Internal structure of Earth

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- Big Unknowns:
  - Composition of the silicate Earth (Mg, Si, Fe, O)
    - Amount of recycled basalt in the mantle
      - In the Transition Zone?
      - In the deep mantle
  - Mineralogy of the Lower mantle
    - Mode % ferropericlase (sets the Mg/Si)
    - Mode % Ca-perovskite (sets amount of Th & U in Earth)
  - Amount of H_2O in the Mantle and H in the Core
  - geothermal (*viscosity*) gradient Mantle and Core
  - Composition of the Core (plus ?? H, C, O, Si, S, ..)
  - Radioactive power in the Mantle and Core

Talk outline

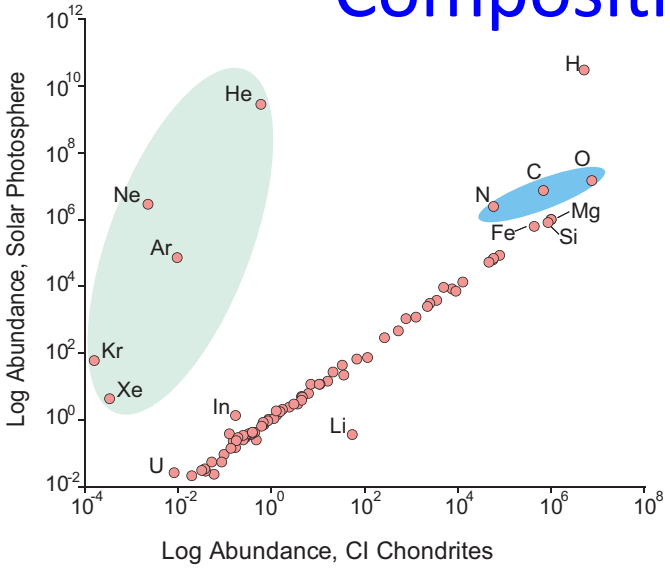
- Core-Mantle-Crust: physical and chemical description
- Earth's thermal story: starting & current condition
- Core: what we know -vs- light element composition
- Mantle: structures, dynamics, water, composition
- Crust: age differences, Moho heat flux, deep lithosphere
- Geoneutrinos & outstanding issues: …

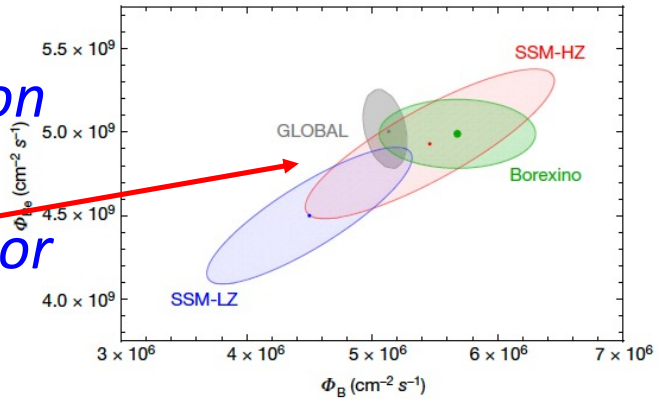
Sun-Earth-Solar system

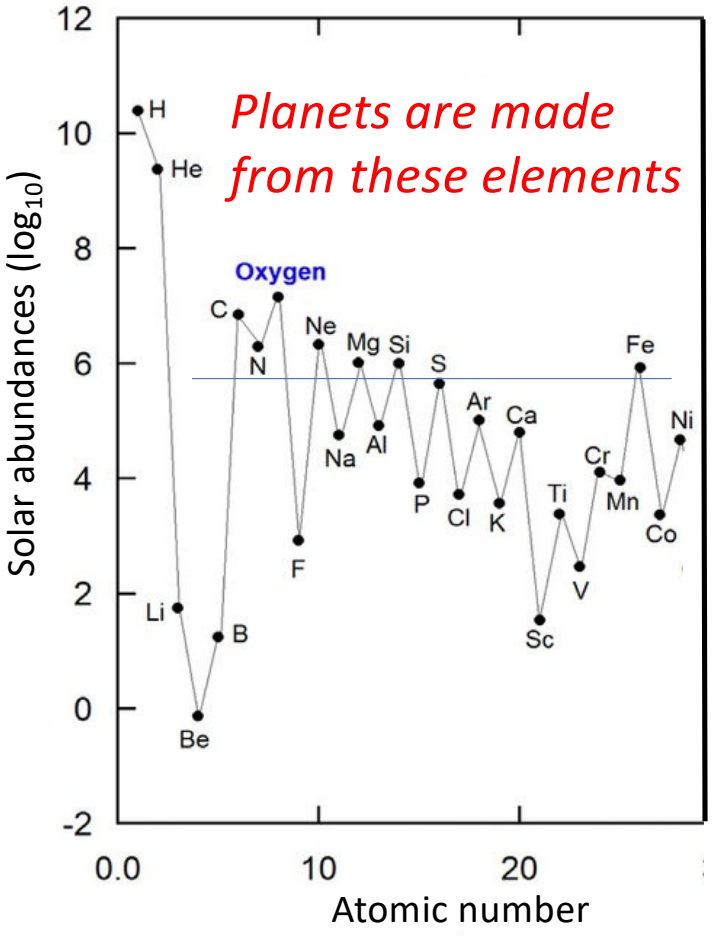
Composition of the sun

Solar composition: a reference frame for the terrestrial planets

Photosphere composition versus ν_e flux from Sun's Interior



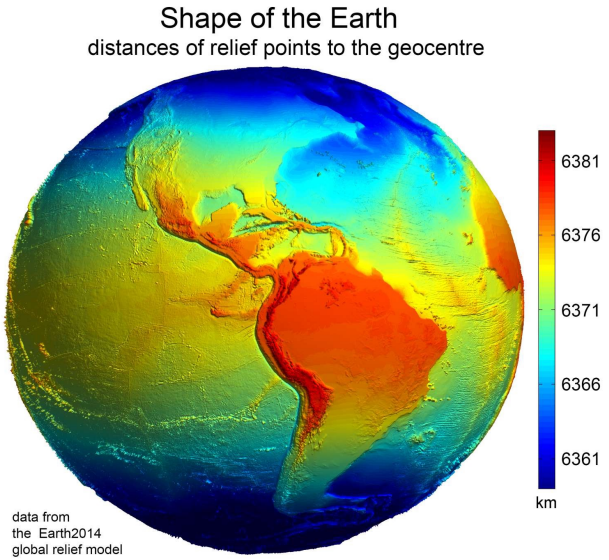




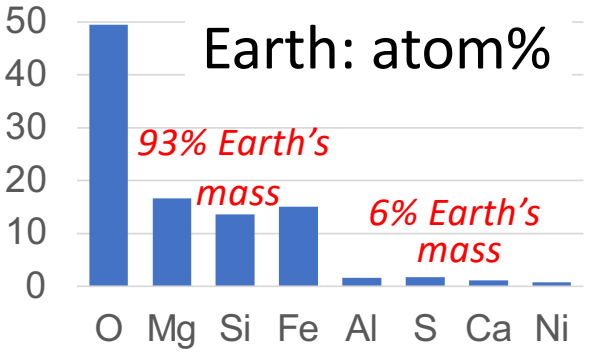
Core-Mantle-Crust

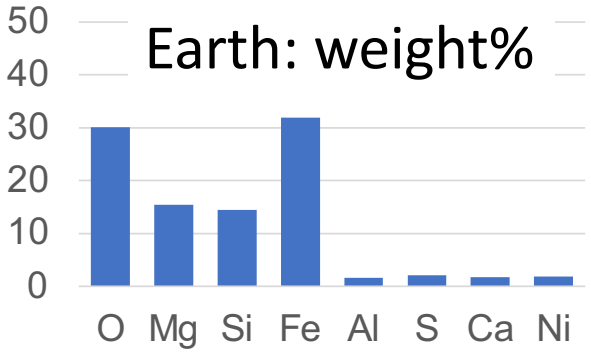
Earth: some attributes

Axis rotation (tilted 23.4°):	500 m/s
Solar orbit (inclination 7.2°):	30,000 m/s
moment of inertia factor:	0.3307
Mass:	5.972×10^{24} kg
Mean density:	5,514 kg/m^3
Mean radius	6371,000 m
Equatorial radius	6378,100 m
Polar radius	6356,800 m



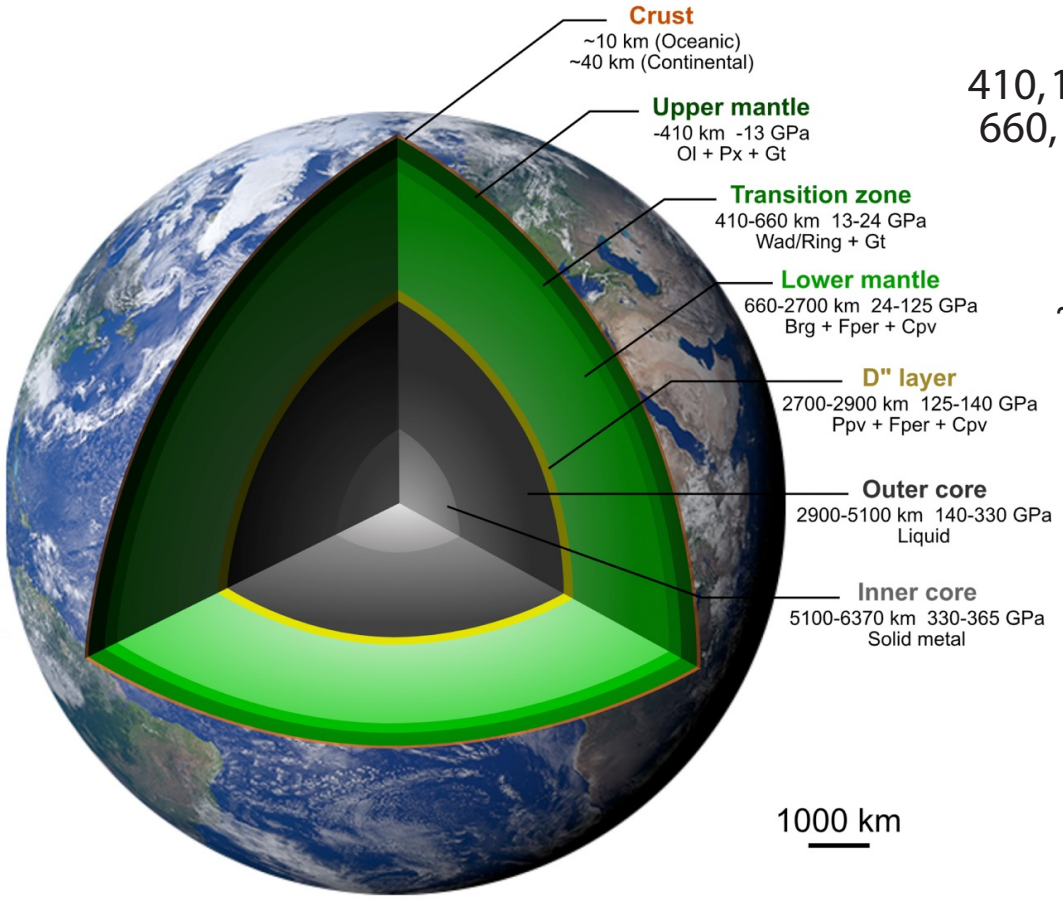
One out of every two atoms in Earth is oxygen



