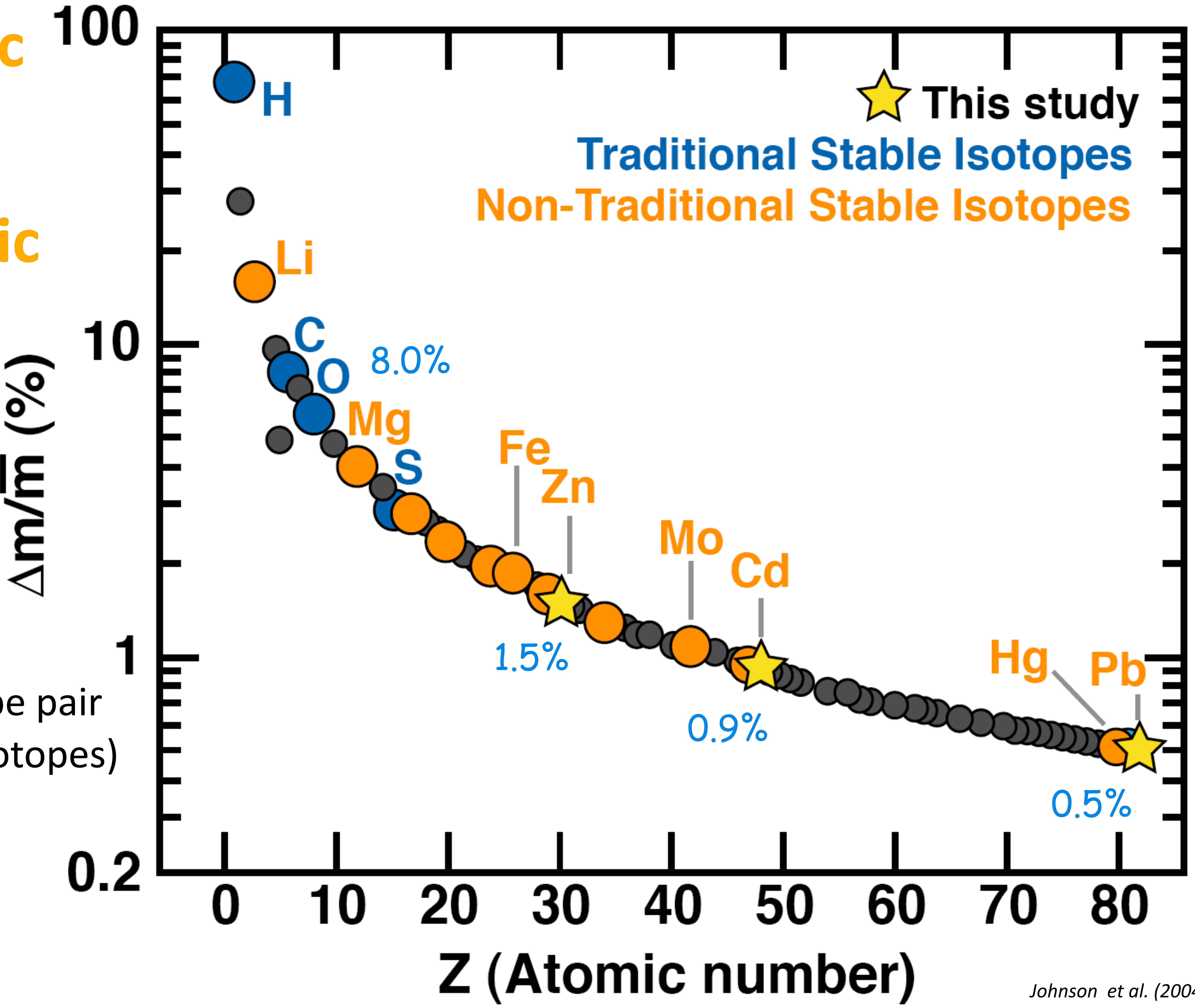


★ **Isotopes:** same Z, different N, i.e. same chemical properties - slight mass differences.

★ Use of **radiogenic isotopes** (e.g., Pb), where the isotopic composition reflects the origin of the sample or source = **fingerprinting.**

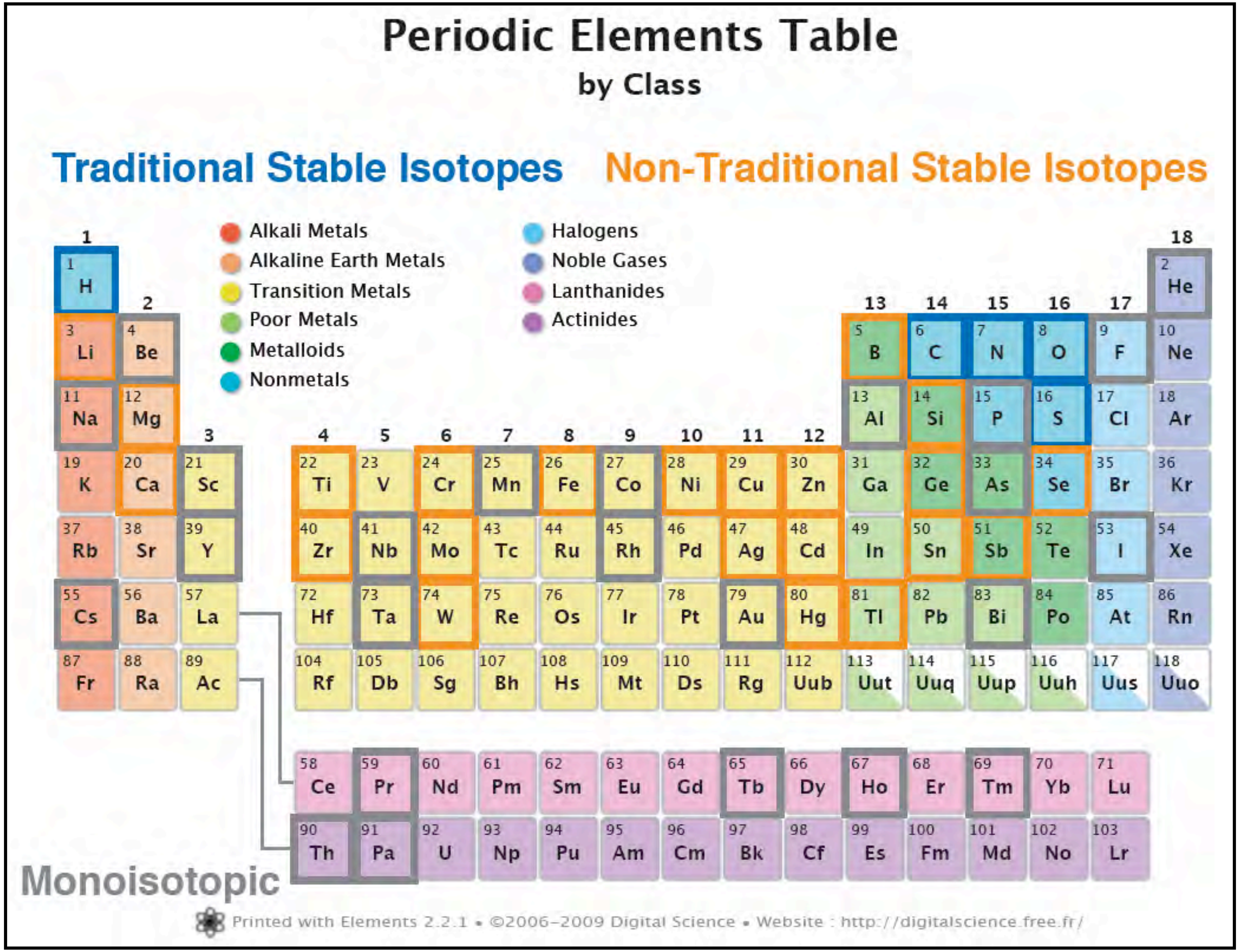
★ or **stable isotopes**, where equilibrium and non-equilibrium (kinetic) isotopic fractionation (mass-dependent) of elements results from physical (e.g., evaporation, diffusion), chemical (e.g., adsorption, redox reaction, crystallization) and biological (e.g., nutrient uptake) processes. The isotopic composition reflects the source (**isotopic baseline**) plus any isotopic fractionation (**process identification**).

The Extent of Isotopic Variability for an Element Decreases with Increasing Atomic Number, for Δm=1



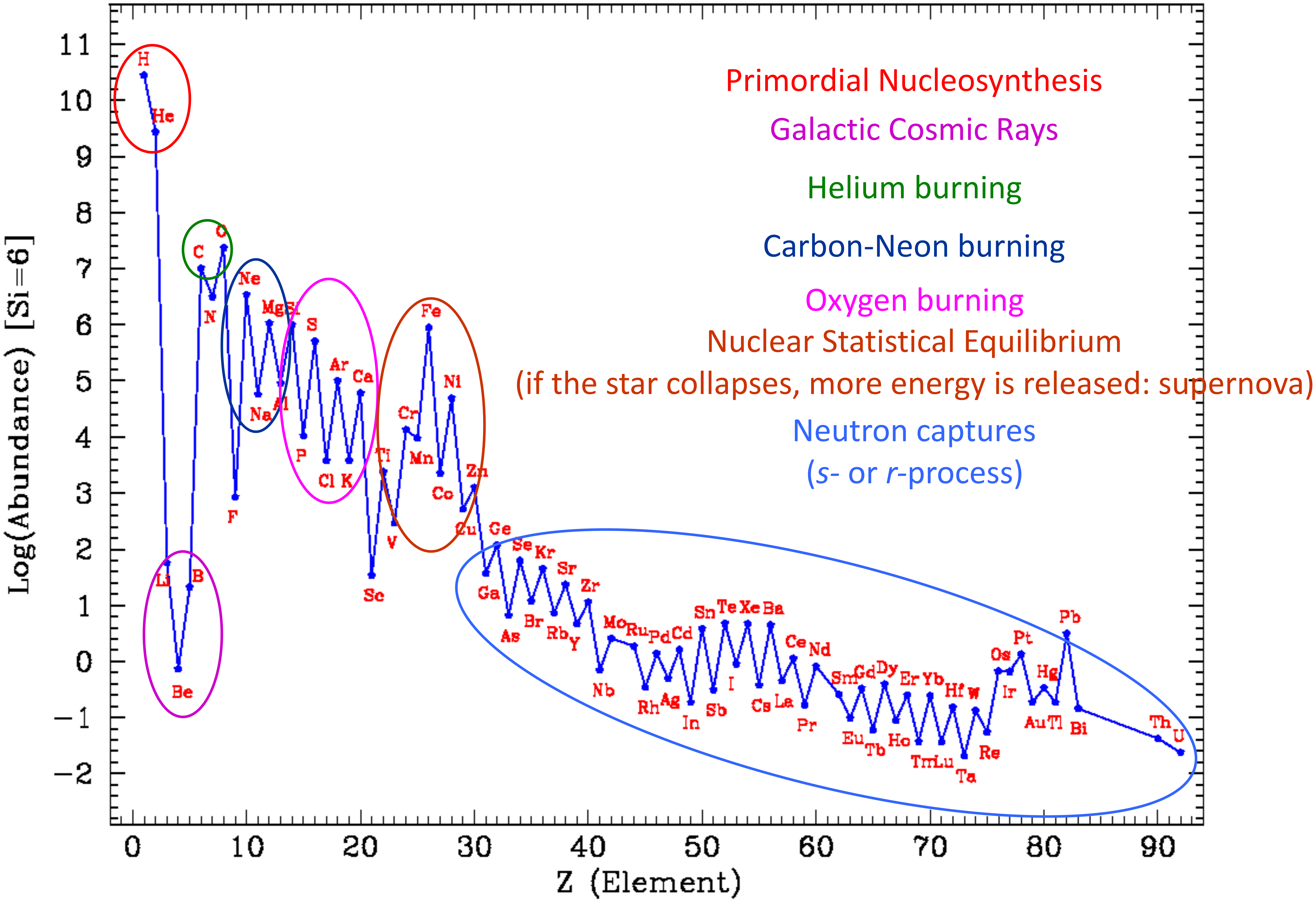
(Δm: mass difference for the isotope pair
m:average mass of the element's isotopes)

Johnson et al. (2004)



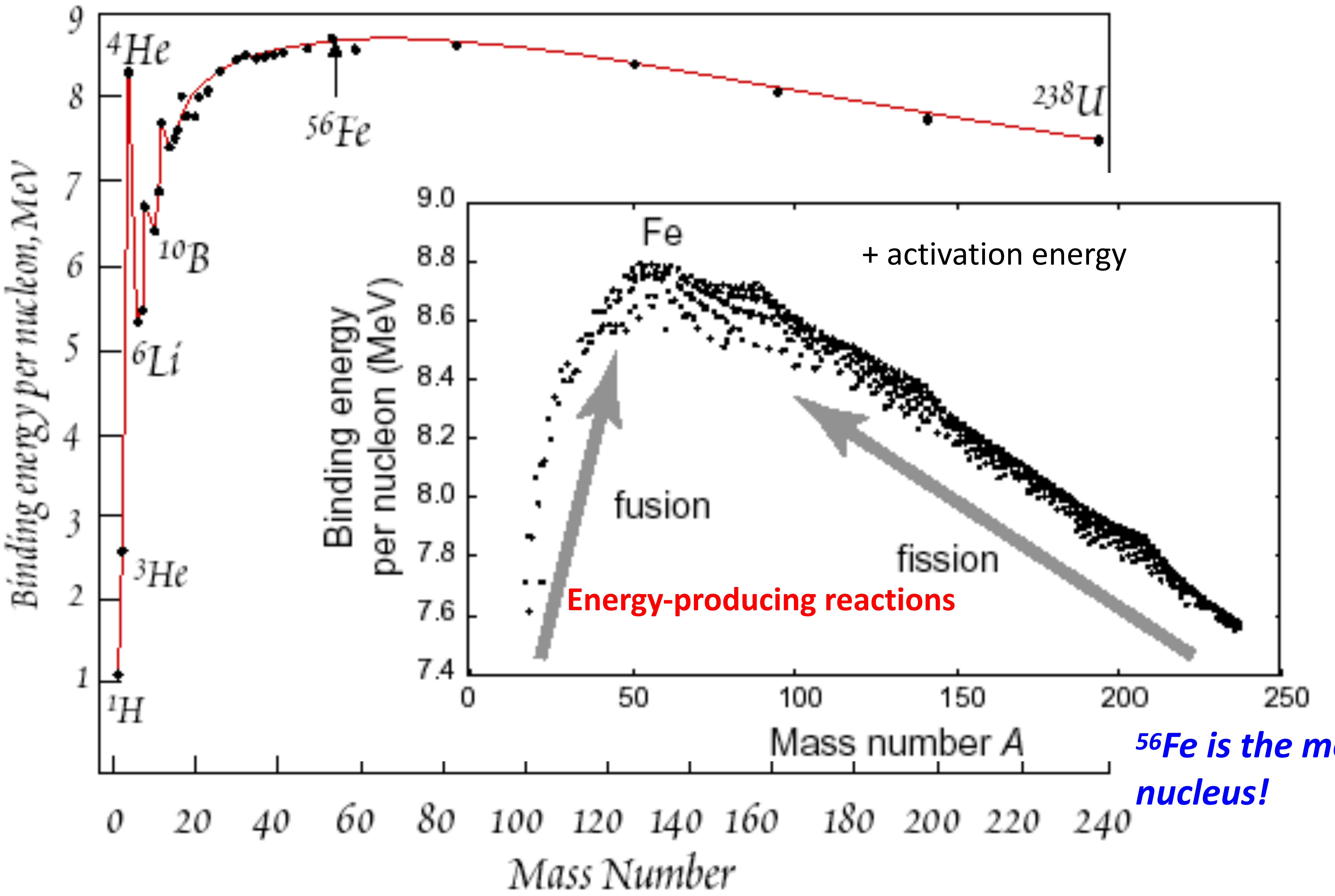
Hazardous Air Pollutants: Sb, Cd, Cr, Hg, Pb, Ni, Se

Priority Pollutants: Sb, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Tl, Zn


Primordial Nucleosynthesis
Galactic Cosmic Rays
Helium burning
Carbon-Neon burning
Oxygen burning
Nuclear Statistical Equilibrium
(if the star collapses, more energy is released: supernova)
Neutron captures
(*s*- or *r*-process)
Log(Abundance) [Si=6]
Z (Element)
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
0
10
20
30
40
50
60
70
80
90
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

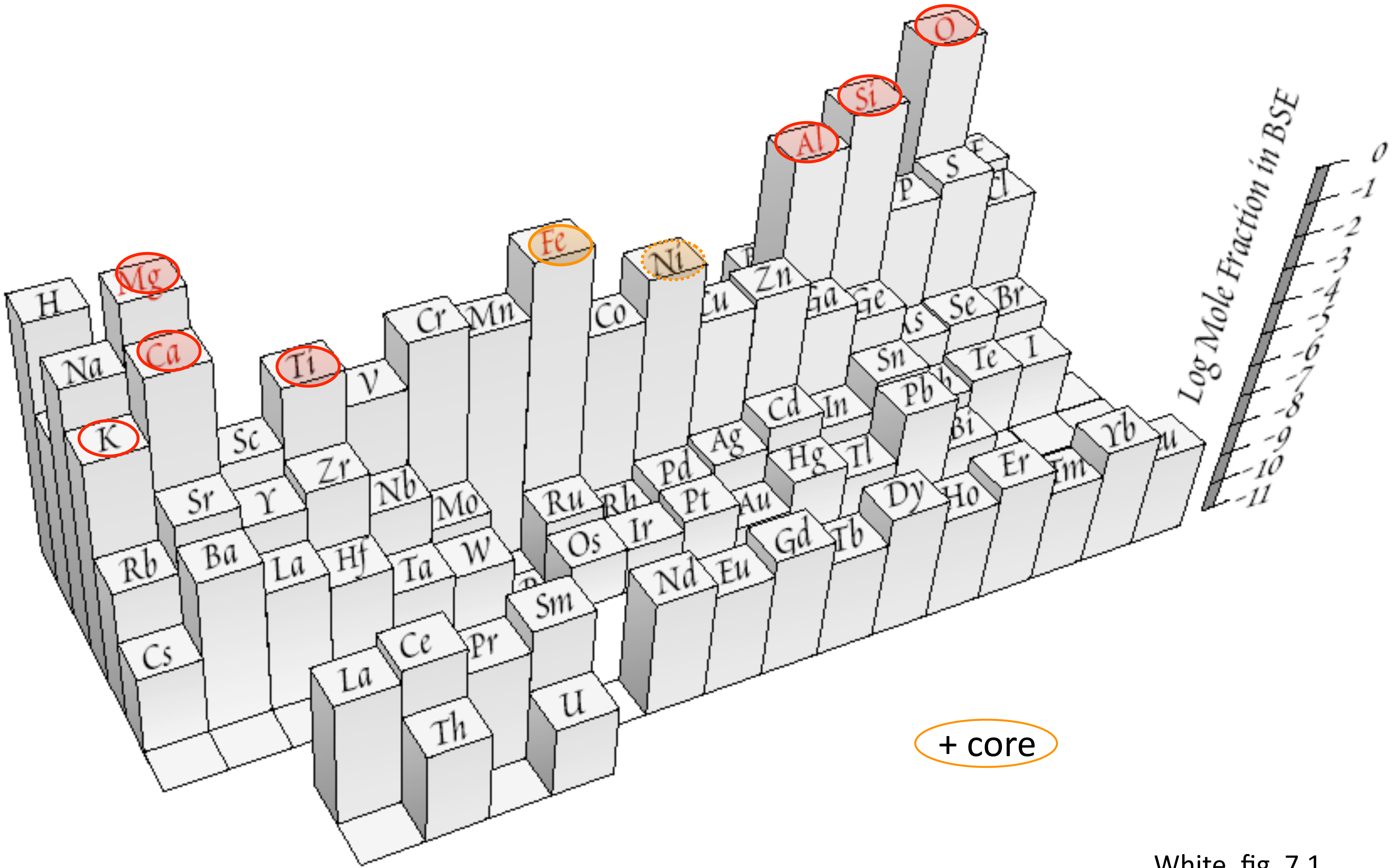
Binding Energy per Nucleon vs. Mass Number

– Controlled by the balance between the strong nuclear attractive force (holding nuclei together) vs. the electromagnetic force (repulsion of positively charged protons within the nucleus)



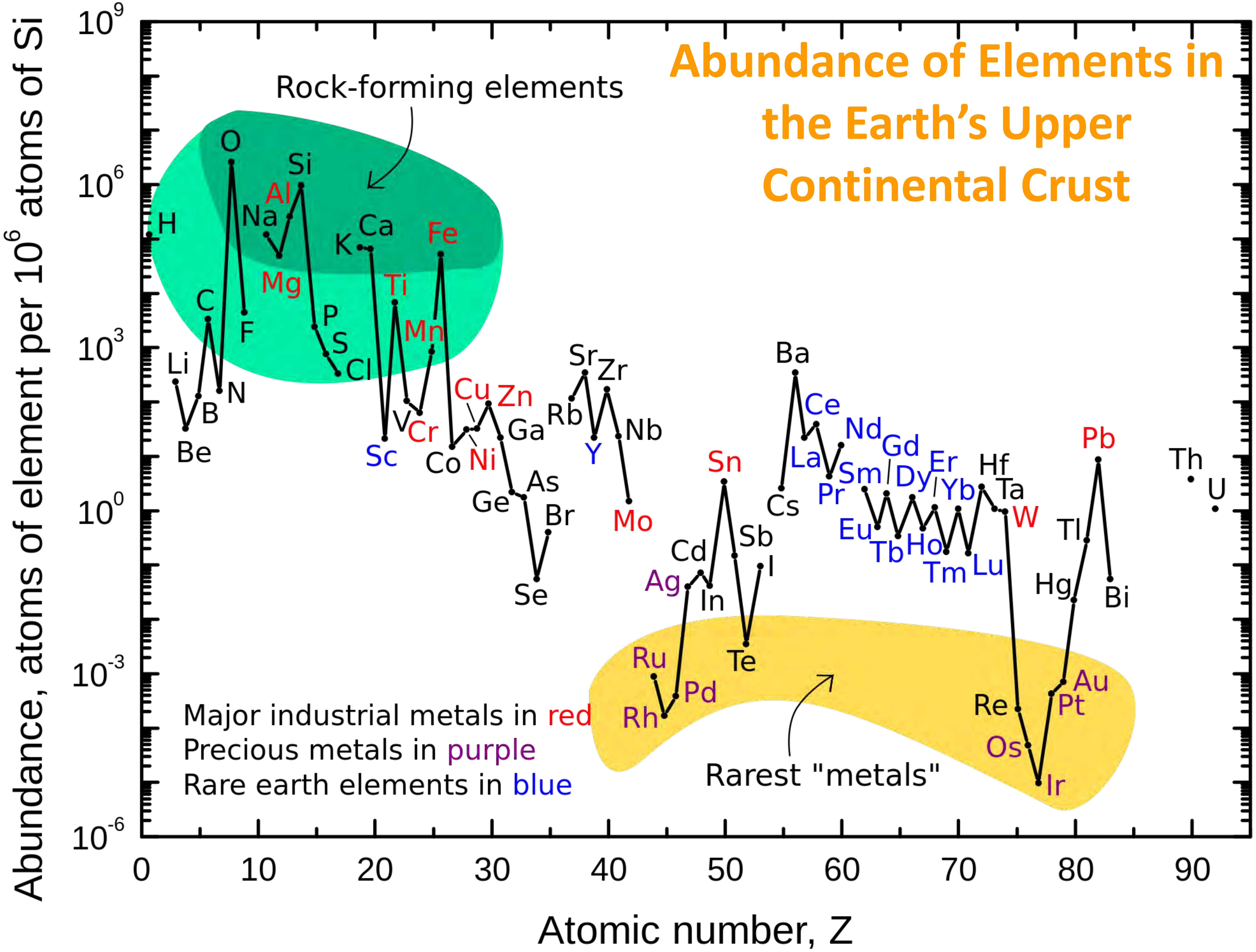
^{56}Fe is the most stable nucleus!

