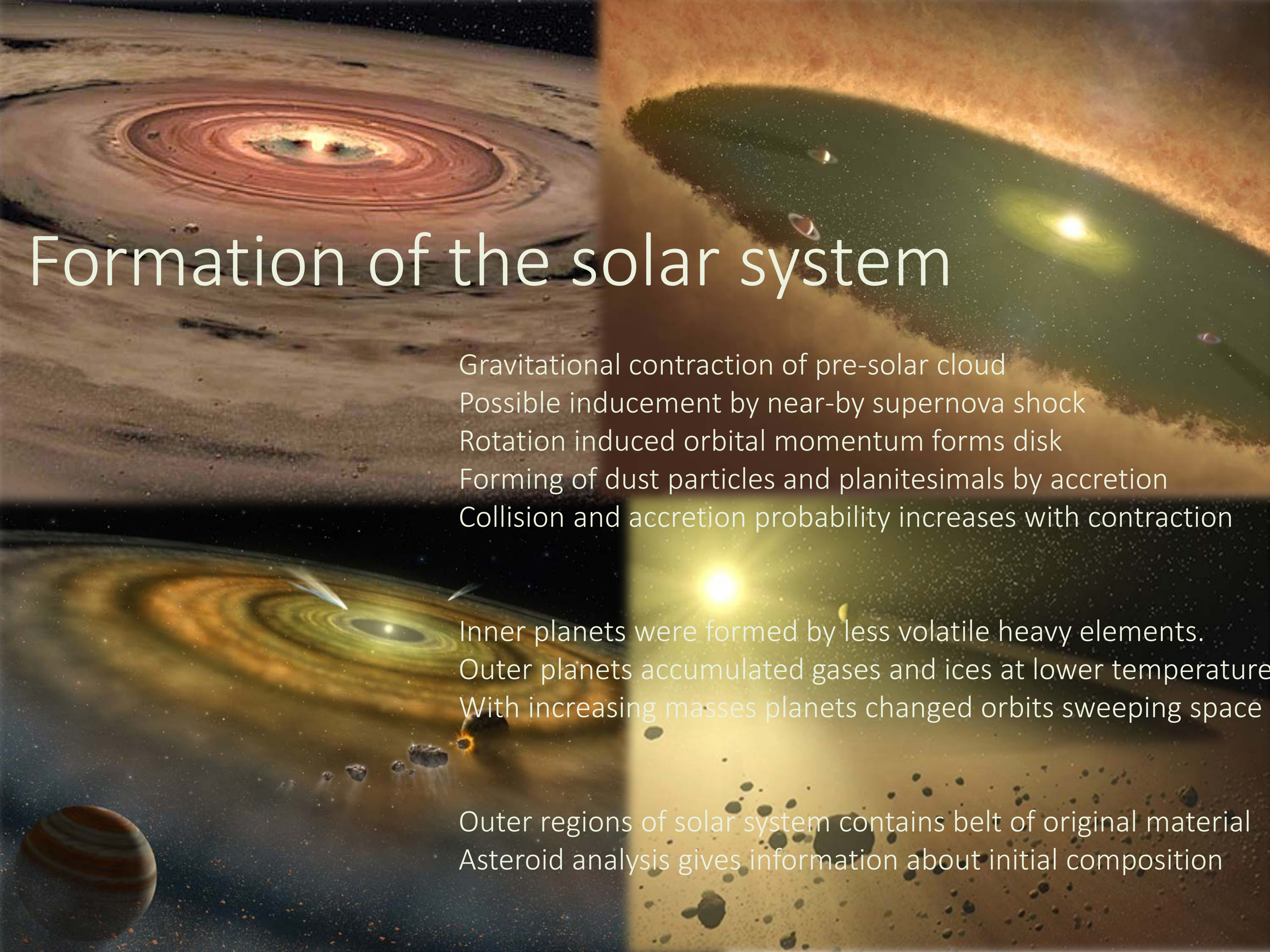
Radioactivity

Lecture 11

The radioactive Earth

The Violent Beginning

Most of the planet's radioactivity was generated in neutron driven nucleosynthesis processes in previous star generations and implemented on earth during the early phases of the formation of the solar system and the subsequent Hadean phase of asteroid bombardment.



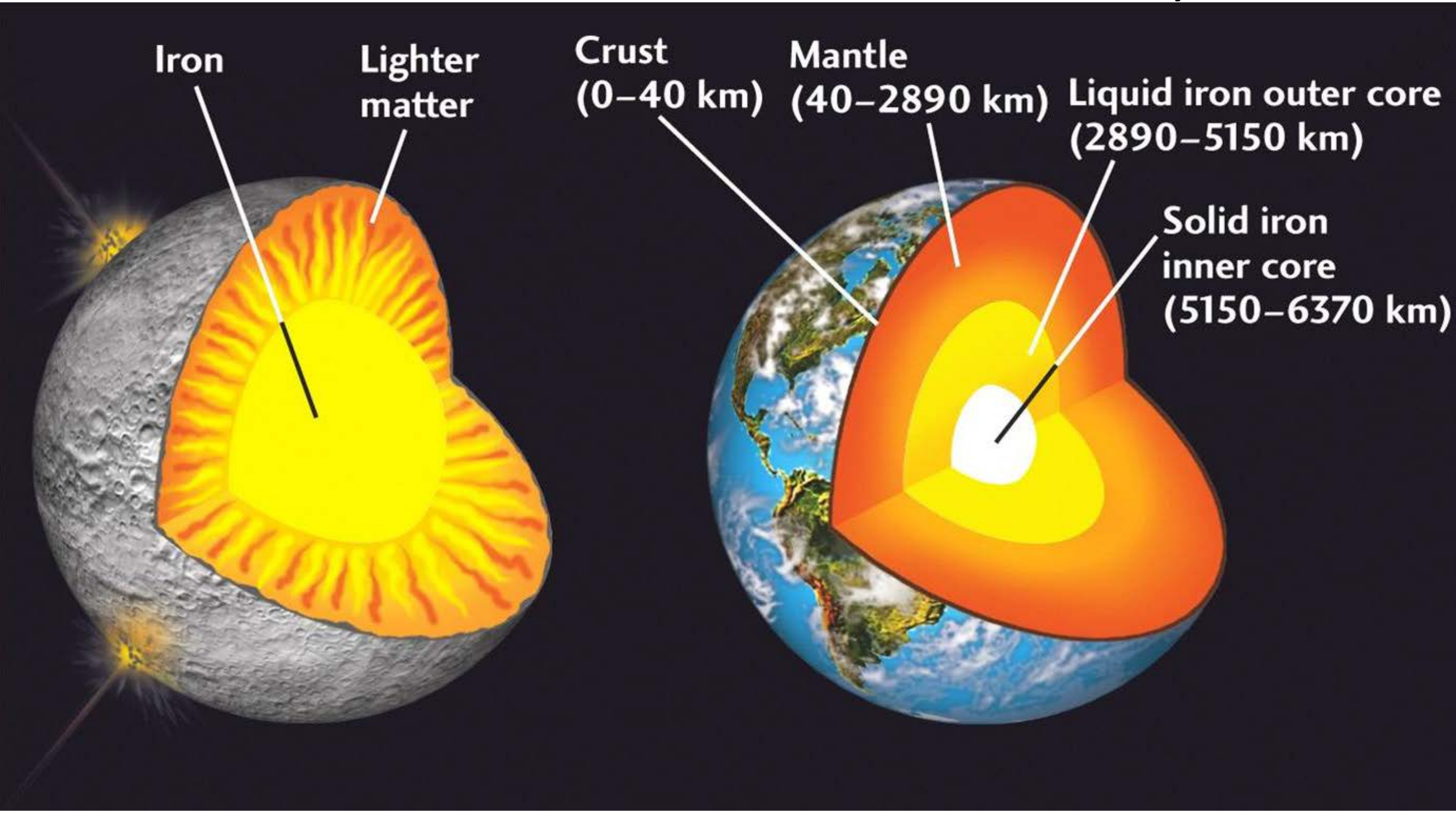
Formation of the solar system

Gravitational contraction of pre-solar cloud
Possible inducement by near-by supernova shock
Rotation induced orbital momentum forms disk
Forming of dust particles and planitesimals by accretion
Collision and accretion probability increases with contraction

