Radioactivity

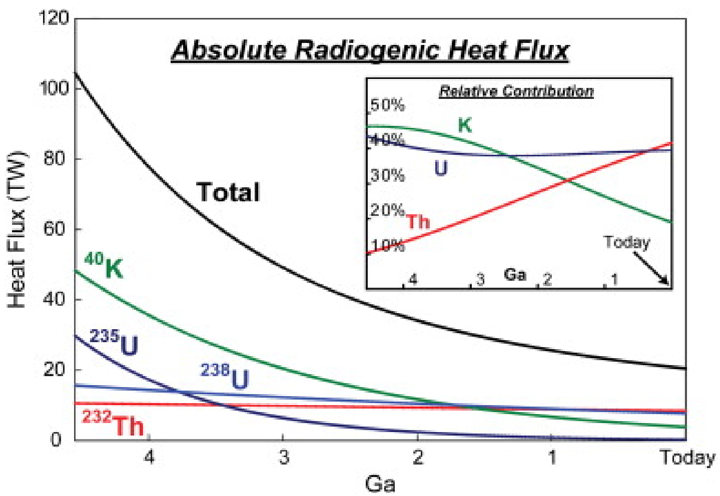
Lecture 12

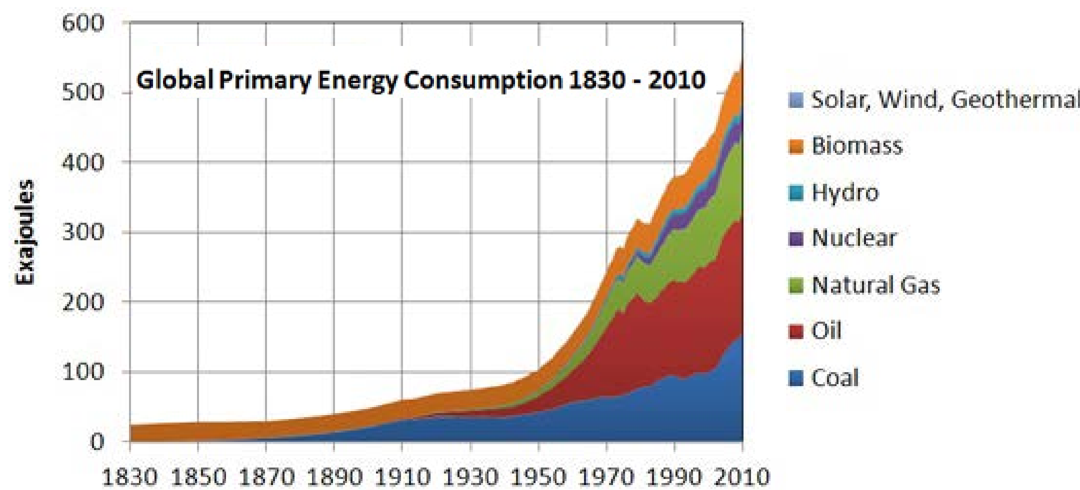
Geological Implications and Consequences

Radiogenic Heat Generation

Decay processes of ^{238}U, ^{232}Th, and ^{40}K
generates today ~ $3 \cdot 10^{-12}$, $3.3 \cdot 10^{-12}$, $1.1 \cdot 10^{-12}$ W/kg
with a mantle mass of $3 \cdot 10^{24}$ kg: 9 TW, 11 TW, 3.3 TW = 23.3TW
corresponds to 388 billion 60W lightbulbs

Initially, 4.5 Billion years ago the heat production by radioactive decay was 104 TW



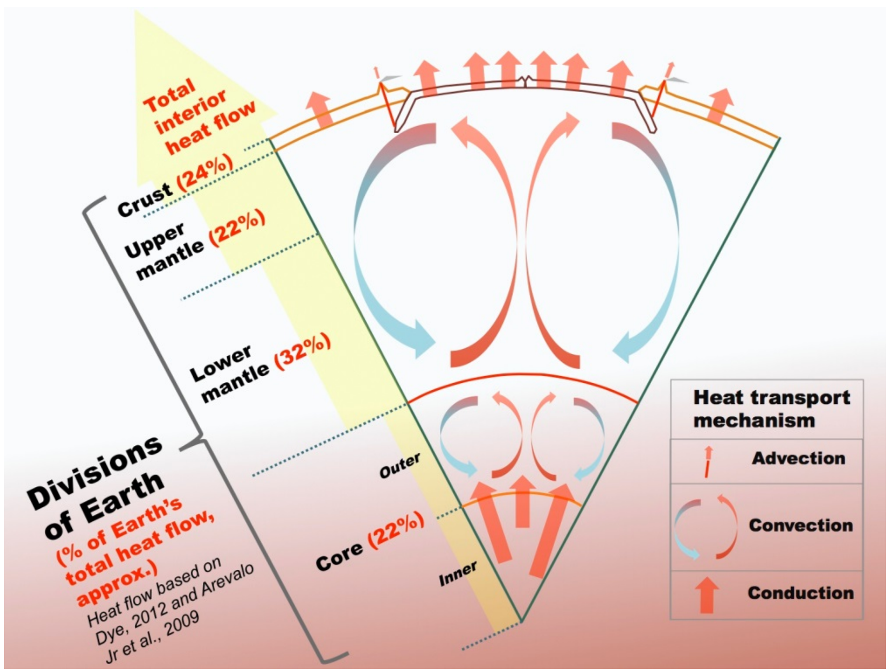


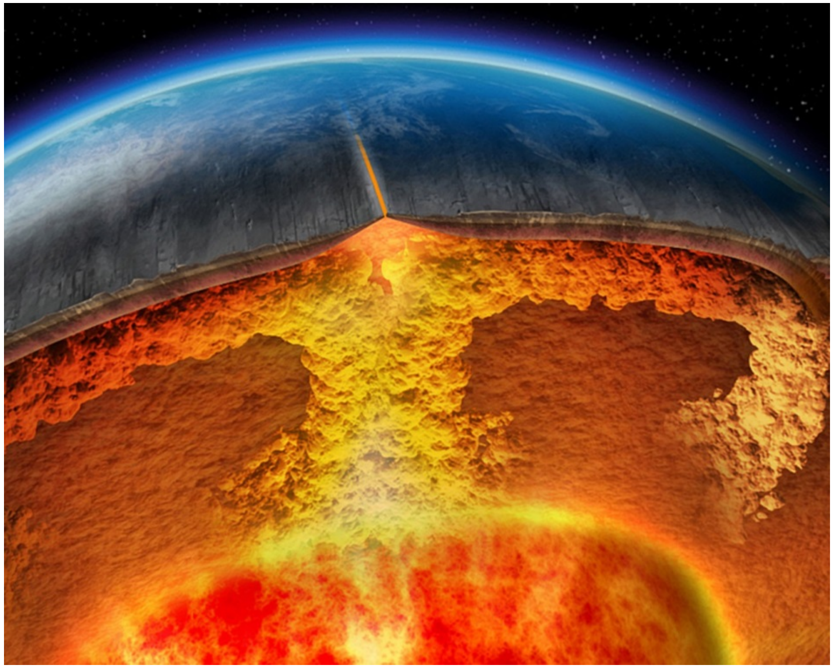
Human energy consumption ~550 Exa-Joules/year=$5.5 \cdot 10^{20}$J/y=$1.75 \cdot 10^{13}$W=17.5TW
61.5% heat loss, 38.5% useful energy loss

Mantle Convection as Cooling Mechanism

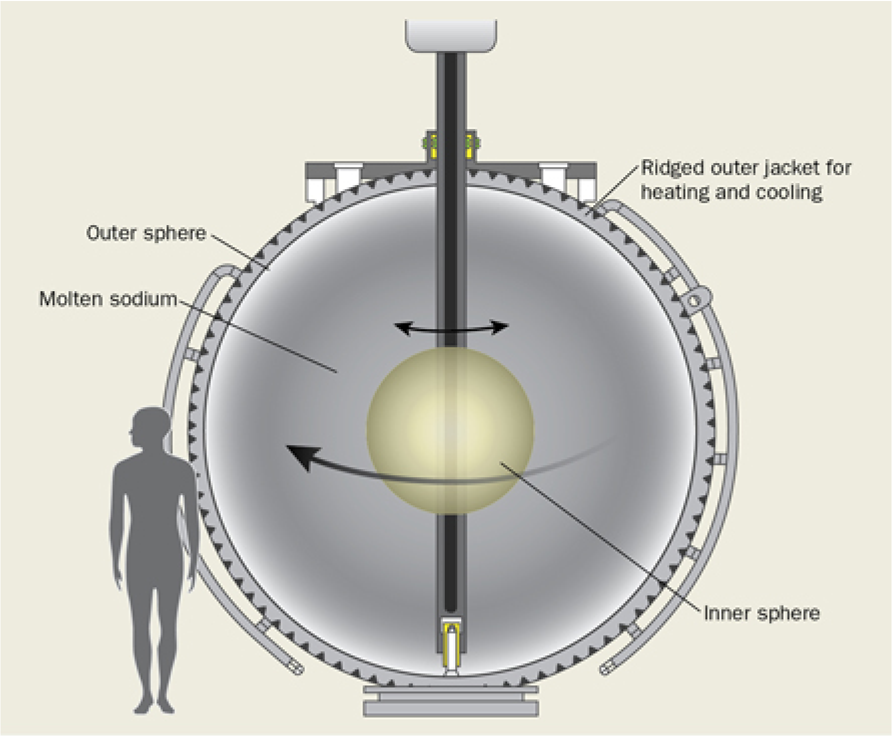
Observed heat flow through the entire earth surface if 43TW, ~ 50% of heat comes from other sources such as contraction and friction processes.

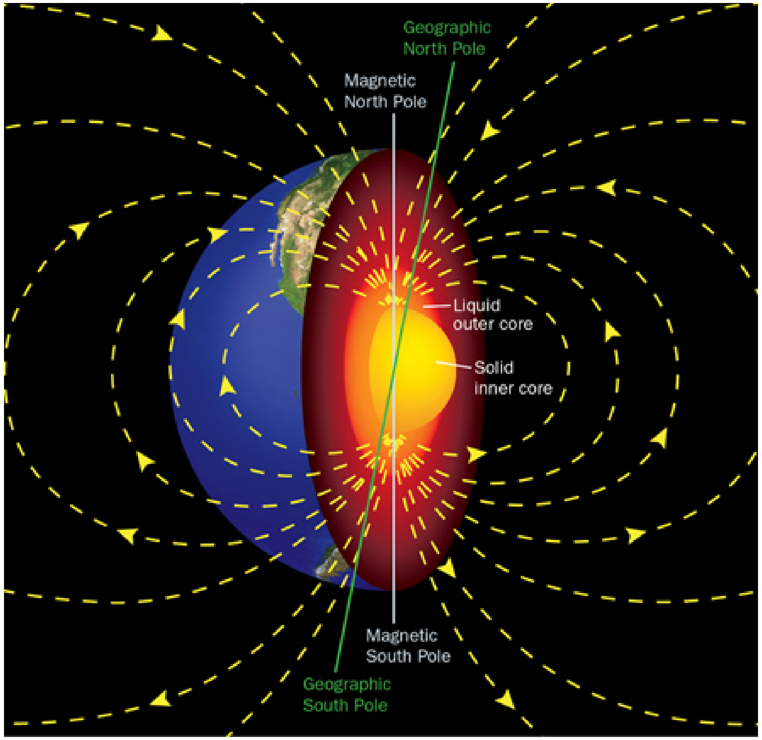
Two kinds of heat transport, conduction and convection. Conduction takes place in metals such as Fe-Ni core, convection in molten rock on earth mantle.