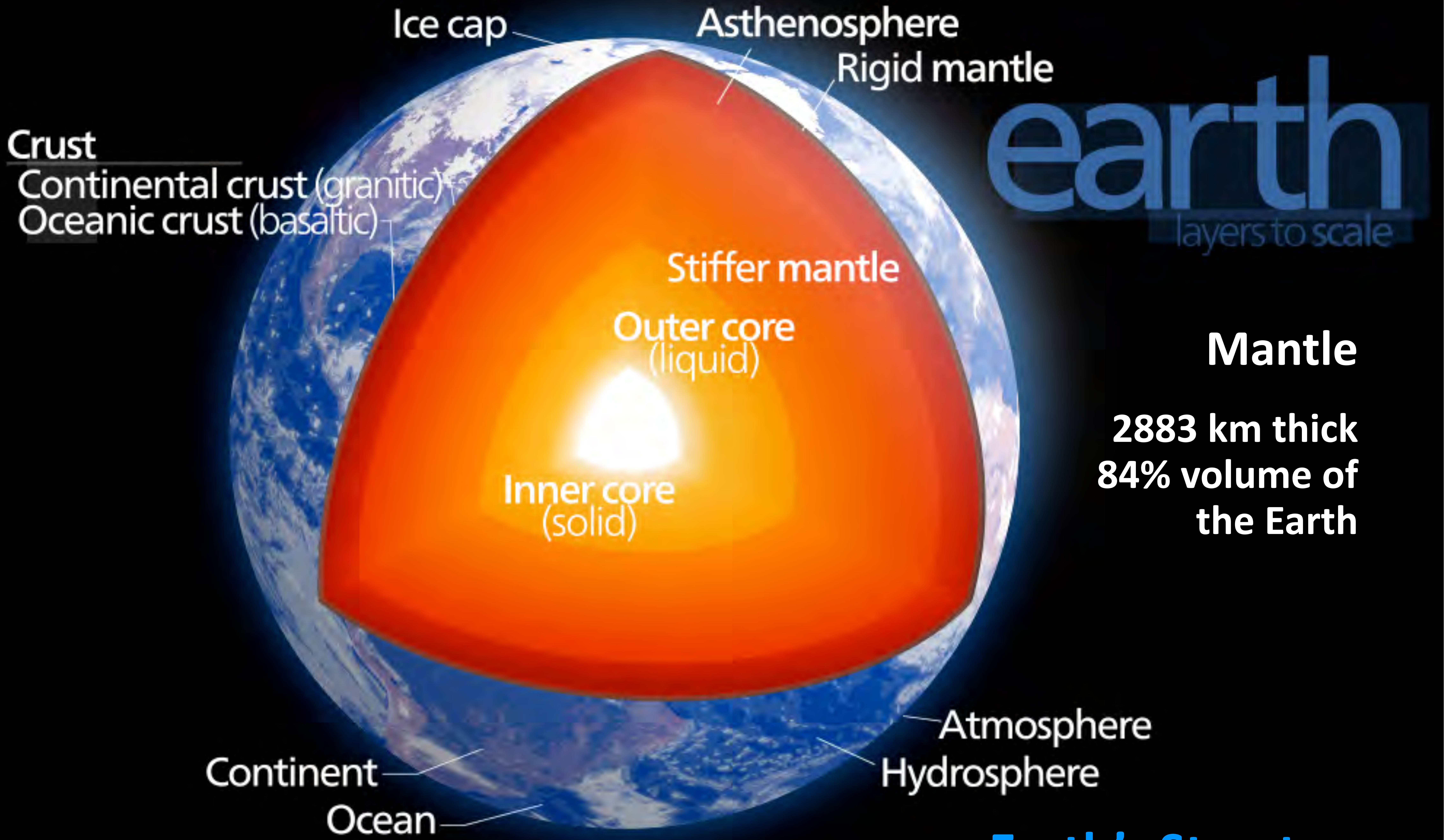
Abundance of the Elements in BSE



+ core

White, fig. 7.1

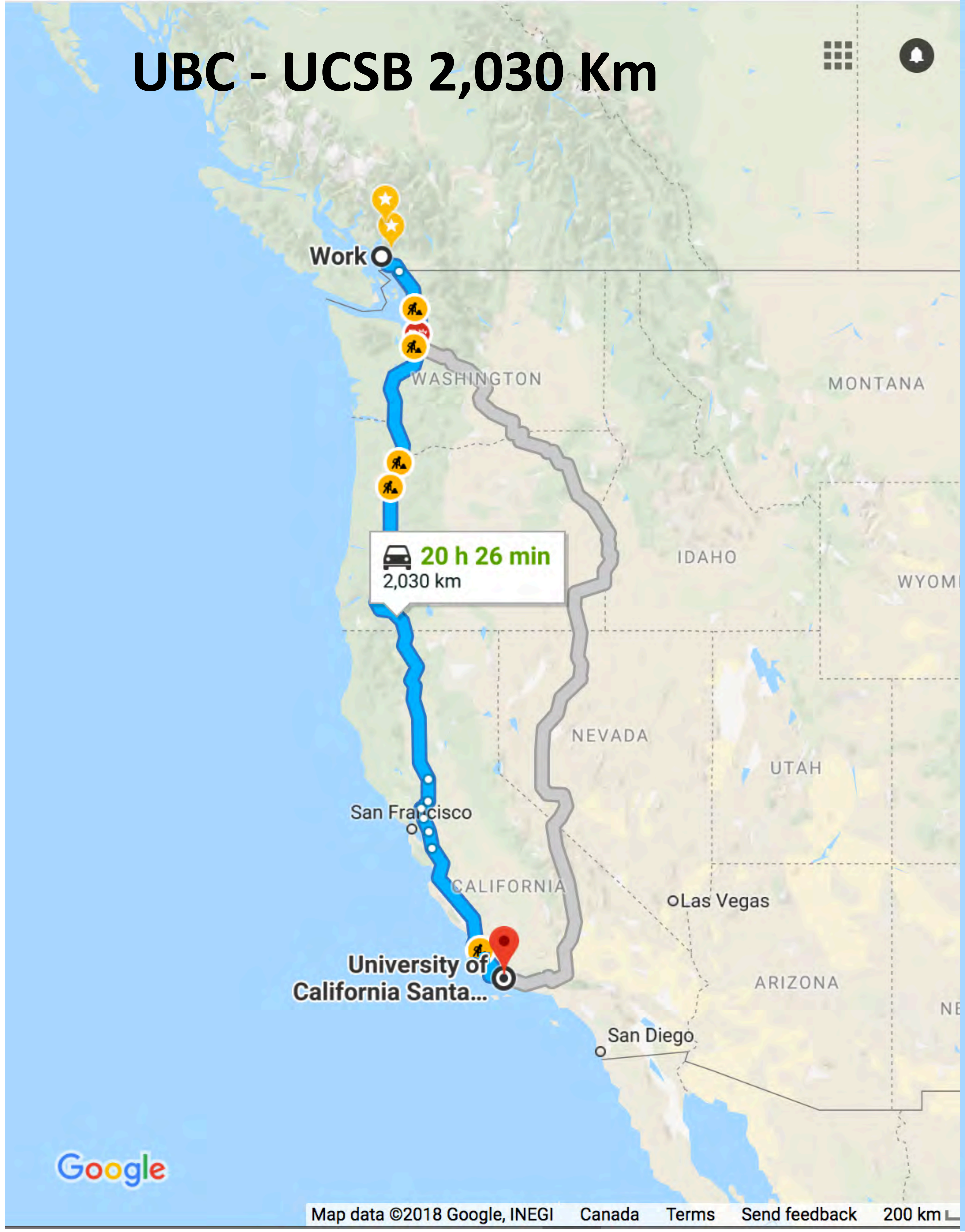

Abundance of Elements in the Earth's Upper Continental Crust
Rock-forming elements
Rarest "metals"
Major industrial metals in red
Precious metals in purple
Rare earth elements in blue
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z
H Li Be B C N O F Na Mg Al Si P S Cl K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Rb Sr Y Zr Nb Mo Ru Rh Pd Ag Cd In Sn Sb Te I Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Th U

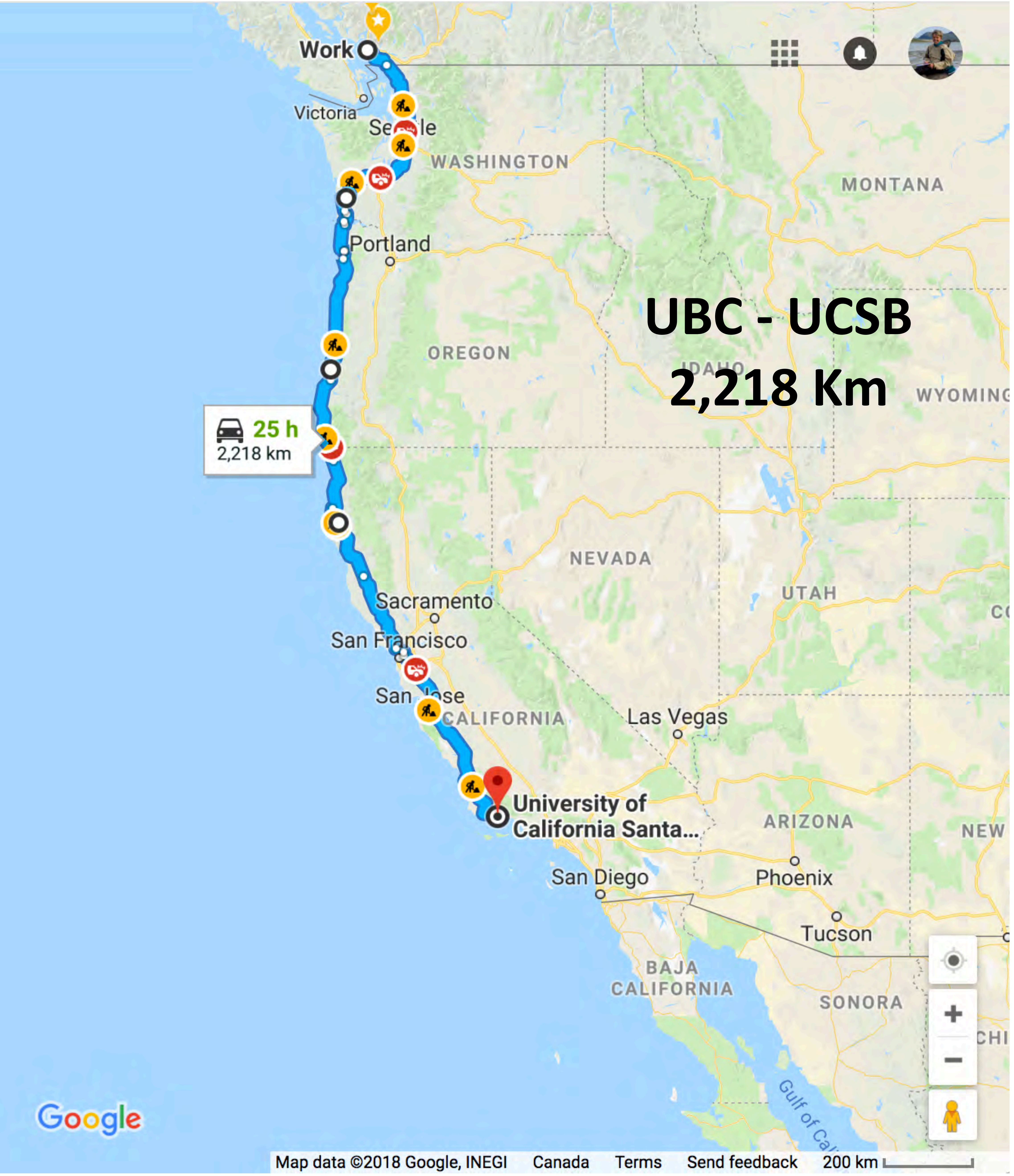


Mantle

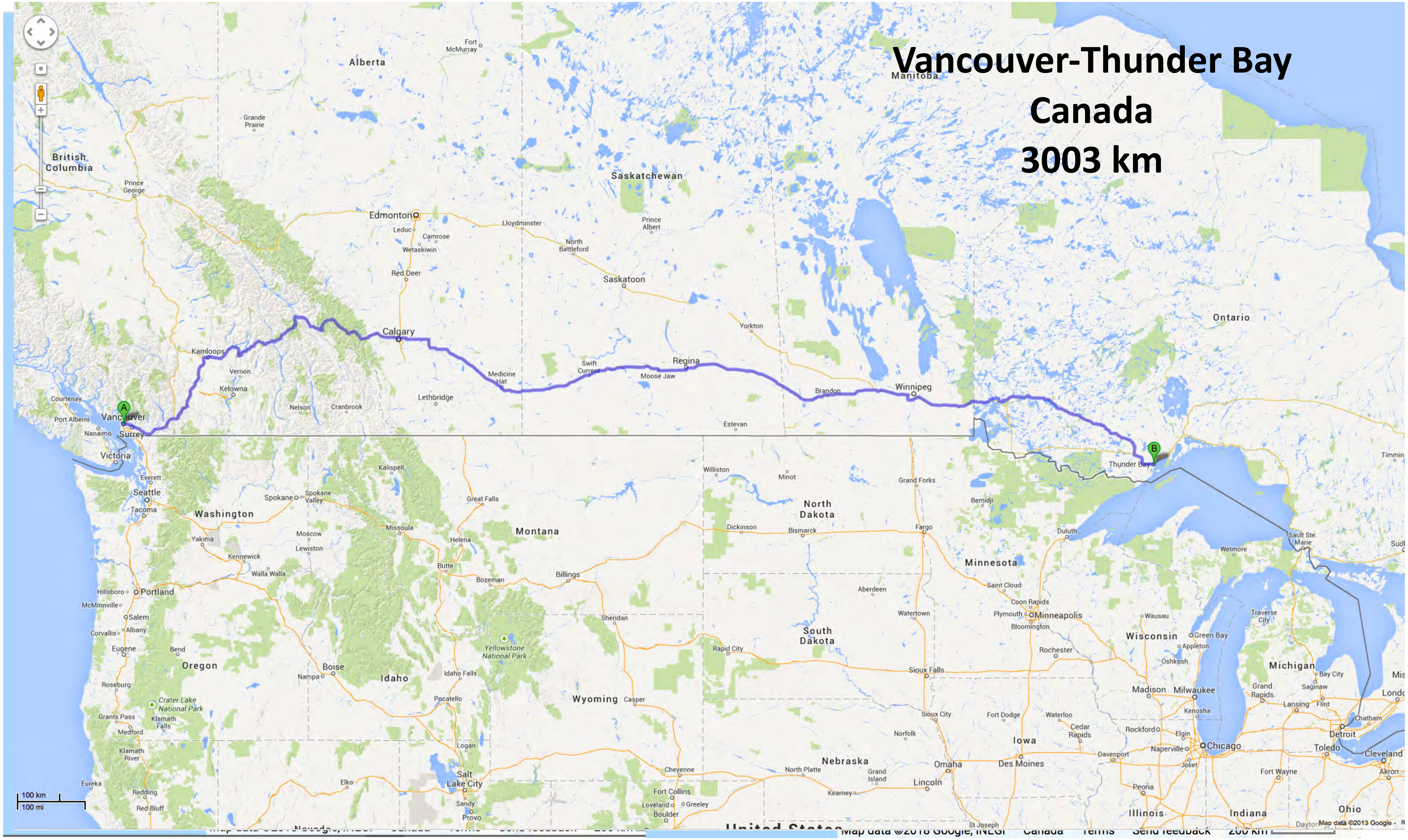
2883 km thick
84% volume of the Earth

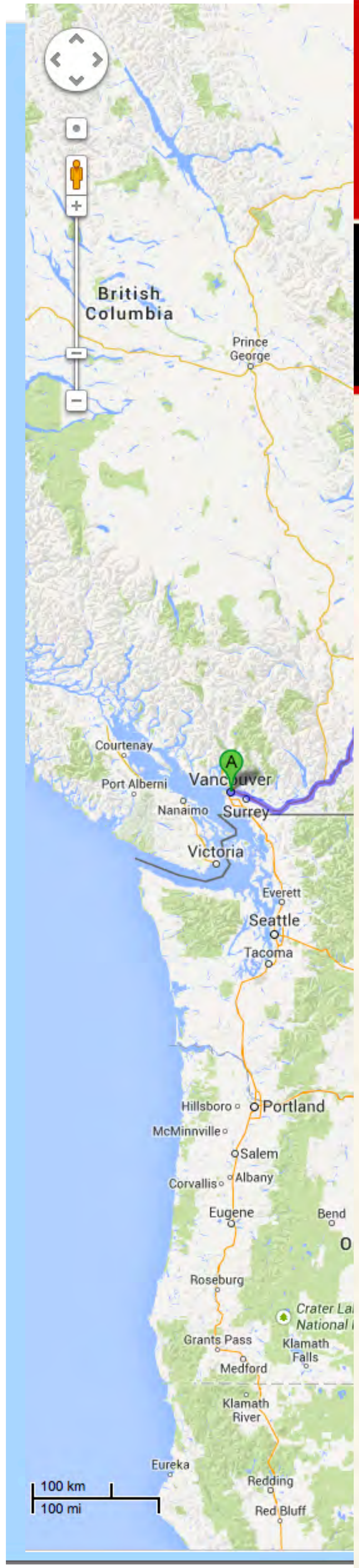
Earth's Structure


UBC - UCSB 2,030 Km
Work
WASHINGTON
MONTANA
IDAHO
WYOMI
20 h 26 min
2,030 km
NEVADA
UTAH
San Francisco
CALIFORNIA
Las Vegas
University of California Santa...
ARIZONA
San Diego
Google
Map data ©2018 Google, INEGI
Canada
Terms
Send feedback
200 km


Work
Victoria
WASHINGTON
MONTANA
Portland
UBC - UCSB
2,218 Km
OREGON
WYOMING
25 h
2,218 km
NEVADA
UTAH
Sacramento
San Francisco
CALIFORNIA
Las Vegas
University of California Santa...
ARIZONA
San Diego
Phoenix
Tucson
BAJA CALIFORNIA
SONORA
Google
Map data ©2018 Google, INEGI
Canada
Terms
Send feedback
200 km

Vancouver-Thunder Bay Canada 3003 km





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Kola Superdeep Borehole (KSDB) - IGCP 408: „Rocks and Minerals at Great Depths and on the Surface"

PRINT

- News
- Scientists
- Location
- Objectives
- Public Data
- Press & Media

Description

The Kola Superdeep Borehole (KSDB-3) reached a final depth of 12,261 m. It was drilled since the seventies in the framework of the programme "Investigation of the continental crust by means of deep drilling" of the former USSR.

The main results of the technical experience gained from this record-deep drilling, of the investigation of the cores and the geophysical logging were presented and discussed at several international congresses and conferences, including the 27th International Geological Congress held in Moscow (1984), and have been published in numerous papers and books. Of these, the following are the best known to the international community of geologists:

- Kozlovsky, Ye.A. (Ed.), 1987. The Superdeep Well of the Kola Peninsula. Springer Verlag, Berlin, 558 p.
- Fuchs, K., Kozlovsky, E.A., Krivtsov, A.I. & Zoback, M.D. (Eds.), 1990. Super-Deep Continental Drilling and Deep Geophysical Sounding. Springer Verlag, Berlin, 436 p.

A third monograph - Mitrofanov, F.P. (Ed.), 1991. Archean Complex in the Section of the KSDB-3. Apatity, Kola Science Centre RAS, published in Russian, presents a discussion of the structure and composition of the Archean complex cut by the Kola Super-Deep Well in the interval of 6.84-12.26 km. For the first time a detailed study of the granitoid substance and the isotope composition of noble gases has been carried out. The description and classification of amphibole-bearing rocks, ore mineralization, mafic silicates, and the knowledge on rock mechanical properties have been significantly extended. Geochronological data and information pertaining to the distribution and composition of hydrocarbon gases and bitumes in the section have been systematized.
The main borehole (and several complementary ones) intersected the entire sedimentary-volcanic sequence of the Lower Proterozoic Pechenga Formation (0 - 6,842 m) and a considerable part (6,842 - 12,261 m) of the Archean granitic-metamorphic complex of the basement (gneisses, amphibolites, migmatites and granitoids).

News Highlights

NSF Workshop: Drilling Active Tectonics and Magmatism
→more...

Call for Pre-Proposals
→more...

ICDP Workshop 'Drilling Overdeepened Alpine Valleys'
→more...

New SAG Composition for 2013
→more...

The Fennoscandian Arctic Russia - Drilling Early Earth Project
→more...