Inner planets were formed by less volatile heavy elements.
Outer planets accumulated gases and ices at lower temperature
With increasing masses planets changed orbits sweeping space

Outer regions of solar system contains belt of original material
Asteroid analysis gives information about initial composition

Sedimentation of Material in Early Earth



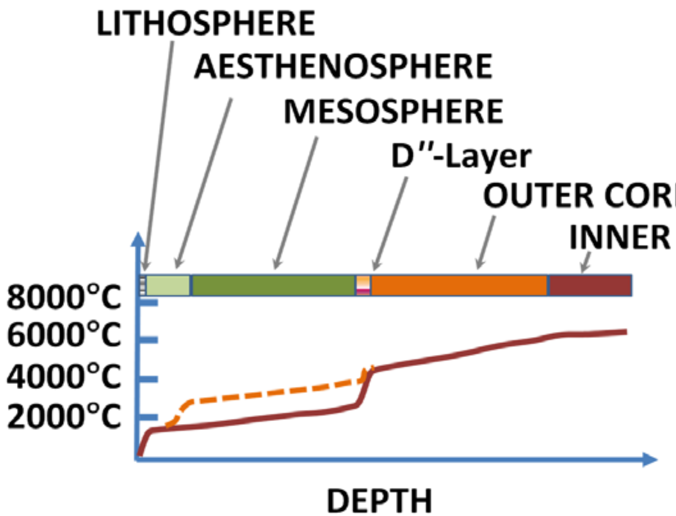
Heavy materials sink to the bottom due to gravitation, sedimentation, and centrifugation and form Fe-Ni core, a chemical incompatible layer of actinide elements forms around it!

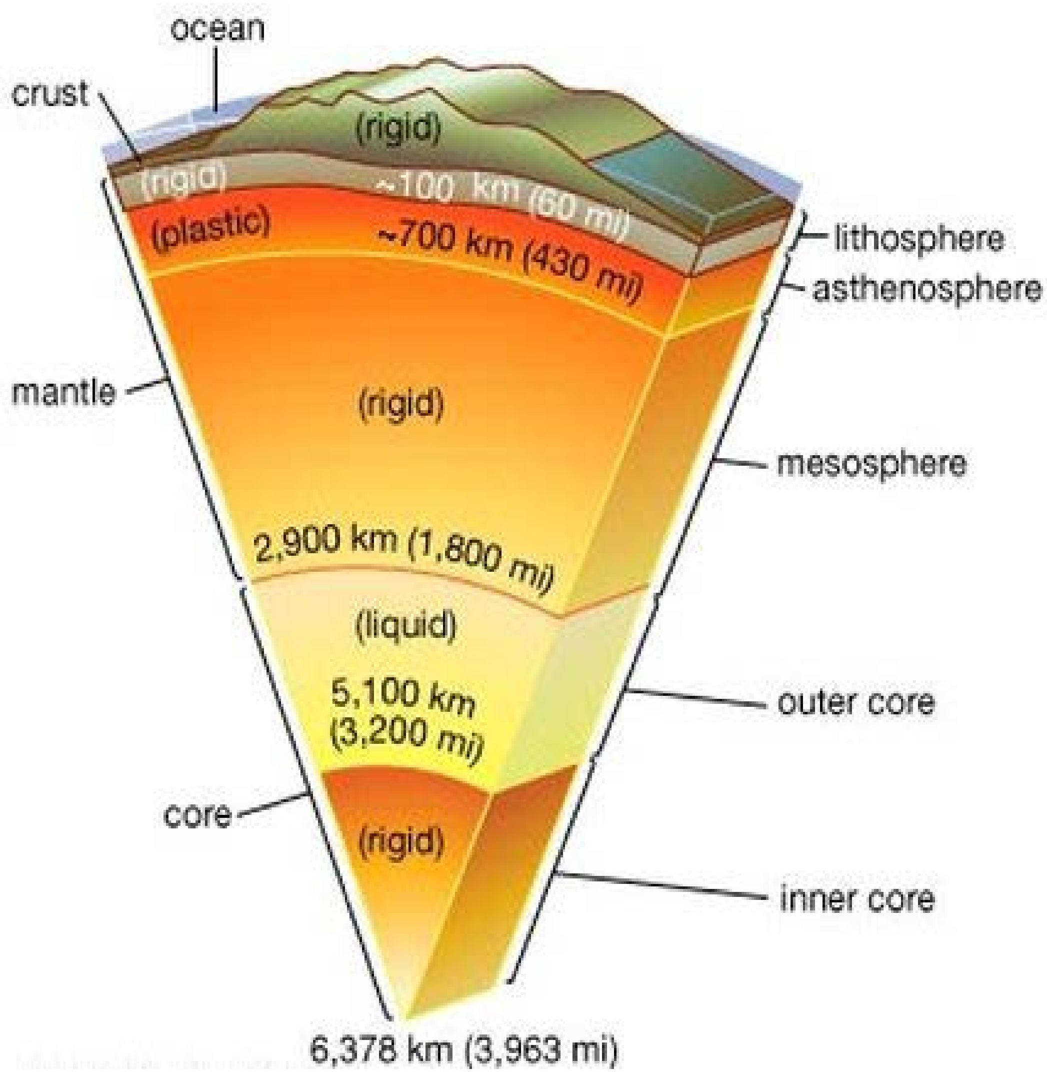
Earth from Space and Earth Parameters

The earth radius is 6370 km, the surface area is $5.1 \cdot 10^8$ km^2. The average density of earth material is ρ=5.5 g/cm^3. The average density of the surface material is 2.5 g/cm^3. The crust thickness ranges between 30 km to 50 km only. That means that that core density must be substantially higher and can be estimated to $\rho \approx$12-14 g/cm^3 . This is four times the density of granite and twice as dense as iron.