The inner Fe-Ni core

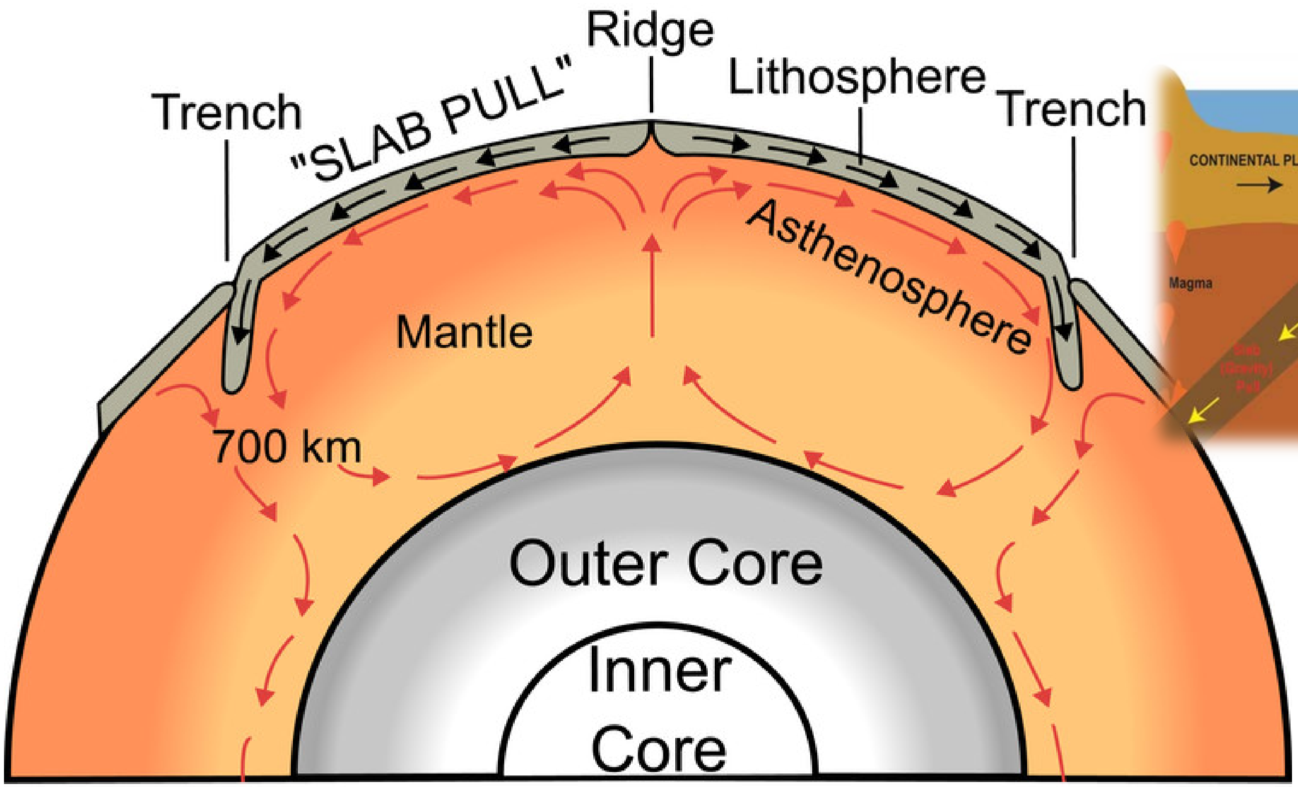


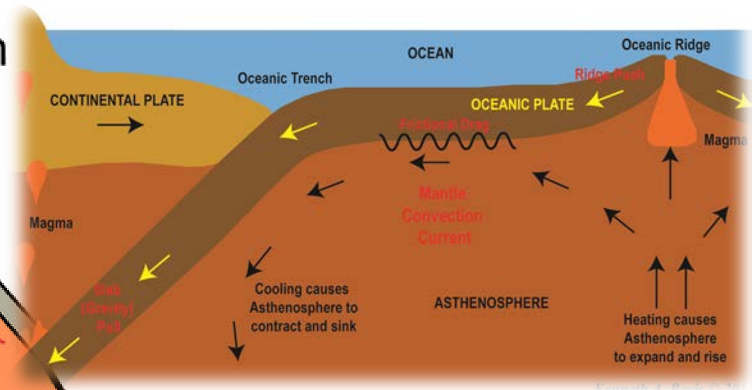


Experiment at the University of Maryland, Science News 138, 26 (2013)

As Earth rotates on its axis, the convective motion of the electrically conducting liquid outer core that is heated by the energy release in the inner core and the lower layer of the outer core creating a dynamo effect that generates and sustains Earth's magnetic field for long periods of time. The energy to sustain the dynamo comes from the rotational motion of Earth. The field is not constant, but the poles are moving and vary. every 800,000 to 10 million years a complete switch in field direction seems to occur!

Mantle Convection and Tectonic Plates

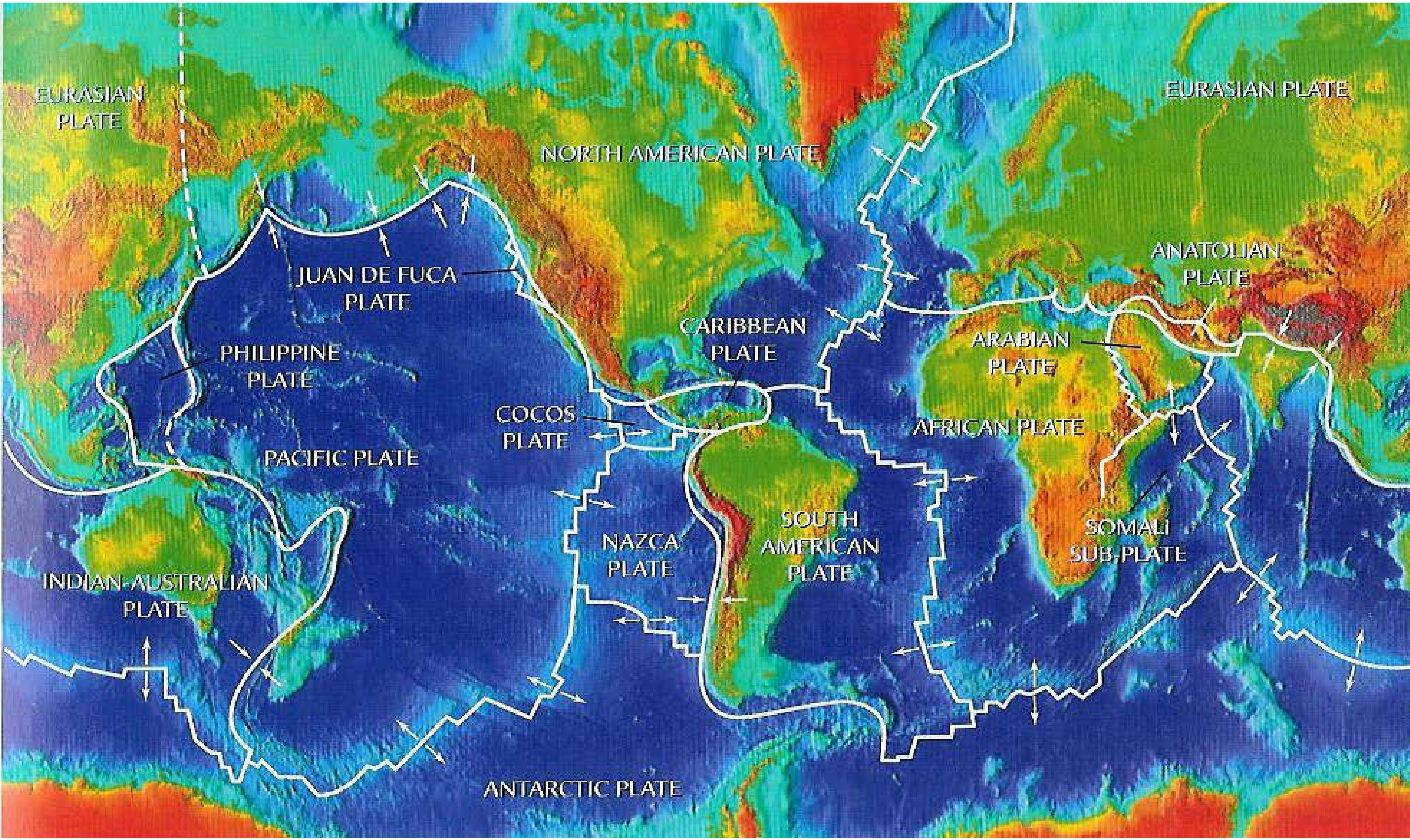




Convective motion of mantle mass drags crust matter with it, causing a motion in the crust material (tectonic motion).

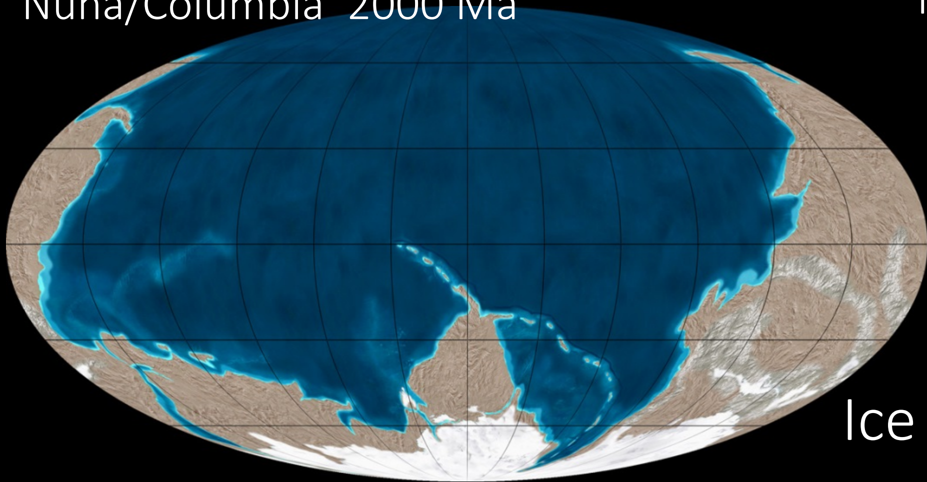
- Causing a motion of the continents (plate tectonics).
- Causes a continuous replenishment of crust matter with outer mantle material.
- The velocity of the motion process can be measured and is about 2-3 cm/year.