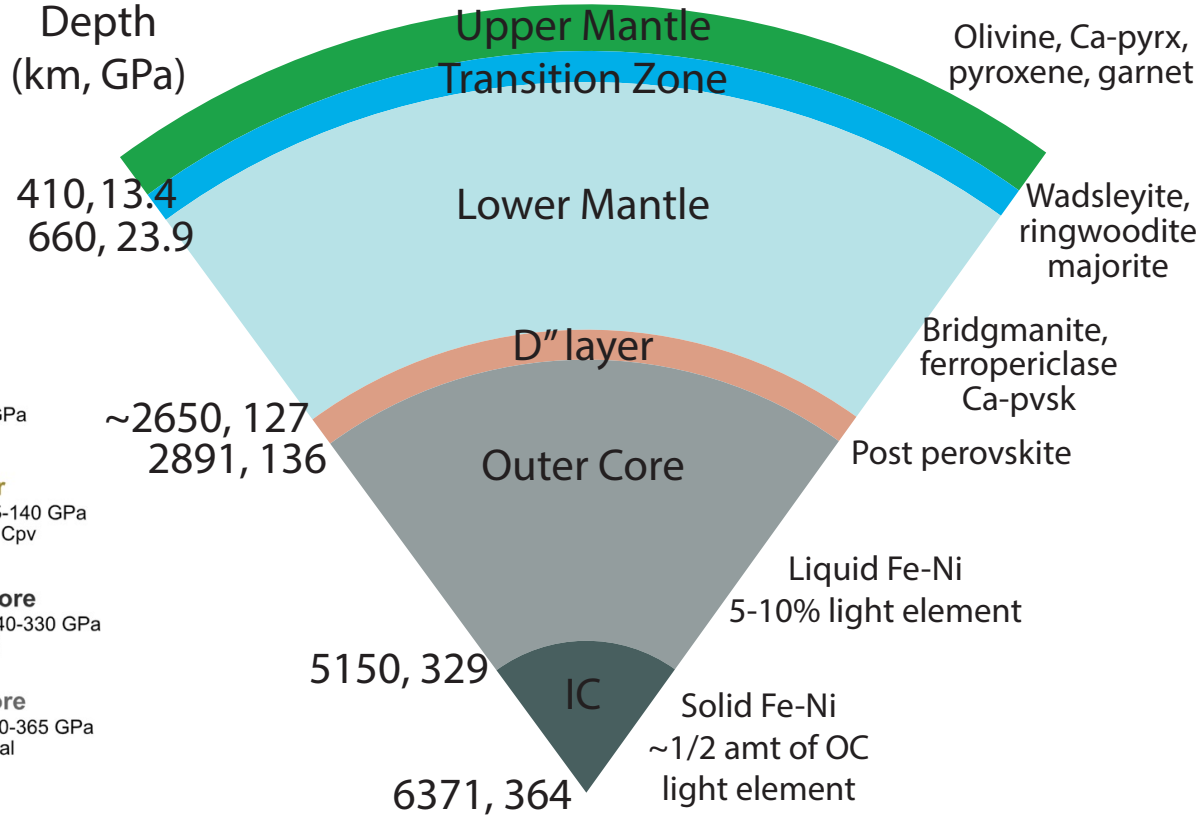


8 elements describe 99% Earth's mass

Core-Mantle-Crust



Mineralogy



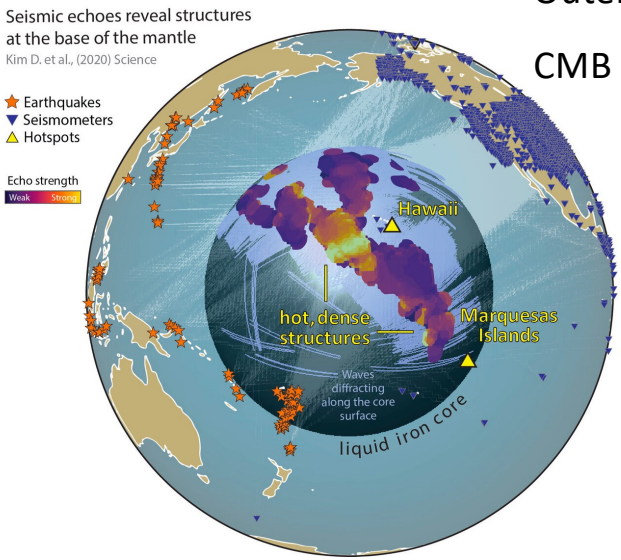
Earth: seismically defined

Core-Mantle-Crust

Radius (~Mars radius = 3390 km):	3483 ± 5 km
Inner core radius (Moon = 1740 km):	1220 ± 10 km
Mass (not well known):	1.93 x 10^{24} kg
Outer core mean density:	11,160 ± 60 kg/m^3
Inner core mean density:	13,070 ± 260 kg/m^3
Ellipticity @ CMB (ε_{CMB})	2.5 x 10^{-3}
Outer core surface topography	<3 km
CMB heat flux	60-110 mW/m^2, 13 ± 3 TW

Earth's core

Lots of structures on the CMB!



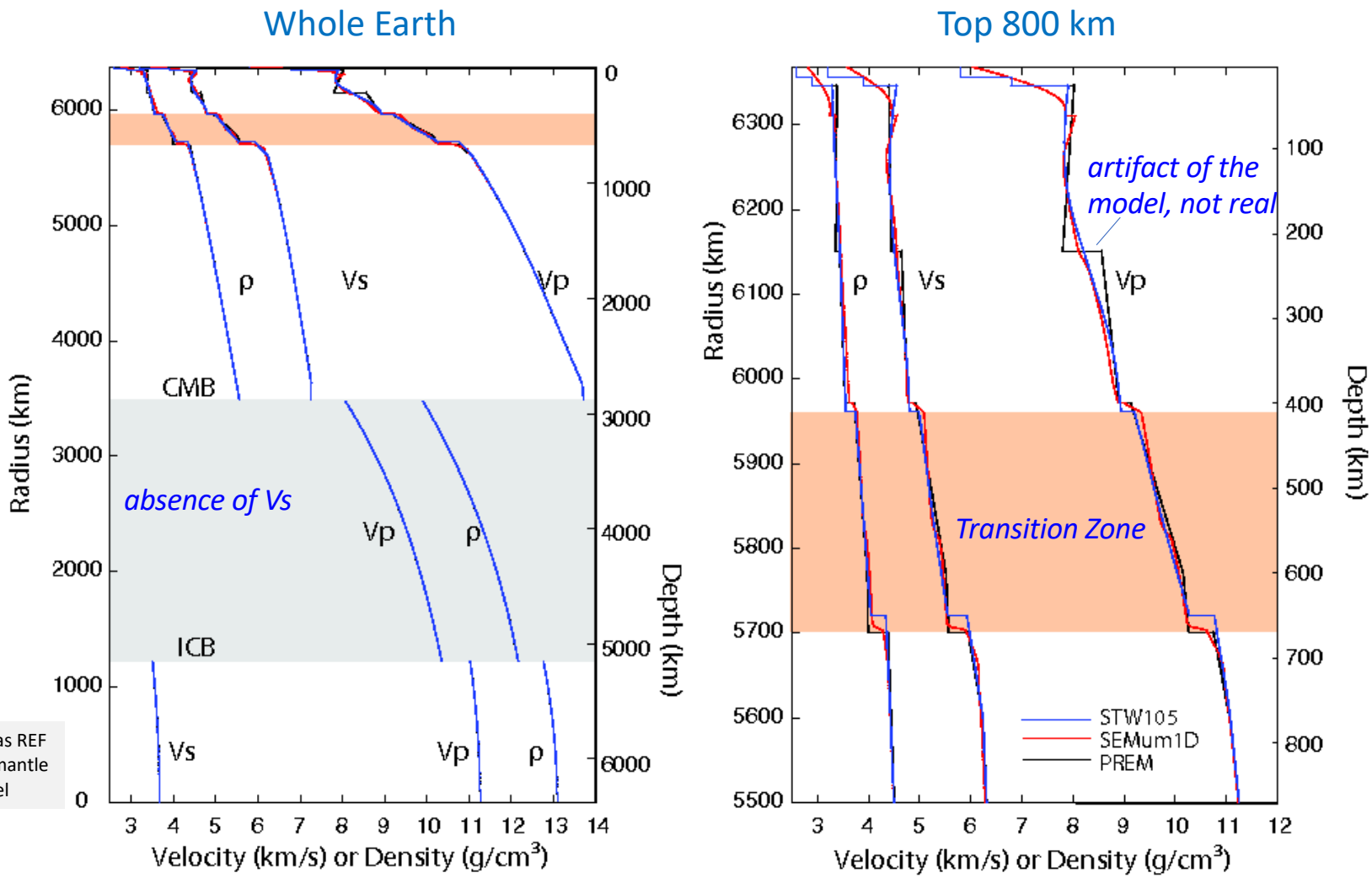
Seismic waves image Earth's structure

"Biased" core compositional perspective

	wt%	at %
Fe	85	80
O	1.0	3.3
Si	1.0	1.9
S	6.5	10.5
Ni	5.2	4.6
Co, Cr, P…	1.2	0.01

Core-Mantle-Crust

Seismic wave discontinuities define Earth's structure



STW105: Reference Earth Model also known as REF
SEMum1D: Spectral Element Method upper mantle
PREM: Preliminary Reference Earth Model

Core-Mantle-Crust

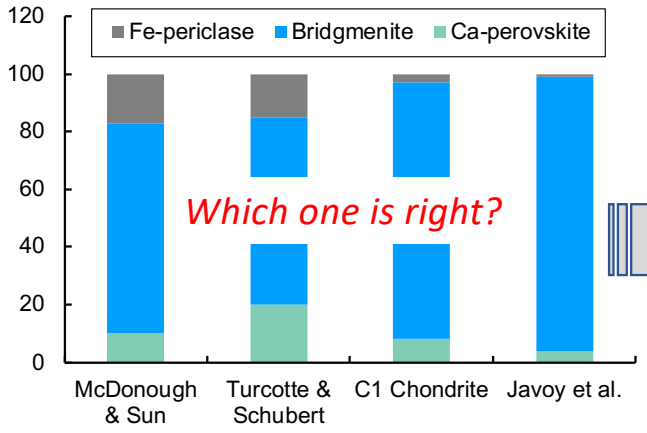
Seismic wave discontinuities are coincident with major phase changes

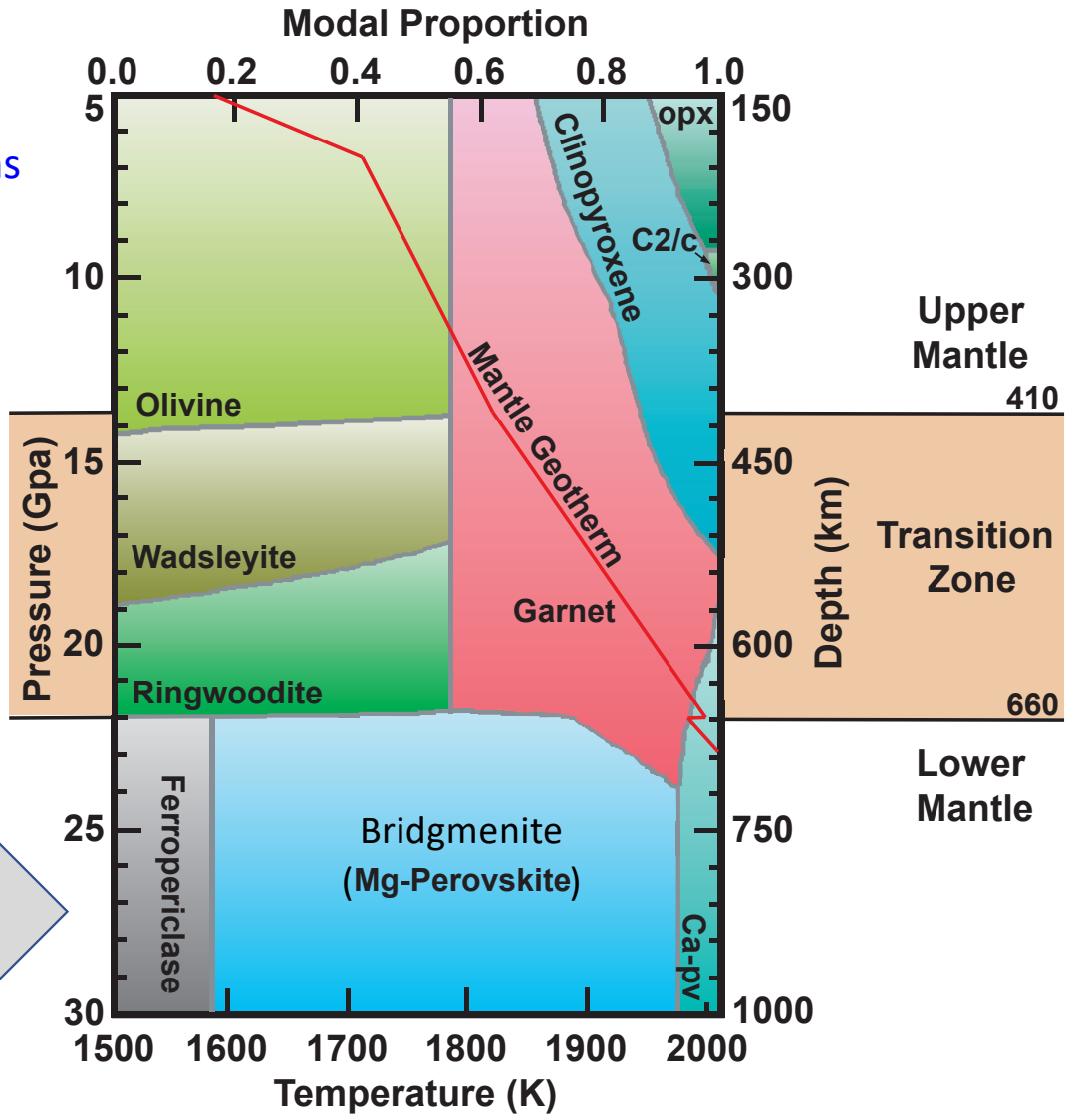
Mantle Phase Transitions

Assumptions:

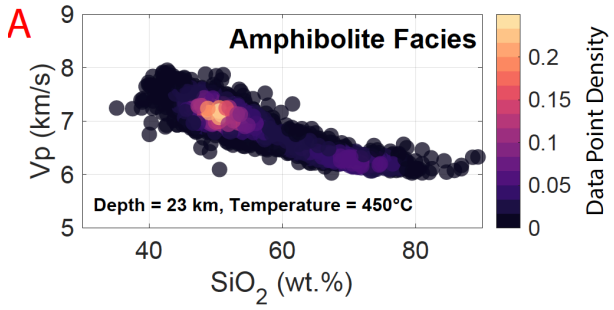
- Isochemical
- Pyrolite model
- Mg# = 89.0
- Geotherm from *Katsura (2022)*