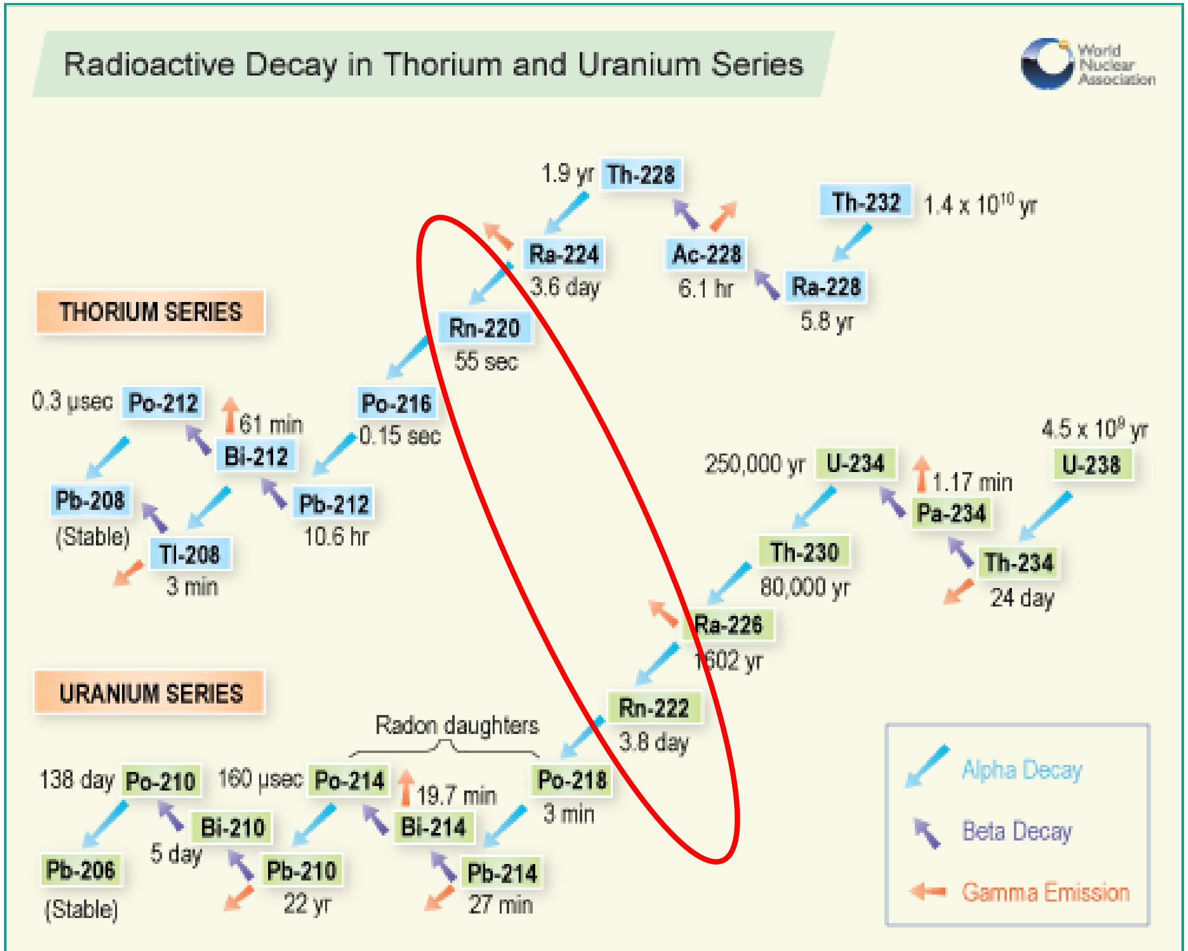
The inner Earth Structure

Temperature within Earth increases with depth. Highly viscous or molten rock at temperatures between 650 to 1,200 °C (1,202 to 2,192 °F) is expected at depths of 50 to 60 miles. The temperature at the Earth's inner core/outer core boundary, around 2,200 miles deep, is estimated to be 5650 ± 600 K. The heat content of the earth is 10^{31} J.





Reminder - Decay Chains



Enrichment of Uranium and Thorium in specific geological stone or mineral configurations, such as granite or shale. This causes a sequence of decays with the timescale dictated by the slowest decay, in these cases ^{232}Th and ^{238}U.

Thorium series: n=10 decays
Uranium series: n=14 decays

Average energy release: 3.5 MeV

Radioactive elements near Earth core

Radioactive potassium, uranium and thorium are thought to be the three main sources of heat in the Earth's interior, aside from that generated by the formation of the planet. Together, the heat keeps the mantle actively churning and the core generating a protective magnetic field as we will see in the next lecture.

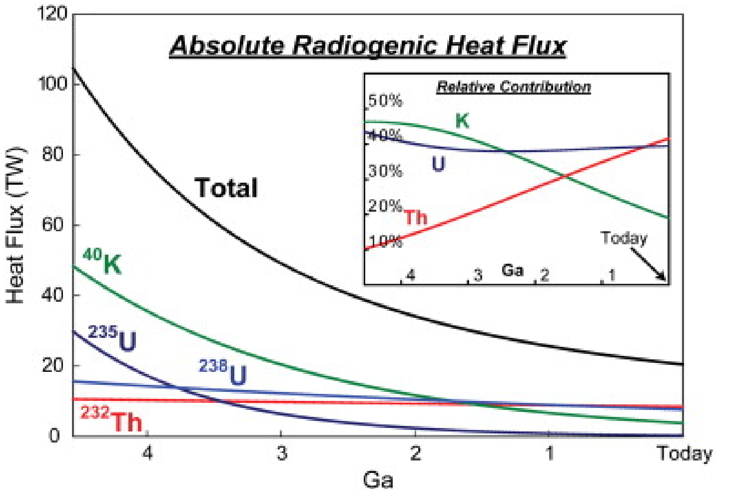
$$Q_{total} = A \cdot Q_{decay} = \lambda \cdot N \cdot Q_{decay} \qquad Q_{decay} = n \cdot Q\left({}^{238}U\right) \qquad n \equiv number\ of\ decays\ in\ decay\ chain$$

$$Q\left({}^{238}U\right) = \frac{\ln 2}{4.5 \cdot 10^{9}\, y} \cdot 3.5 MeV = 5.4 \cdot 10^{-10}\, \frac{MeV}{y} = 1.7 \cdot 10^{-17}\, \frac{MeV}{s} = 2.75 \cdot 10^{-30}\, \frac{J}{s} = 2.75 \cdot 10^{-30}\, W$$

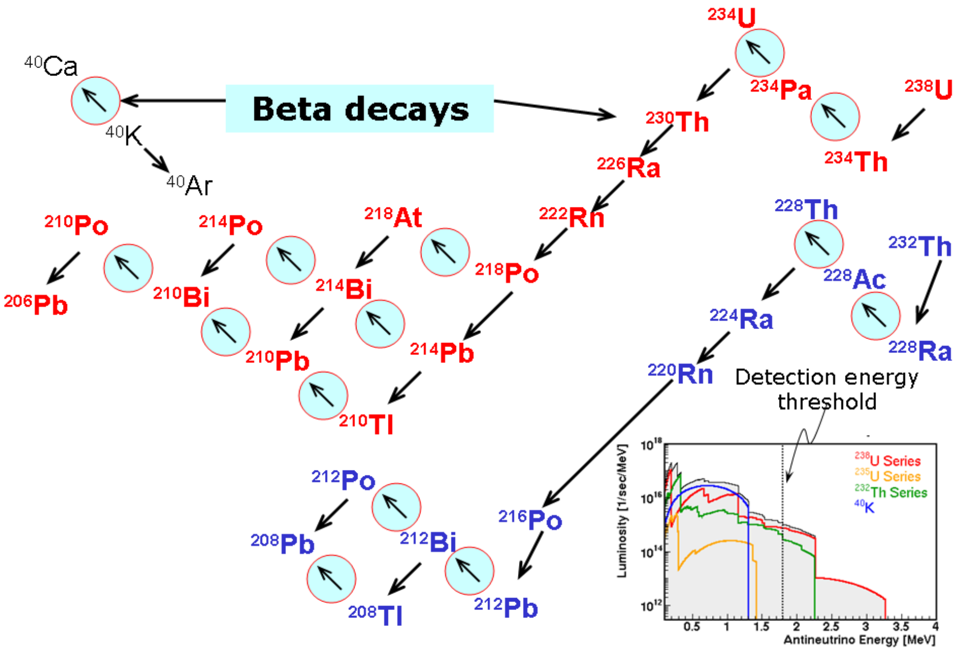
$$1 MeV = 1.6 \cdot 10^{-13}\, J \qquad N\left({}^{238}U\right) = \frac{1000}{238} \cdot 6.022 \cdot 10^{23} = 2.53 \cdot 10^{24}\, \frac{particles}{kg\ isotope}$$