The Continental Shelves Today

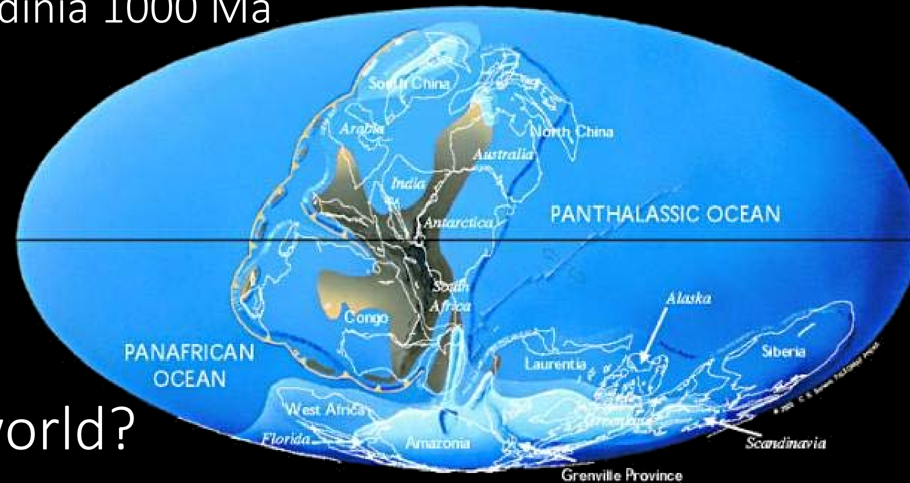


Paleo-Continental Distributions

Nuna/Columbia 2000 Ma

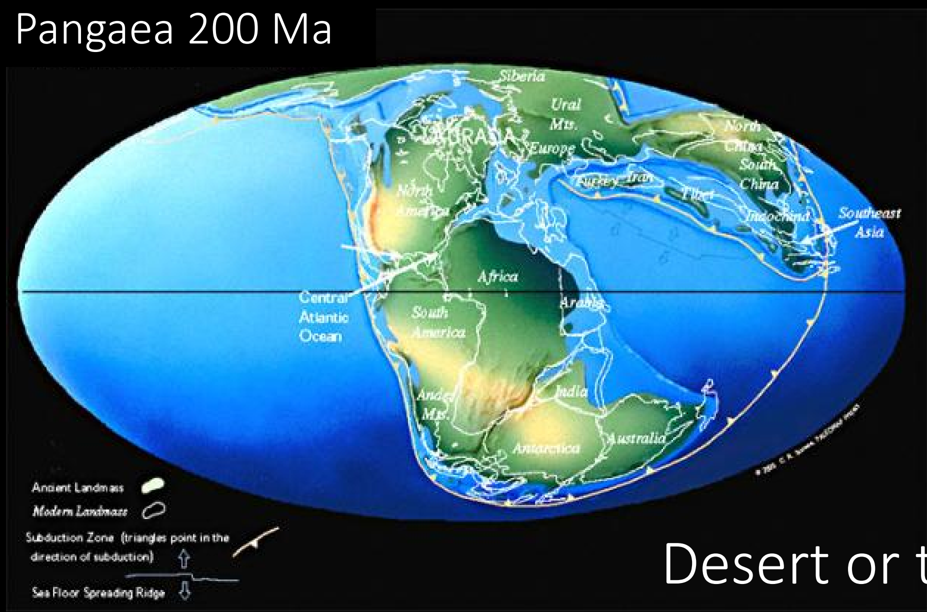


Rodinia 1000 Ma

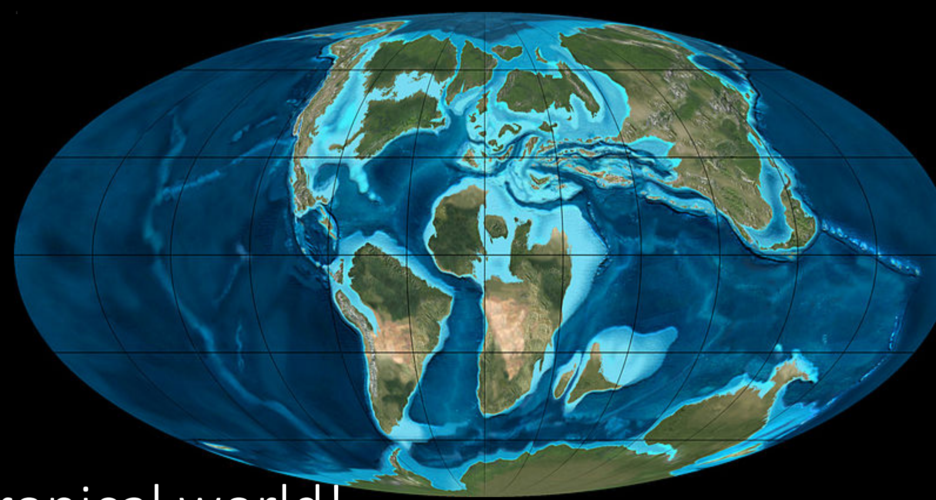


Ice world?

Pangaea 200 Ma

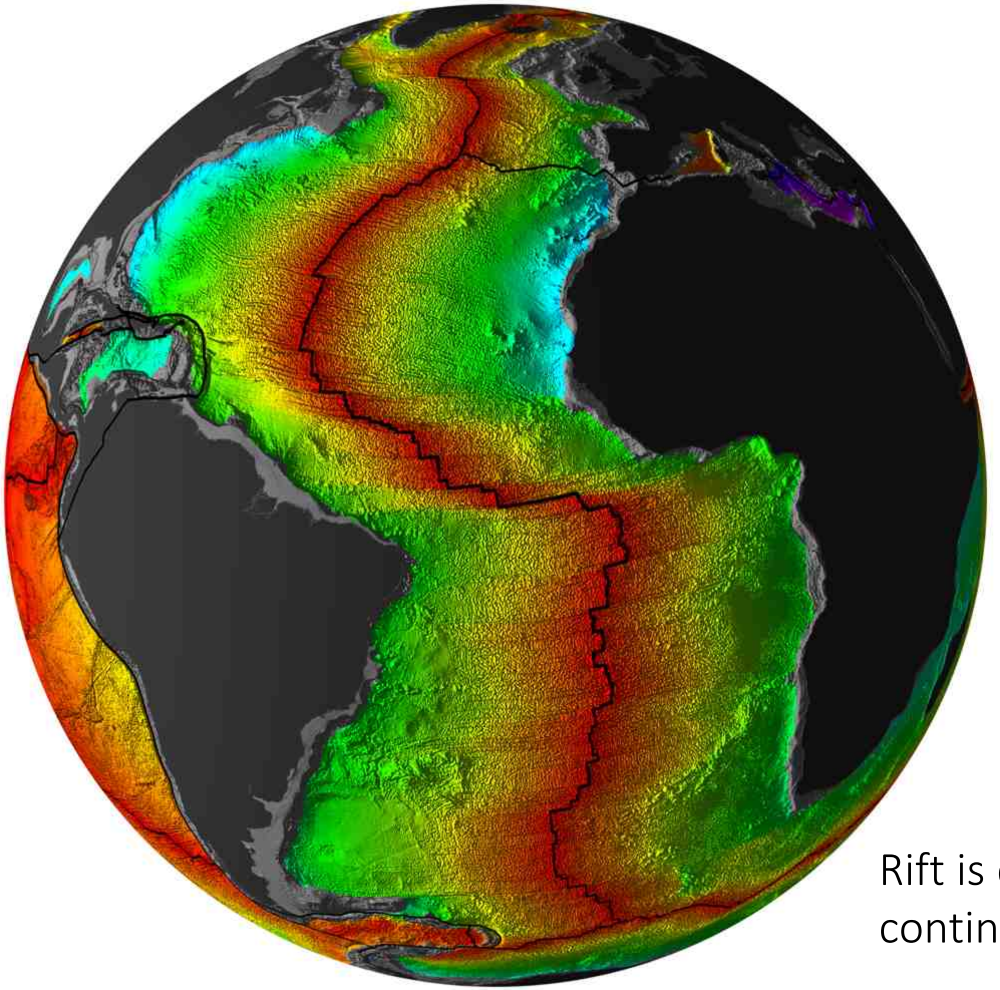


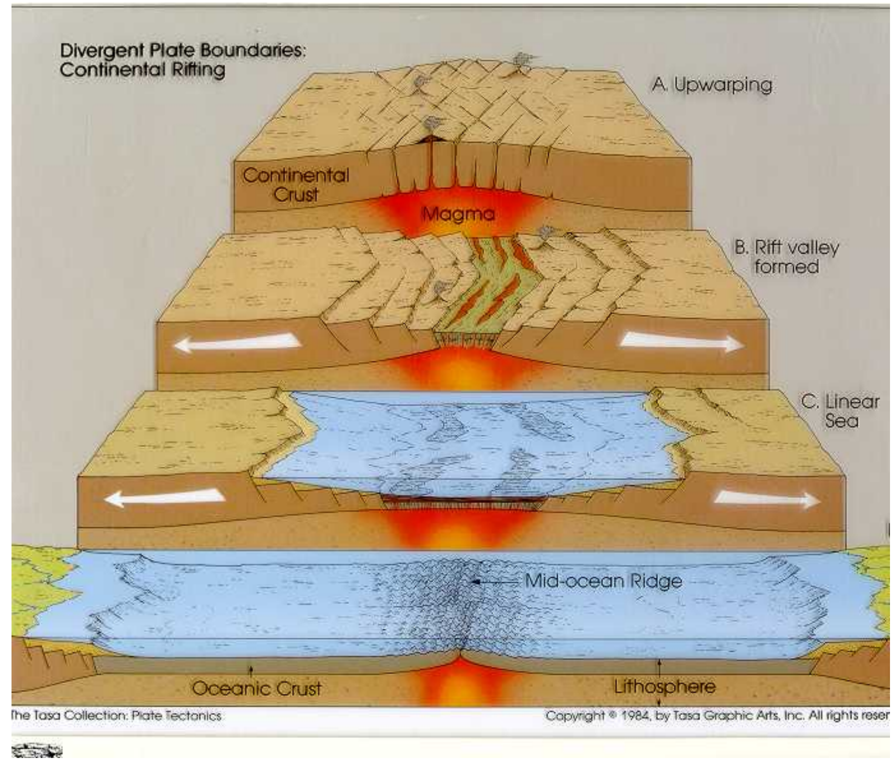
Gondwana 100 Ma



Desert or tropical world!