Scientific Drilling Issue 14 Online
→more...

ICDP Workshop: Japan Beyond-Brittle Project (JBBP)
→more...

ICDP Workshop 2013: Mochras Revisited
→more...

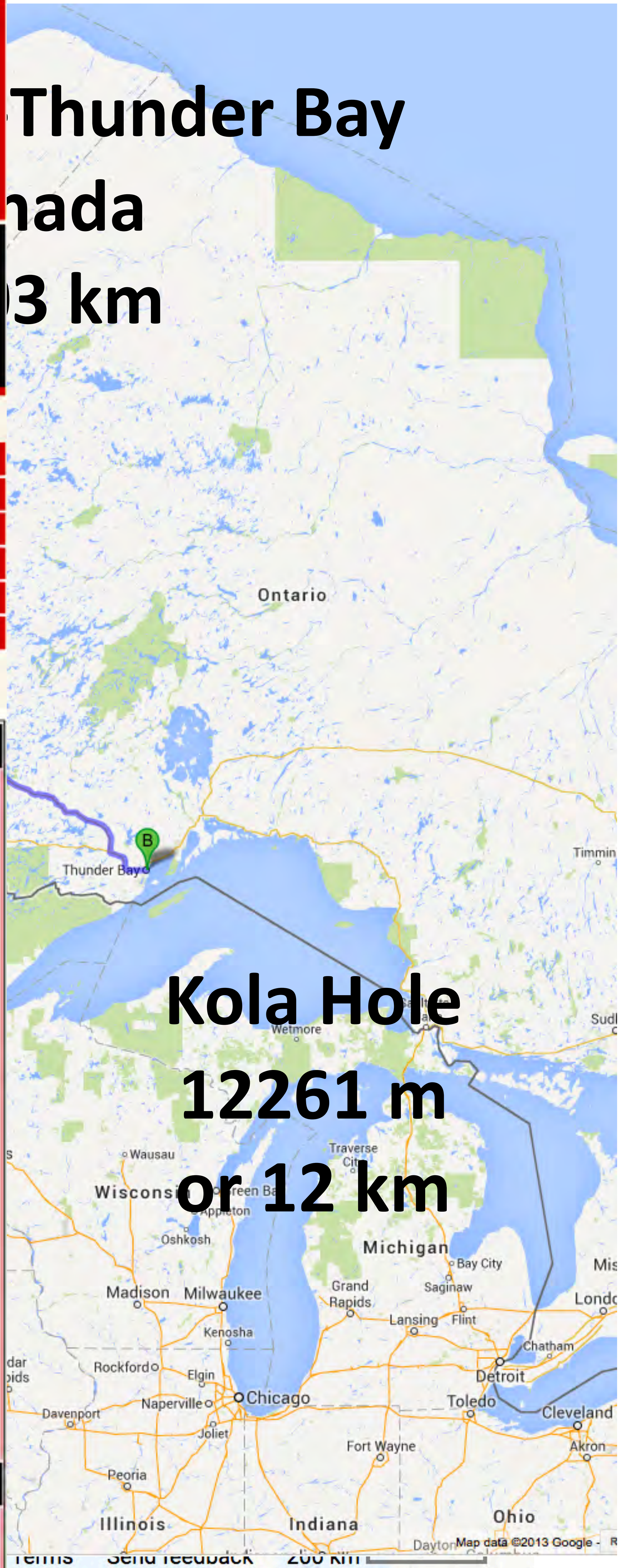
Imaging the Past to Imagine our Future
→more...

ICDP Activities at the 34th IGC
→more...

Daily News from Sites

→Dead Sea: Close to 400 meters. Drilling continues last night as levels of H2S dropped beneath dangerous levels. The...

Thunder Bay
nada
3 km



Kola Hole
12261 m
or 12 km

Part of complete coverage on
CNN Labs

LABS

The $1 billion mission to reach the Earth's mantle

By Tom Levitt, for CNN
October 2, 2012 -- Updated 1854 GMT (0254 HKT)

A team of international scientists are planning to drill into the Earth's mantle in an attempt to answer questions about the origins and evolution of life. The drills will need to get through around 6 km of oceanic crust to reach the mantle.

HIDE CAPTION

Mission impossible?

1 2 3 4 5 >

Part of complete coverage on
CNN Labs

Sci-fi writers and scientists join forces
October 27, 2012 -- Updated 1620 GMT (0020 HKT)

A new research body at Arizona State University is bridging the gap between the lab and the most evocative inventions of the sci-fi genre.

Scientists to simulate human brain
October 12, 2012 -- Updated 1402 GMT (2202 HKT)

It sounds like a sci-fi nightmare, but scientists working on the Human Brain Project hope to improve understanding of diseases of the mind.

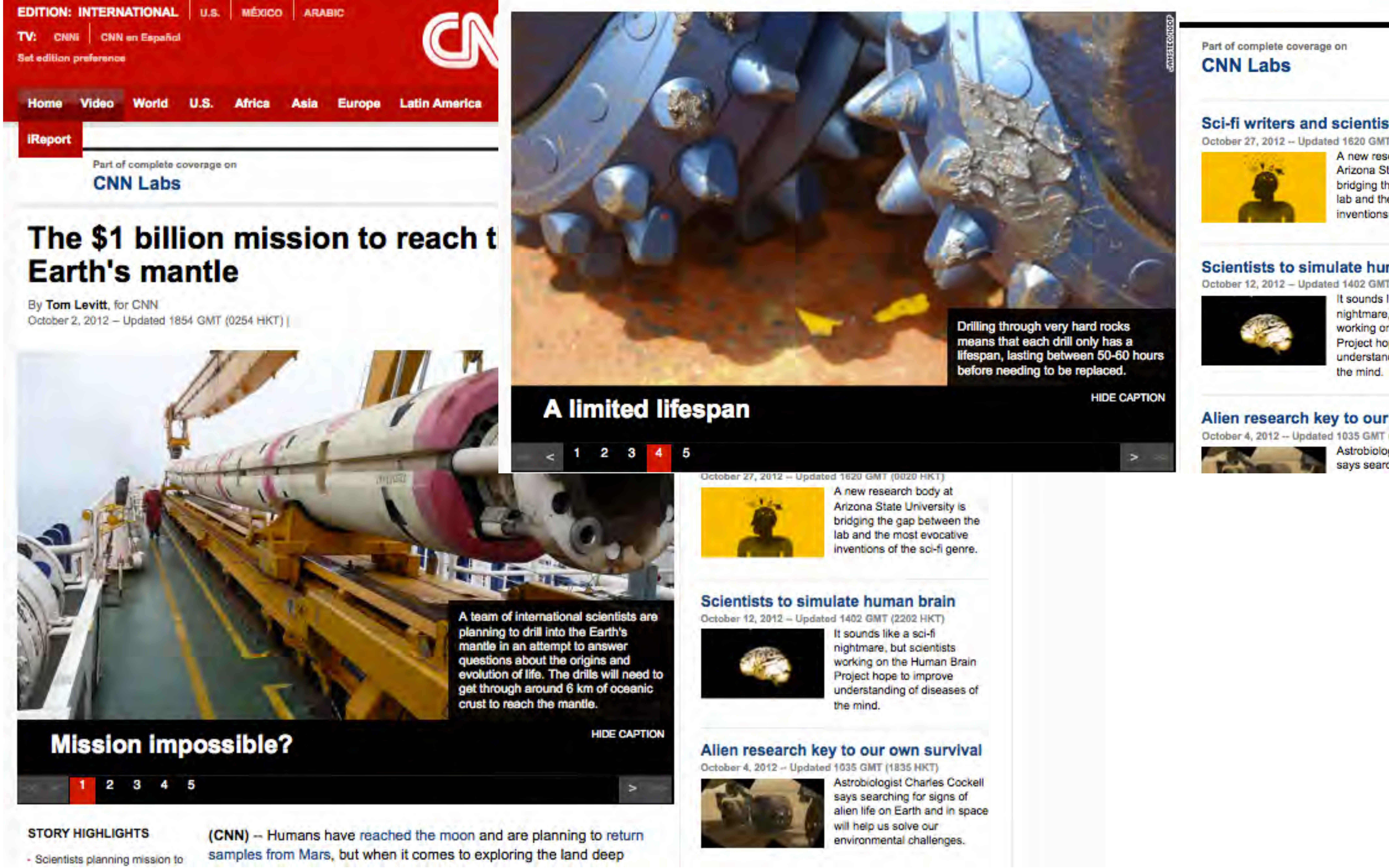
Alien research key to our own survival
October 4, 2012 -- Updated 1035 GMT (1835 HKT)

Astrobiologist Charles Cockell says searching for signs of alien life on Earth and in space will help us solve our environmental challenges.

STORY HIGHLIGHTS

- Scientists planning mission to

(CNN) -- Humans have reached the moon and are planning to return samples from Mars, but when it comes to exploring the land deep



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Part of complete coverage on

CNN Labs

The $1 billion mission to reach t Earth's mantle

By **Tom Levitt**, for CNN

October 2, 2012 -- Updated 1854 GMT (0254 HKT) |

A team of international scientists are planning to drill into the Earth's mantle in an attempt to answer questions about the origins and evolution of life. The drills will need to get through around 6 km of oceanic crust to reach the mantle.

HIDE CAPTION

Mission impossible?

1 2 3 4 5 >

Drilling through very hard rocks means that each drill only has a lifespan, lasting between 50-60 hours before needing to be replaced.

HIDE CAPTION

A limited lifespan

< 1 2 3 4 5 >

STORY HIGHLIGHTS

- Scientists planning mission to

(CNN) -- Humans have reached the moon and are planning to return samples from Mars, but when it comes to exploring the land deep

October 27, 2012 -- Updated 1620 GMT (0020 HKT)

A new research body at Arizona State University is bridging the gap between the lab and the most evocative inventions of the sci-fi genre.

Scientists to simulate human brain

October 12, 2012 -- Updated 1402 GMT (2202 HKT)

It sounds like a sci-fi nightmare, but scientists working on the Human Brain Project hope to improve understanding of diseases of the mind.

Alien research key to our own survival

October 4, 2012 -- Updated 1035 GMT (1835 HKT)

Astrobiologist Charles Cockell says searching for signs of alien life on Earth and in space will help us solve our environmental challenges.

Part of complete coverage on

CNN Labs

Sci-fi writers and scientis

October 27, 2012 -- Updated 1620 GMT

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Alien research key to our

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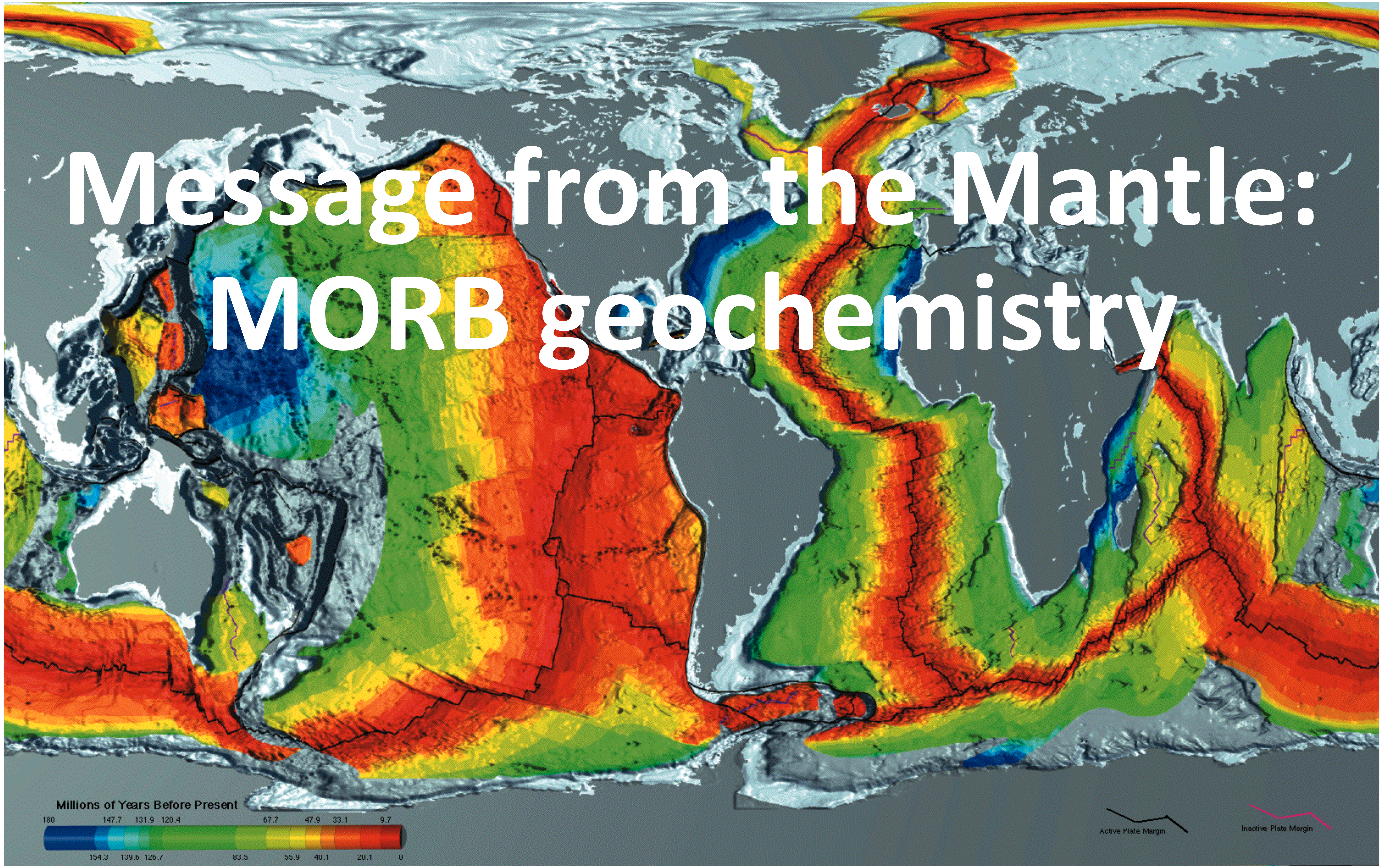
Astrobiolog says searc

Age of the Oceanic Crust



Dark red = zero-age; dark blue = 180-200 million years before present

NOAA

Framework: elements/isotopes – data - source/model

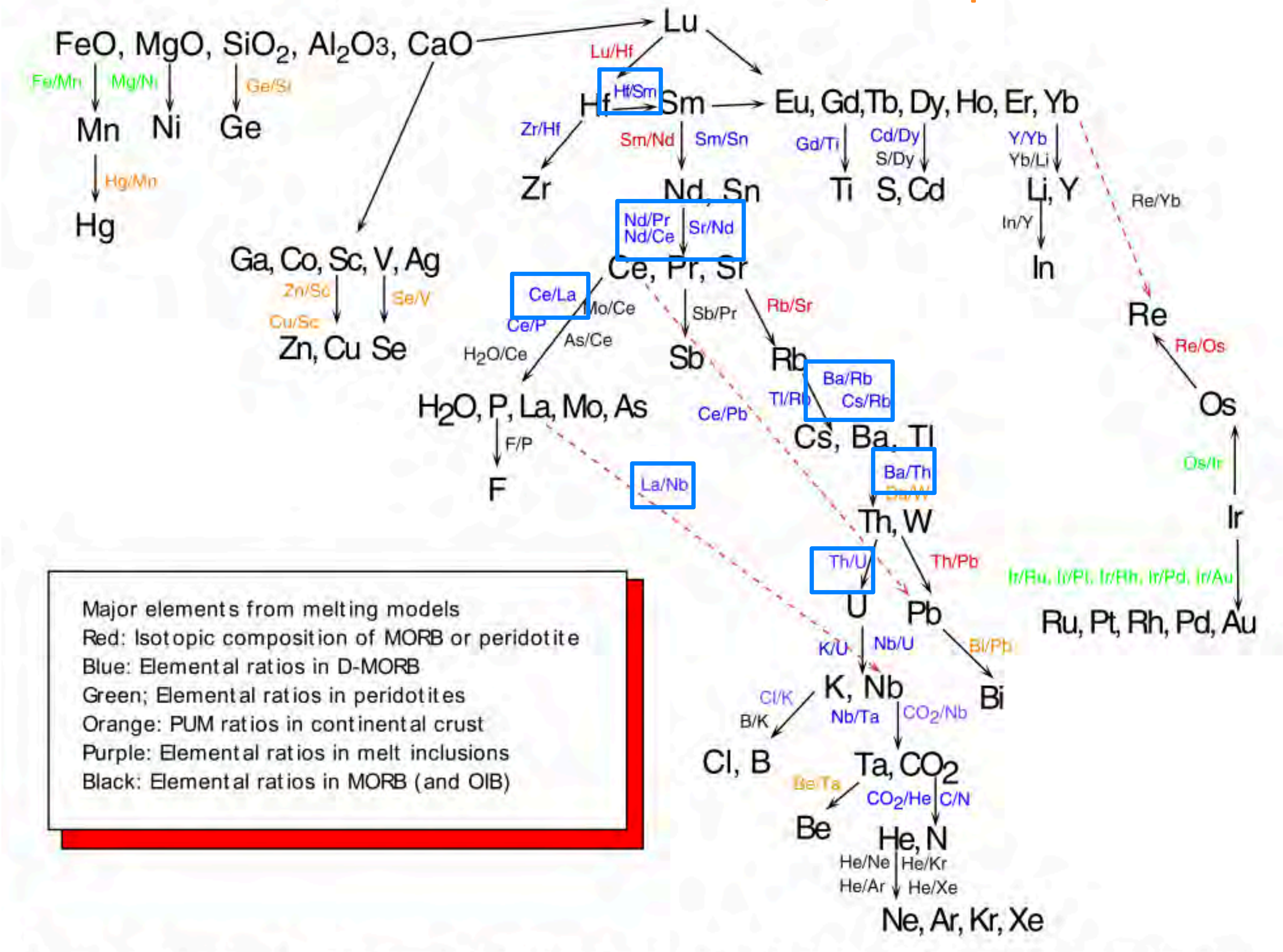


Figure 1. Genealogy of the elements in the DM. Chart showing the dependencies of the concentrations on the trace element ratios.

Salters & Stracke, Composition of the Depleted Mantle, G-cubed, 2004

DM is not directly accessible, so its composition has to be inferred via constraints derived from rocks whose composition and origin are related to the DM.

1. Use parent-daughter ratios
2. Using TE ratios and patterns in MORB
3. Composition of peridotites (compatible elements), chondritic meteorites and continental crust.

The genealogy shows how Salters and Stracke derived the estimates for the individual elements and the inter-relationships between those estimates.

The estimates will be more accurate the closer the relation between the source of information and the DM.

MORB (melting products) and peridotites (residues) are directly related by partial melting. Isotopic compositions of MORB = isotopic composition of source, i.e. the DM. The calculated P/D ratios form the framework for the estimates for other TE ratios.

TE ratios of highly incompatible elements are not fractionated, so they are the same than in the source.

MORB & Initial Isotopic Ratios: Source

$$(^{87}Sr\ /\ ^{86}Sr)_t = (^{87}Sr\ /\ ^{86}Sr)_0 + (^{87}Rb\ /\ ^{86}Sr)_t\ (e^{\lambda 87Rb t}-1)$$

The isochron equation above shows that the $^{87}Sr/^{86}Sr$ ratio in a given system depends on:

- the $^{87}Sr/^{86}Sr$ at time t=0.
- the $^{87}Rb/^{86}Sr$ ratio of the system (in most cases, directly proportional to Rb/Sr)
- the time elapsed since t=0
- The decay constant (lambda) of ^{87}Rb

MORB: t=0

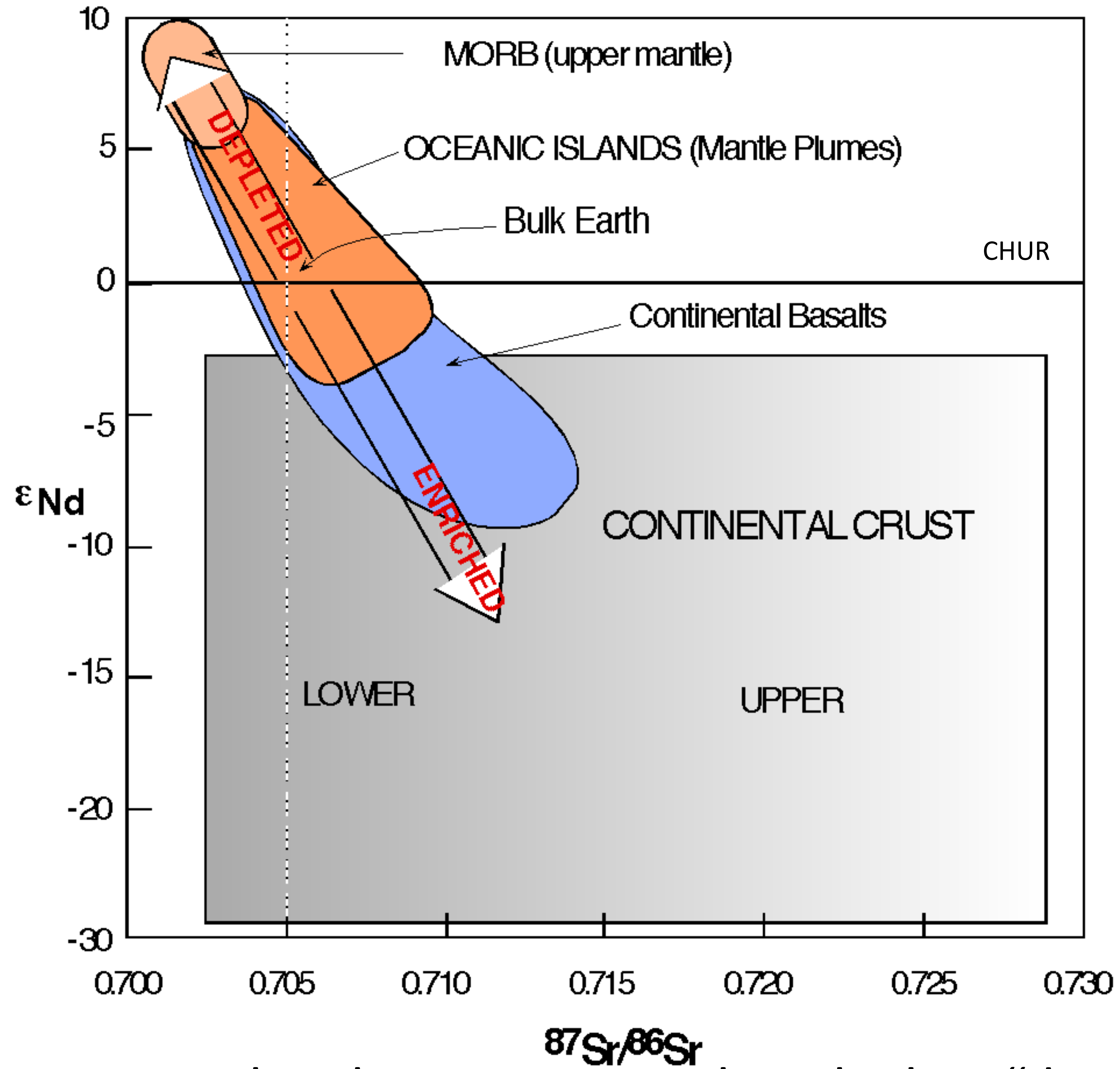
$(^{87}Sr/^{86}Sr)_t = (^{87}Sr/^{86}Sr)_0$