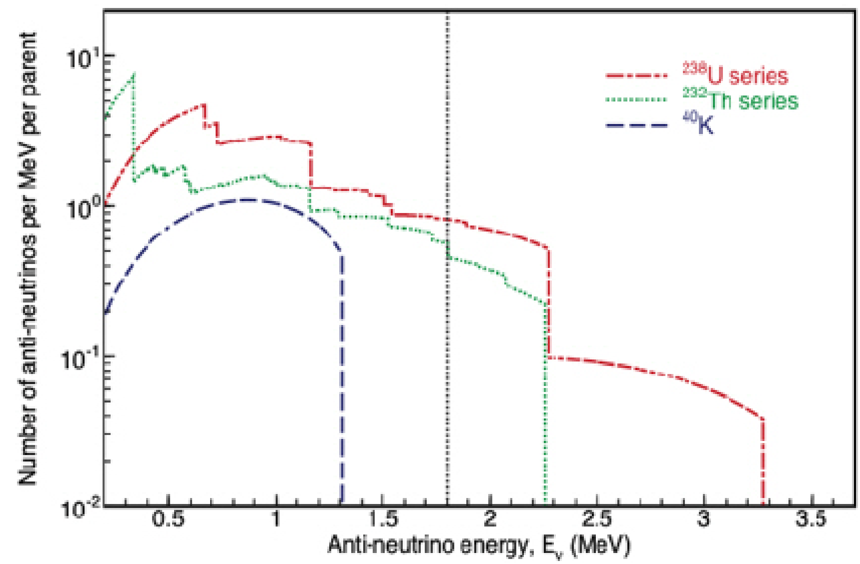
$$Q_{decay} = 3.85 \cdot 10^{-29}\, W \qquad Q_{total} = 2.53 \cdot 10^{24} \cdot 3.85 \cdot 10^{-29}\, \frac{W}{kg} = 9.74 \cdot 10^{-5}\, \frac{W}{kg\ isotope}$$

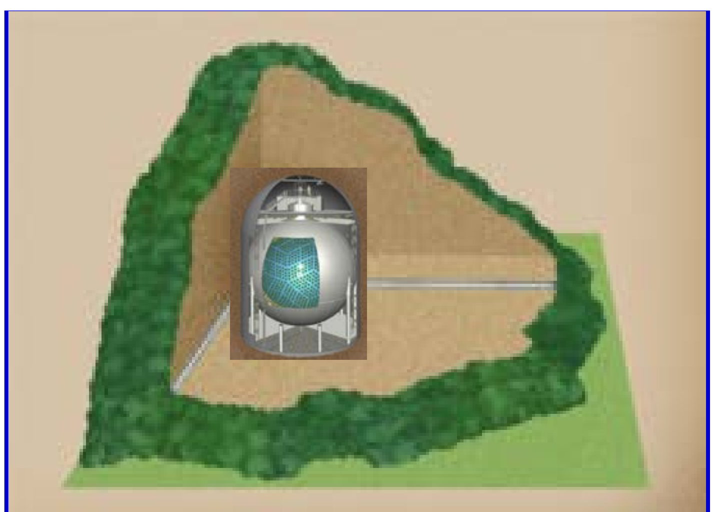
Isotope	Heat release [W/kg isotope]	Half-life [years]	Mean mantle concentration [kg isotope/kg]	Heat release [W/kg]
^{238}U	9.75×10^{-5}	4.47×10^{9}	30.8×10^{-9}	3.00×10^{-12}
^{235}U	5.69×10^{-4}	7.04×10^{8}	0.22×10^{-9}	1.25×10^{-13}
^{232}Th	2.64×10^{-5}	1.40×10^{10}	124×10^{-9}	3.27×10^{-12}
^{40}K	2.92×10^{-5}	1.25×10^{9}	36.9×10^{-9}	1.08×10^{-12}



Neutrino Signal to check the radioactivity conditions inside earth







Neutrino production associated with β-decay of radioactive elements e.g.

$^{234}Th \Rightarrow {}^{234}Pa + \beta^- + \bar{\nu} \Rightarrow {}^{234}U + \beta + \bar{\nu}$

Neutrinos/anti-neutrinos are measured in underground detector arrays such as Kamland (Kamioka, Japan and Borexino (Gran Sasso, Italy)

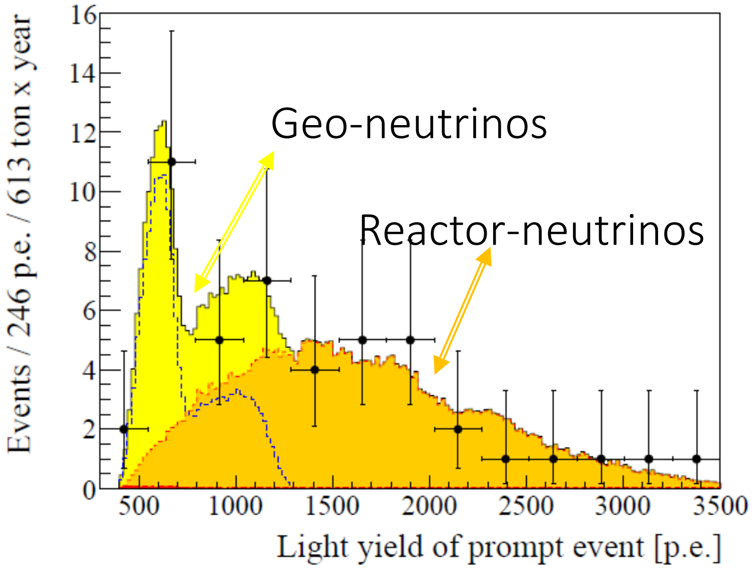
Geologically significant anti-neutrino sources