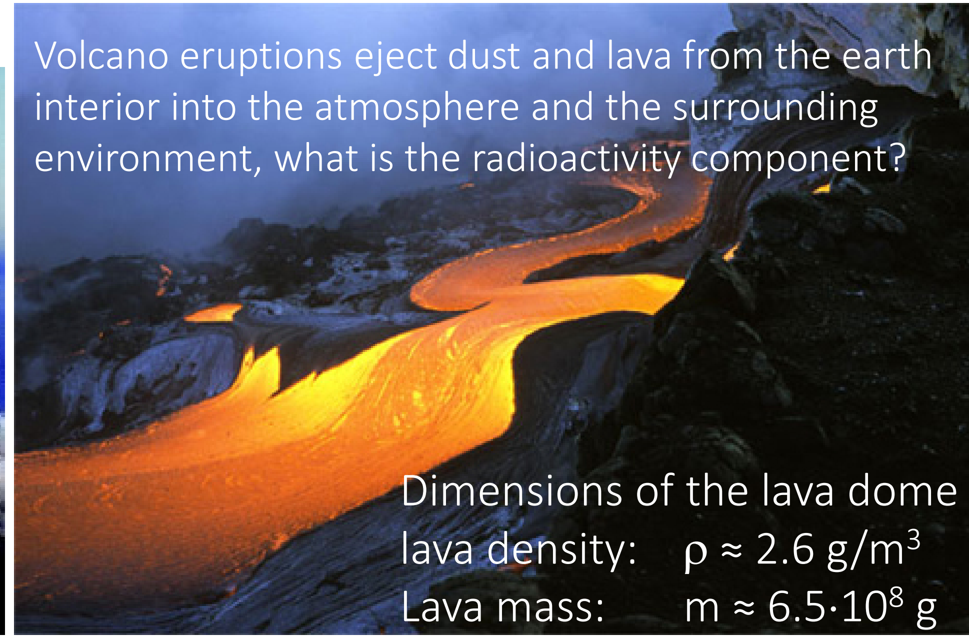
Plate Boundaries, Rifts, and Ridges

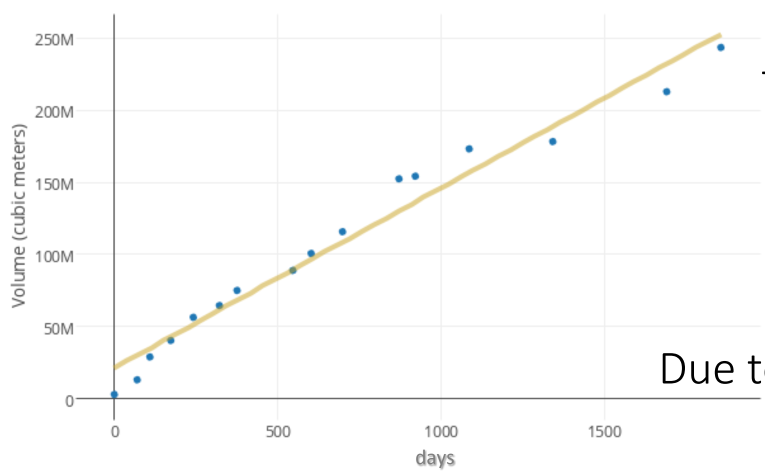




Rift is driven by ascending magma that drives the continents apart with a velocity of ~2cm/year

Volcano Eruptions





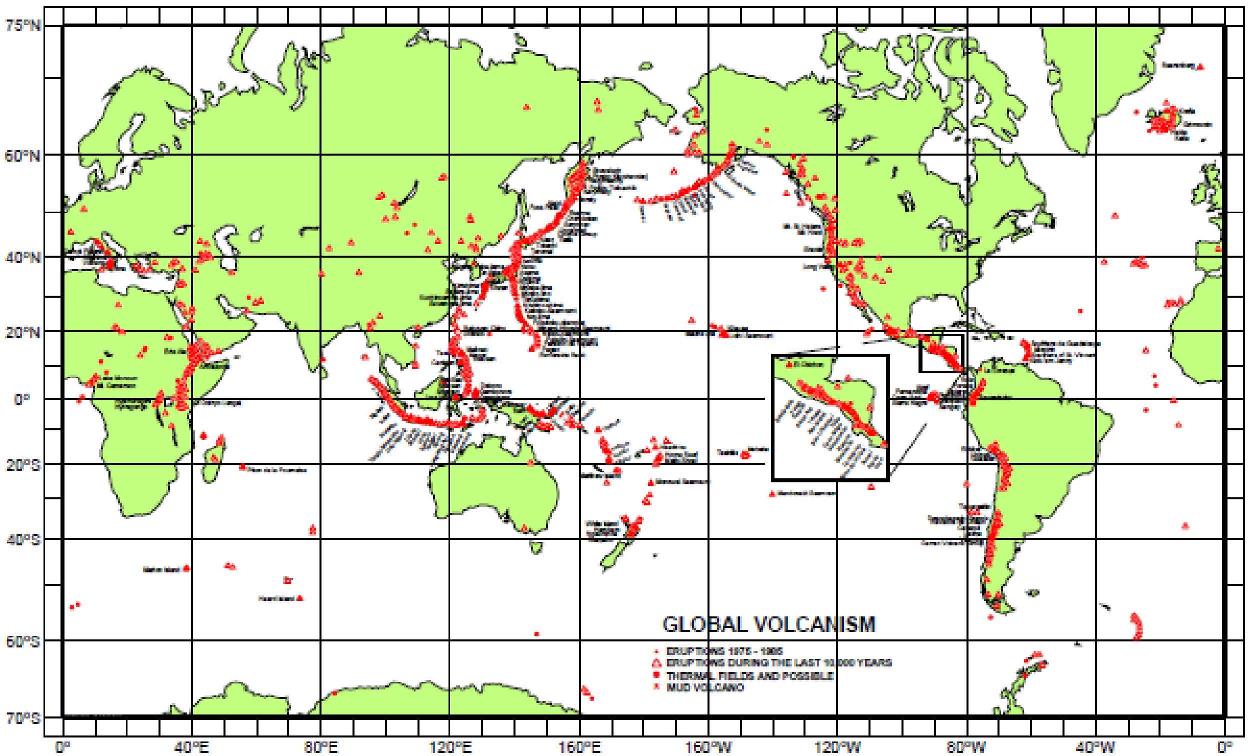
U content: 0.2 ppm
Th content: 0.55 ppm

Ingenious rock:
U content: 2.5 ppm
Th content: 1.3 ppm

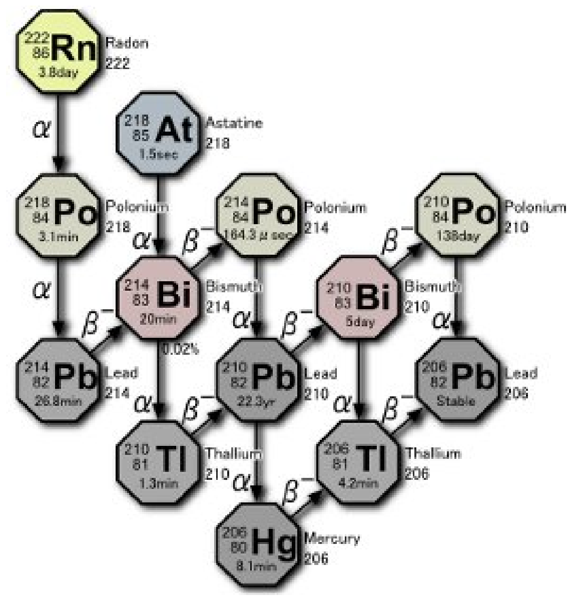
Due to special chemistry in molten lava material.

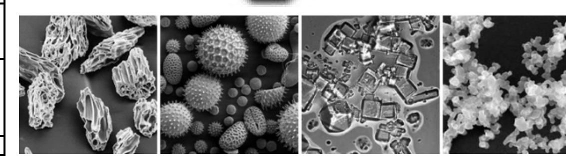
Volcanic Plumes

Radon ^{222}Rn($T_{1/2}$=3.8d) is a highly volatile element and the radioactive daughter isotopes ^{210}Pb ($T_{1/2}$=22.3y) and ^{210}Po ($T_{1/2}$=138d) has been found in substantial amounts in volcanic plumes (0.045 Bq/m^3 to 0.83 Bq/m^3), global volcanism ensures a certain amount of ^{210}Pb activity plus its long-lived radioactive daughter ^{210}Po attached to dust and aerosols in the atmosphere.



On average about 20 volcanoes erupt at any given time worldwide, 50–70 volcanoes erupt throughout a year.