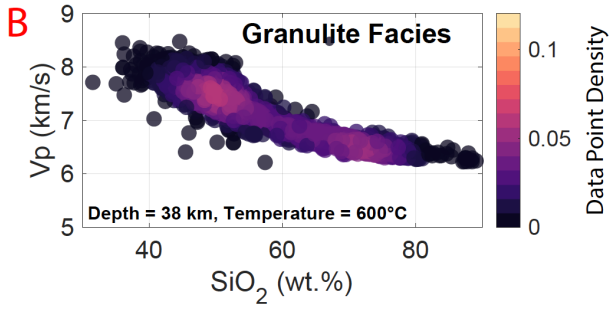
Mantle compositional models

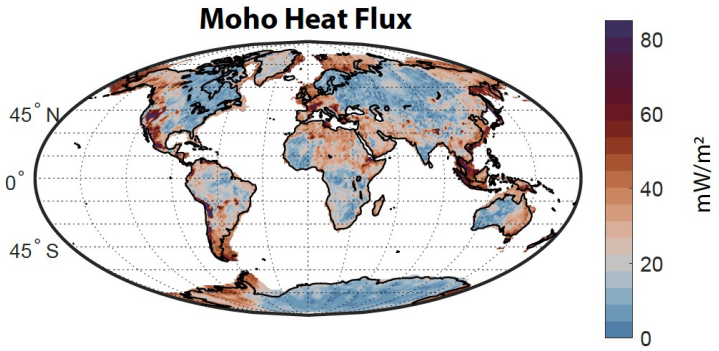


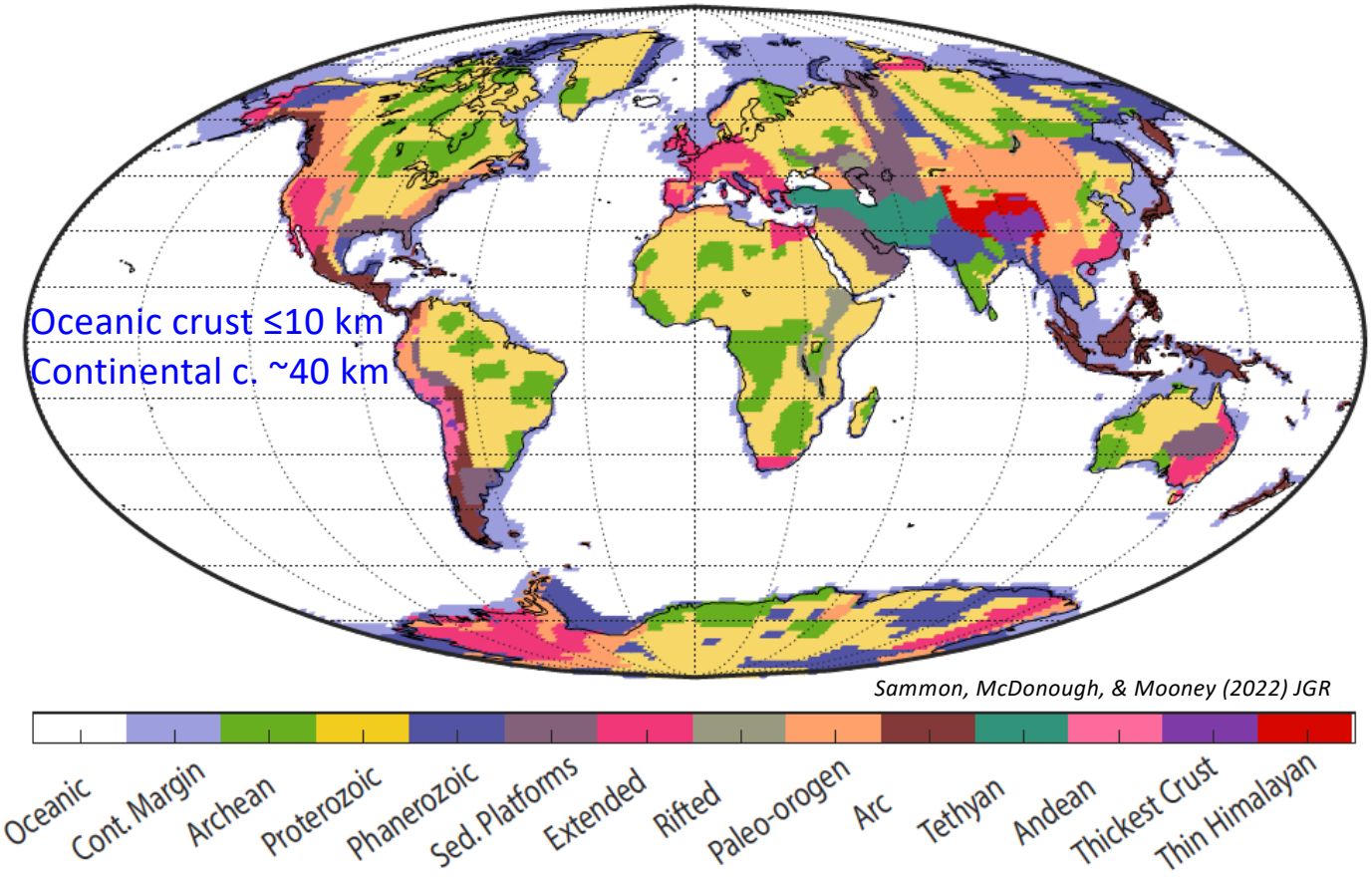


Core-Mantle-Crust



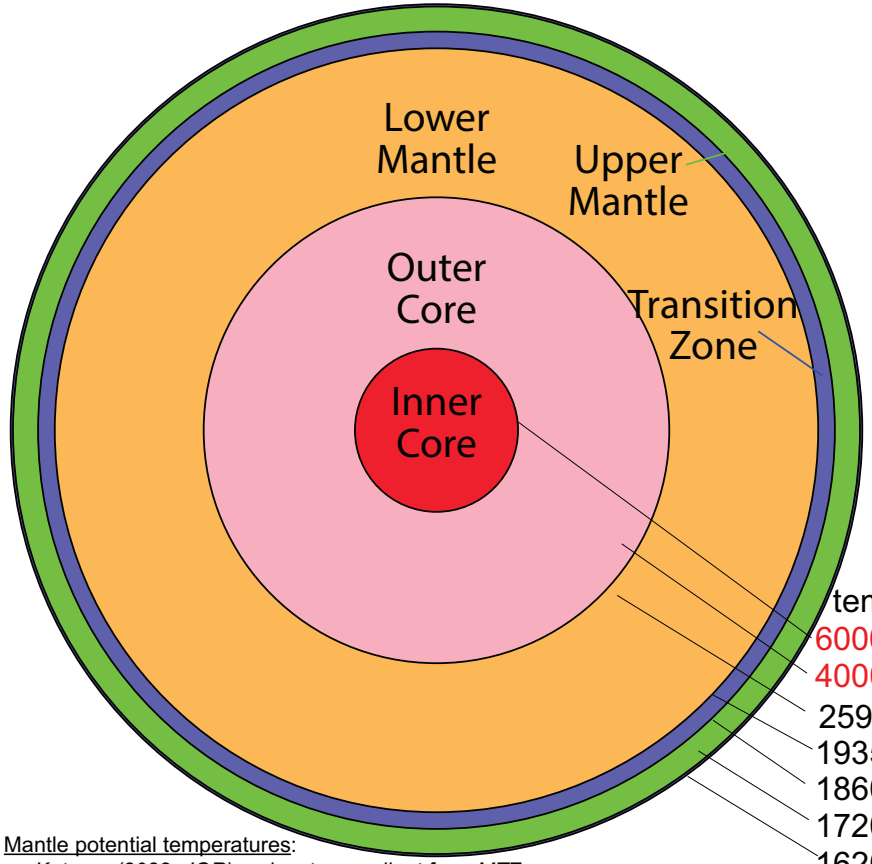






The top of the Earth is demonstrably heterogeneous.
So too, this might be the case for the bottom of the mantle.

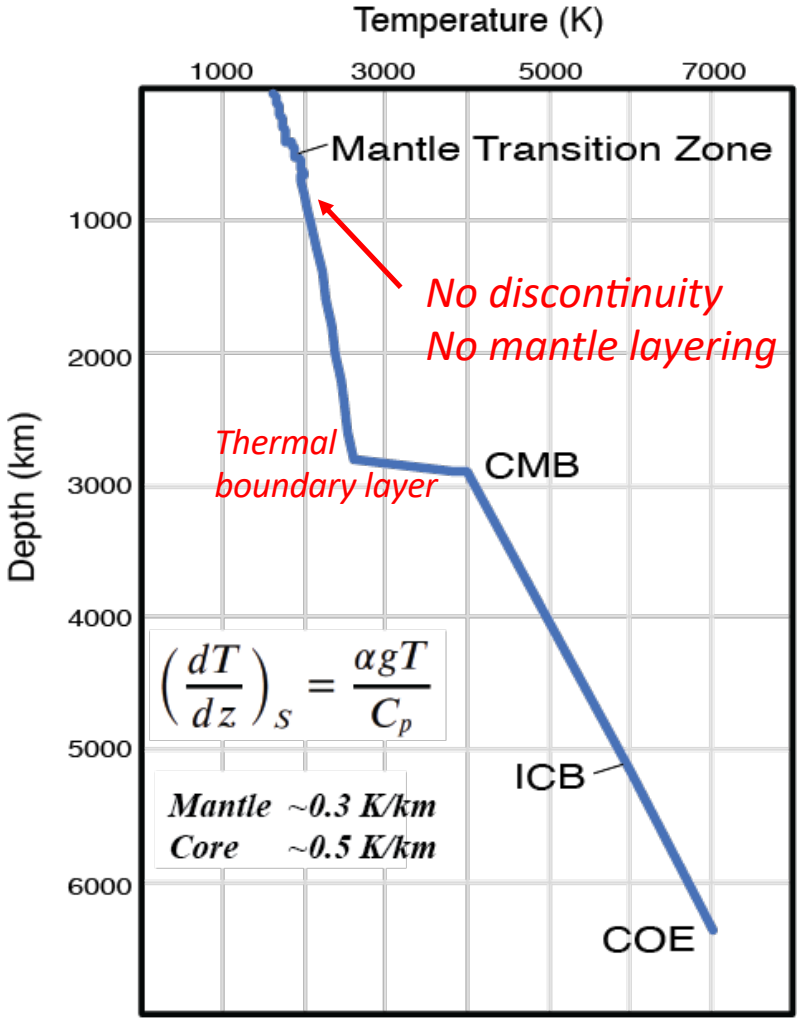
Earth's thermal story



temperature	depth
6000±1000 K	5150 km
4000 ± 500 K	3000 km
2590 ± 60 K	2800 km
1935 ± 40 K	660 km
1860 ± 40 K	410 km
1720 ± 40 K†	200 km
1620 ± 40 K*	0 km

*mantle potential temperature
†200 km depth temperature

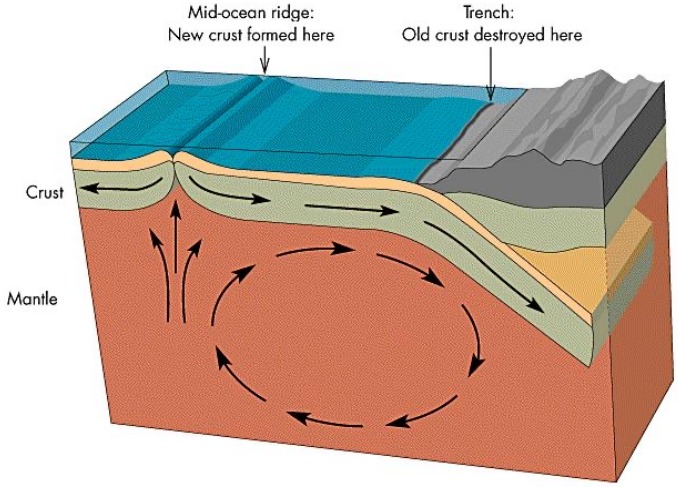
Mantle potential temperatures:
Katsura (2022, JGR), calcuates gradient from MTZ
Mantle temperatures: *assumes ~0.35 K/km from 410 km depth*
Core temperatures: *Tsuchiya et al and Fischer (2016) AGU monograph*



How much fuel is left to drive Plate Tectonics?