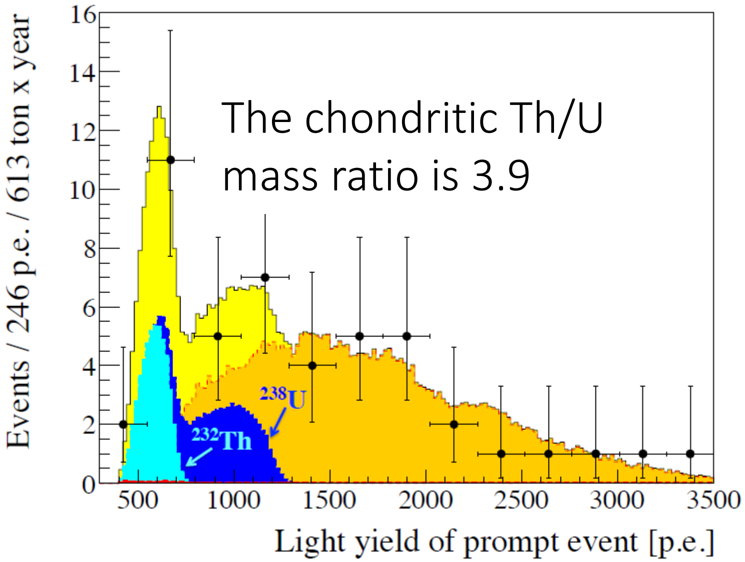
$$
\begin{array}{rcl}
{}^{238}_{92}\mathrm{U} & \longrightarrow & {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\,\mathrm{MeV} \\
{}^{235}_{92}\mathrm{U} & \longrightarrow & {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\,\mathrm{MeV} \\
{}^{232}_{90}\mathrm{Th} & \longrightarrow & {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\,\mathrm{MeV} \\
{}^{40}_{19}\mathrm{K} & \xrightarrow{89.3\,\%} & {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\,\mathrm{MeV} \\
{}^{40}_{19}\mathrm{K} + e^- & \xrightarrow{10.7\,\%} & {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\,\mathrm{MeV}
\end{array}
$$

Measured with underground detectors in Terrestrial Neutrino

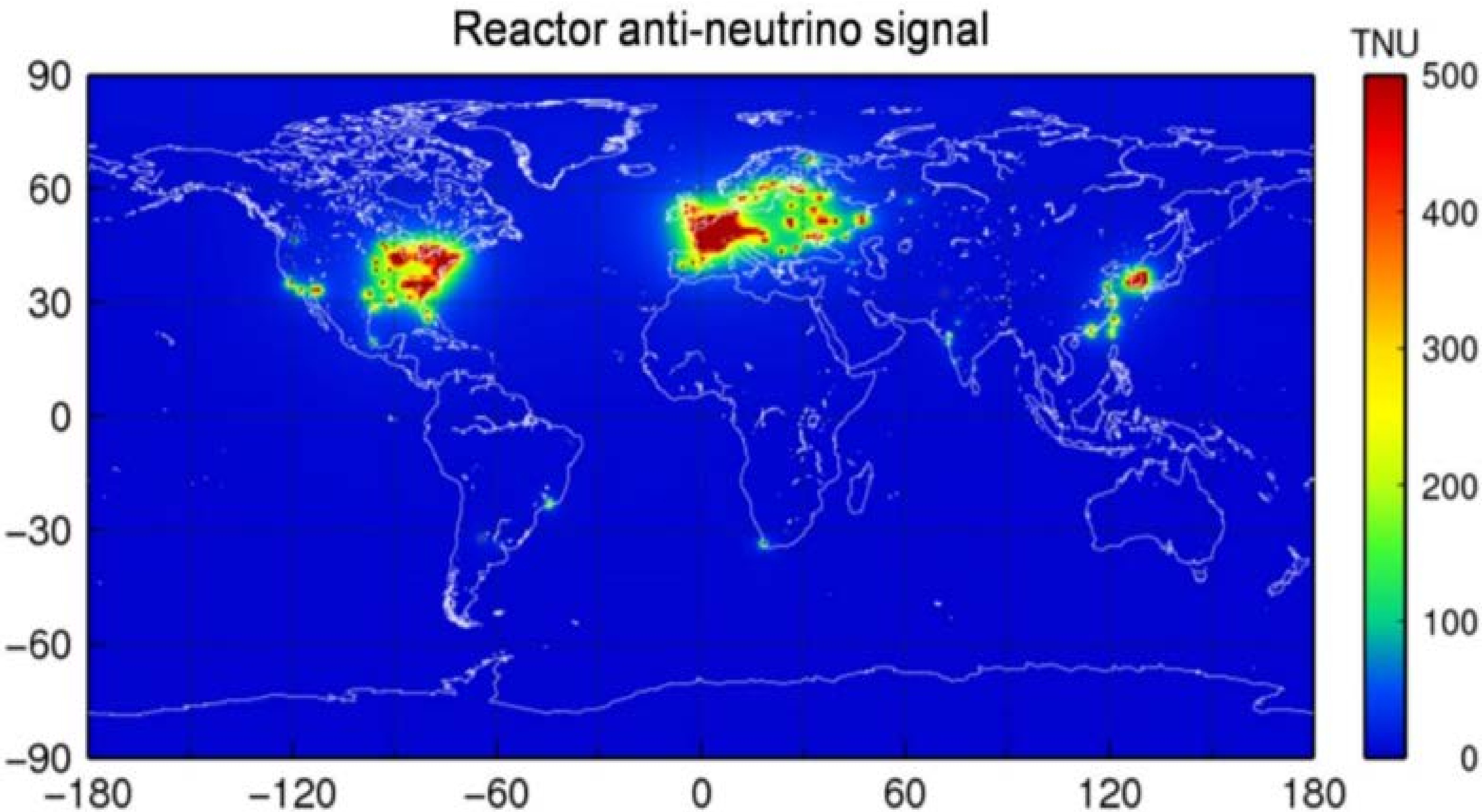
$$S({}^{232}\mathrm{Th})[\mathrm{TNU}] = 4.07 \times \phi({}^{232}\mathrm{Th}) \quad [10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$

$$S({}^{238}\mathrm{U})[\mathrm{TNU}] = 12.8 \times \phi({}^{232}\mathrm{Th}) \quad [10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}]$$