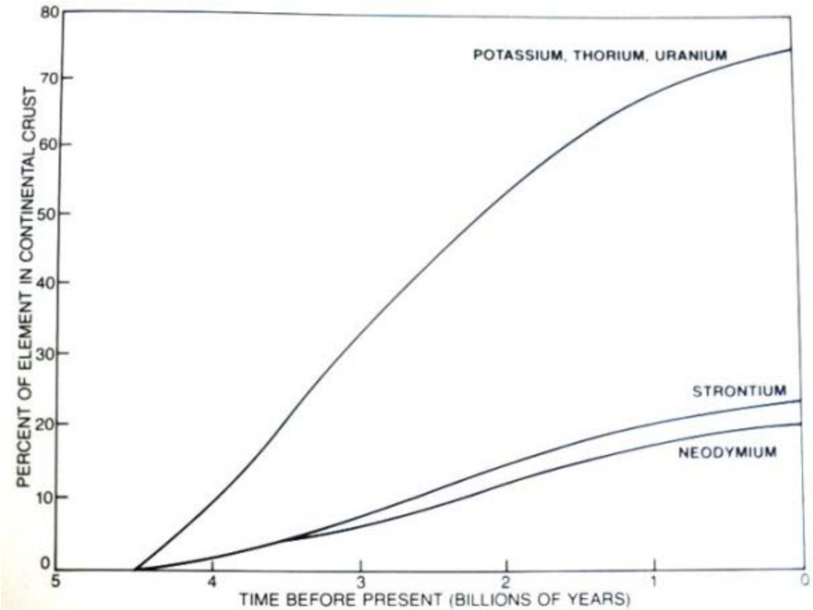
ash, dust, spores, smoke particles

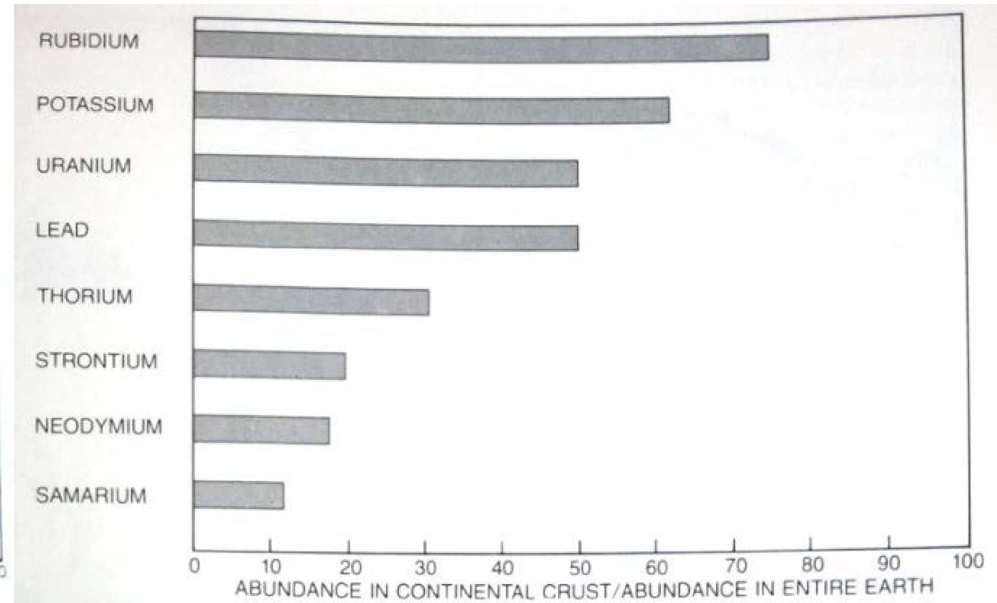
Annual Radioactivity Output of Volcanoes

Annual dust output on average 20 Tg/y = $2 \cdot 10^{13}$/y with a density of $\rho \approx 2500$ kg/m^3
$\Rightarrow 8 \cdot 10^6$ m^3/y!

With an average activity of 0.045 Bq/m^3 to 0.83 Bq/m^3 this translates into an annual release of 360,000 Bq ($2.6 \cdot 10^5$ Bq) to 6,640,000 Bq ($6.6 \cdot 10^6$ Bq) into the atmosphere; mostly locally deposited, fractions will be dispersed globally by high altitude winds.

Crust Enrichment in Radioactivity through
Hadean Bombardment and Convective Mantle Deposition

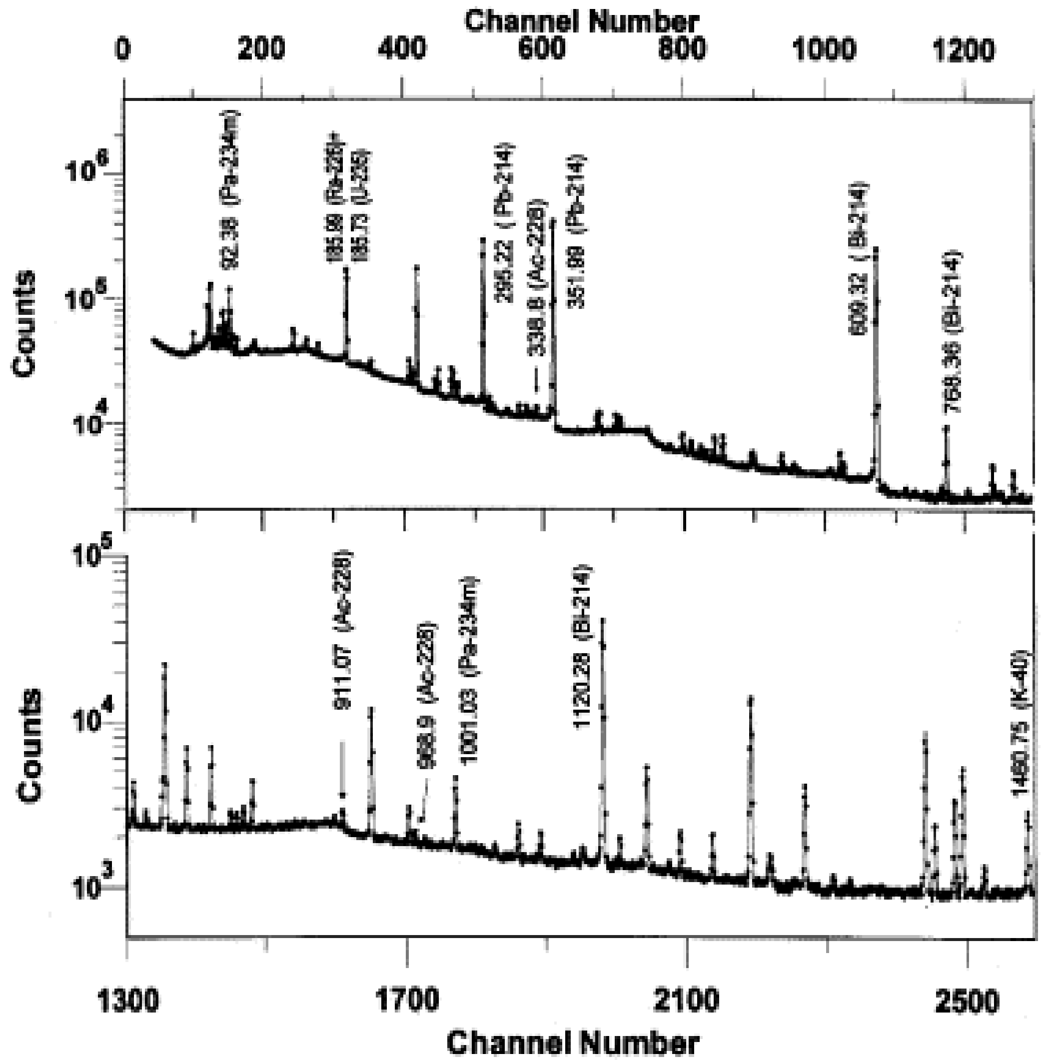


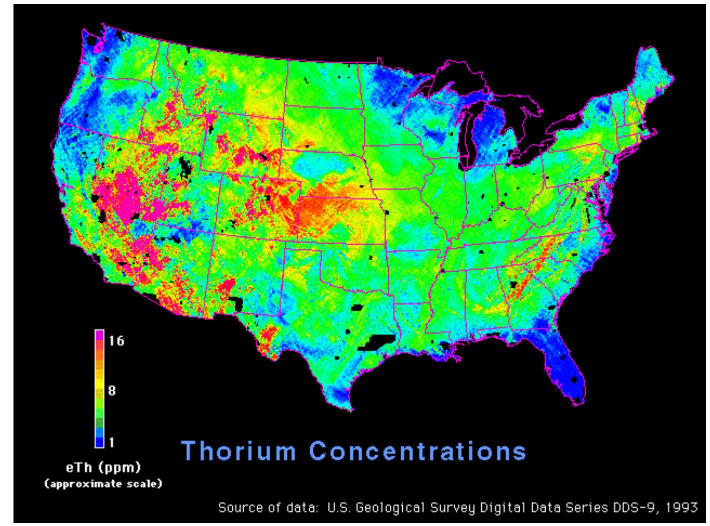


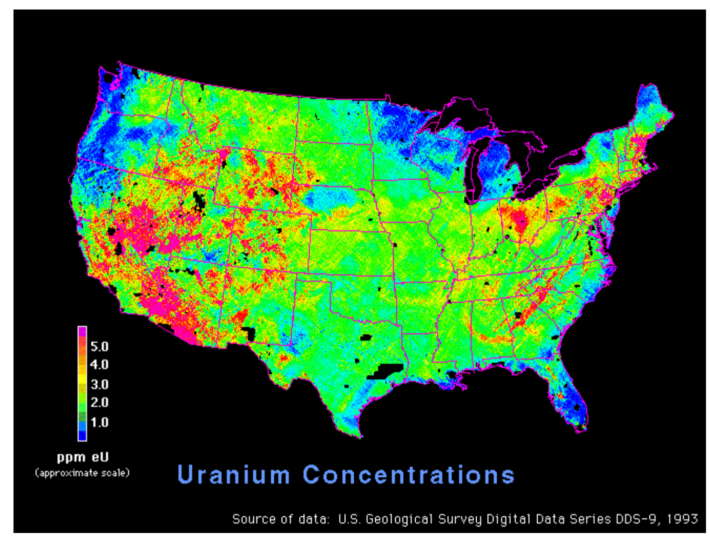
Model predictions for enrichment of crust material in radioactive elements through mantle convection. Early material crystalized in materials such as granite that has a particularly high Uranium and Thorium content. The distribution of the U, Th materials as well as the rare earth metals such as Neodymium within the crust and the surface depends on the subsequent geo-chemical and geological processes during the cooling phase.

Natural Decay Chains

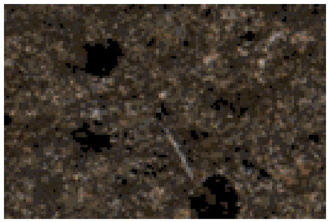
Sequence of alpha decay and beta decay from ^{232}Th and ^{238}U to ^{208}Pb and ^{206}Pb