Current surface heat flux

46 ± 3 TW



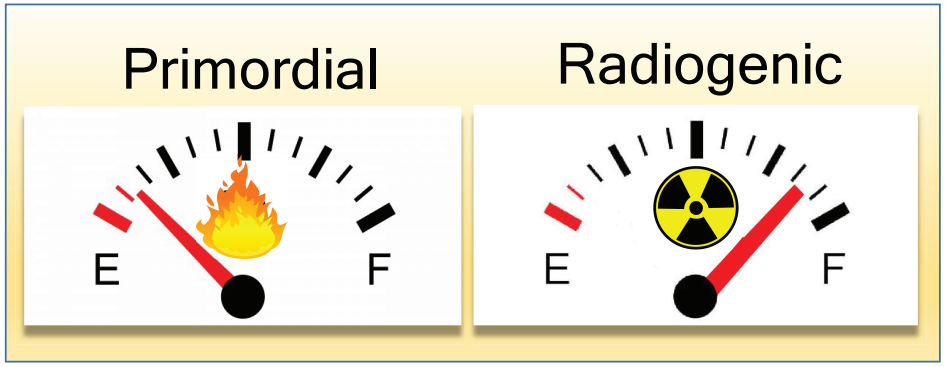
Initial conditions

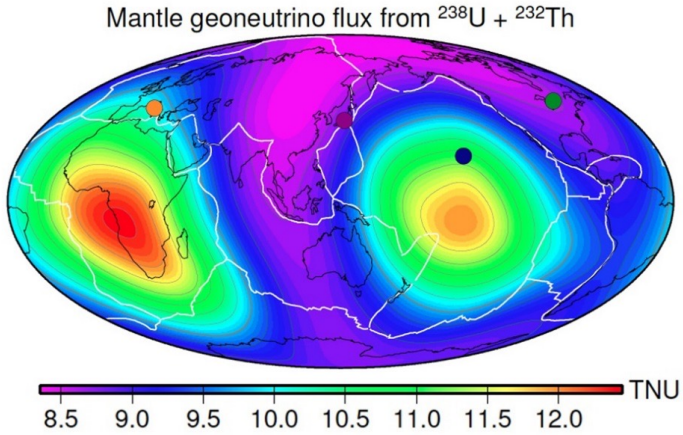
Accretion + core formation

$\sim 10^{32}$ J

… perhaps

$\sim 10^{5}$ TW





Earth's thermal evolution during accretion

Model starting condition

Beware of assumptions

Big unknowns

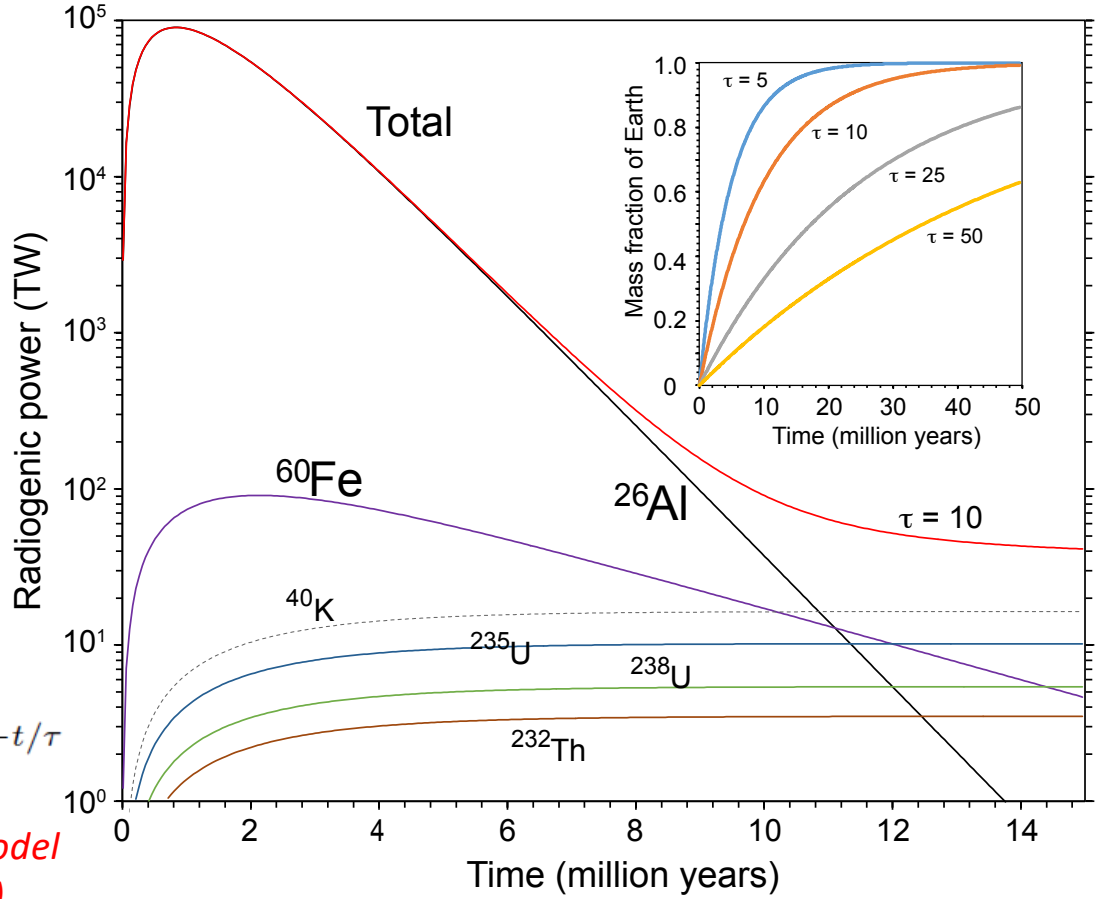
- Presences of atmosphere
- Earth's tau-age
- Moon formation age
- Age of core formation

$h = C_P \Delta T / \Delta t$

Earth's temperature ⬆ by ~3000 K (ΔT) in 1 myrs (Δt), Cp ~1kJ/kg s, h= 0.1 μW/kg

$$\frac{m}{M}(t) = 1 - \exp^{-t/\tau}$$

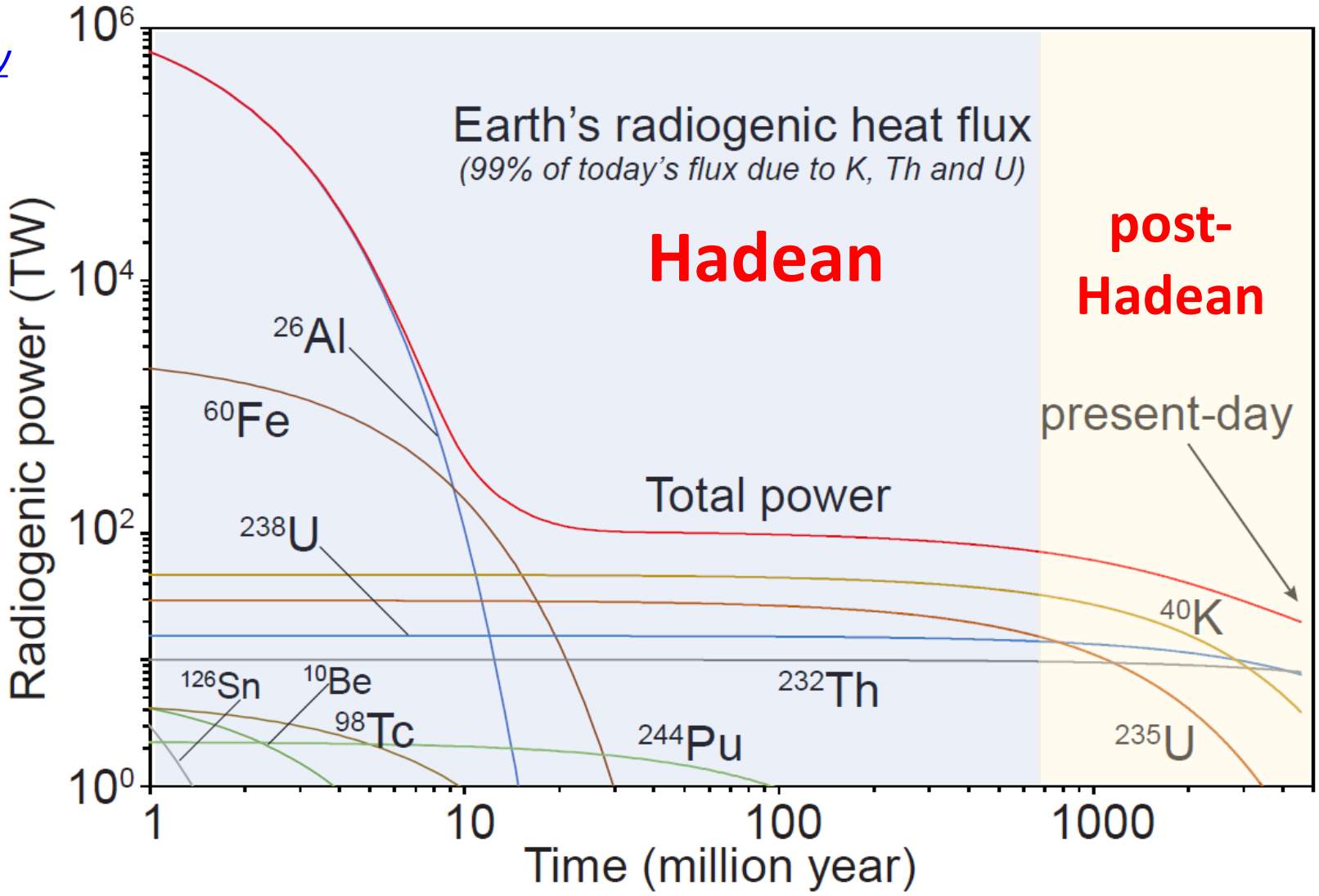
assumed growth model (Wetherill, 1980)



Earth's thermal story

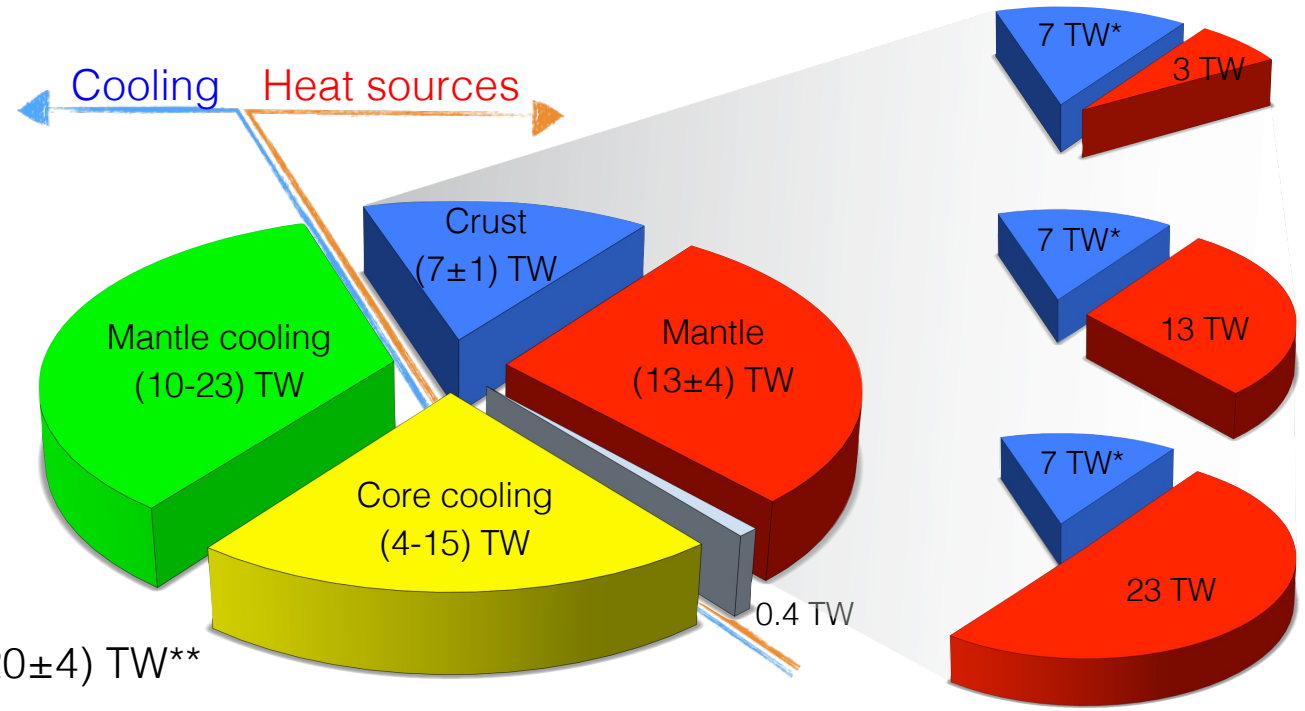
How fast does Earth lose heat?

Presence of an atmosphere is important



Earth's thermal story

Surface heat flow
(46±3) TW



BSE: (20±4) TW**

Bulk Silicate Earth (BSE) models:

- Low H ~10 TW
- Middle H ~20 TW
- High H ~30 TW

Silicate Earth … models vary by a factor of 3
Mantle … models vary by a factor of 20

*Sammon et al. (2022)
**McDonough & Sun (1995)

Core

Keep these words in mind

Remember, always,
the words of
Francis Birch (1952)

Unwary “readers” should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few examples of equivalents follow:

High-pressure form	Ordinary meaning
certain	dubious
undoubtedly	perhaps
positive proof	vague suggestion
unanswerable argument	trivial objection
pure iron	uncertain mixture of all the elements

Core

Understanding the core means understanding its formation

This metallic core has a radius of about 3,400 kilometers and an average density of about 10. It probably, from analogy with meteorites, contains a considerable amount, up to about 5 per cent or so, of phosphides (schreibersite, $(Fe,Ni)_3P$), carbides (cohenite, Fe_3C), sulphides (troilite, FeS), and carbon (diamond and graphite).

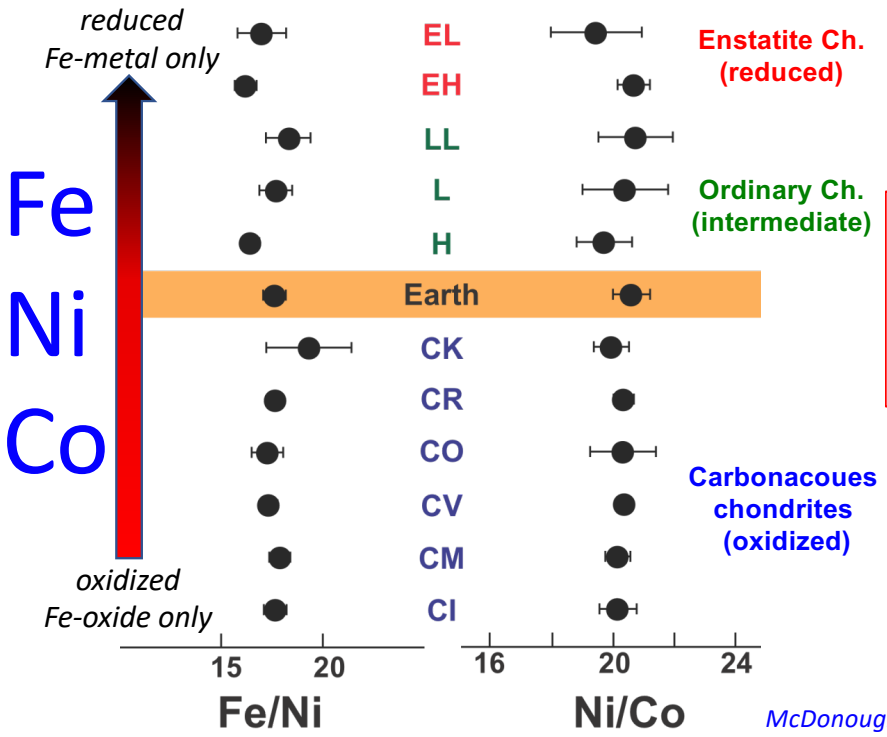
Washington 1925

"There is no reason to believe that the core is a particularly clean system" — D.J. Stevenson (1981)

"All discussions of the nature of the light element suffer from too few data and too many extrapolations" — R. Brett (1984)