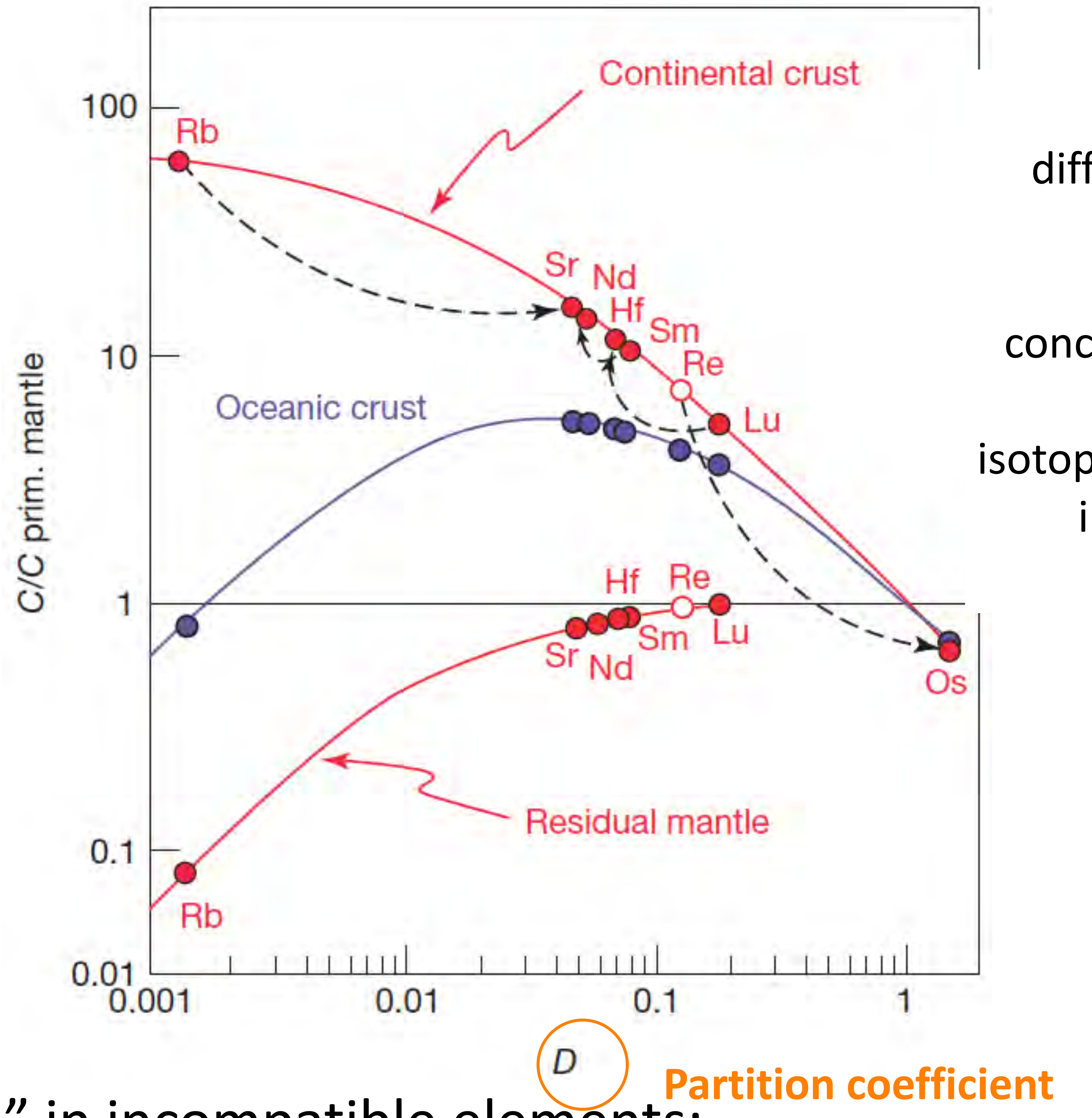
$(^{143}Nd/^{144}Nd)_t = (^{143}Nd/^{144}Nd)_0$

and same for Pb, Hf, etc.

→ *The measured isotopic ratios of MORB samples do not have to be corrected for the presence of radiogenic daughter isotopes!*

“Depleted” MORB Isotope Geochemistry





Relative differences in parent-daughter concentrations of major isotopic systems in different reservoirs

Hofmann ToG 2003

MORB samples the upper mantle, which is “depleted” in incompatible elements:

- MORB has low Rb/Sr compared to continental crust = unradiogenic $^{87}Sr/^{86}Sr$.
- MORB has high Sm/Nd compared to continental crust = radiogenic $^{143}Nd/^{144}Nd$.
- Depleted MORB and its source, depleted mantle (DM or DMM), have low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ (or ε_{Nd}) values relative to all other reservoirs in the Earth

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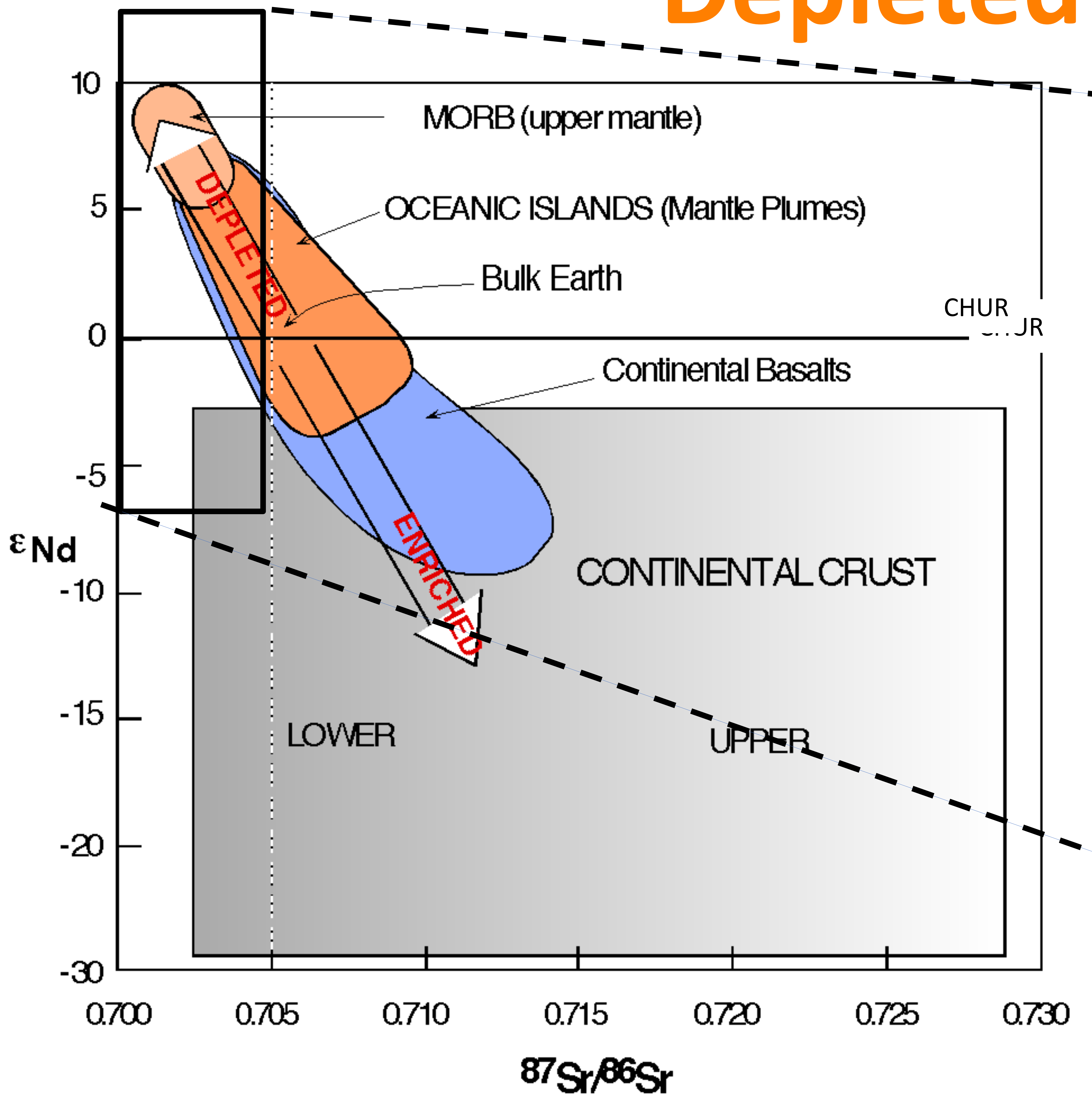
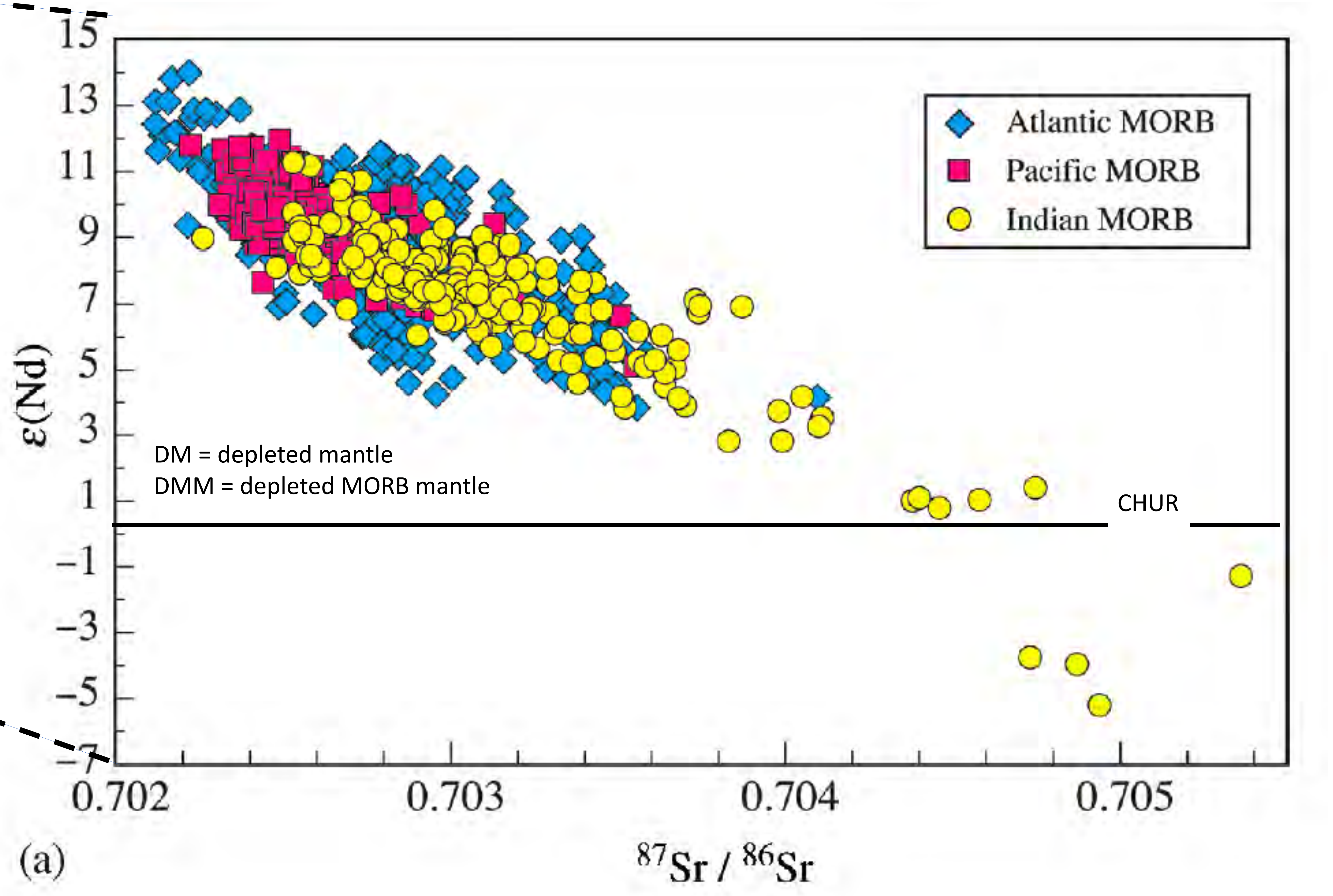
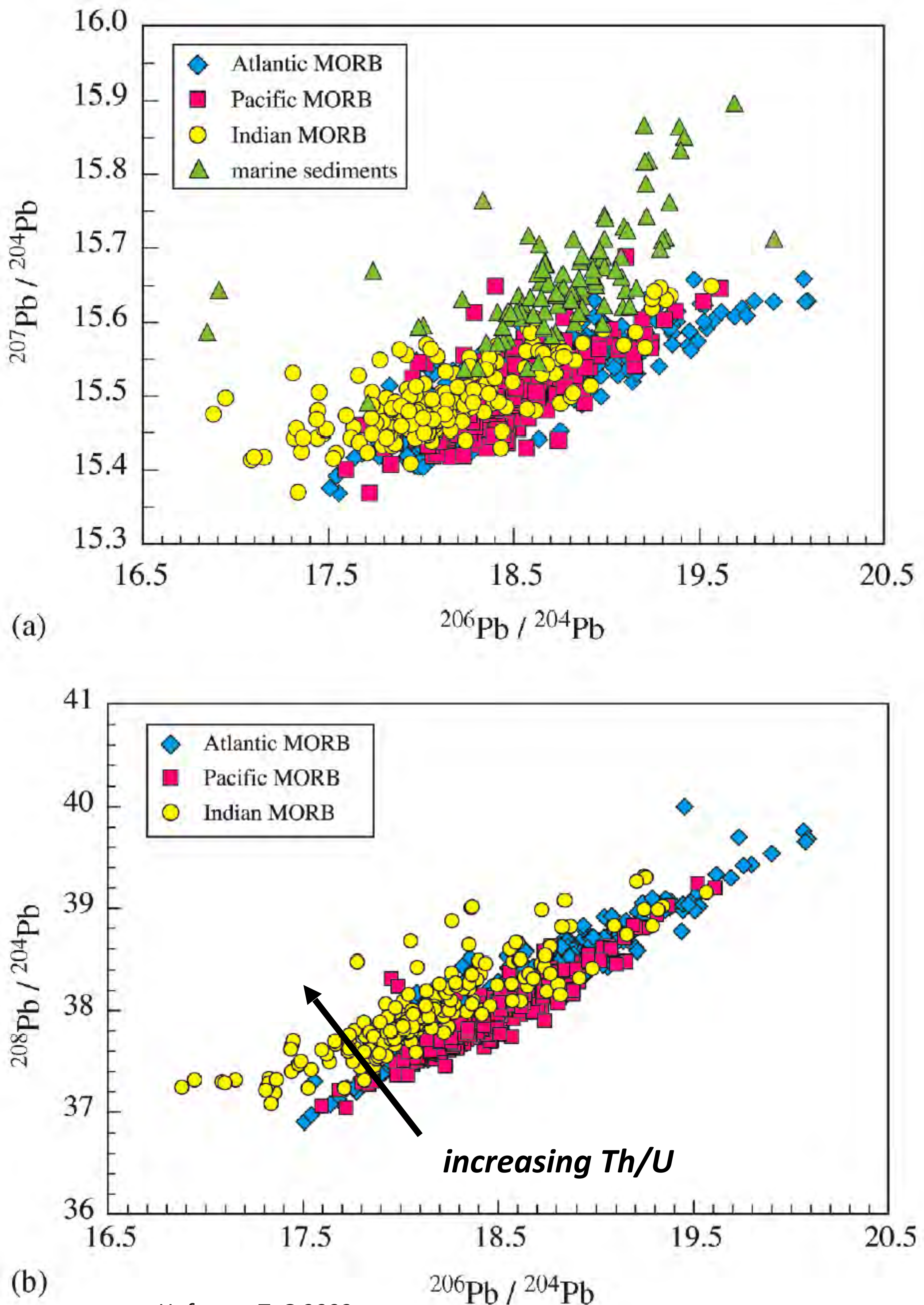




MORB from the Indian Ocean is distinctly higher in $^{87}Sr/^{86}Sr$ and lower in ε_{Nd} than MORB from the Pacific and Atlantic ocean basins

Hofmann ToG 2003

MORB & Pb Isotopes



Hofmann ToG 2003

Pb isotopic compositions are expressed as ratios of the radiogenic daughter isotopes (^{206}Pb, ^{207}Pb, ^{208}Pb) to the stable isotope of Pb (^{204}Pb):

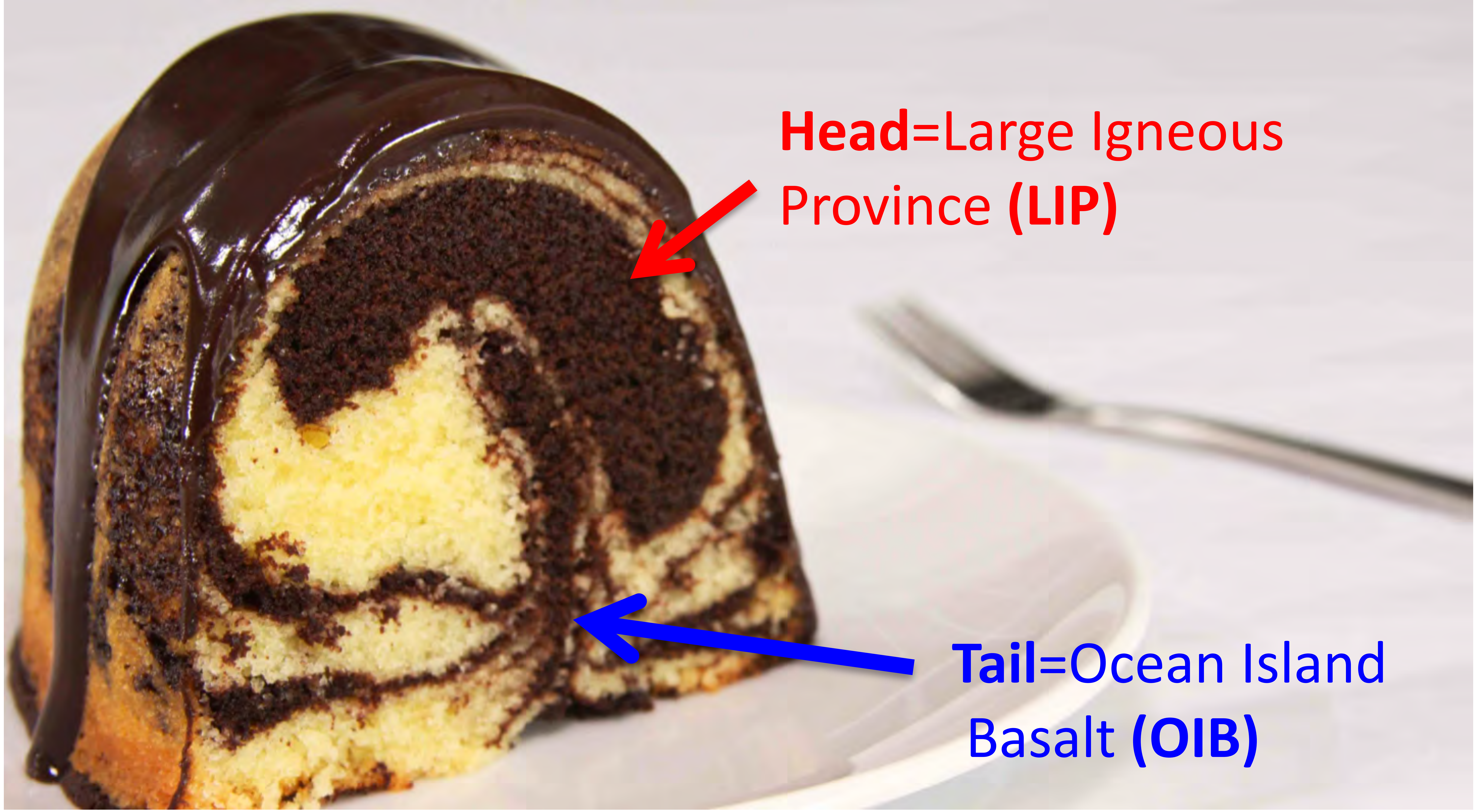
- Note that these diagrams have a common denominator on both axes (^{204}Pb), thus linear relationships may represent either isochrons or mixing.