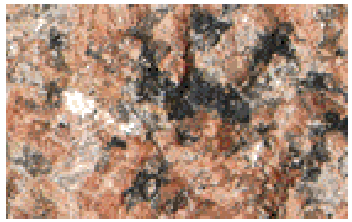




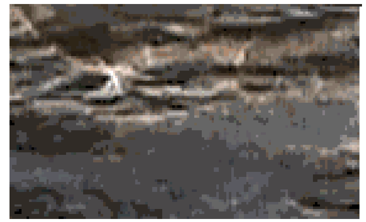
Uranium Distribution



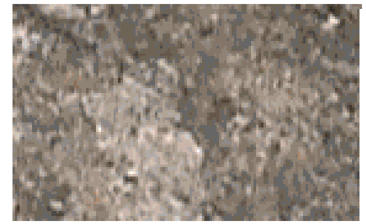
Basalt



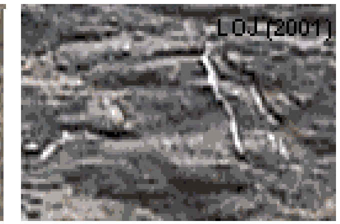
Granite



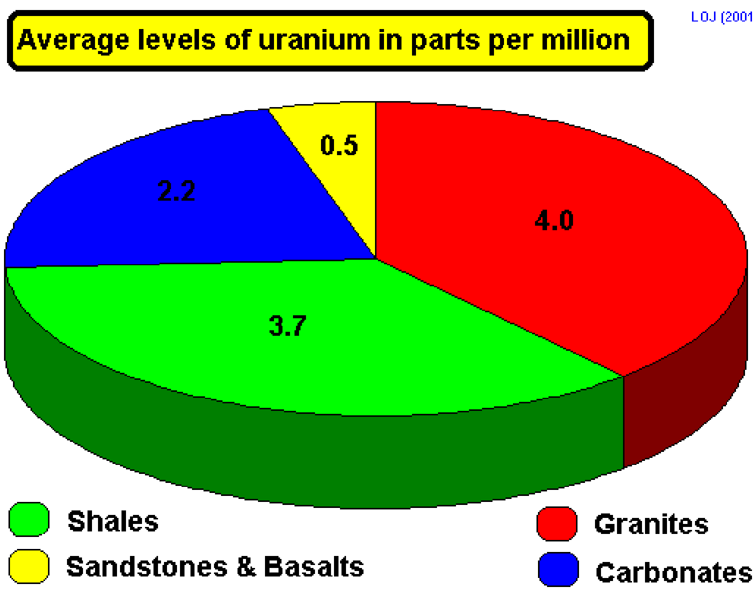
Shale

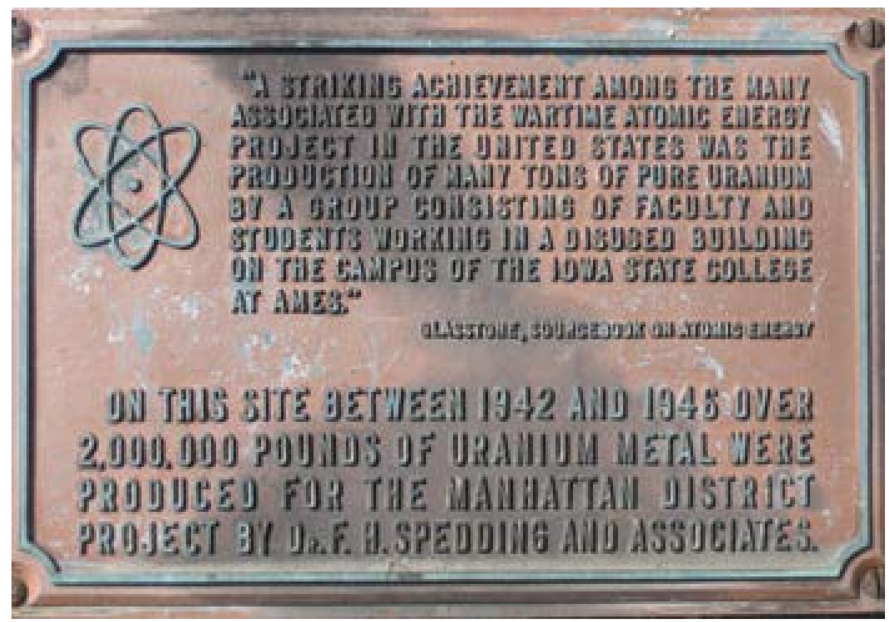


Sandstone



Limestone

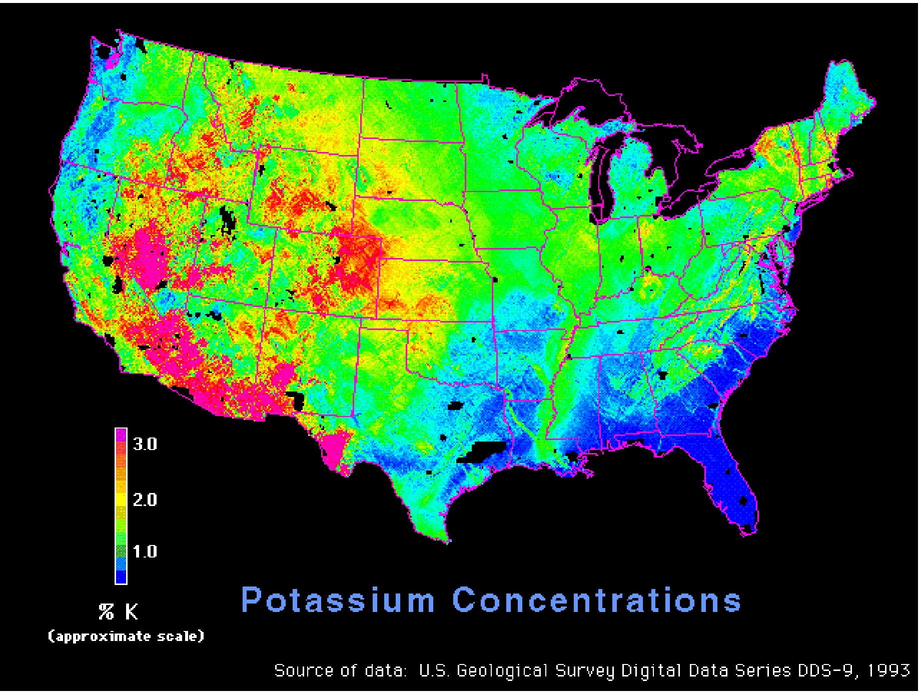


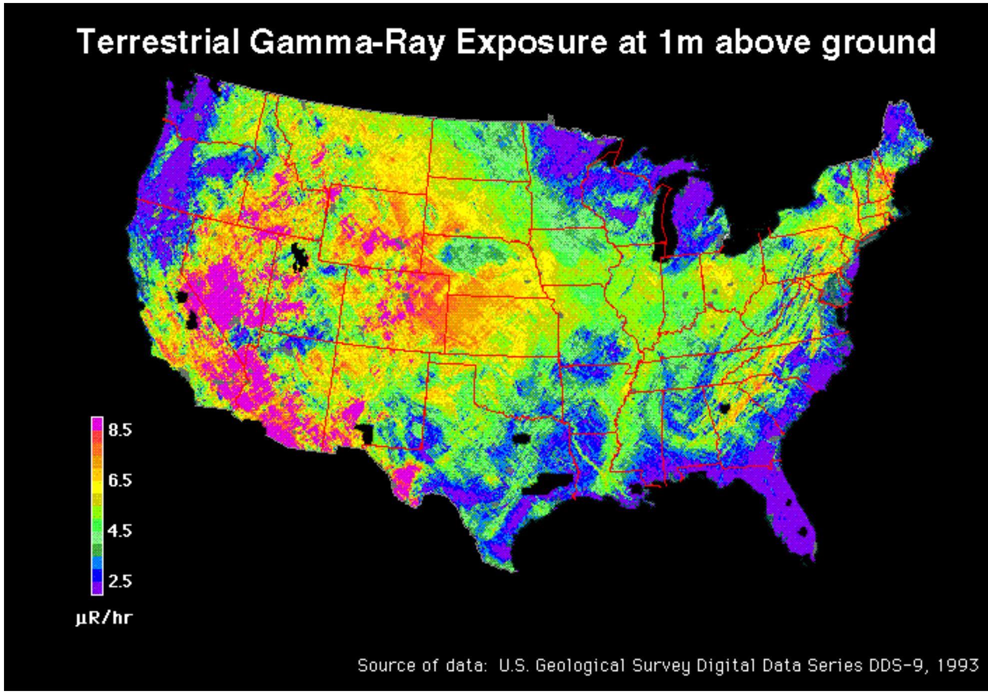


Primarily ^{238}U (99.27%) but with a certain fraction of ^{235}U (0.72%).

Uranium has 92 protons, ^{238}U has 146 neutrons, ^{235}U has 133 neutrons!

Potassium and overall Dose by γ Radiation





In South Bend area:	D = 2.5 μRem/h = $2.5\cdot10^{-8}$ Sv/h=0.2 mSv/y
In US South West:	D = 8.5 μRem/h = $8.5\cdot10^{-8}$ Sv/h=0.74 mSv/y
Total Dose in the US:	D= 620 mRem/y=6.2mSv/year (3%-10%)
Total natural Dose in US:	D= 310 mRem/y=3.1mSv/year (6%-20%)

Radioactivities in Rocks

Ranges[a,b] and Averages of the Concentrations of ^{40}K, ^{232}Th, and ^{238}U in Typical Rocks and Soils[c]

Material	Potassium-40		Thorium-232		Uranium-238	
	% total K	Bq kg^{-1}	ppm	Bq kg^{-1}	ppm	Bq kg^{-1}
Igneous rocks						
Basalt (crustal ave.)	0.8	300	3–4	10–15	0.5–1	7–10
Mafic	0.3–1.1	70–400	1.6, 2.7[d]	7, 10[d]	0.5, 0.9[d]	7, 10[d]
Salic	4.5	1100–1500	16, 20[d]	60, 80[d]	3.9, 4.7[d]	50, 60[d]
Granite (crustal ave)	>4	>1000	17	70	3	40
Sedimentary rocks						
Shale sandstones	2.7	800	12	50	3.7	40
Clean quartz	<1	<300	<2	<8	<1	<10
Dirty quartz	2?	400?	3–6?	10–25?	2–3?	40?
Arkose	2–3	600–900	2?	<8	1–2?	10–25?
Beach sands	<1	<300	6	25	3	40
Carbonate rocks	0.3	70	2	8	2	25
All rock (range)[a]	0.3–4.5	70–1500	1.6–20	7–80	0.5–4.7	7–60
Continental crust (ave.)	2.8	850	10.7	44	2.8	36
Soil (ave.)	1.5	400	9	37	1.8	22