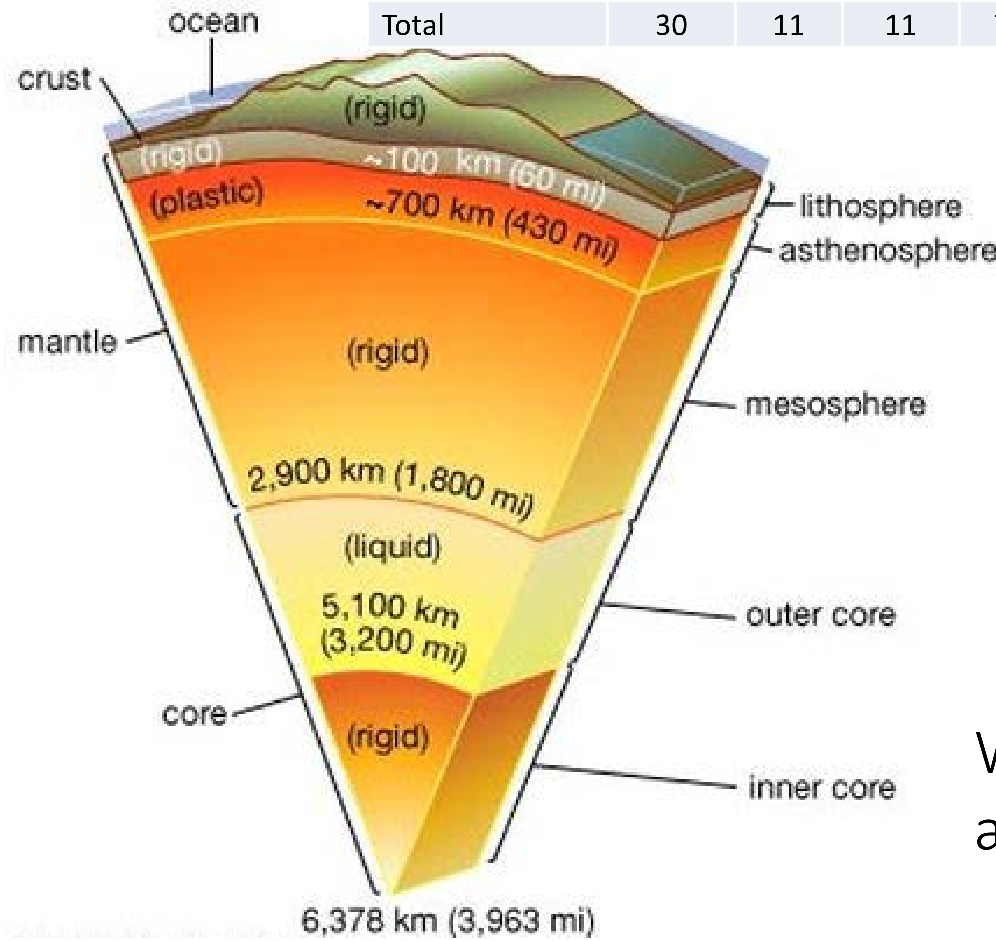


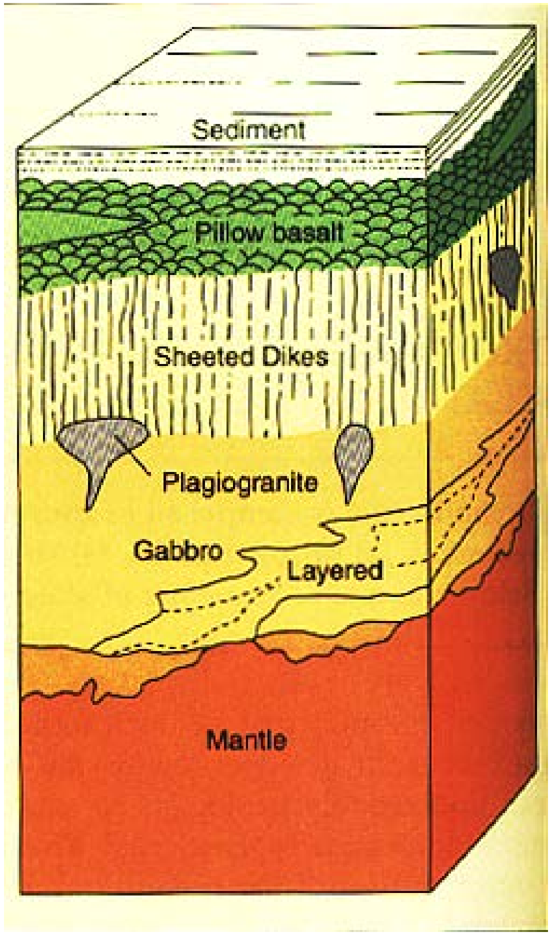
A world-wide flux map combining geoneutrinos from natural ^{238}U and ^{232}Th decay in the Earth's crust and mantle as well as manmade reactor- emitted by power reactors worldwide.



The distribution of radioactivity in Earth

	Aktivity	[10^{24} Bq]		Heat [10^{12} W]		
Isotope	^{40}K	^{232}Th	^{238}U	^{40}K	^{232}Th	^{238}U
Earth Core	2	-	-	0,5	-	-
Earth Mantle	27	10	10	6	5	6
Asthenosphere	0.5	1	1	0.5	1	1
Total	30	11	11	7	6	7

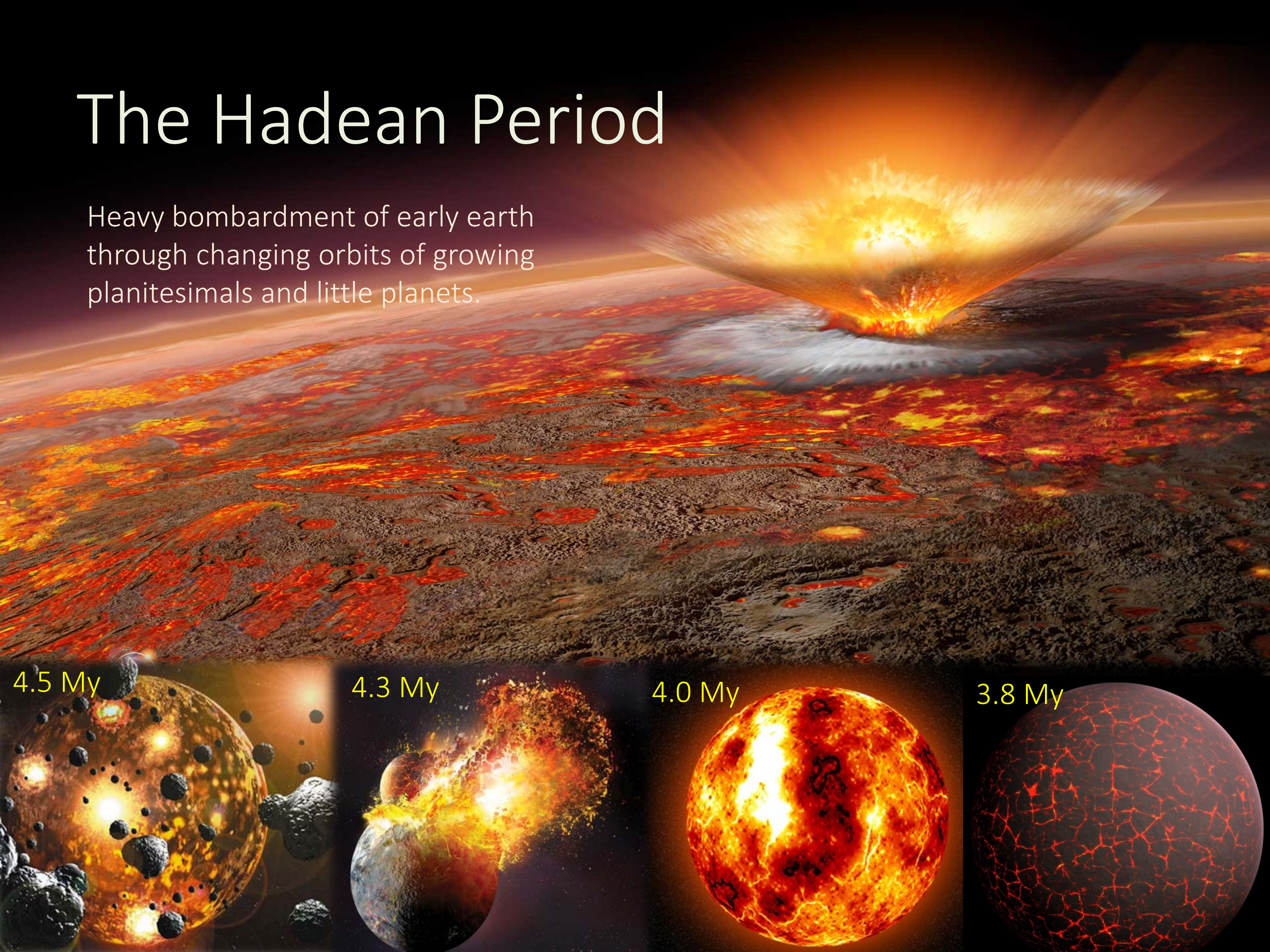




What determines the radioactivity at the surface and in the crust?