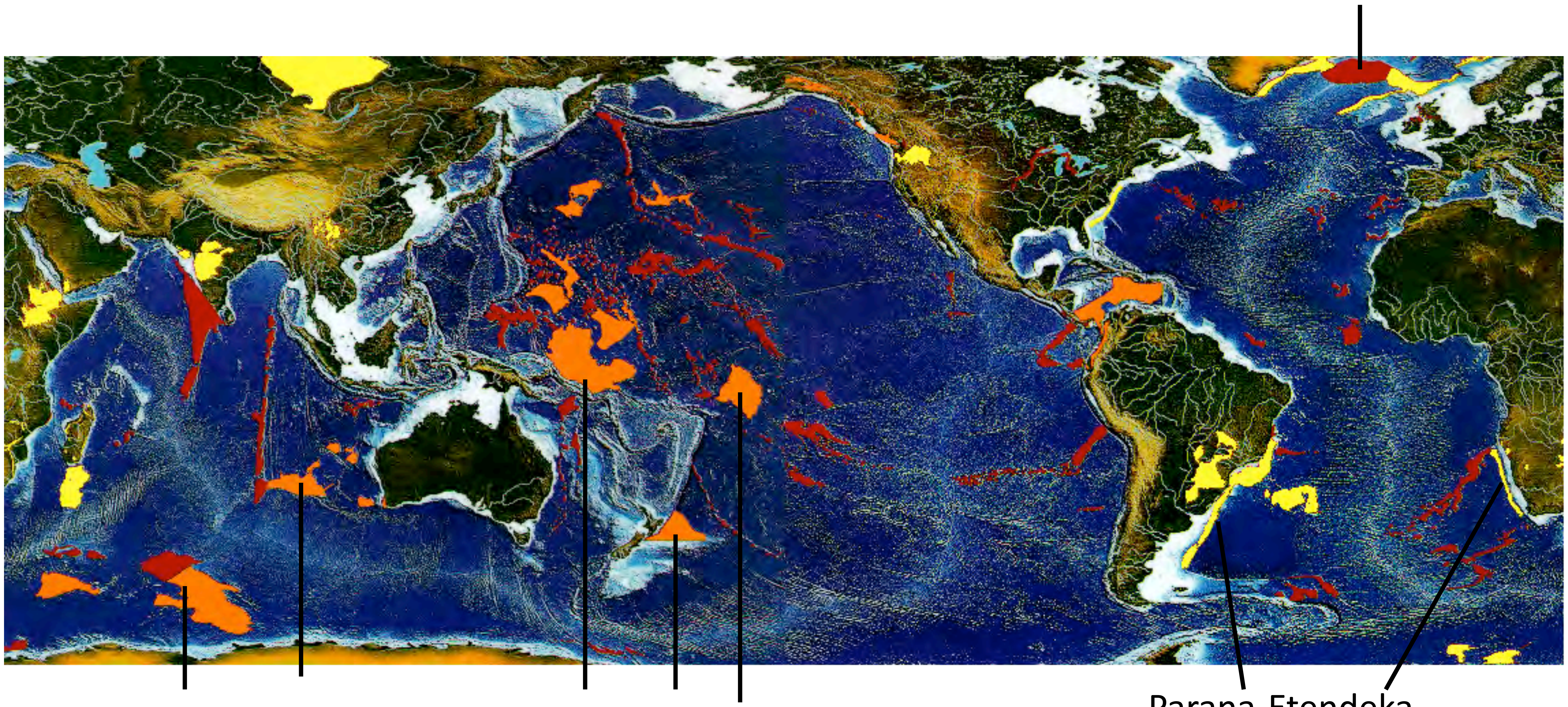
Observations*:

- There is no single Pb isotope composition of MORB.
- MORB are relatively unradiogenic in Pb compared to most other reservoirs (more on this later), therefore MORB mantle has relatively low U/Pb and Th/Pb.
- Indian MORB are shifted to higher $^{208}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ value (implies a distinct Th/U ratio of Indian Ocean mantle).

**Compare with OIB isotope variations in lectures to come.*

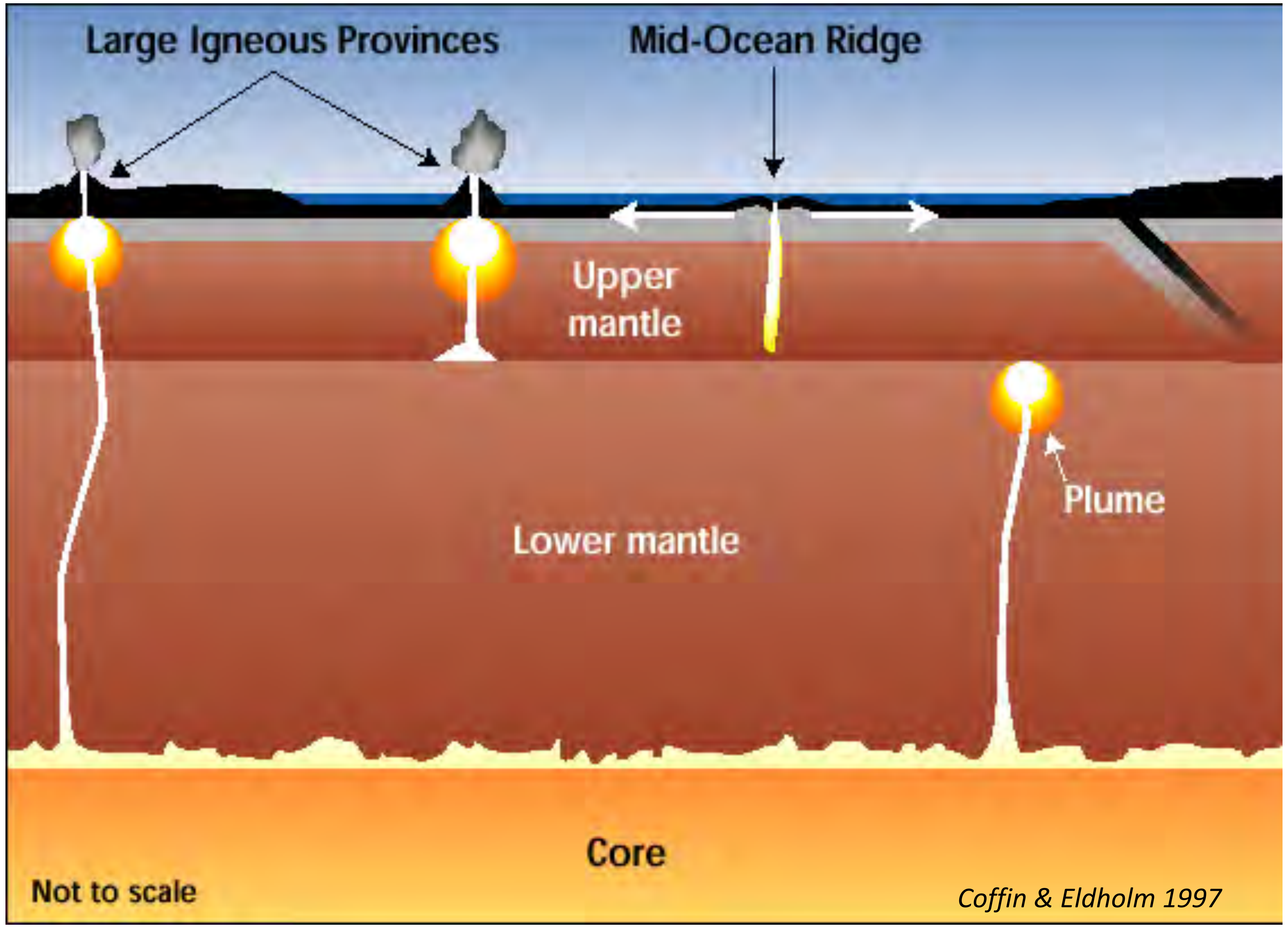
Message from the Mantle: OIB geochemistry



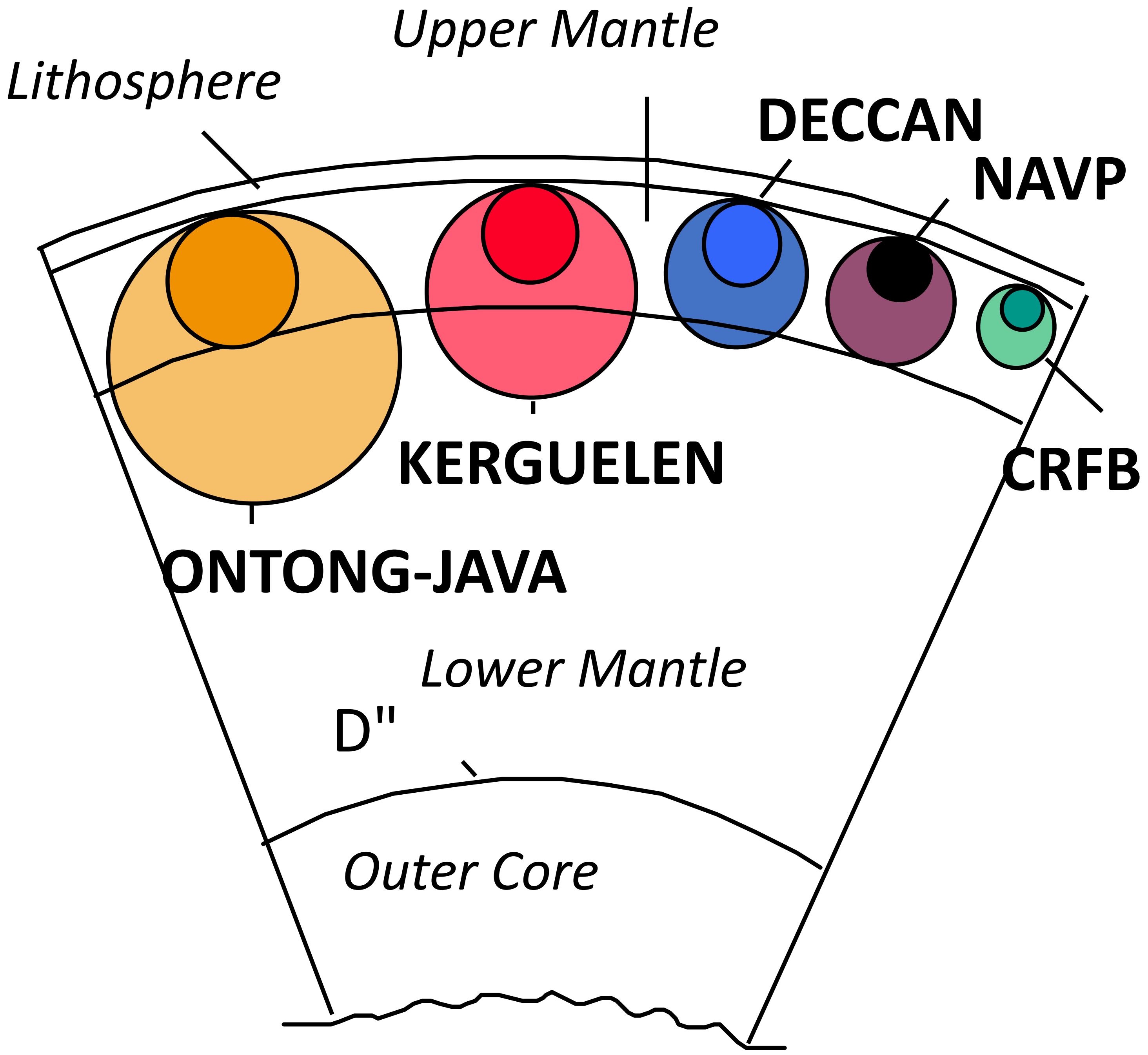


adapted from Coffin et al. (2006)
**Goodliffe & Martinez (1997)*
Mahoney J. J. & Coffin M. F. (eds.) (1997)

Large Igneous Provinces & Mantle Plumes



Rising plumes of hot, solid material migrate through the Earth's mantle; where the head of the plume reaches the base of the lithosphere, partial melting begins to form basaltic magma that rises to the surface to form a LIP.



Minimum and maximum "spherical" diameters of mantle melting required for 5 LIPs assuming
5% (large circle) and
30% (small circle) partial melting.

NAVP = North Atlantic Volcanic Province
CRFB = Columbia River Flood Basalts

Modified from Coffin & Eldholm 1994

Activity: LIP volumes

Assuming 5% and 30% partial melting, and knowing the volume of the following LIPs, calculate the volume of the mantle sampled to form this giant field of lavas:

Ontong-Java: 36×10^6 km^3

Kerguelen: 20×10^6 km^3

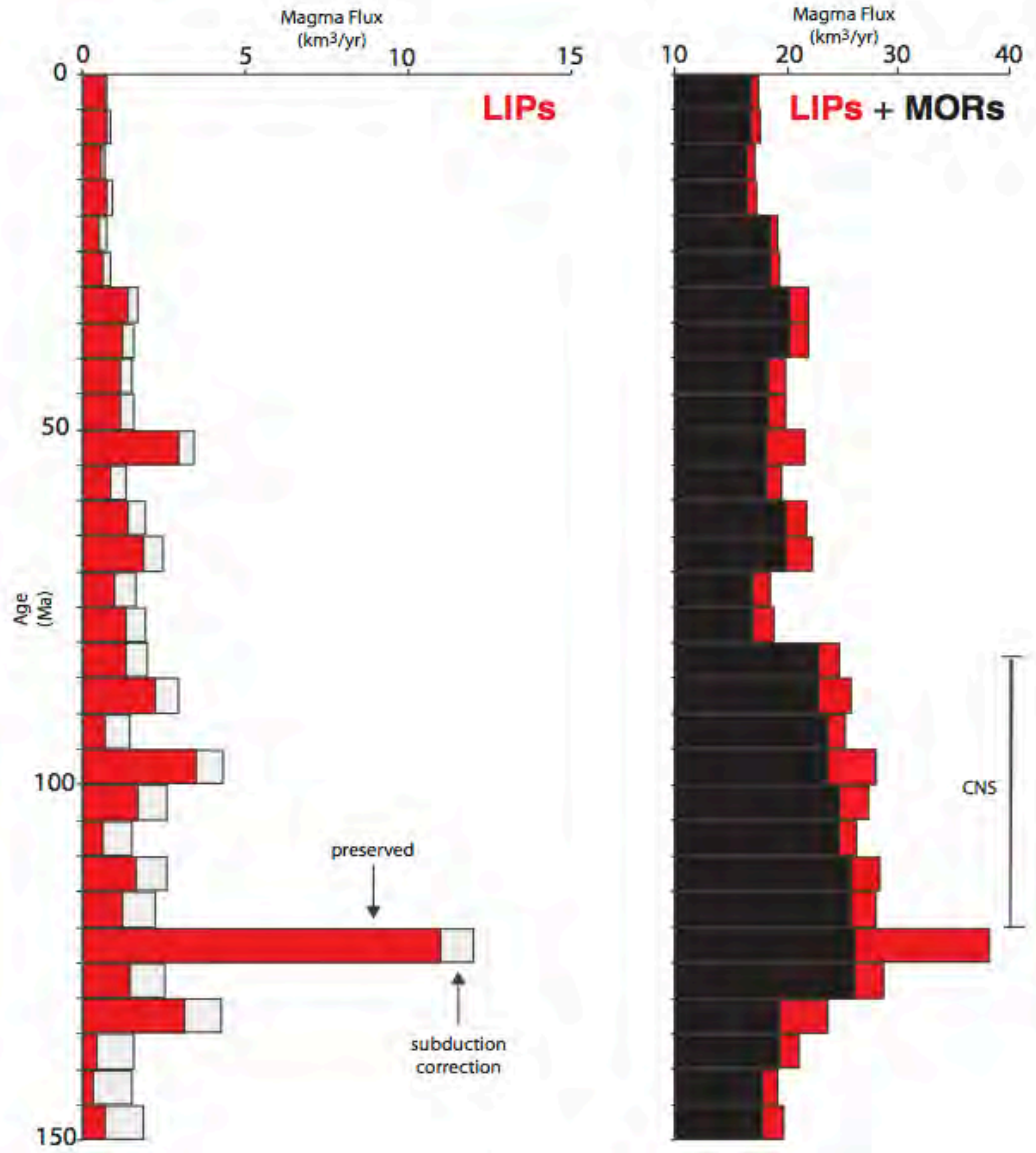
OJP and KP have about the same surface area but OJP is significantly thicker.

Columbia River basalts:
1.3×10^6 km^3

The volume of a sphere is: $$V = \frac{4}{3}\pi r^3$$

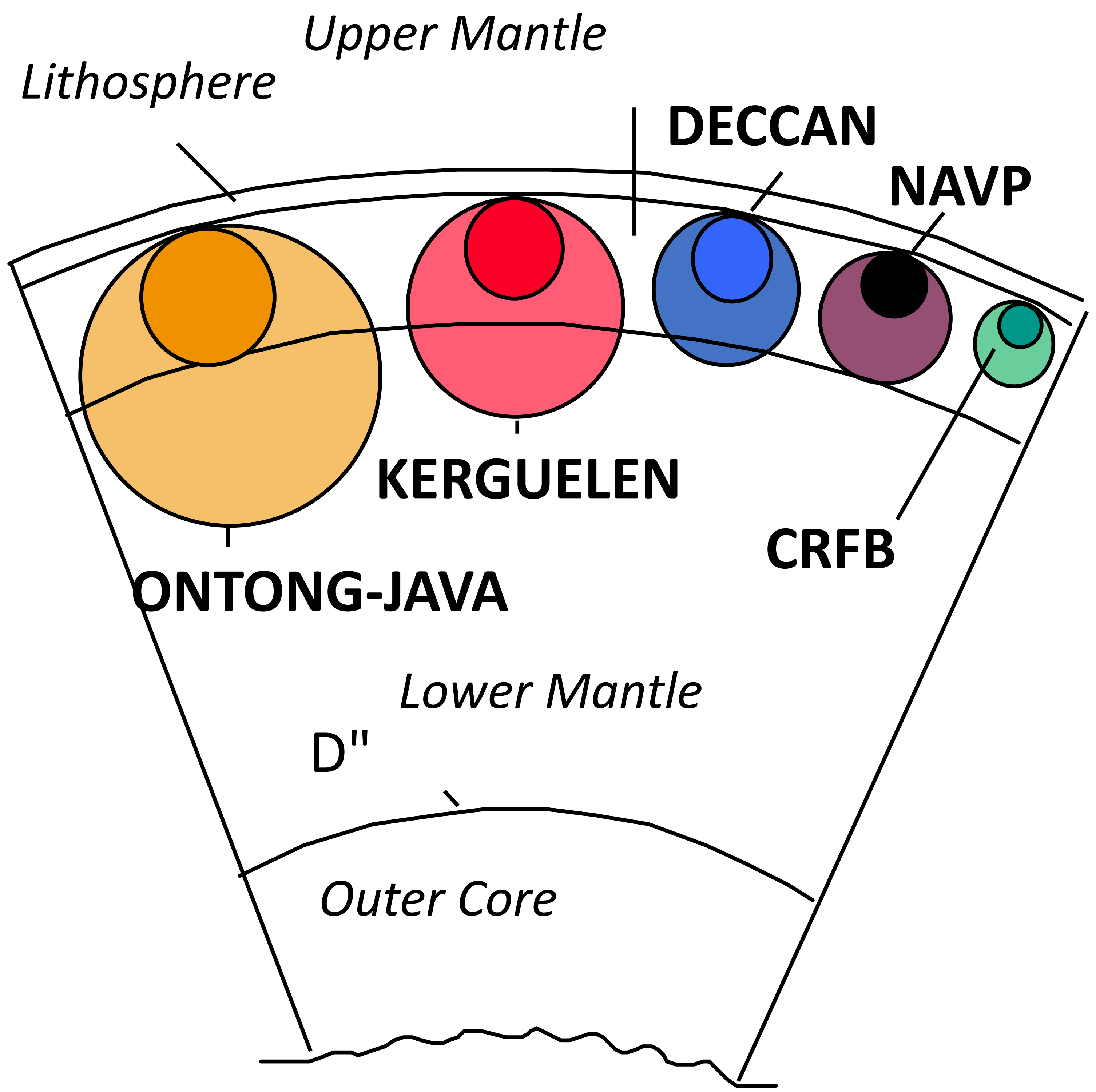
What is the minimum depth sampled?
Π = 3.142

Coffin et al 2006



Volume of Mantle Sampled to Form LIPs

	LIP (km^3)	Volume mantle 5, 30% partial melt	Radius	Diameter
OJP	3.60 10^7	7.20 10^8 1.20 10^8	556 306	1112 612
Ker	2.00 10^7	4.00 10^8 6.67 10^7	457 252	914 503
CRB	1.30 10^6	2.60 10^7 4.33 10^6	184 101	368 202