Core

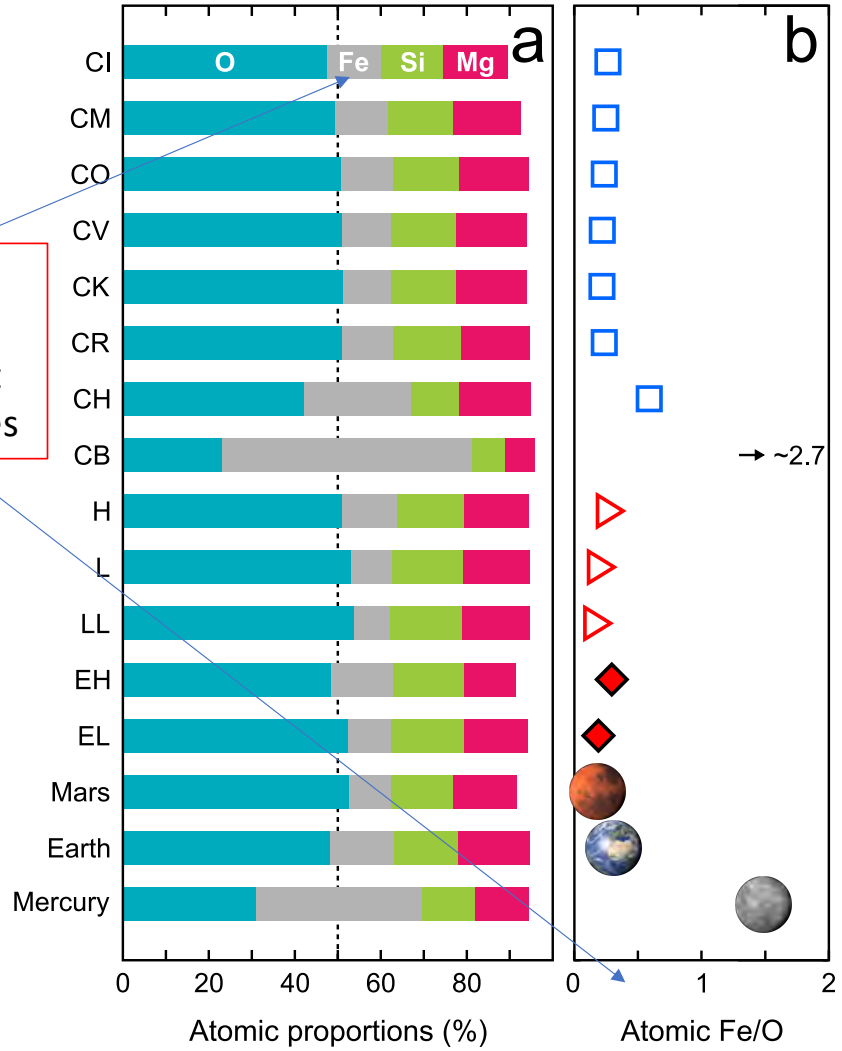
Constraints on core composition



McDonough (TOG, 2014)

Fe (wt%)	Fe/Ni	Ni/Co	
	17.5±0.4	20.4±0.4	avg. chondrite
6.3	32±3	19±2	BSE
32	17.5	20.4	bulk Earth
86	17	21	Core

Significant variations in iron content of chondrites



McDonough & Yoshizaki (PEPS, 2021)

Core

Excellent review:

Light elements in the Earth's core

NATURE REVIEWS | EARTH & ENVIRONMENT
2021

Kei Hirose[1,2] ✉, *Bernard Wood*[3] *and Lidunka Vočadlo*[4]

"… the likely range of compositions for the outer core (Fe + 5% Ni + **1.7% S** + 0–4.0% Si + 0.8–5.3% O + 0.2% C + **0–0.26% H** by weight)"

Kawaguchi etal (*including Kei Hirose*) (2022, American Mineralogist)

"Assuming that S is the only light element…. , we estimated a **5.3–6.6 wt% S** content in the Earth's outer core."

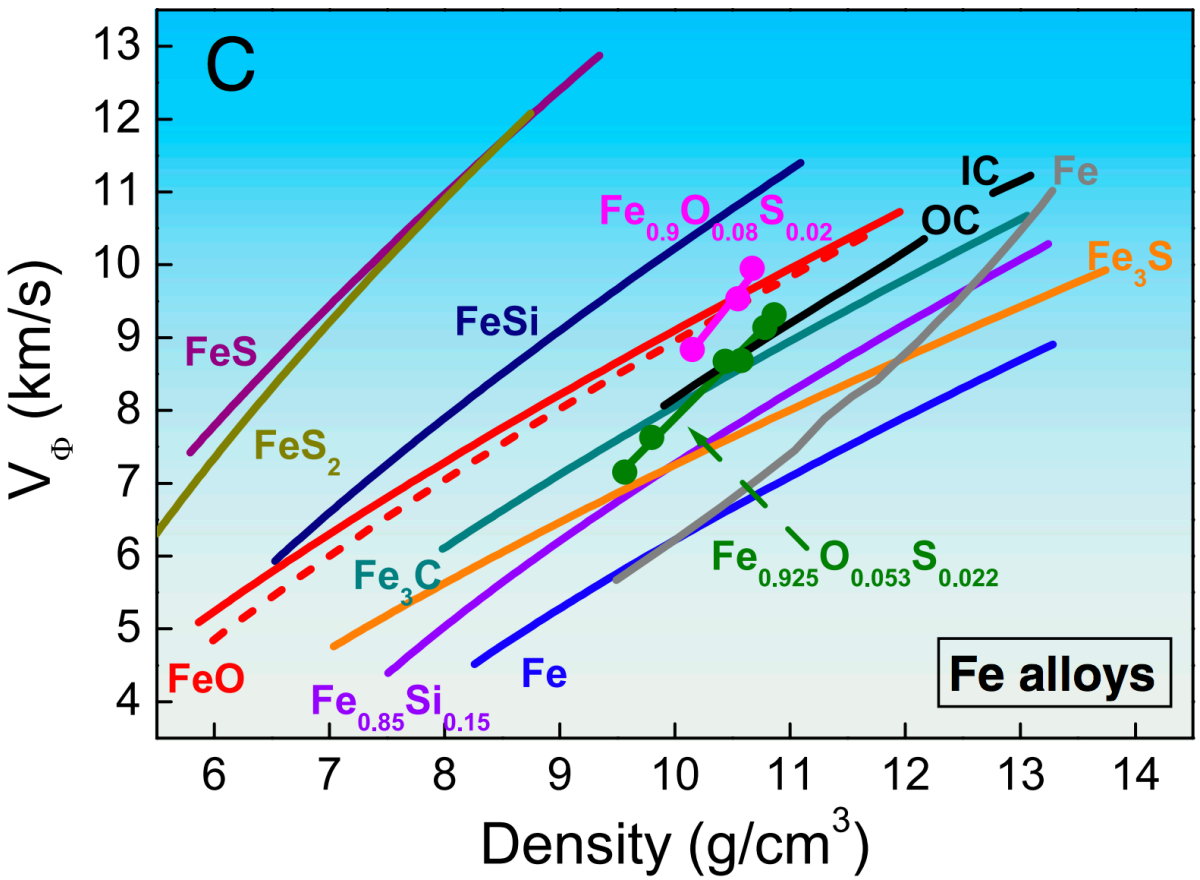
Tagawa et al (*including Kei Hirose*) (2021, Nature Communications)

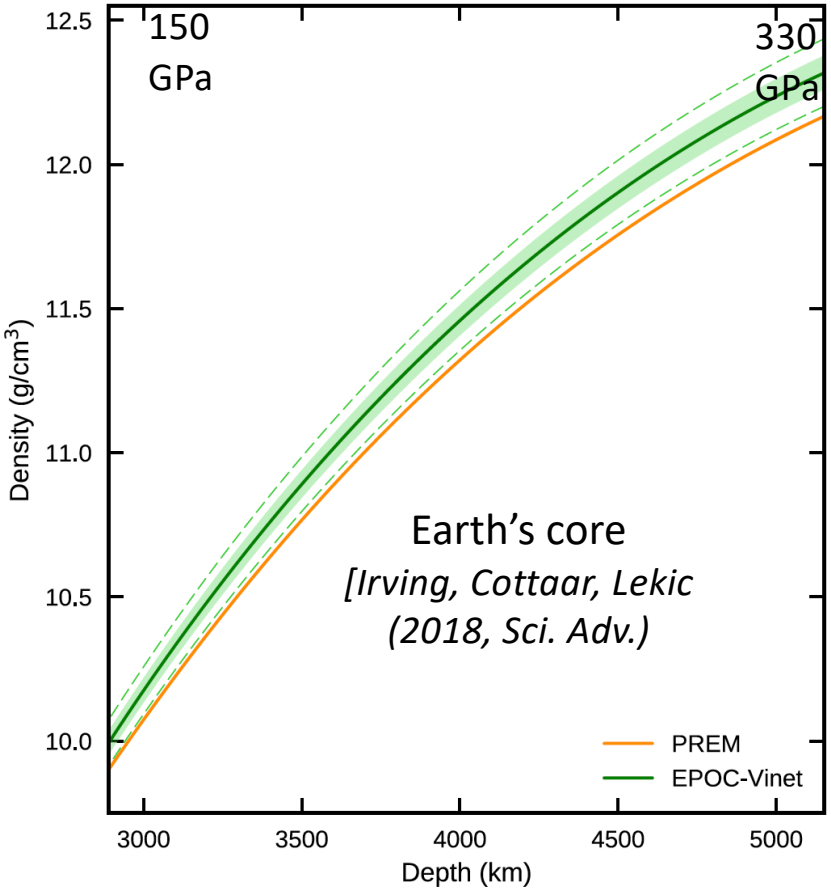
"… metal–silicate partitioning of hydrogen suggests **0.3–0.6 wt% H** was incorporated into the core, …"

Apologies to Kei Hirose…
2021-2022 publications

What light element works…

Core

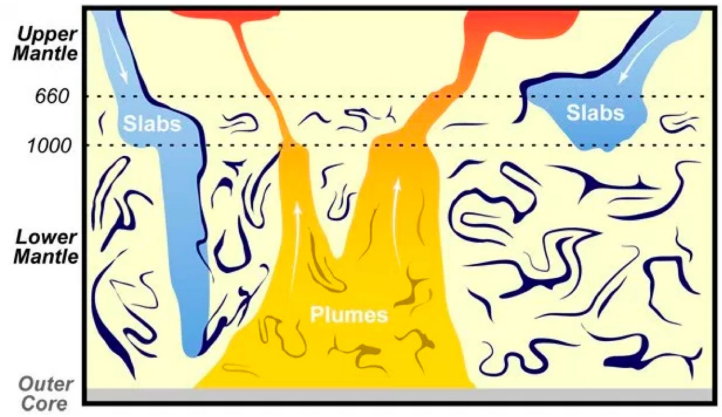


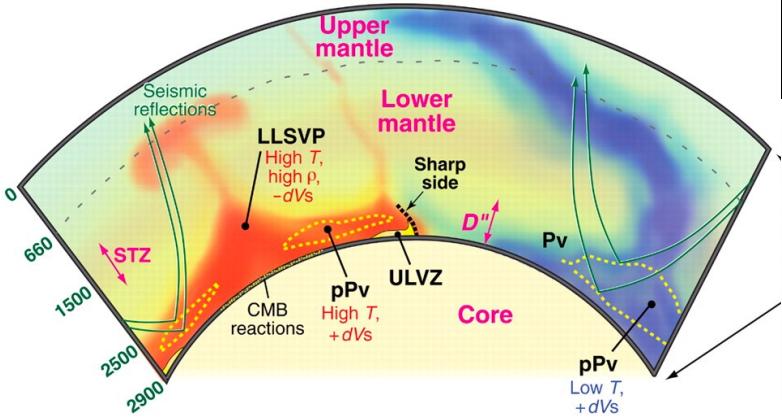


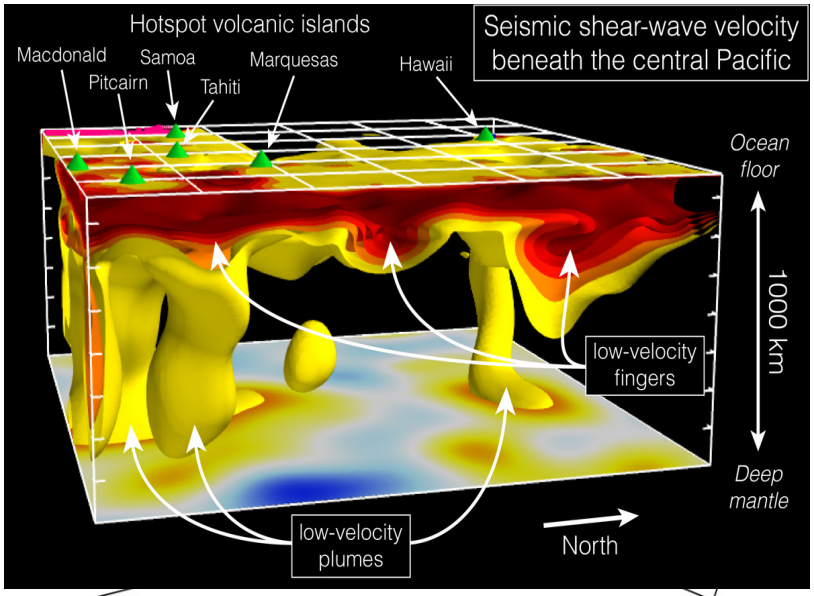
Sound velocities of Fe and Fe-Si alloy in the Earth's core
Mao et al. (2012, PNAS)

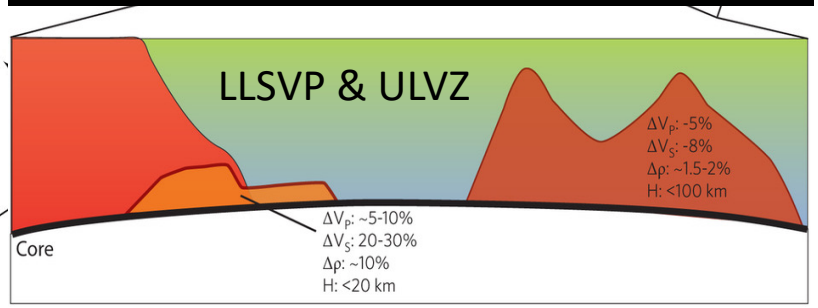
What is in the mantle?