The Hadean Period

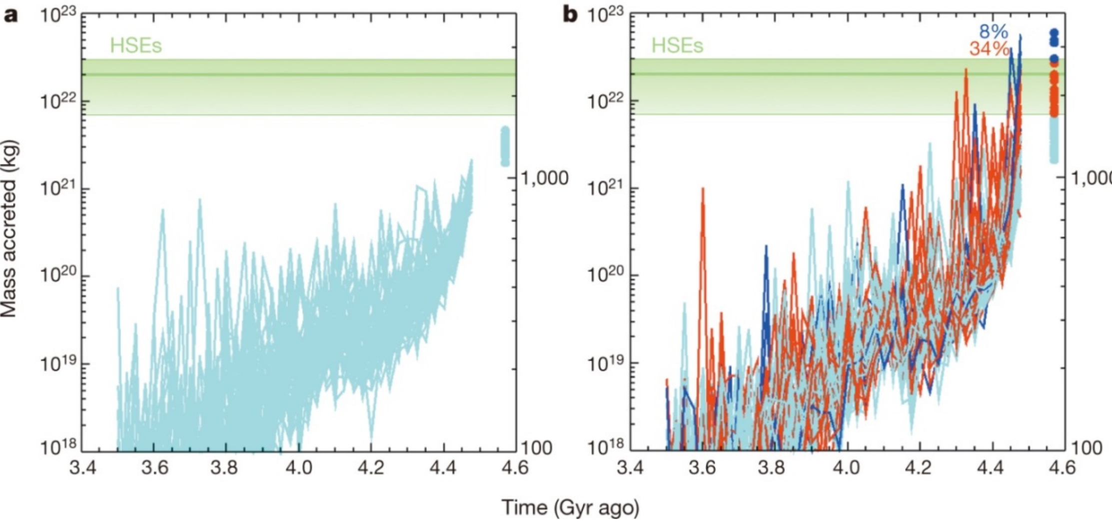
Heavy bombardment of early earth through changing orbits of growing planitesimals and little planets.



The Hadean Age Determinations

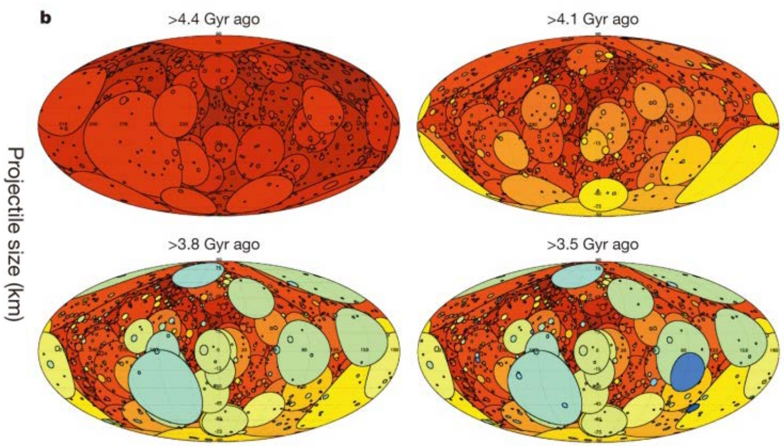
S Marchi *et al. Nature* **511**, 578-582 (2014) doi:10.1038/nature13539

Mass accreted by the Earth during the late accretion phase.

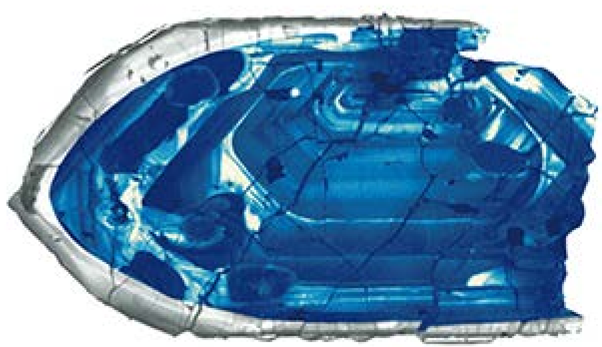


Decline of accretion rate and size of accreted bodies with time

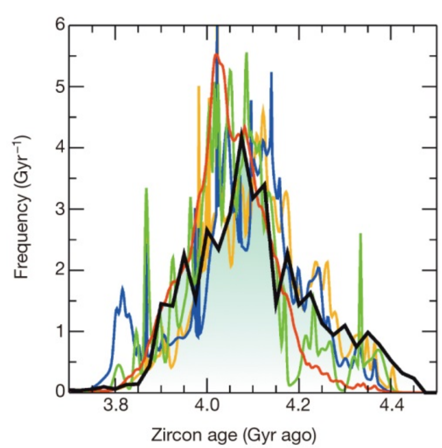
Crater impact on earth surface



Planet wide melting and mixing of surface and asteroid materials the earlier composition vanished