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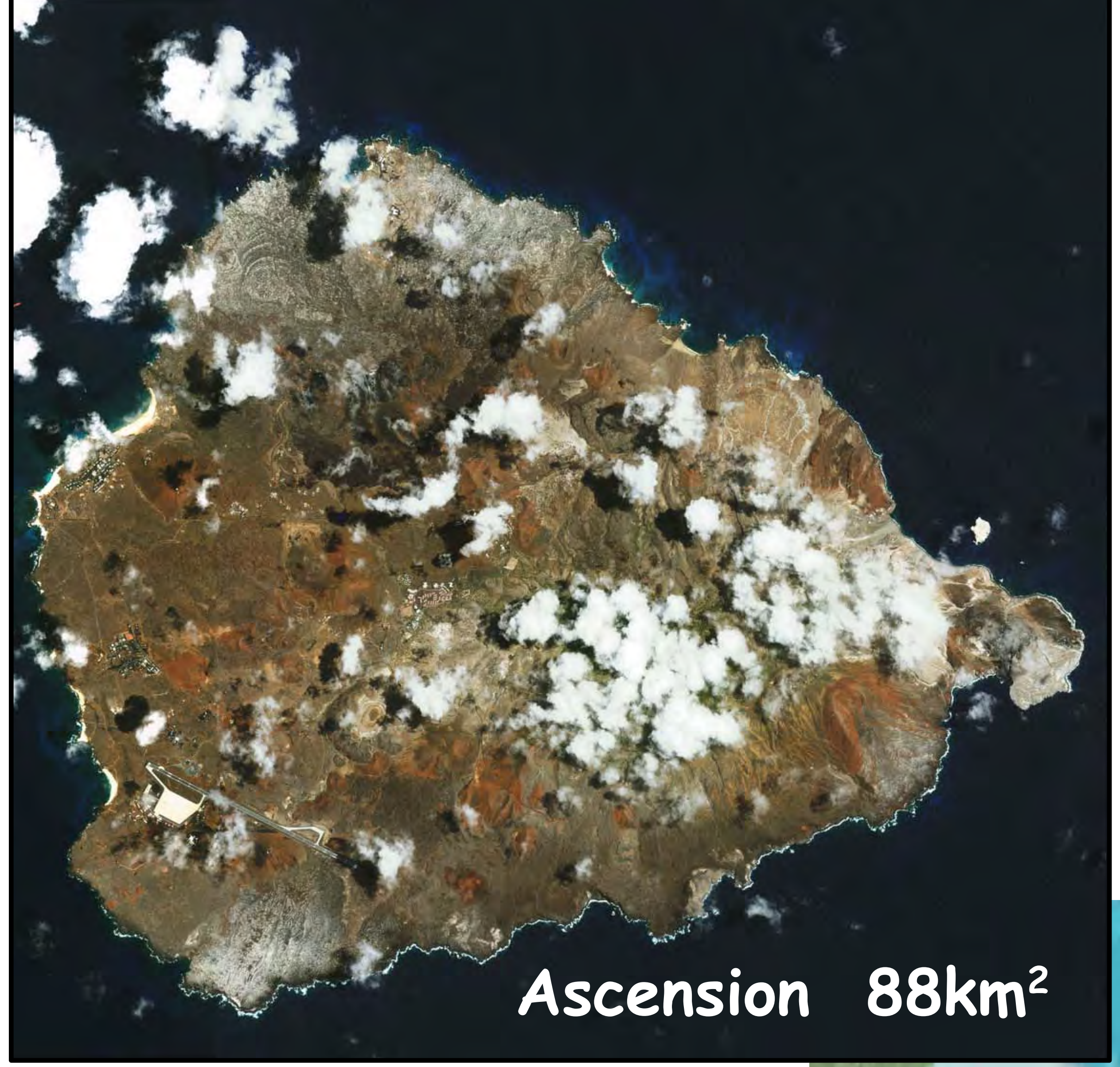
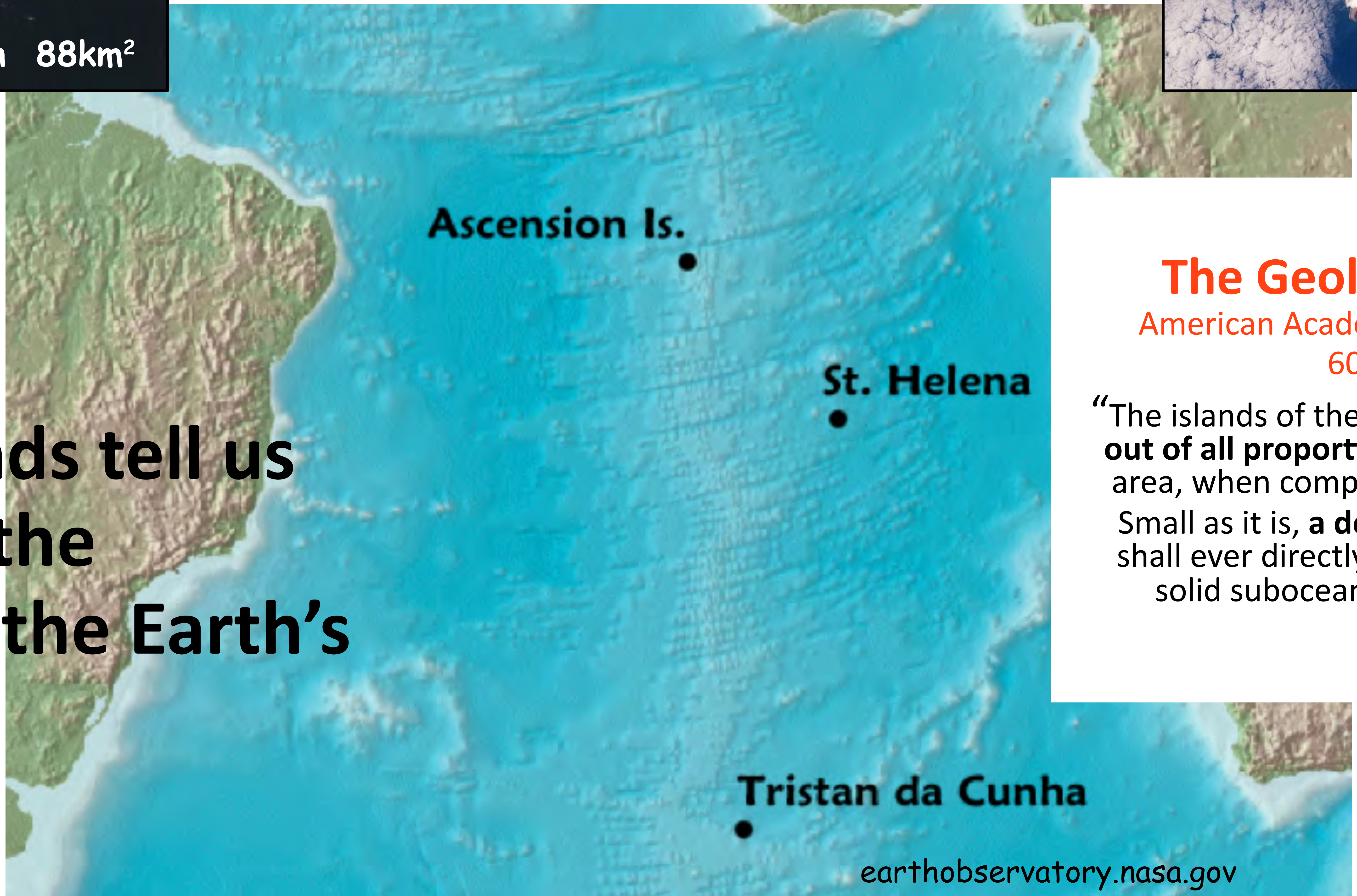


Atlantic Ocean



Oceanic Islands tell us much about the chemistry of the Earth's Mantle

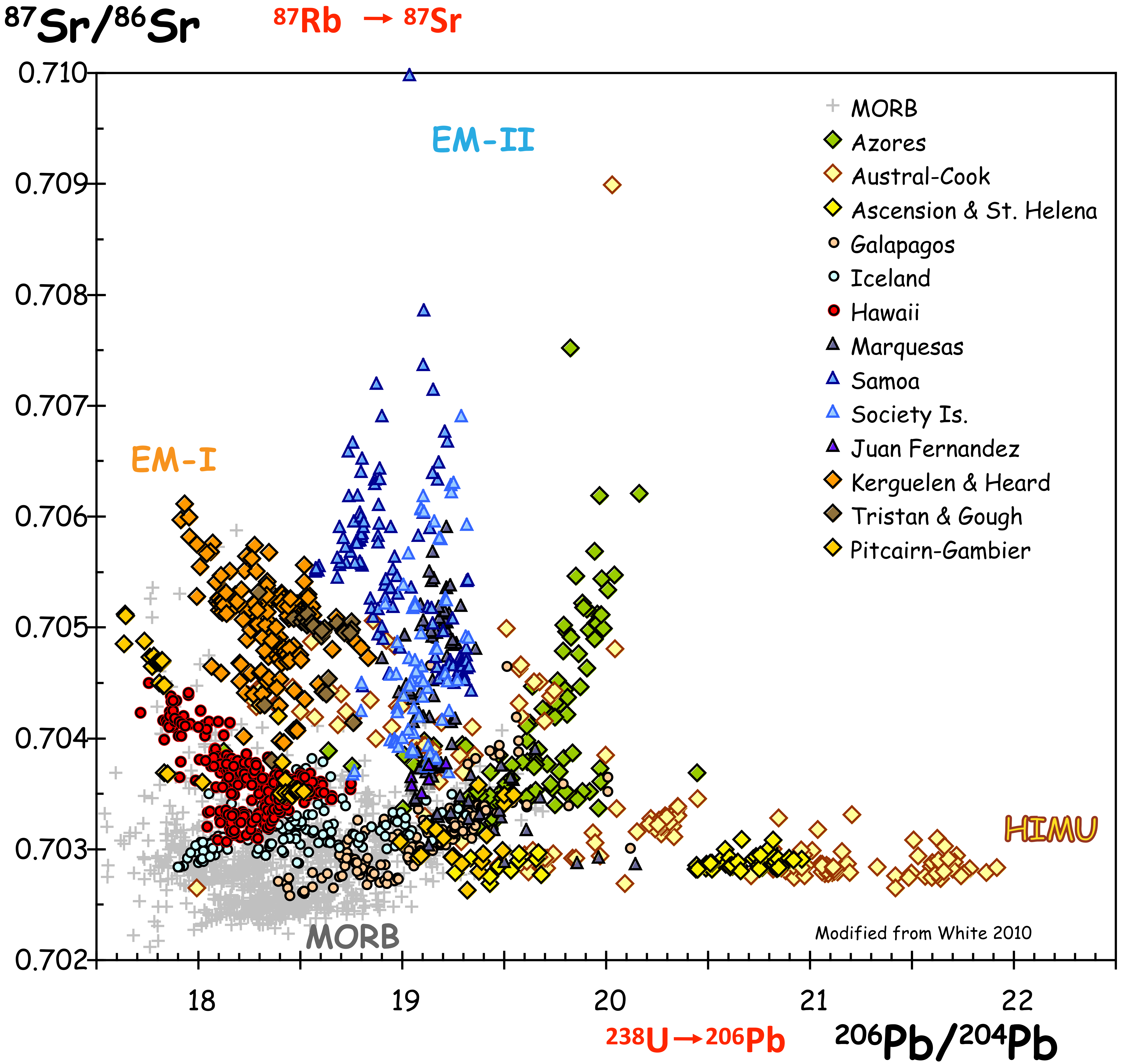
R.A. Daly
The Geology of Ascension Island

American Academy of Arts and Sciences Proceedings 60:1-80 (+21 plates), **1925**

"The islands of the deep oceans have geological importance **out of all proportion** to their individual areas or their total area, when compared with equal areas of the continents. Small as it is, **a deep-sea island tells us practically all** we shall ever directly ascertain concerning the nature of the solid suboceanic material throughout a much more extensive region."

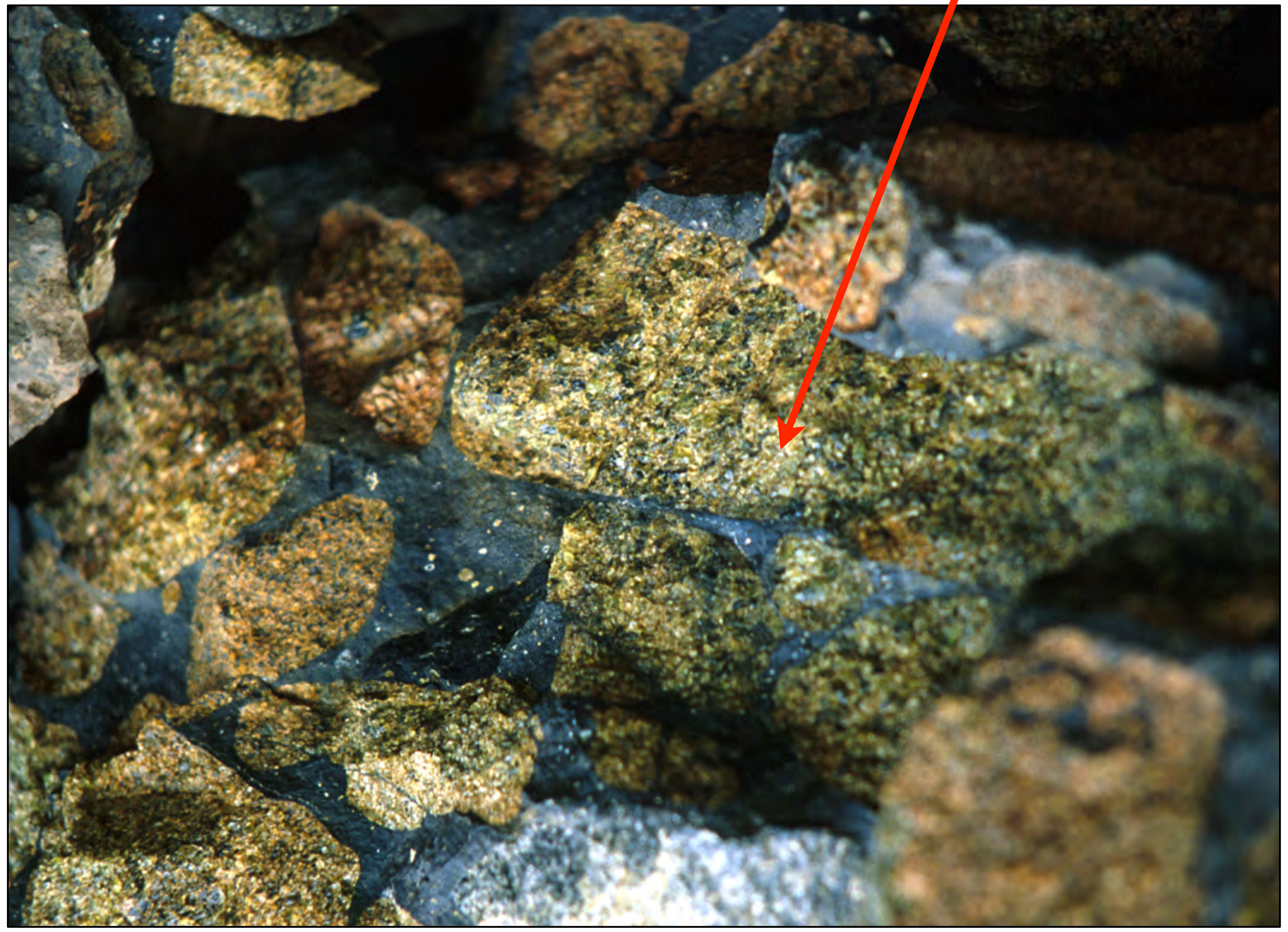
OIB Source Components: Hawai‘i and Kerguelen both have EM-I characteristics

"fingerprinting mantle sources"



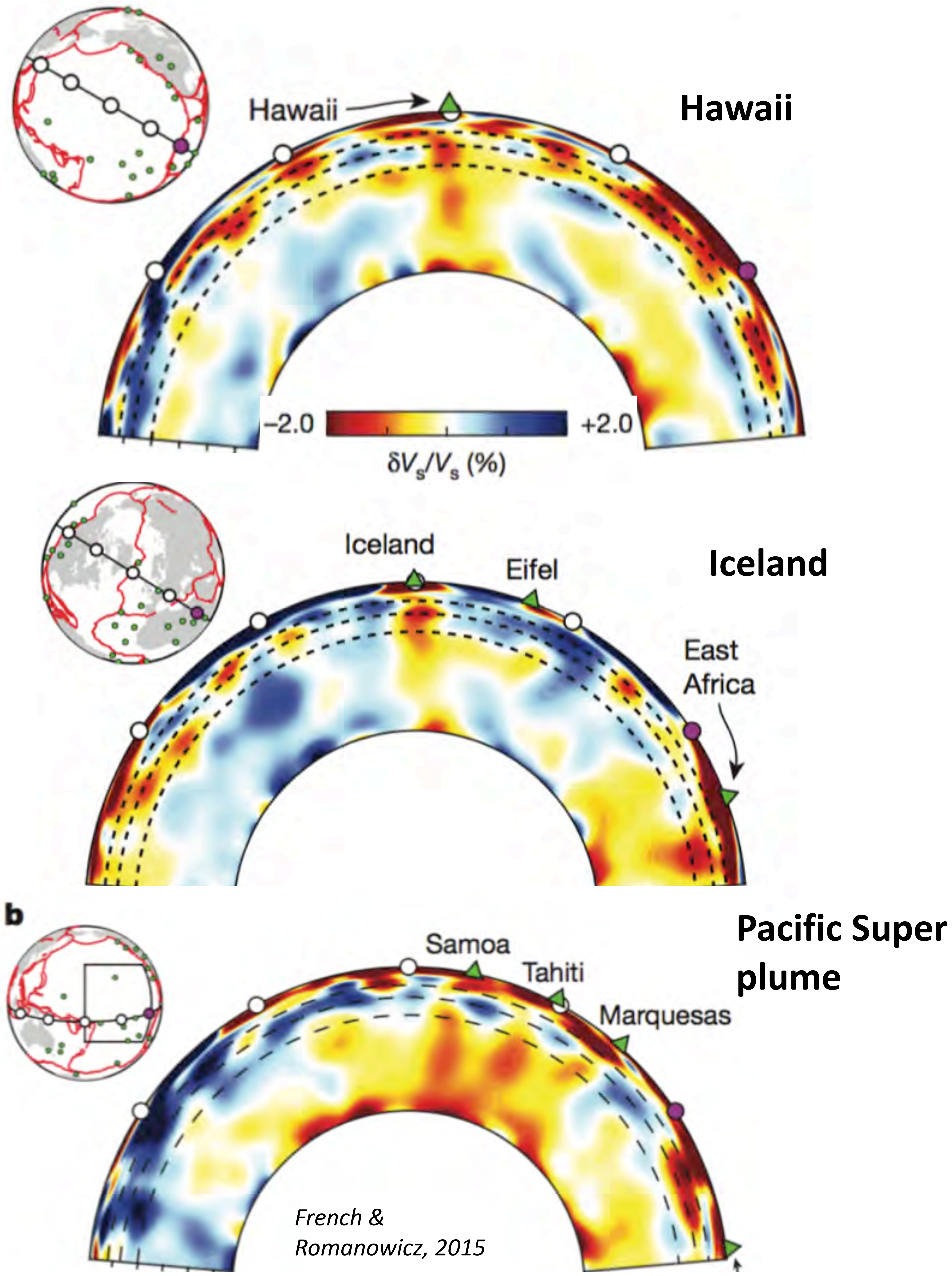
Lavas as Probes of the Mantle's Composition

Radiogenic isotopes (e.g., $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$) and some trace element ratios <u>are not changed</u> between solid and melt.

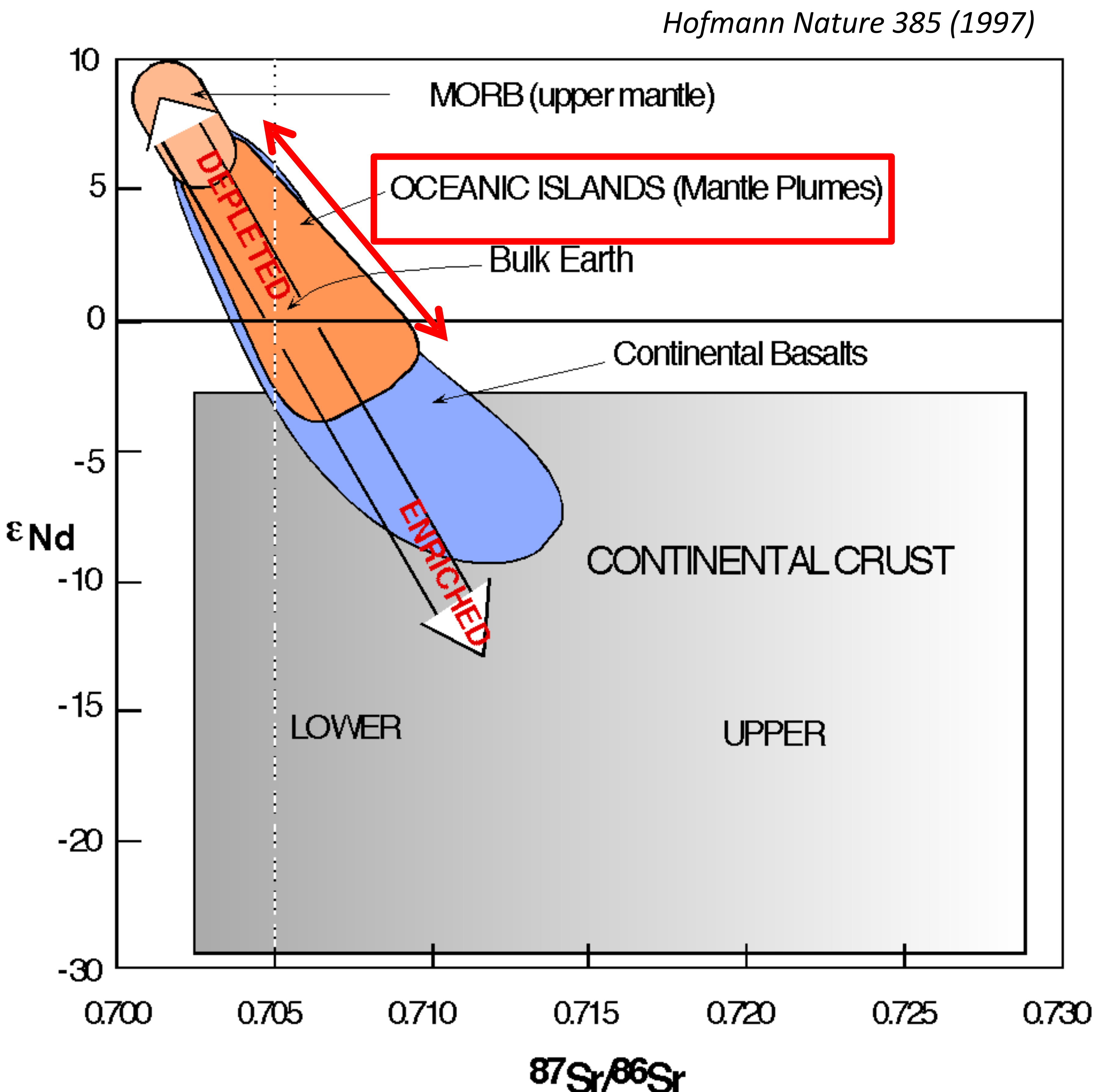


$^{87}Sr/^{86}Sr$ solid mantle (peridotite) = $^{87}Sr/^{86}Sr$ melt (basalt)