Many structures and heterogeneities in the mantle





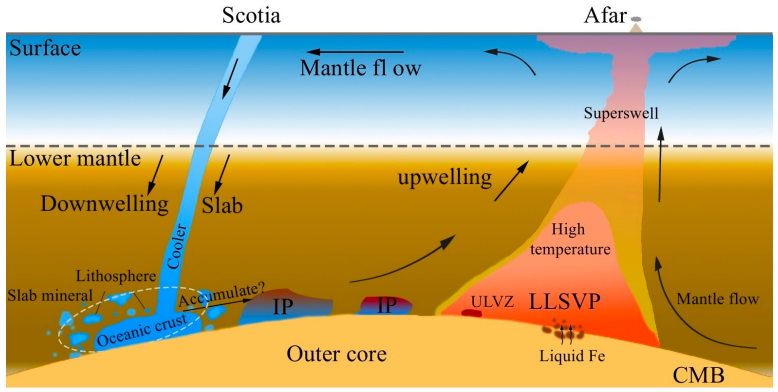


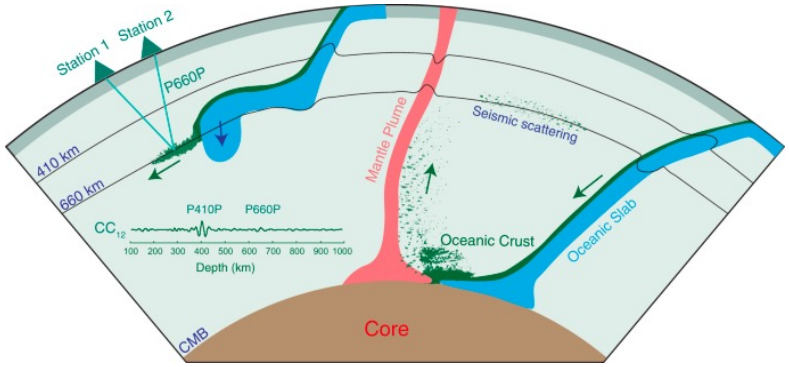


Mantle

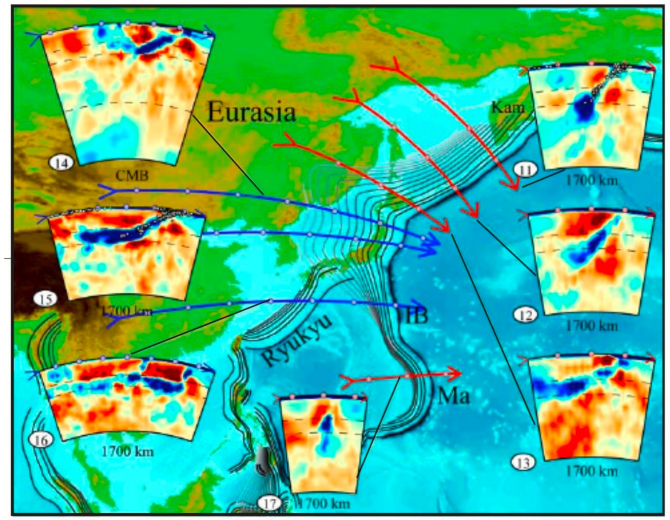
Oceanic lithosphere enters mantle via oceanic trenches

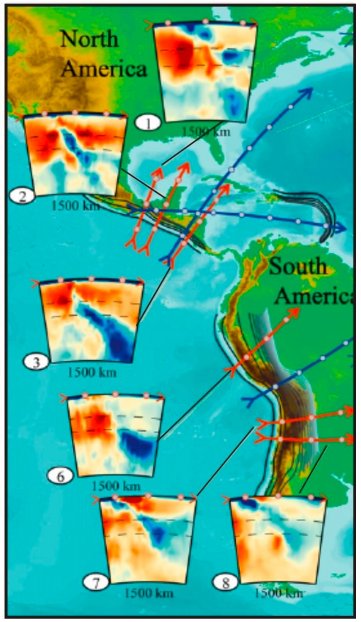
Seismic tomography versus interpretive cartoons

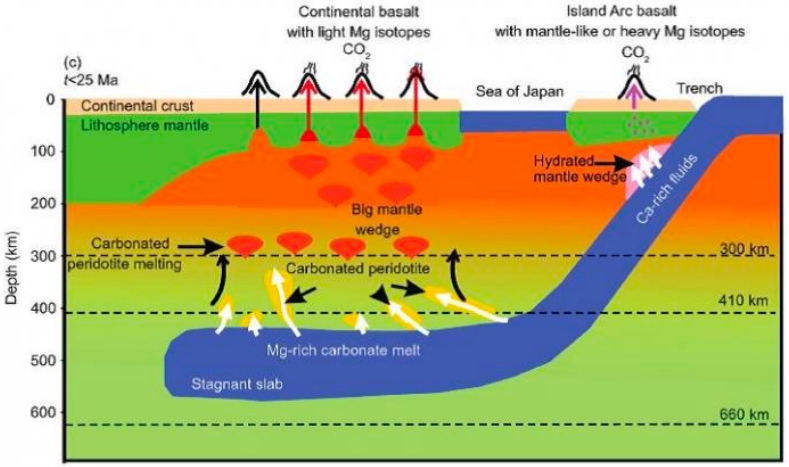




Feng et al (2021, Nat. Comm.)



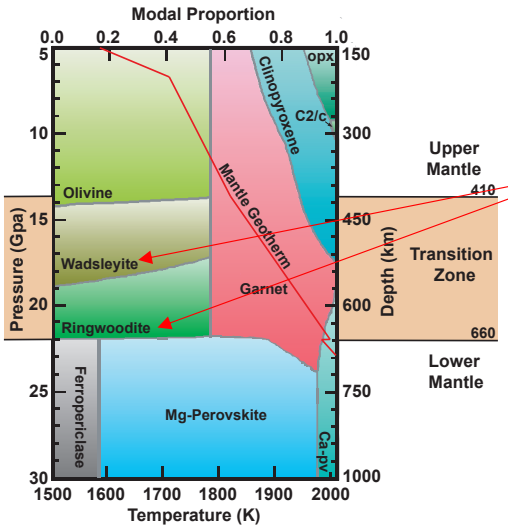




Mass exchange

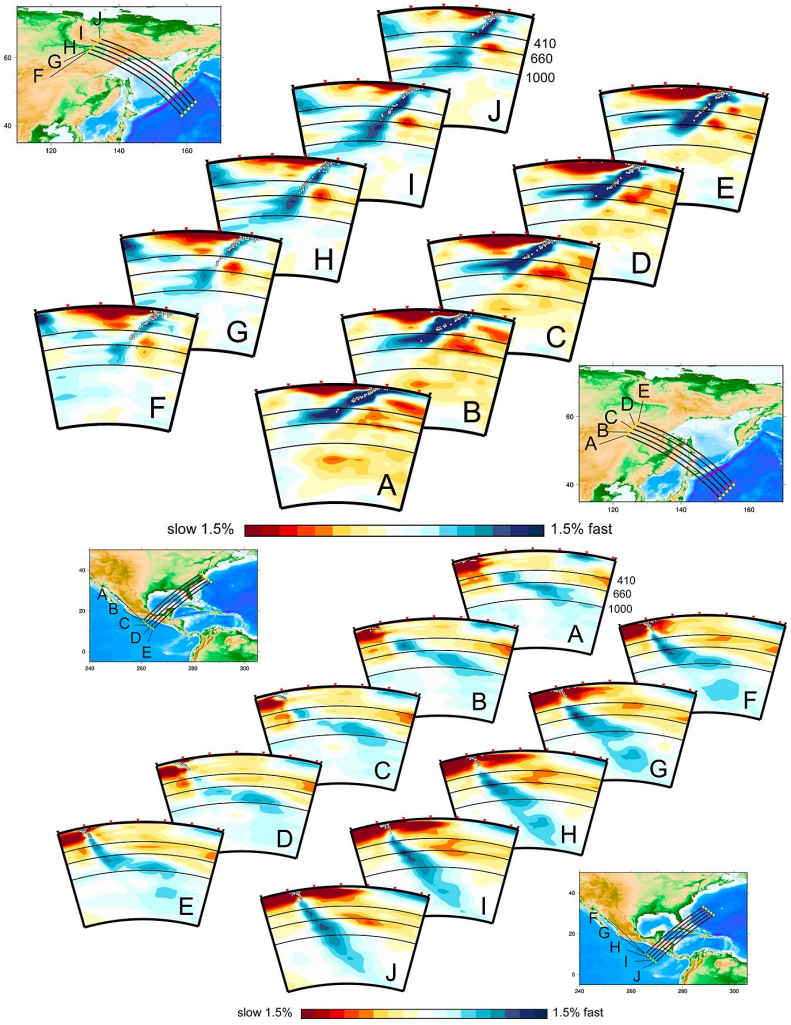
Volatile transport: CO_2, H_2O, NH_4

Oceanic lithosphere bends & stagnates @ 400 – 1000 km *and/or* subducts to the CMB



Transition zone minerals can store lots of water…

How much???

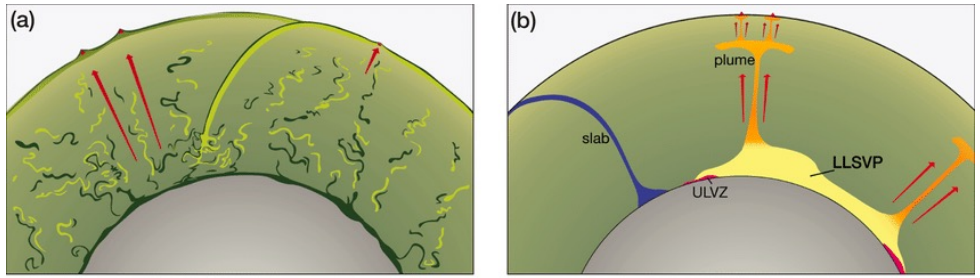


Fukao & Obayashi (2013) JGR_SE

Models remain uncertain.

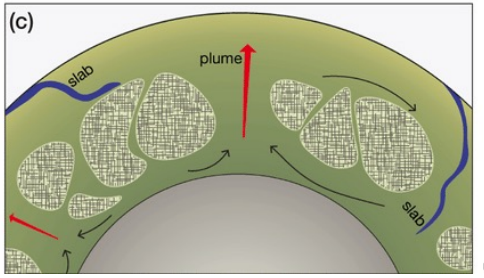
Anywhere from 1 to 10 oceans of water in mantle today

Mantle

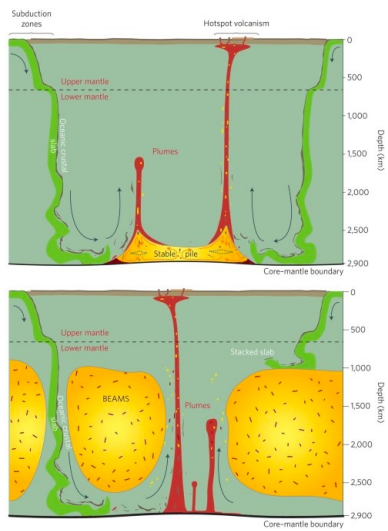


Primordial structures in the mantle?

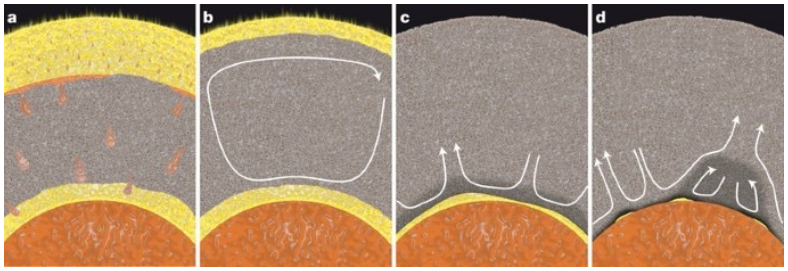
- Evidence for early differentiation
- Compositional distinction between Upper and Lower mantle



Gülcher et al (2021, Solid Earth)



Balmer et al (2018, Nat. Geo)



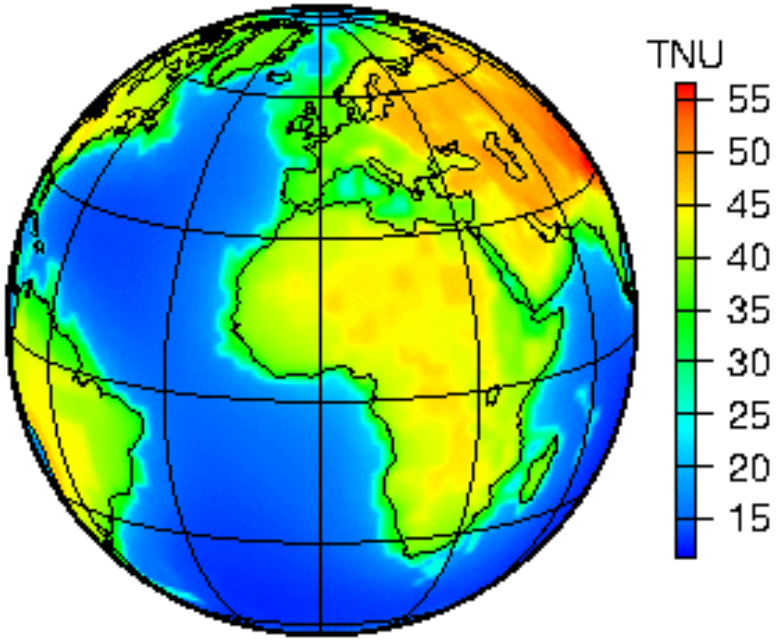
Labrosse et al (2007, Nature)

Evidence???