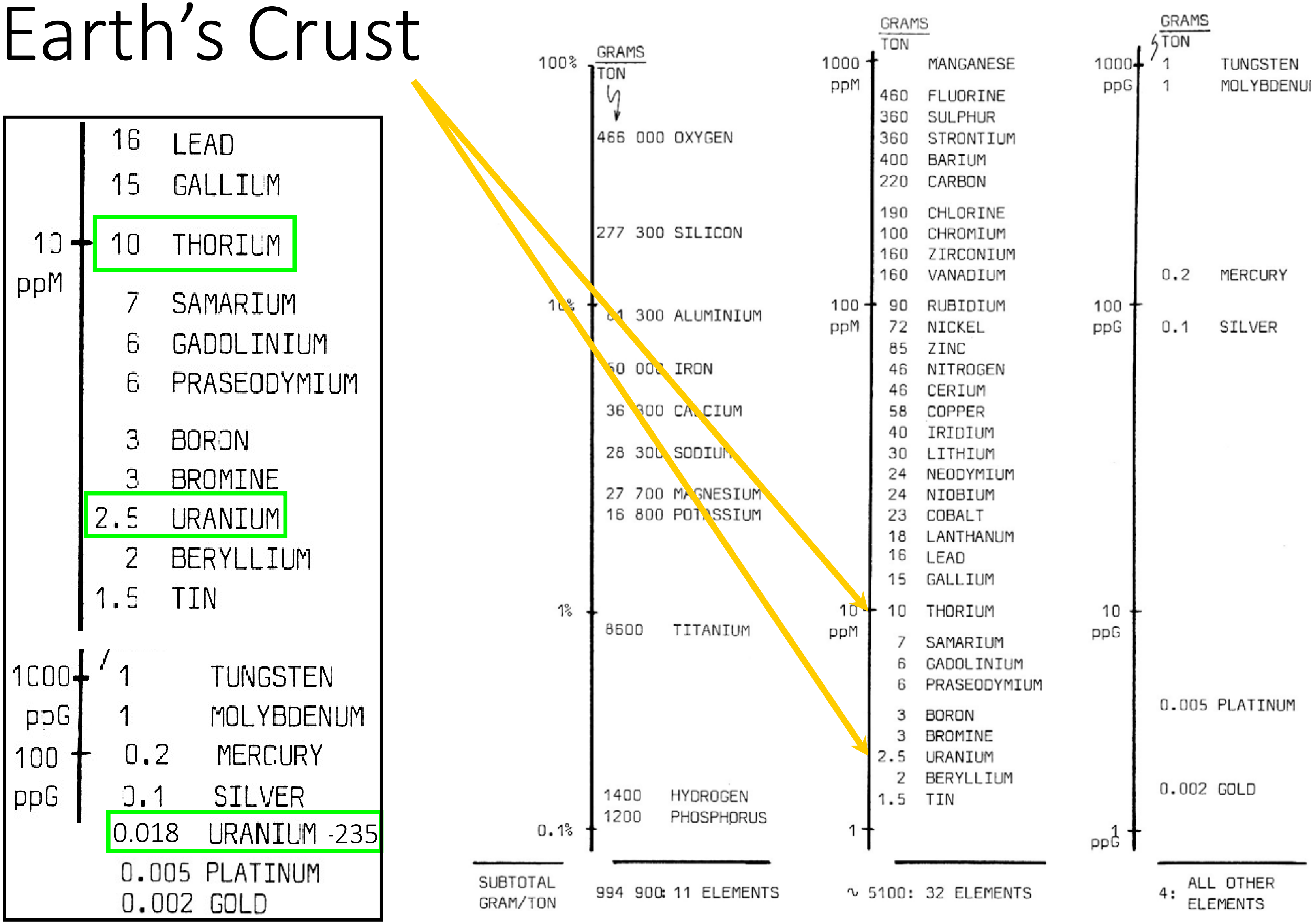


Oldest known mineral Zircon 4.4 My crystalized after cooling contains



Zircon ages (coloured curves correspond to different data sets: orange, ^{207}Pb–^{206}Pb ages; blue, U–Pb ages; green, ^{207}Pb–^{206}Pb ages; red, U–Pb ages) show a distinct peak at 4.0–4.2 Gyr ago. In agreement with simulations.

Thorium and Uranium Abundant in the Earth's Crust



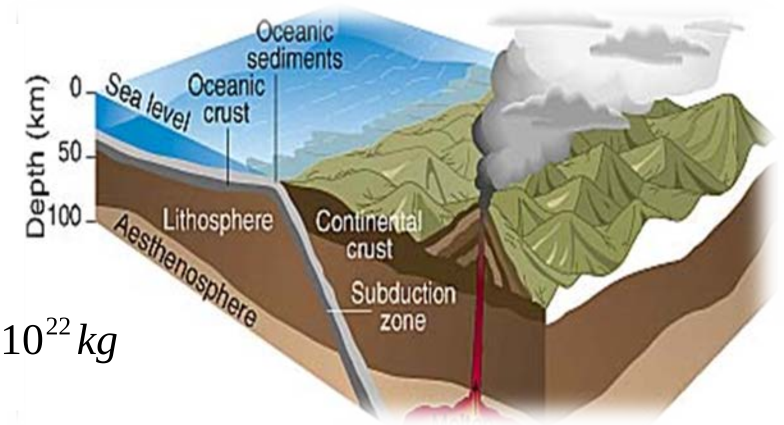
Earth Crust Activity

By combining the volume of the earth *crust* with the density one can derive the average *mass* of the *crust (depending on assumptions on crust thickness and density.*

$$V_{shell} = V_{earth} - V_{innersphere} = \frac{4}{3}\pi \cdot \left(r_e^3 - r_i^3\right) = \frac{4}{3}\pi \cdot \left(r_e^3 - \left(r_e - d\right)^3\right)$$

$$V_{shell} = \frac{4}{3}\pi \cdot \left(6370^3 - \left(6370 - 40\right)^3\right) = 2.0 \cdot 10^{10}\, km^3 = 2 \cdot 10^{25}\, cm^3$$

$$\rho = 2.5 \frac{g}{cm^3} \quad \Rightarrow \quad M = \rho \cdot V = 5 \cdot 10^{25}\, g = 5 \cdot 10^{19}\, tons = 5 \cdot 10^{22}\, kg$$



One can calculate the average radiation load distributed over the earth crust
M(^{232}Th)=10 g/ton M(^{238}U)=2.5 g/ton M(^{40}K)=16800·0.00021 g/ton= 3.53 g/ton

$$M\left({}^{232}Th\right) = 10 \frac{g}{tons} \cdot 5 \cdot 10^{19}\, tons = 5 \cdot 10^{20}\, g \quad M\left({}^{238}U\right) = 1.25 \cdot 10^{20}\, g \quad M\left({}^{40}K\right) = 1.77 \cdot 10^{20}\, g$$

$$N\left({}^{232}Th\right) = M\left({}^{232}Th\right) \cdot \frac{6.022 \cdot 10^{23}}{232} = 1.3 \cdot 10^{42} \quad N\left({}^{238}U\right) = 3.2 \cdot 10^{41} \quad N\left({}^{40}K\right) = 2.7 \cdot 10^{42}\ particles$$

The Average Radiogenic Load

The number of radioactive nuclei in the earth crust allows us to calculate the average radiogenic load distributed over the earth crust. Reality shows pronounced distribution!

$$N\left({}^{232}Th\right)=1.3\cdot 10^{42}\ particles \quad N\left({}^{238}U\right)=3.2\cdot 10^{41}\ particles \quad N\left({}^{40}K\right)=2.7\cdot 10^{42}\ particles$$

$$A\left({}^{232}Th\right)=\lambda\cdot N\left({}^{232}Th\right)=\frac{\ln 2}{T_{1/2}}\cdot N\left({}^{232}Th\right)=\frac{0.69}{1.405\cdot 10^{10}\cdot 3.14\cdot 10^{7}\,s}\cdot 1.3\cdot 10^{42}=2.03\cdot 10^{24}\,Bq$$

$$\Rightarrow \frac{A\left({}^{232}Th\right)}{M_{crust}}=\frac{2.03\cdot 10^{24}\,Bq}{5\cdot 10^{22}\,kg}=41\frac{Bq}{kg}$$

$$A\left({}^{238}U\right)=\lambda\cdot N\left({}^{238}U\right)=\frac{\ln 2}{T_{1/2}}\cdot N\left({}^{238}U\right)=\frac{0.69}{4.5\cdot 10^{9}\cdot 3.14\cdot 10^{7}\,s}\cdot 3.2\cdot 10^{41}=1.56\cdot 10^{24}\,Bq$$

$$\Rightarrow \frac{A\left({}^{238}U\right)}{M_{crust}}=11\frac{Bq}{kg}$$

$$A\left({}^{40}K\right)=\lambda\cdot N\left({}^{40}K\right)=\frac{\ln 2}{T_{1/2}}\cdot N\left({}^{40}K\right)=\frac{0.69}{1.28\cdot 10^{9}\cdot 3.14\cdot 10^{7}\,s}\cdot 2.7\cdot 10^{42}=4.64\cdot 10^{25}\,Bq$$

$$\Rightarrow \frac{A\left({}^{238}U\right)}{M_{crust}}=928\frac{Bq}{kg}$$

Be aware, these are average numbers due to initial assumptions and to large local fluctuations because of geological chemical and mineralogical processes!

What is the impact of the radioactive Earth?

- Mantle Convection
- Tectonic Drift
- Volcanic Activity
- Natural Reactors
- High Dose Areas
- Radon exposure