Geophysical Imaging of Mantle Plumes at Depth

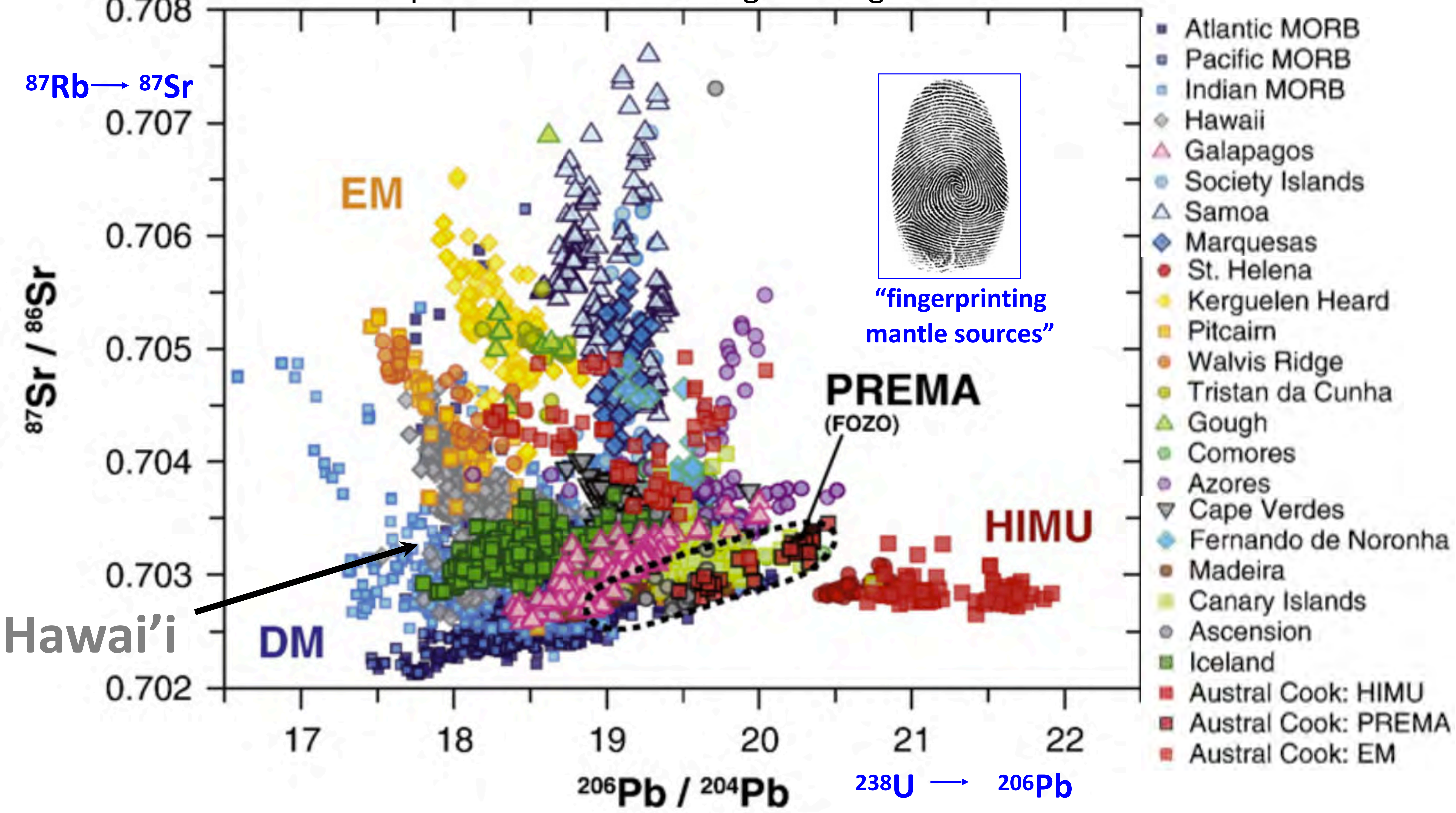


Subducted components (sediment, oceanic crust, oceanic lithosphere) injected into the lower mantle have the potential to be sampled by mantle plumes



Oceanic Islands, Mantle Plumes and Mantle End-Members

Isotopic ratios are time-integrated signatures



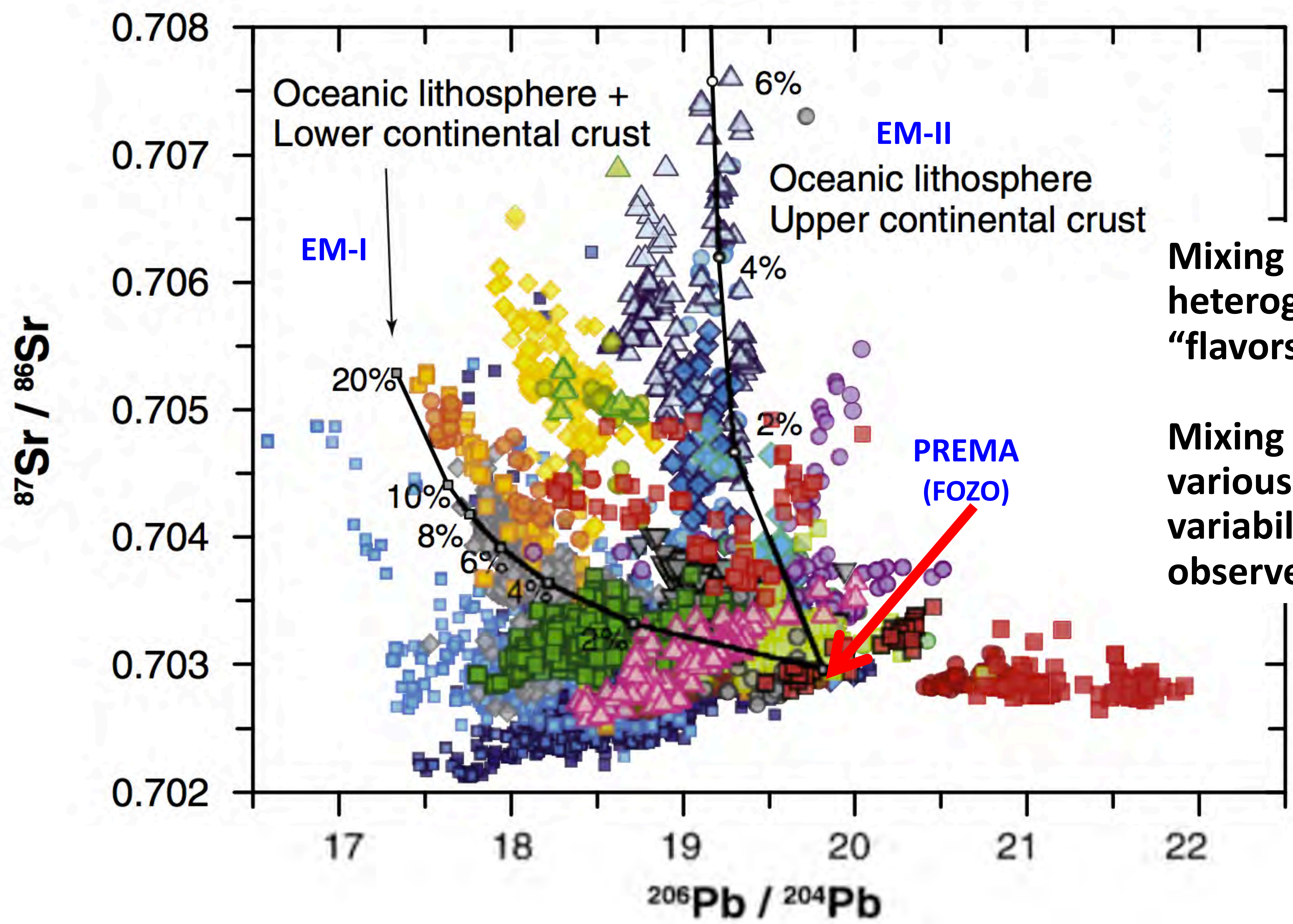
Stracke, 2012

Mantle Components & Reservoirs

Certain oceanic islands or groups of islands are characterized by specific isotopic compositions and can be used to “map” a series of distinct **mantle components** or reservoirs, which may be identifiable separate volumes in the mantle or extremes of a continuum of compositions:

- **DMM** = depleted MORB mantle, the continuously depleted upper mantle reservoir, source of mid-ocean ridge basalts.
- **EM-1** = enriched mantle 1, mantle that reflects addition of crustal materials, either recycling of delaminated subcontinental lithospheric mantle, or recycling of subducted ancient pelagic sediment.
- **EM-2** = enriched mantle 2, mantle that reflects addition of recycled oceanic crust.
- **HIMU** = high μ, where μ = U/Pb (and Th/Pb), reflecting recycling of “enriched” oceanic lithosphere that has been infiltrated by low-degree partial melts.
- A **common mantle component** variously referred to as:
  - PREMA = prevalent mantle
  - C = “common”’ component
  - FOZO = focal zone

Oceanic Islands, Mantle Plumes and Mantle End-Members



Mixing different sources of mantle heterogeneity creates different "flavors" of OIBs

Mixing different components in various proportions results in the variability in composition we observe in global OIBs

Stracke, 2012

Isotopic Mixing Modelling

We can model the mixing of melts with different concentrations and isotopic compositions using a simple equation

Component 1

Component 2

Mixture of Components 1 and 2

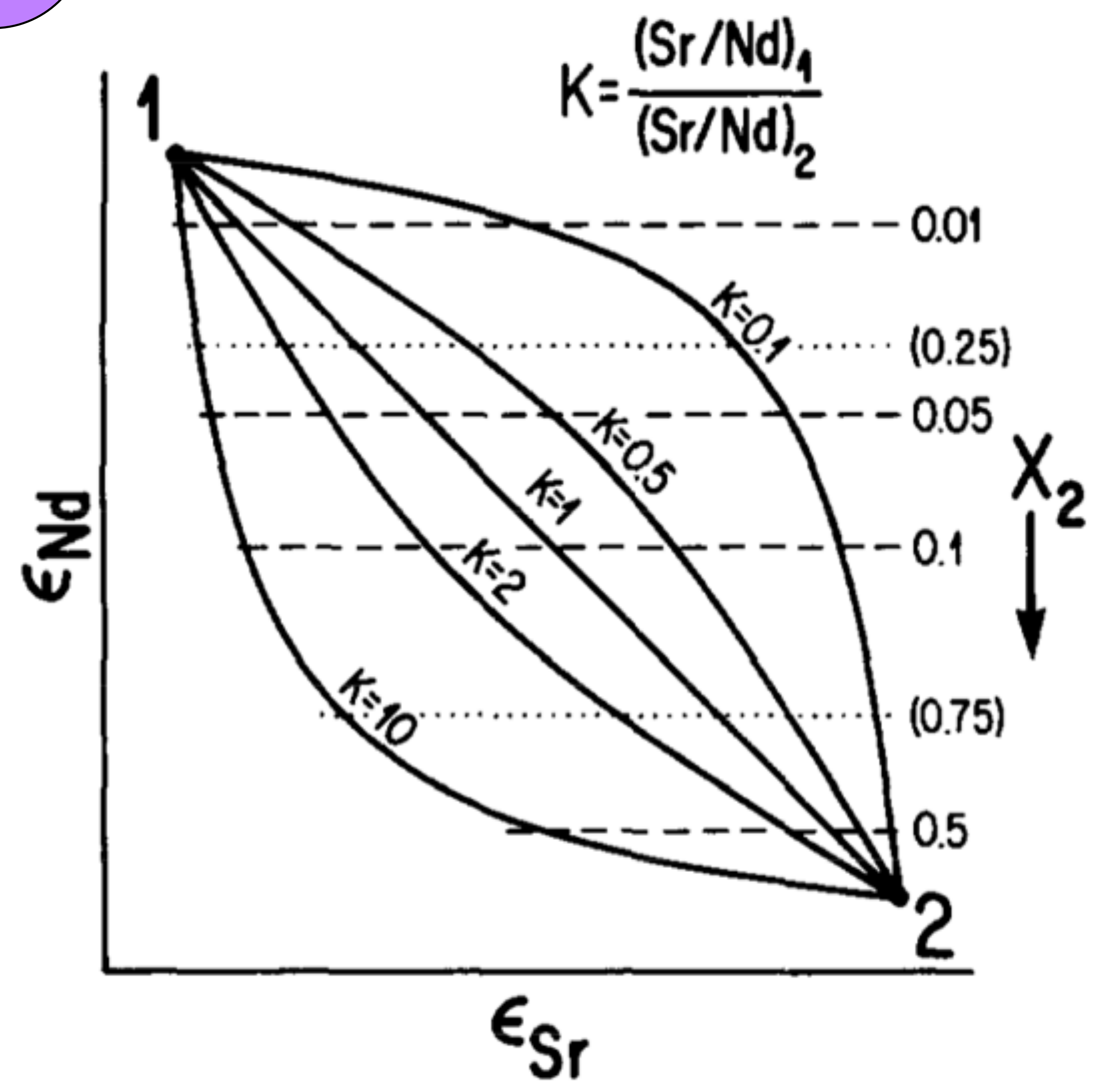
$({}^{87}Sr/{}^{86}Sr)_1$ + $({}^{87}Sr/{}^{86}Sr)_2$ = $({}^{87}Sr/{}^{86}Sr)_3$

Weighed mean: intermediate in composition between $({}^{87}Sr/{}^{86}Sr)_1$ & $({}^{87}Sr/{}^{86}Sr)_2$

$$\frac{\left[(x)([Sr])_1\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_1\right]+\left[(1-x)([Sr])_2\left(\frac{{}^{87}Sr}{{}^{86}Sr}\right)_2\right]}{\left[x([Sr])_1+(1-x)([Sr])_2\right]}$$

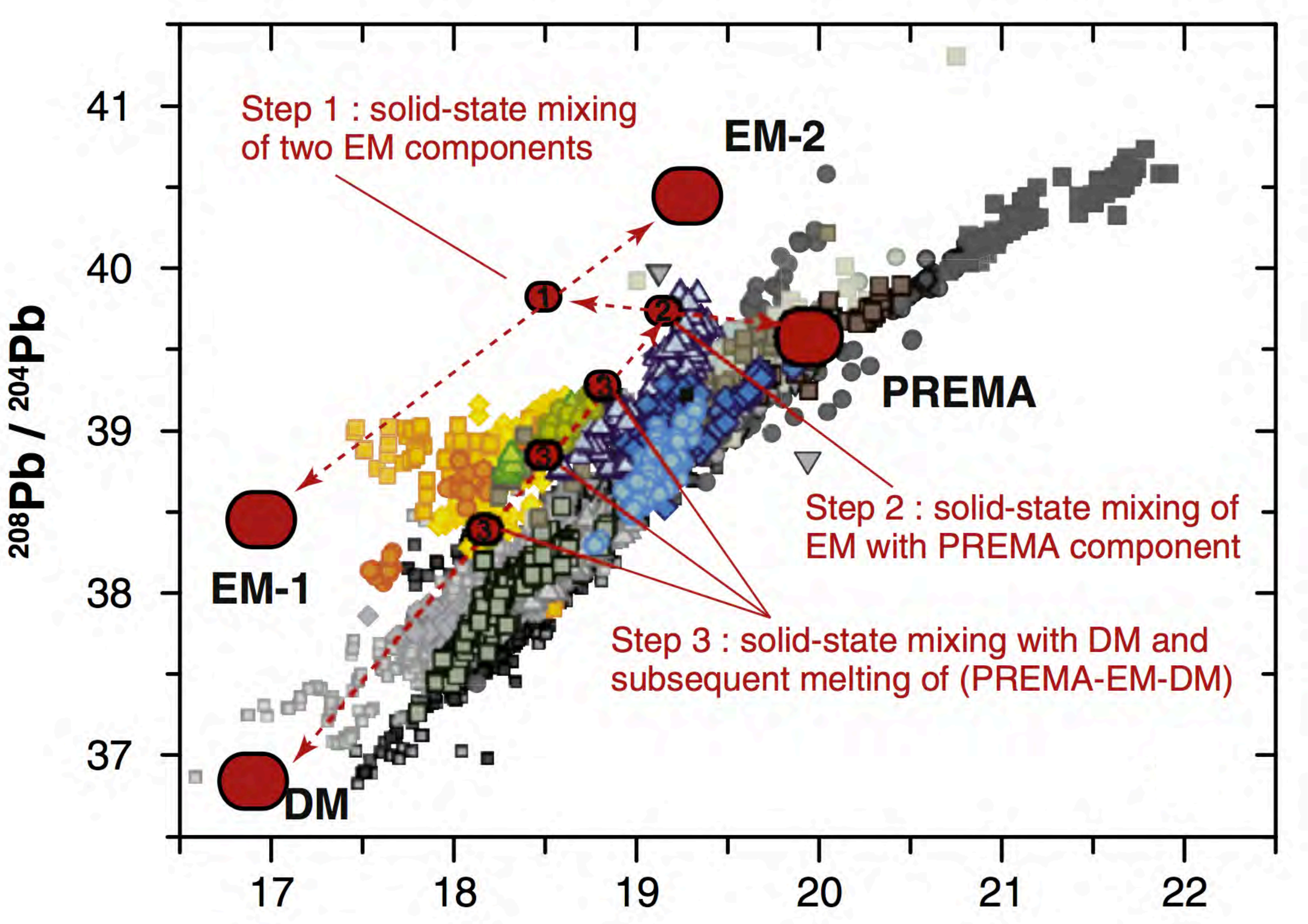
x = weight fraction of component 1 or 2

1 and 2 = two components being mixed



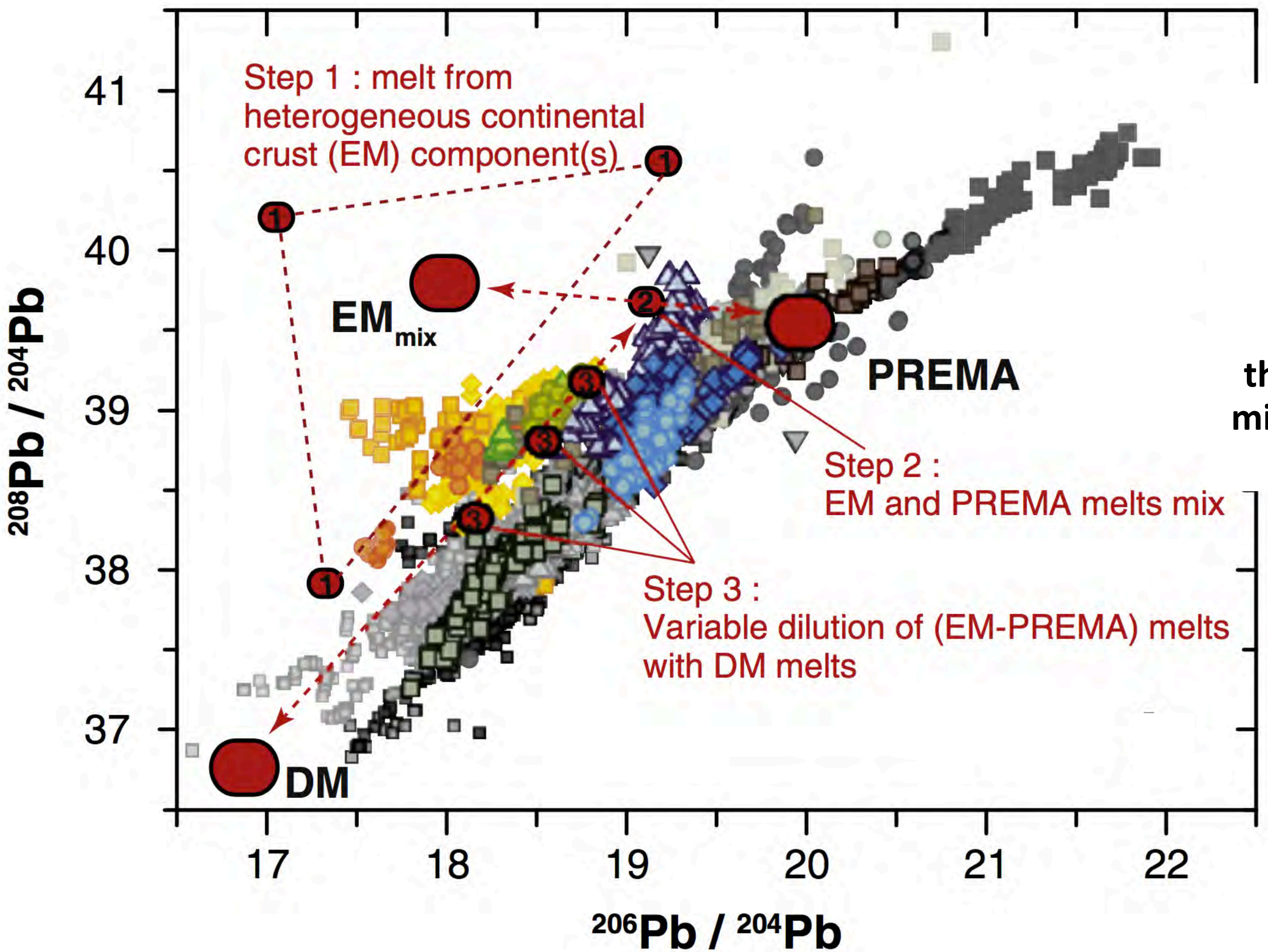
DePaolo and Wasserburg, 1979

Oceanic Islands, Mantle Plumes and Mantle End-Members



Stracke, 2012

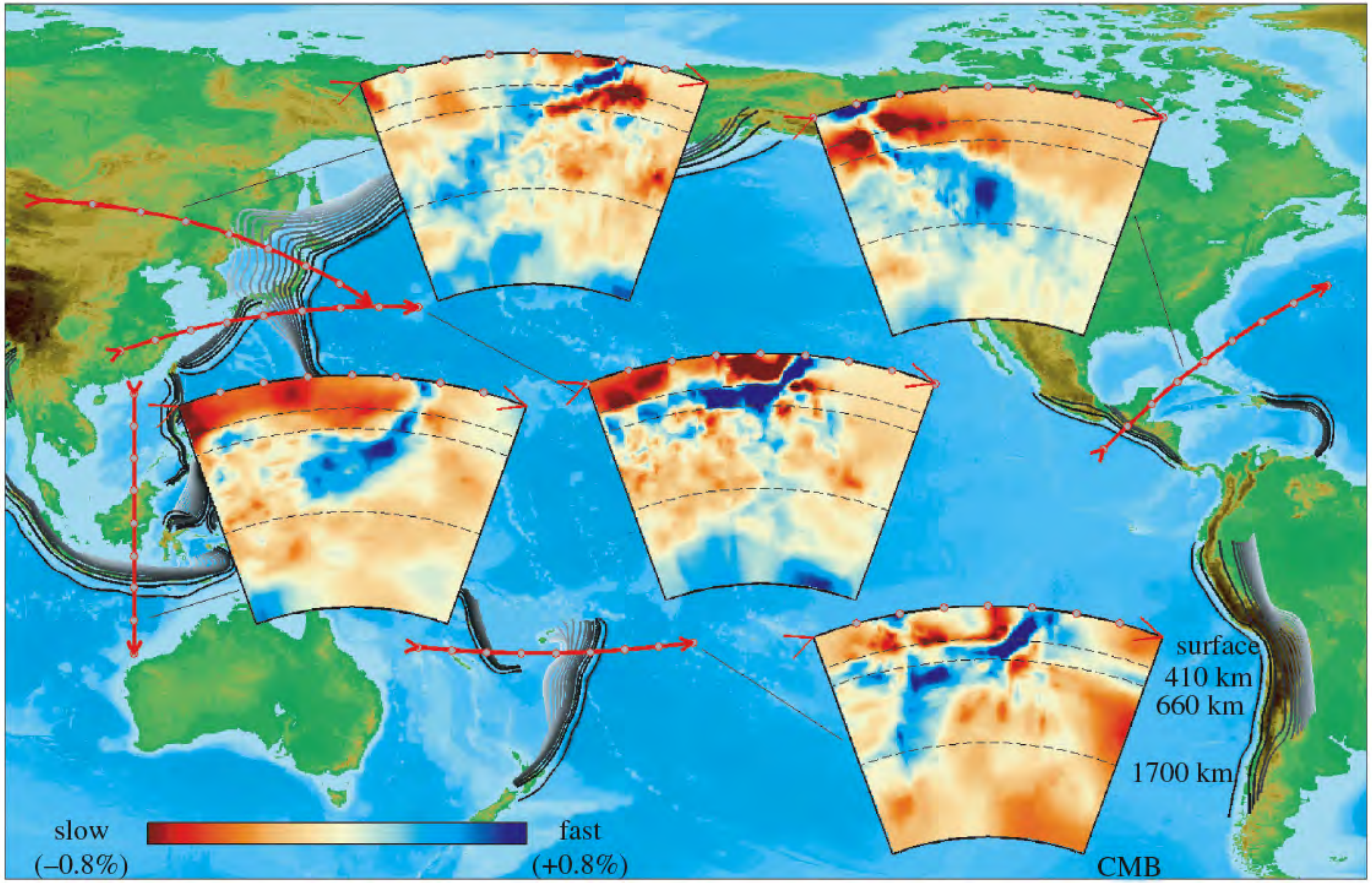
Oceanic Islands, Mantle Plumes and Mantle End-Members



Mixing can happen in steps

Mixing is more likely to occur when materials melt and are collected in a common magmatic system rather than through solid-state mechanical mixing of the mantle (*very* slow process)

Stracke, 2012



Albarède & Van der Hilst 2002

Subducting Slabs & Recycling

– Down-going subducted oceanic lithosphere can be traced by seismic tomography using P- and S- wave variations.