Natural Reactors, Oklo in Gabun

Observational Evidence

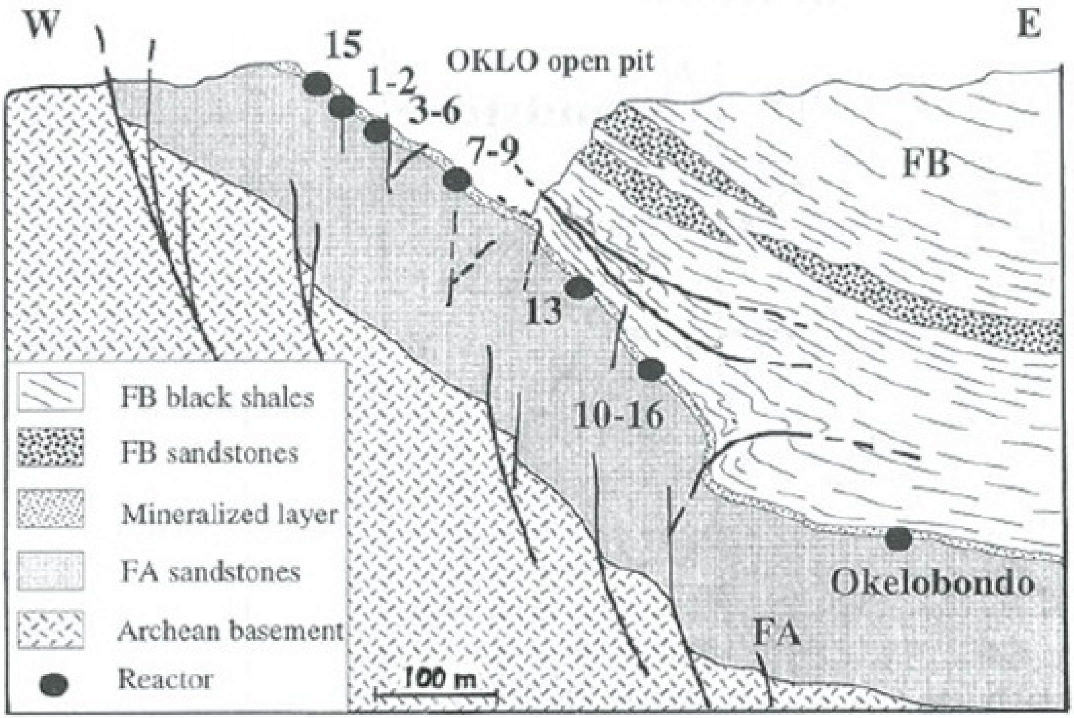
Near provincial capital Francevillette Gabun, French controlled colonial area.
Uranium mining established in the late 1940ies.
Mining for Uranium mineral Uranium Vanadate

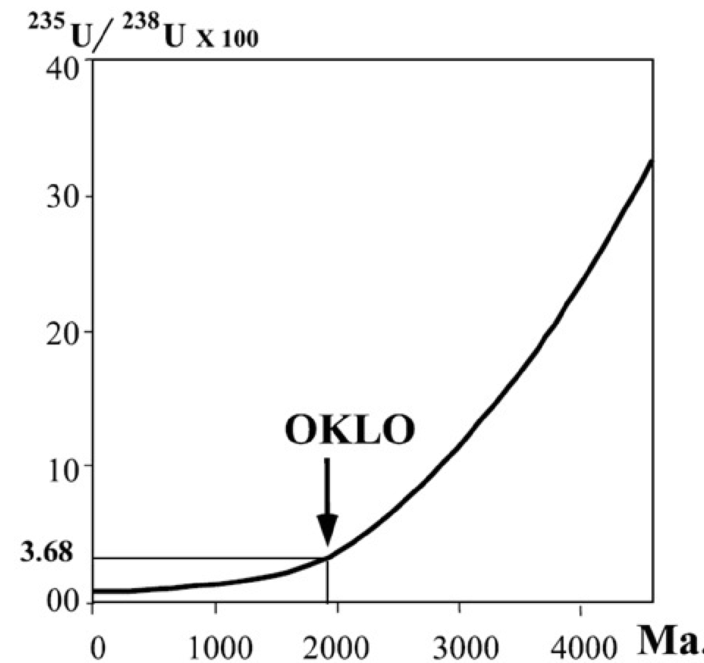
Slightly lower fraction of ^{235}U isotope component 0.717% compared to the average of 0.720% in local deposition.

A natural reactor needs an enrichment of ^{235}U of up to 3% over a distance a 70 cm to thermalize the neutrons for fission. The surrounding environment should be able to act as moderator, sand with water. Lack of Li and B is advantageous since those would act as neutron absorbers.

In Oklo rift 17 natural reactor sites were identified along the uranium containing rock vain. Those were formed and burned about 2 Billion years ago.

The Oklo Reactor Conditions

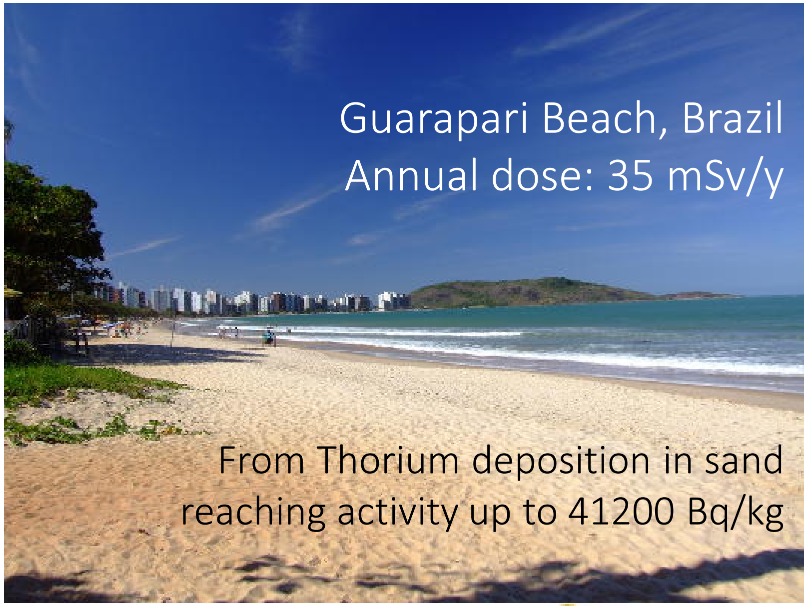


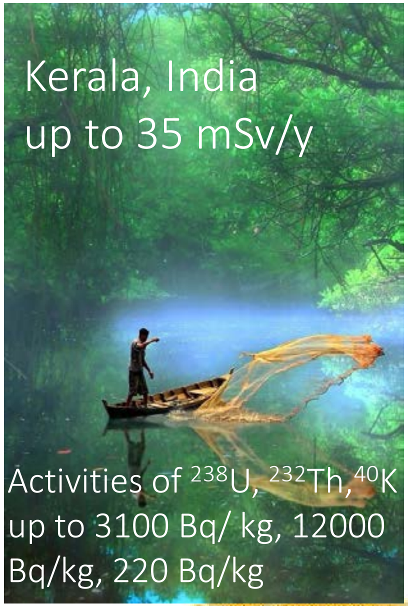


Geologic cross-section of the Oklo uranium deposits, showing the locations of the nuclear reactors. The nuclear reactors are found in the FA sandstone layer with the sandstone acting as moderator. Reactor shut down naturally because of decline in ^{235}U content. Fission products remained local, there was no diffusion into environment.

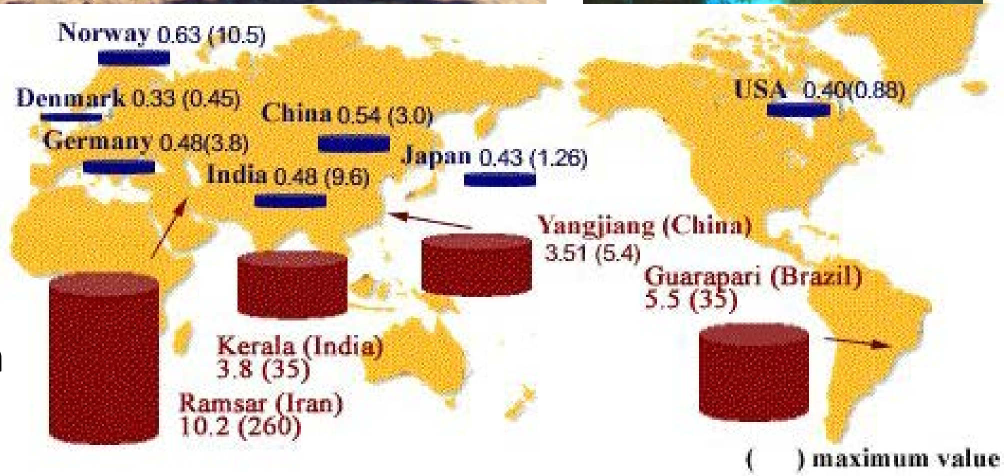
$^{235}U/^{238}U$ in the Earth's crust over time. When the Gabon natural nuclear reactors operated about two billion years ago, the Earth's crust contained approximately 3.68% of ^{235}U.

High Dose Areas from Ramsar to Guarapari





These and other places show substantially enhanced dose values compared to the average total dose of 3 mSv/y for the world population. The average radiogenic dose is only 0.5 mSv/y. Ramsar provides maximum radiation level to its inhabitants, Kerala, and Guarapari are in second place followed by Yangjiang, China!



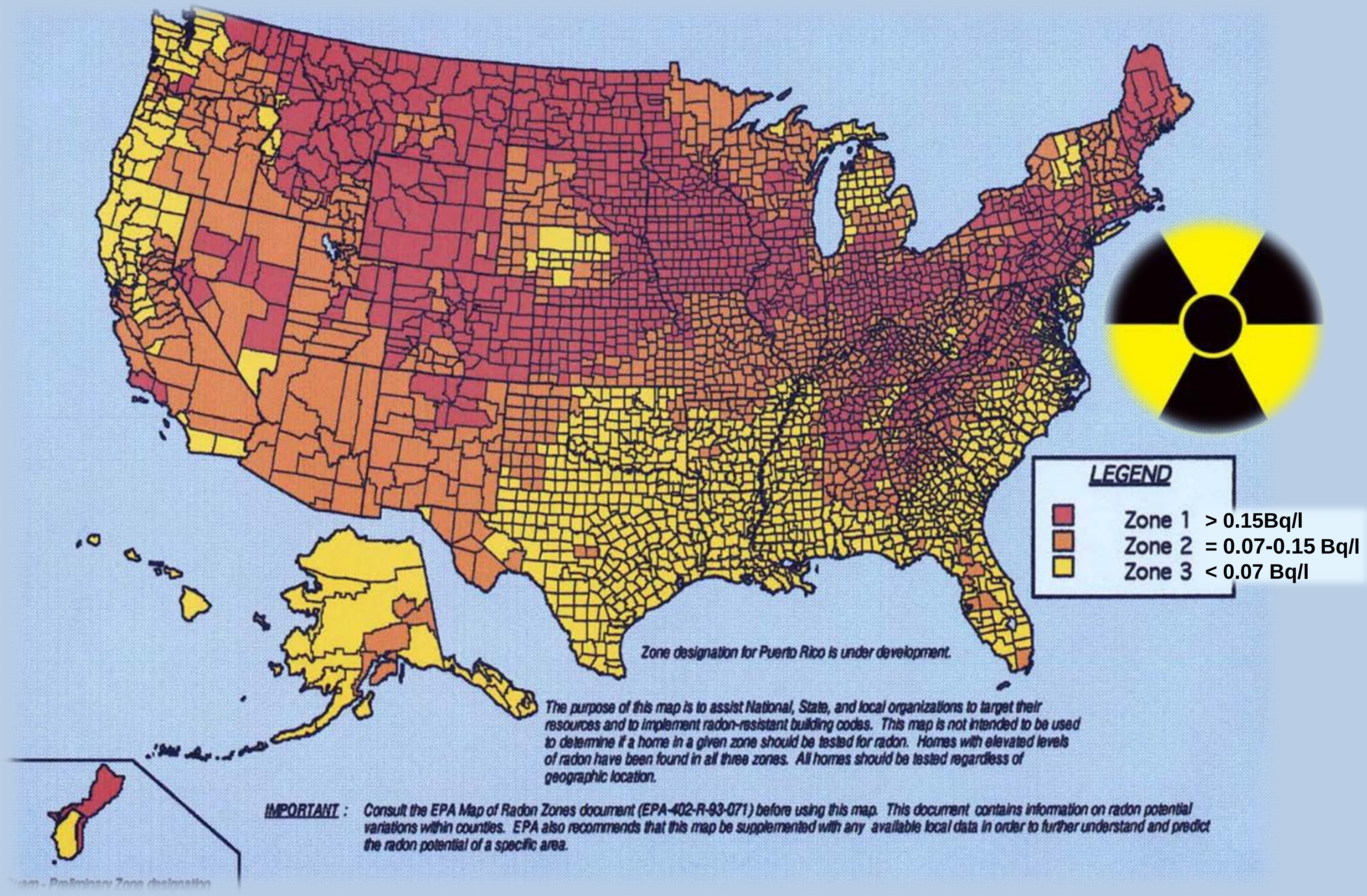
High Background Radiation Areas around the World in mSv/year.