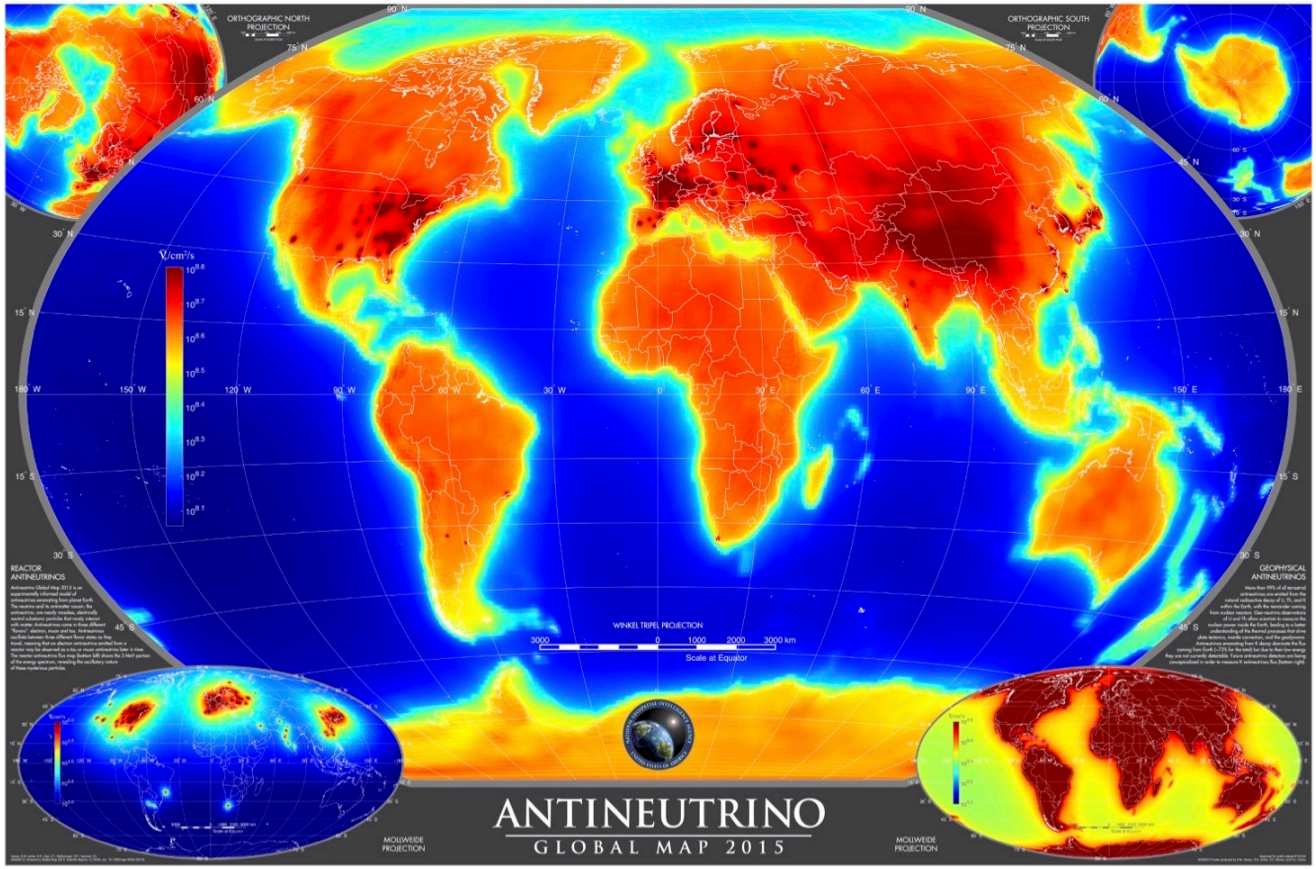
Chemical and isotopic evidence is absent. I remain unconvinced!

Crust

Geoneutrinos: a success story (mostly)



Antineutrino Map: geoneutrinos + reactor neutrinos

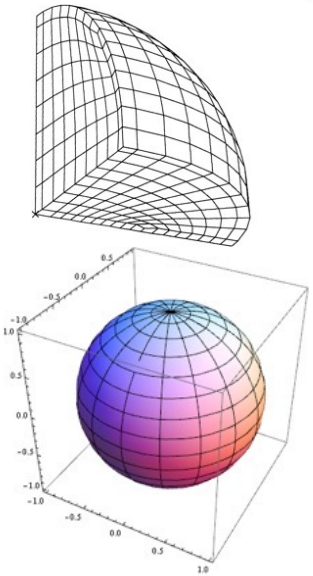


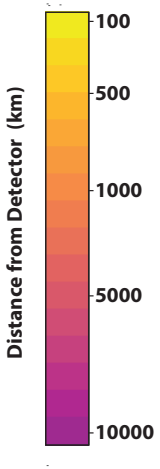
Crust

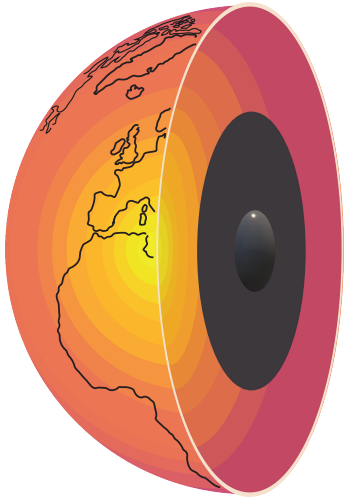
Predicting geoneutrino flux

Antineutrino flux spectrum $d\Phi/dE_\nu$ at position **r** from a given radionuclide distributed with abundance A in the Earth

$$\frac{\mathrm{d}\phi(\boldsymbol{r}, E_\nu)}{\mathrm{d}E_\nu} = D\frac{\mathrm{d}n(E_\nu)}{\mathrm{d}E_\nu}\iiint \frac{A(\boldsymbol{r}')\rho(\boldsymbol{r}')P_{ee}(E_\nu, |\boldsymbol{r}-\boldsymbol{r}'|)}{4\pi|\boldsymbol{r}-\boldsymbol{r}'|^2}\mathrm{d}^3\boldsymbol{r}'$$







Inputs from geoscience:

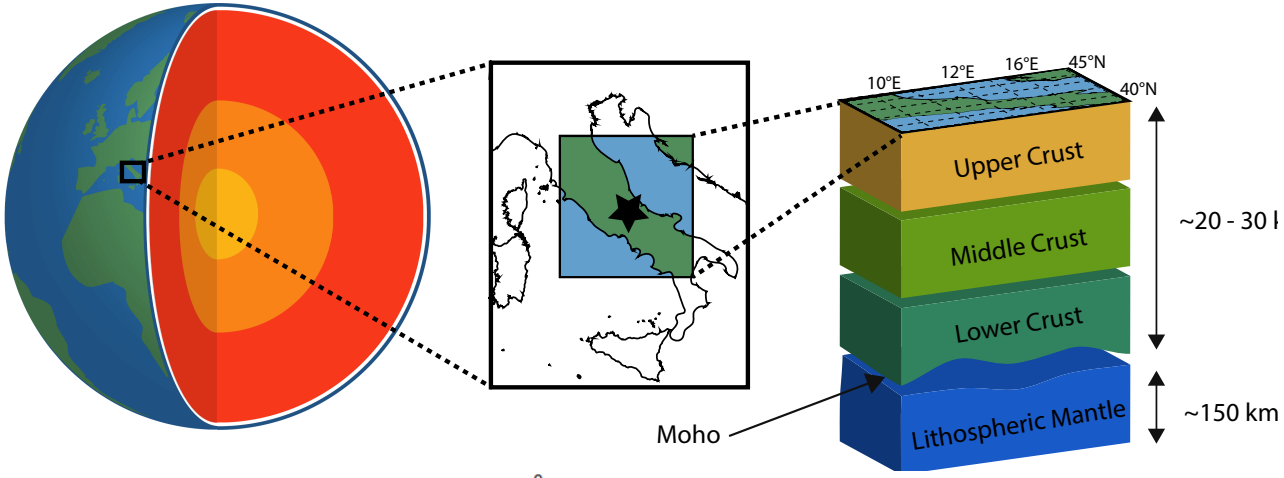
- chemical abundances A:
- density ρ

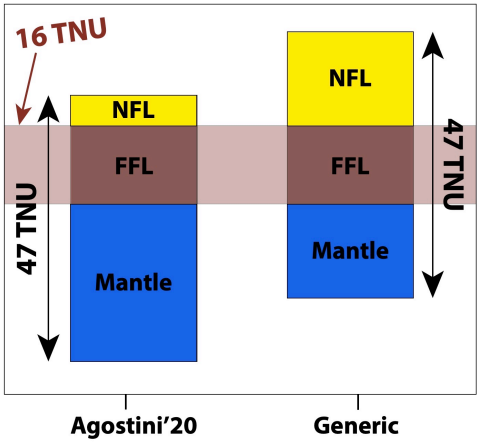
Inputs from nuclear/particle physics:

- decay rate D
- antineutrino intensity spectrum dn/dE_ν,
- antineutrino survival probability P_{ee}

Crust : Borexino

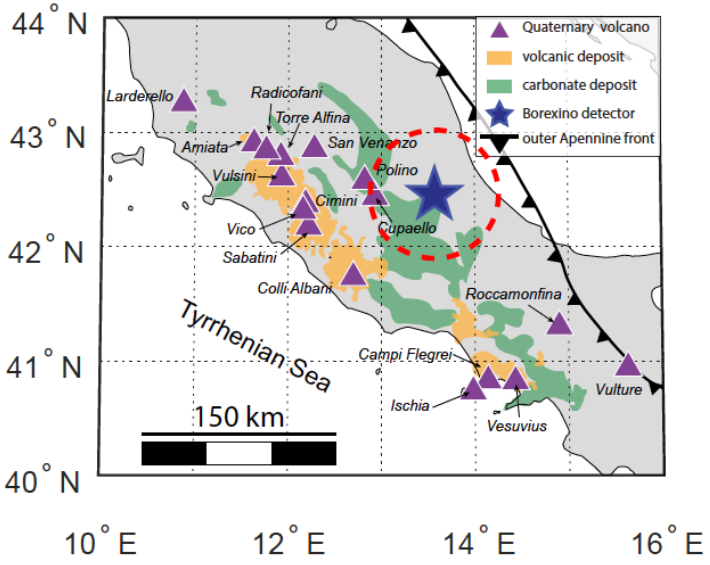
Agostini et al (2020, PRD) H_{earth} = 38 TW???

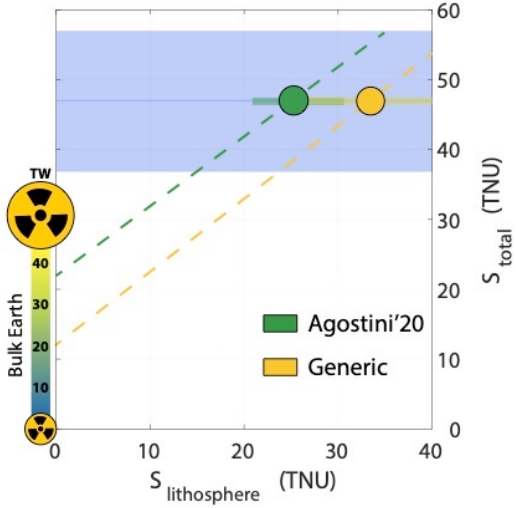




Why geologist should do geology and physicist do physics!

Sammon & McDonough (2022, EPSL) H_{earth} =20 TW



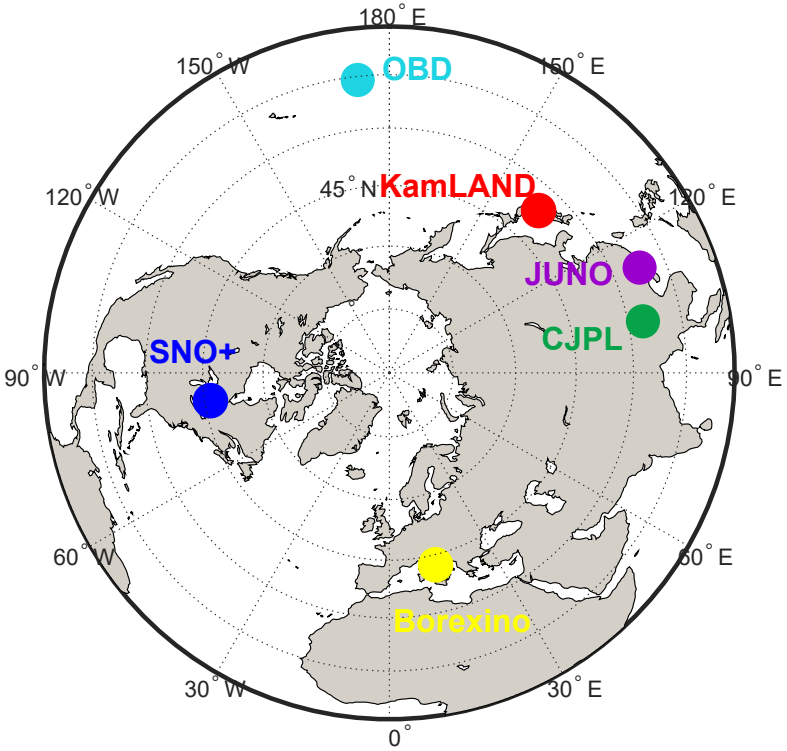


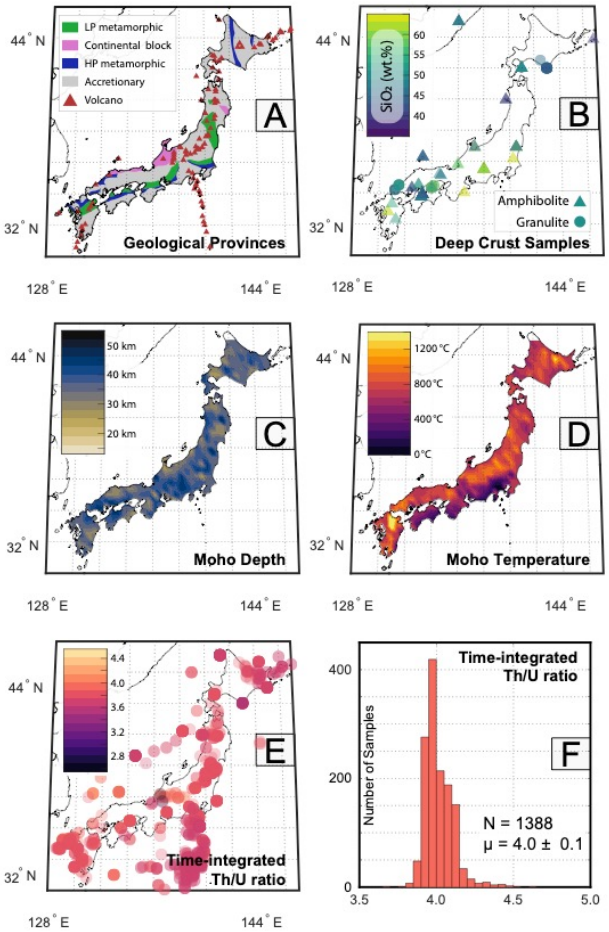
Sammon & McDonough (2022, EPSL)