– Subducted material: peridotites, harzburgites, gabbros, tholeiitic and alkali basalts, terrigenous and pelagic sediments, and lower crustal metamorphic rocks.

Recycled Material Mass Balance

Sediment – 0.3-0.7 km^3/year subducts

In 3 Ga that's equal to subducting 1/3 of the modern continents

Oceanic Crust – 20 km^3/year subducts

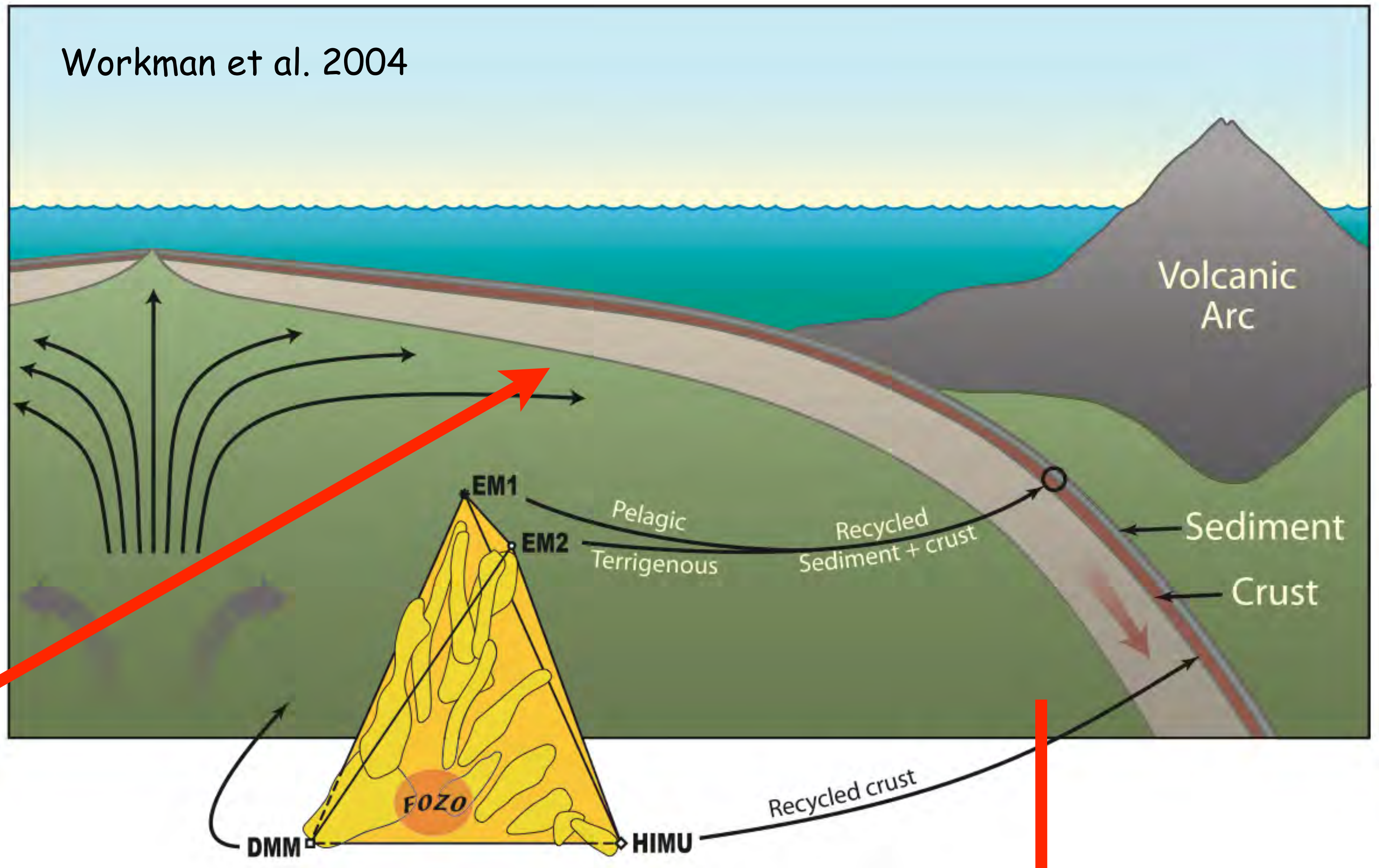
In 3 Ga that's equal to ~60 billion km^3, which is 5% of the mantle's mass

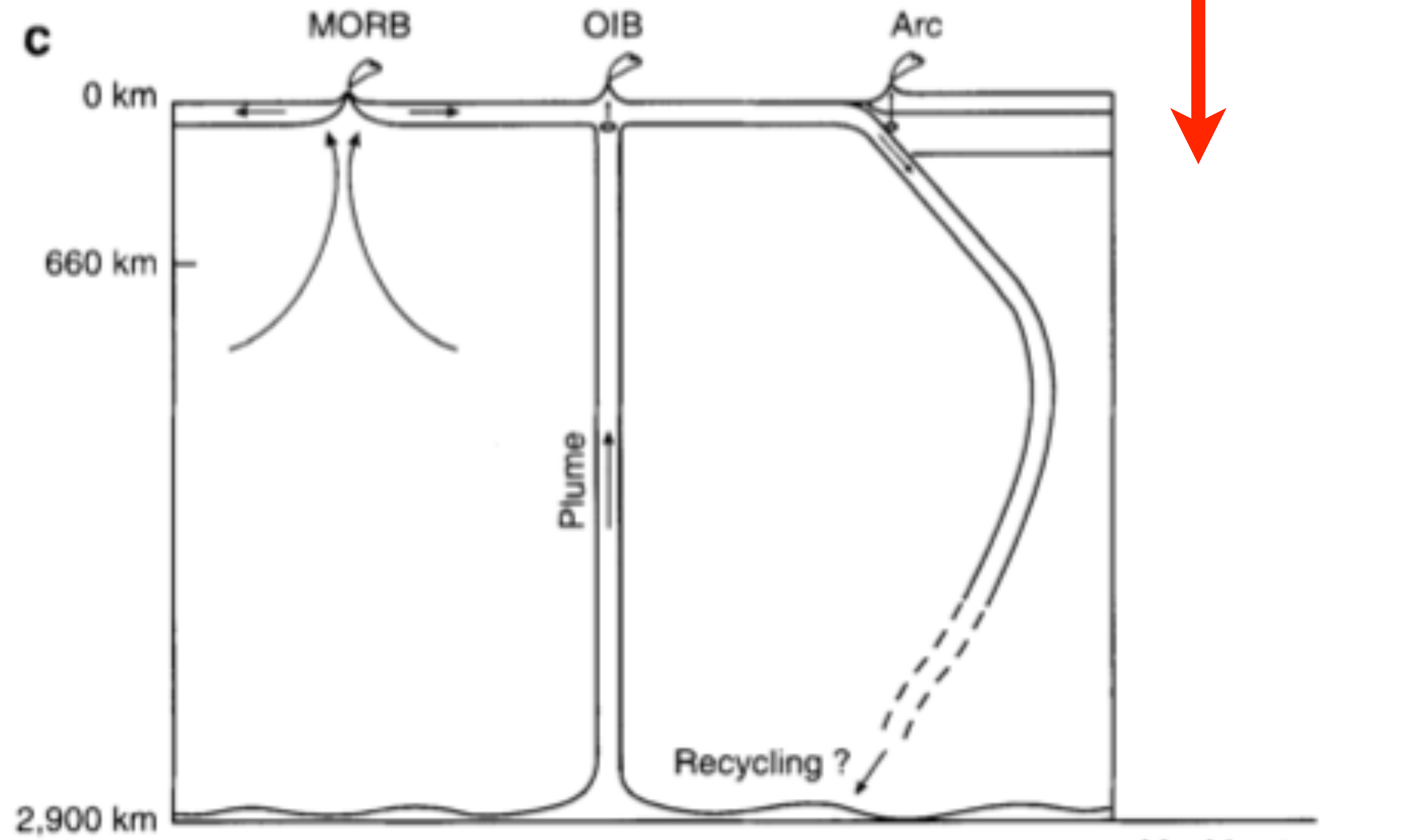
How could the mantle not be heterogeneous?

Recycling Hypothesis

1) Oceanic plates (crust and sediment) enter into the mantle at subduction zones,
2) They are returned to the surface in mantle upwellings - plumes.
3) Crust and sediment are melted beneath hotspots.

Rivers contribute >85% of ocean floor sediment





Hofmann 1997

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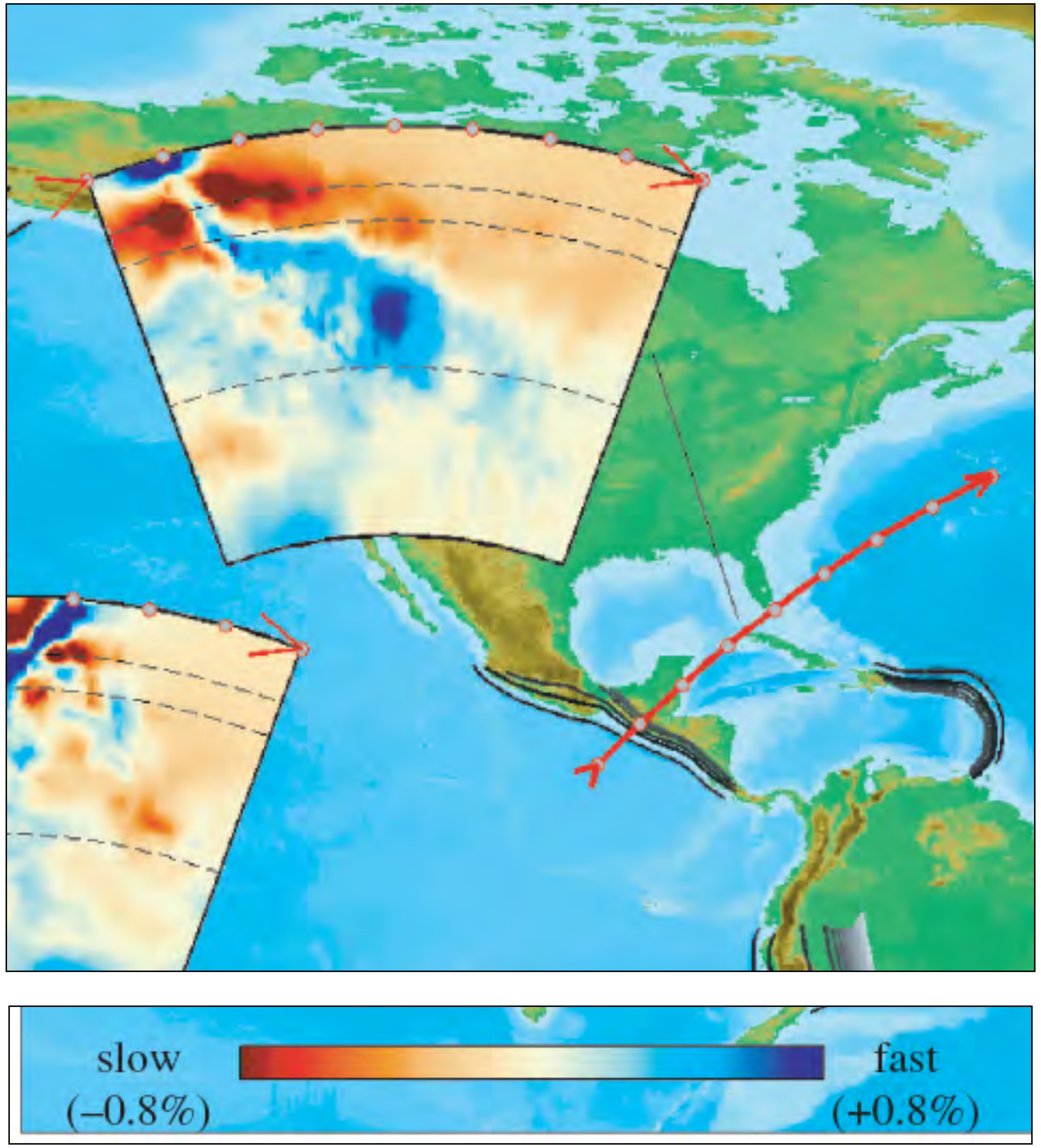
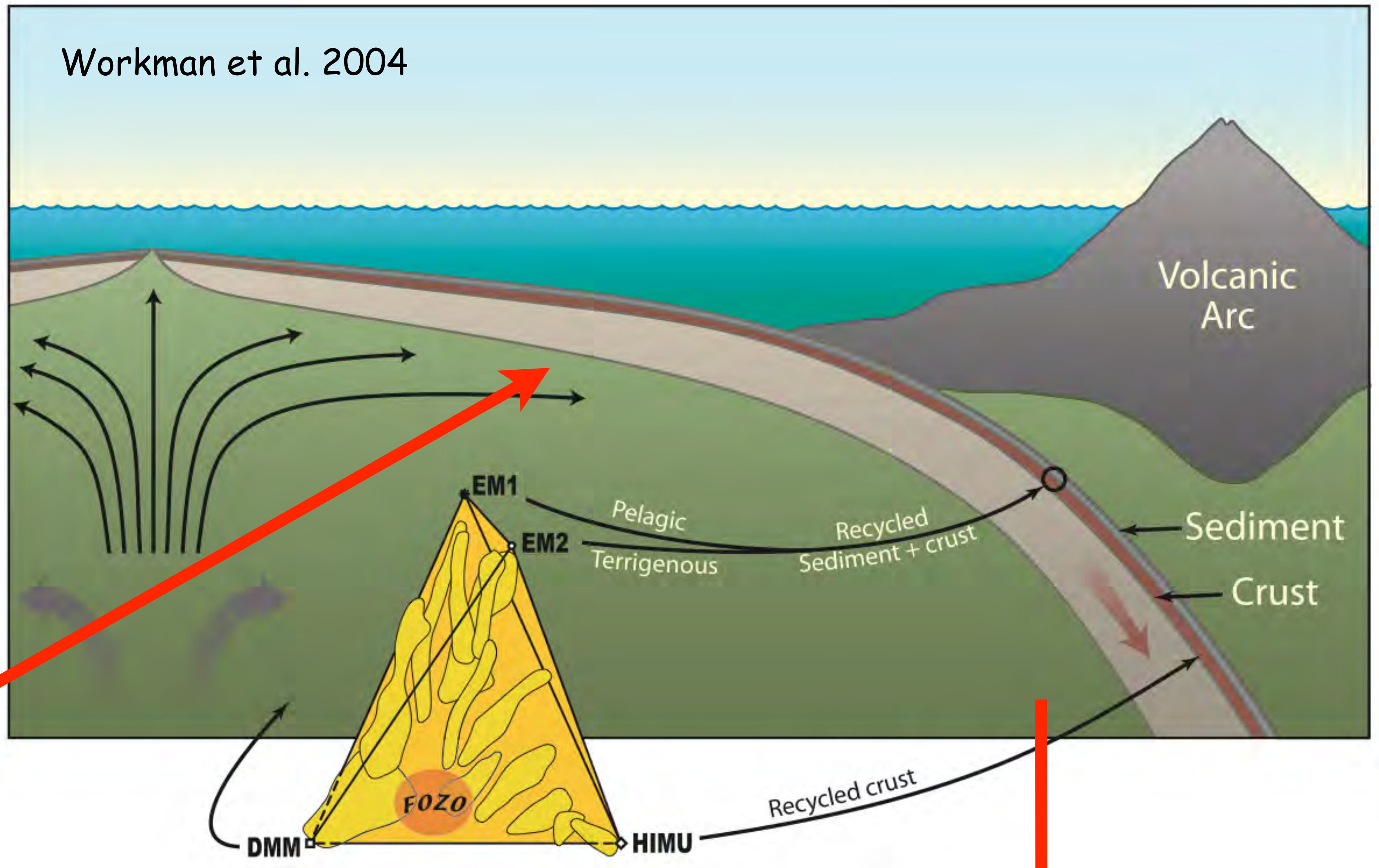
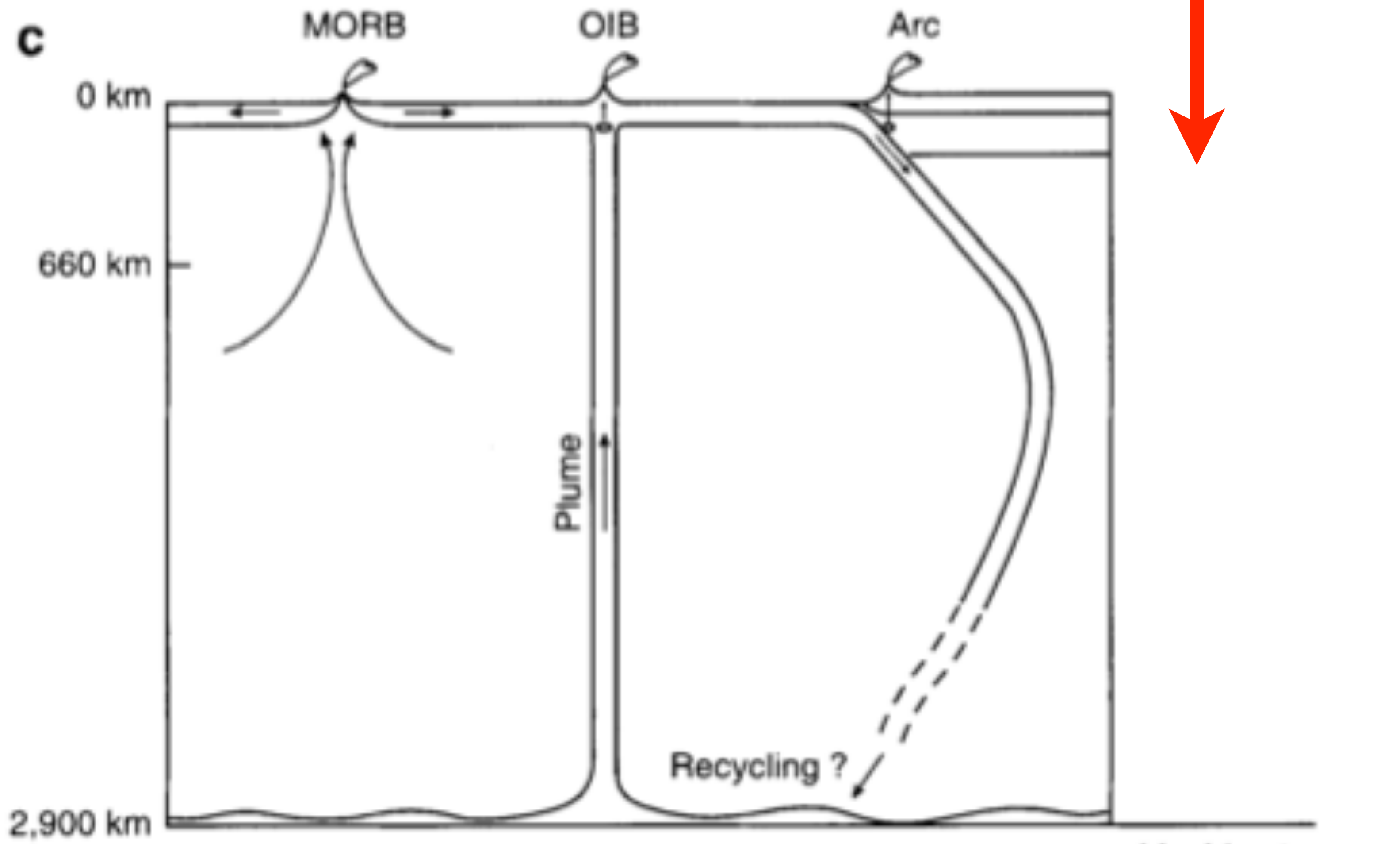


Albarède & Van der Hilst 2002





Hofmann 1997

Dynamic Models and Mantle Heterogeneity

Dynamic model of the mantle compositional heterogeneity after 4.65 Ga of mixing:

– Variable mixing of recycled and primordial materials

– Most of the mantle is depleted in composition, i.e. has been partially melted