Indications for Radiation Exposure related Health Consequences?

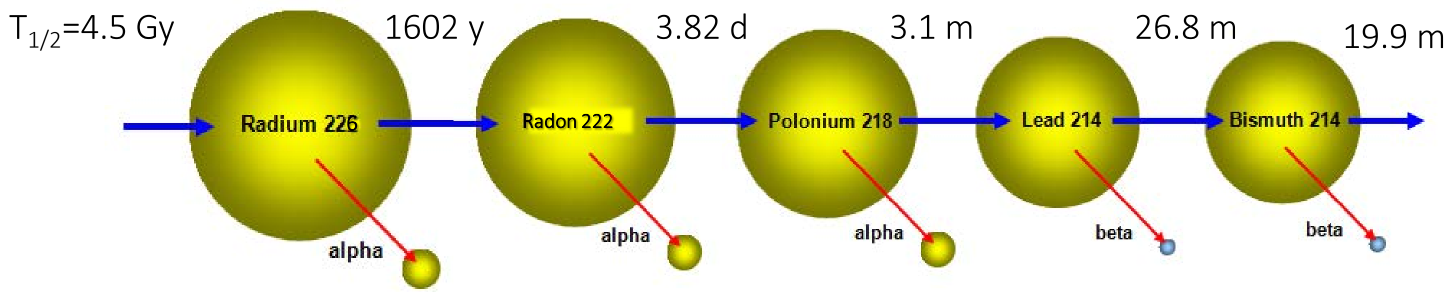
Studies on the approximately 2,000 people living in the highest NBR areas show a slightly lower rates of lung cancer – an unexpected result considering the elevated levels of radioactive radon gas in their homes. Mortality rate comparable to average population. Enhanced cell enzymatic cell repair mechanism.

Also in Guarapari and Kerala no indication of health effects in terms of cancer and mutation rates.

Radon, Danger lurks in the Basement

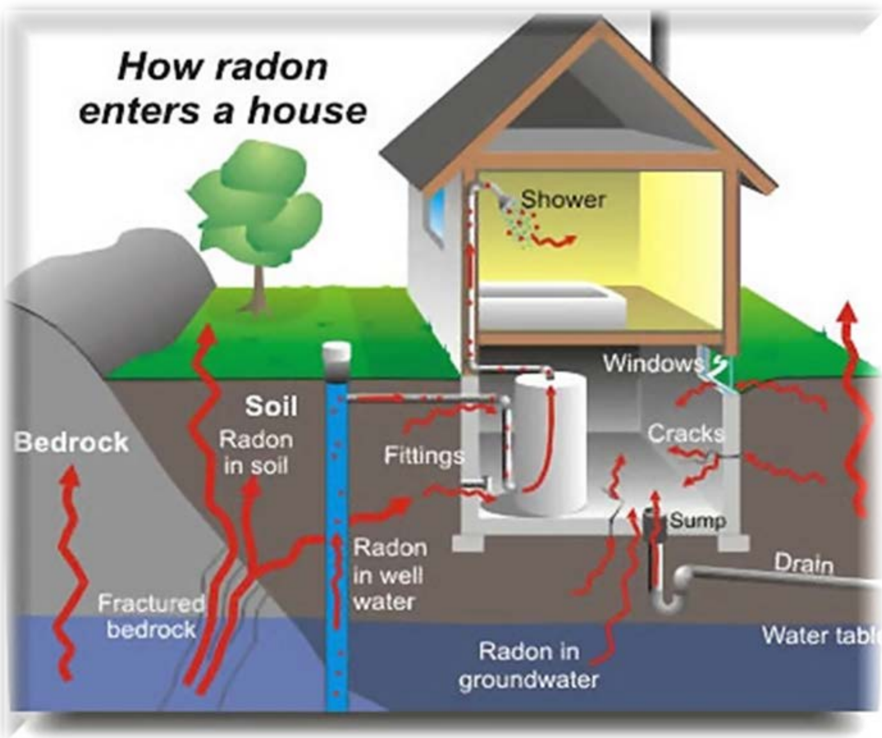


Radon Decay and Deposition

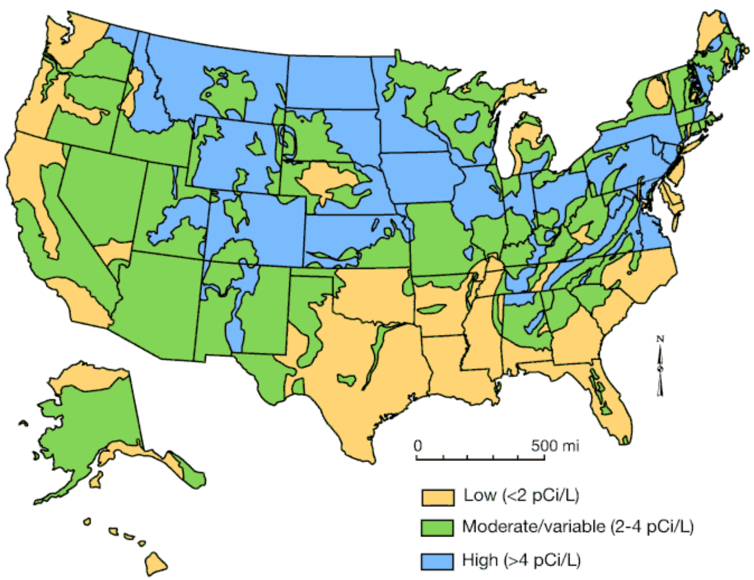


Radon is a noble gas with no chemical binding to rock material. The average content in crust is $4{\cdot}10^{-13}$ mg/kg. It diffuses slowly to the surface and leaks out into atmosphere. Since it is a heavy gas it accumulates near ground. Global radon emissions from soil are estimated to be $8.88{\cdot}10^{19}$ Bq ^{222}Rn, followed by release from groundwater $1.86{\cdot}10^{19}$ Bq , oceans $1.27{\cdot}10^{18}$ Bq , human activities phosphate residues $2.0{\cdot}10^{17}$ Bq annually. By inhaling it gets into lung and can deposit radioactive daughters in particular from short-lived ^{220}Rn from ^{232}Th decay chain. The emitted α radiation can damage the sensitive lung cells and materials leading to cancer.

Increased Radon emission in granite mountain ranges

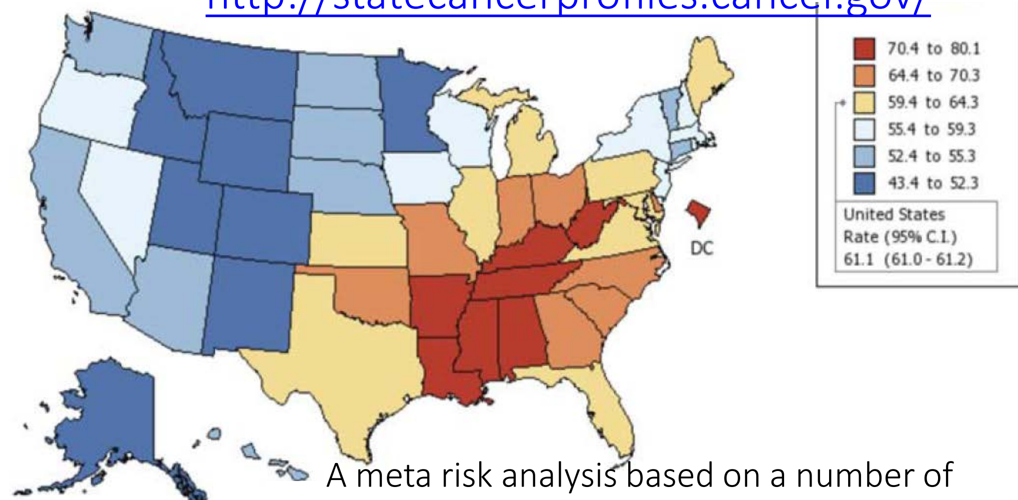


Evidence in Comparison of Cancer and Radon Emission Rate?

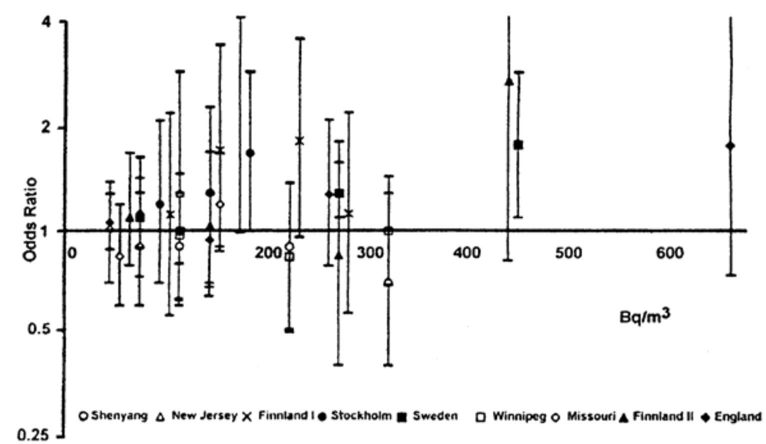


Environmental Protection Agency EPA
https://www.epa.gov/radon

National Cancer Institute
http://statecancerprofiles.cancer.gov/



A meta risk analysis based on a number of international studies shows no statistical evidence for a radon lung-cancer correlation!



The data show an anti-correlation between the two studies, high Radon emission correlates with low cancer rates and vice versa! Other factors, poverty, smoking, ...