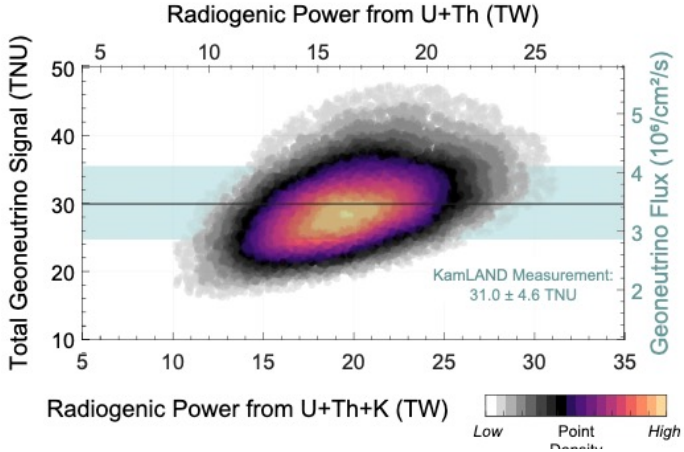
Crust: KamLAND

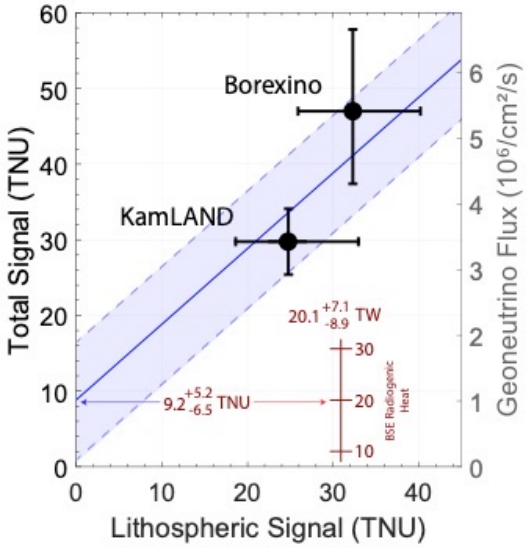
Abe et al (2022, GRL) H_{earth} = 15 TW

McDonough & Sammon (2022, review) H_{earth} =20 TW





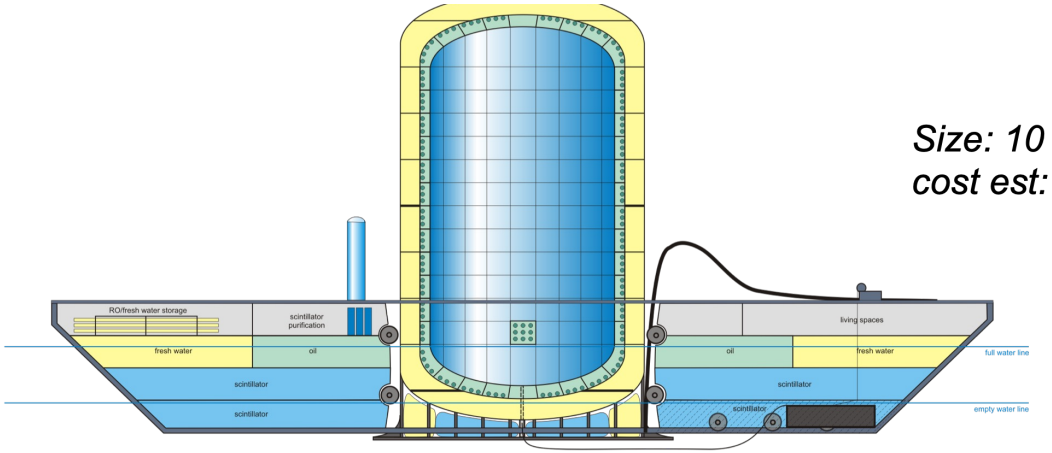




OBD

Ocean BottomDetector

An experiment with
Physics & Geology

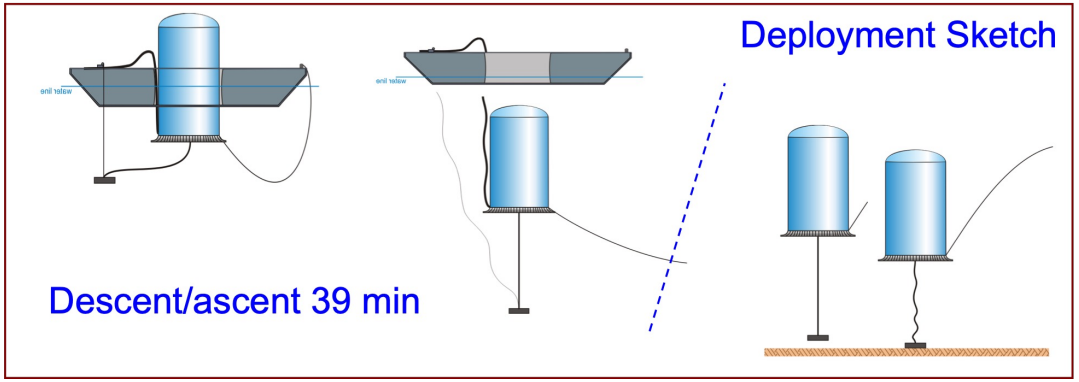


Size: 10 to 50 kT
cost est: $300M to $600M

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

A Deep Ocean

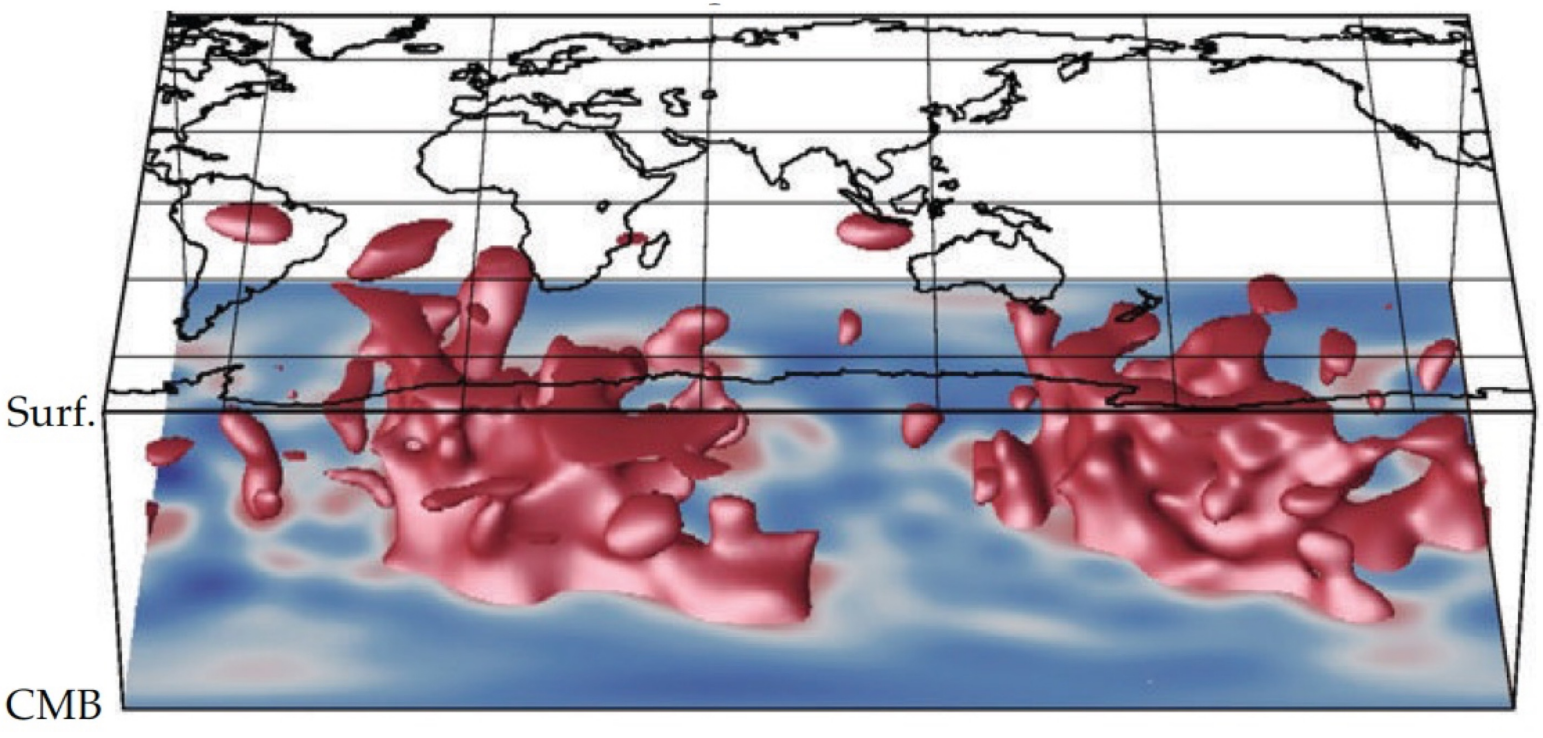
$\bar{\nu}_e$ Electron
Anti-Neutrino
Observatory



What's hidden in the mantle?

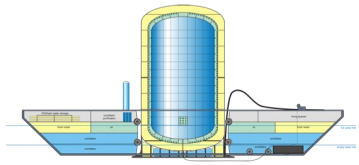
Can we image it with geonus?

Seismically slow "red" regions in the deep mantle

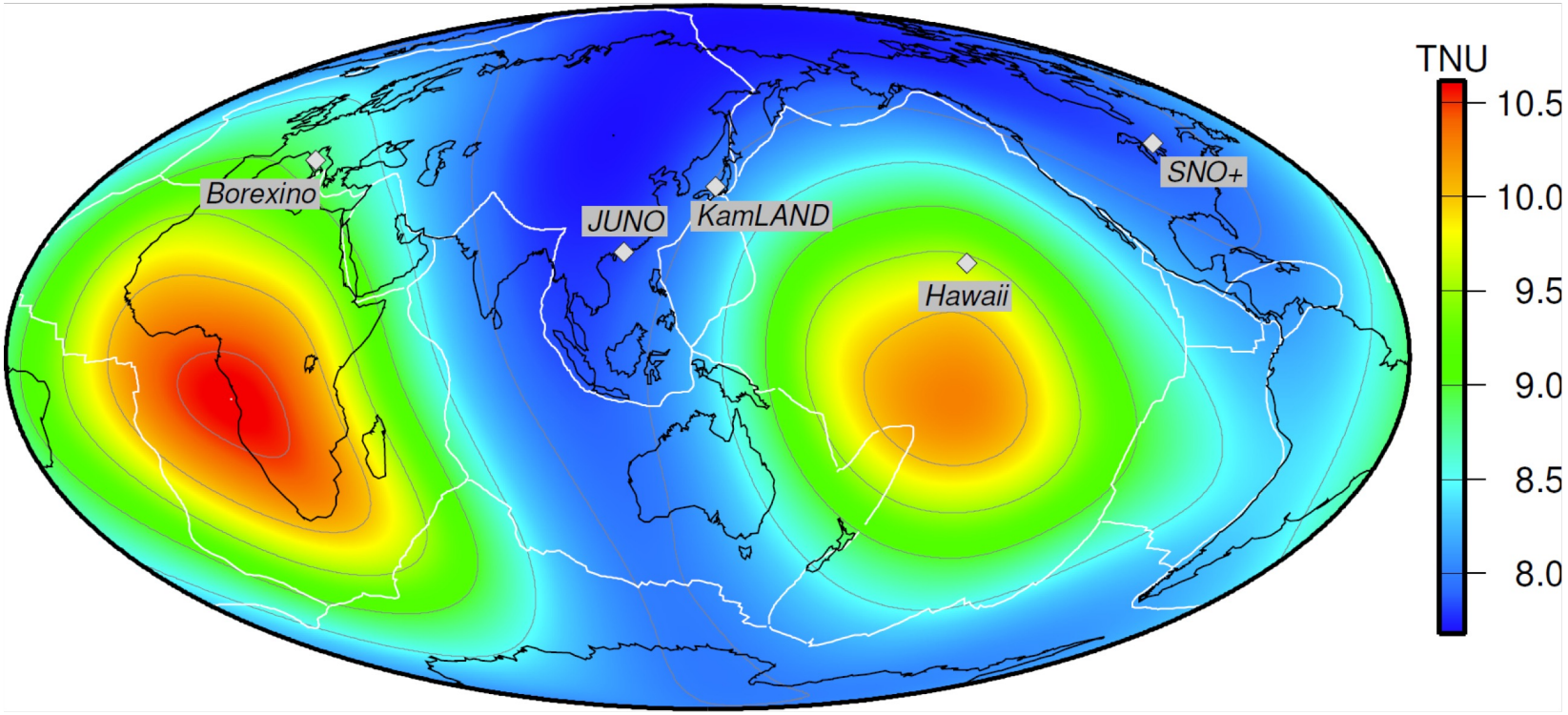


From Alan McNamara after Ritsema et al (Science, 1999)

Testing Earth Models



Mantle geoneutrino flux (^{238}U & ^{232}Th)



- Big Unknowns:
  - Composition of the silicate Earth (Mg, Si, Fe, O)
    - Amount of recycled basalt in the mantle
      - In the Transition Zone?
      - In the deep mantle
  - Mineralogy of the Lower mantle
    - Mode % ferropericlase (sets the Mg/Si)
    - Mode % Ca-perovskite (sets amount of Th & U in Earth)
  - Amount of H_2O in the Mantle and H in the Core
  - geothermal (*viscosity*) gradient Mantle and Core
  - Composition of the Core (plus ?? H, C, O, Si, S, ..)
  - Radioactive power in the Mantle and Core