Radioactivity

Lecture 12
Geological Implications and Consequences
Radiogenic Heat Generation

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

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

Human energy consumption $\sim 550$ Exa-Joules/year = $5.5 \cdot 10^{20}$ J/y = $1.75 \cdot 10^{13}$ W = 17.5 TW

61.5% heat loss, 38.5% useful energy loss
Mantle Convection as Cooling Mechanism

Observed heat flow through the entire earth surface is 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.
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

Ice world?

Pangaea 200 Ma

Desert or tropical world!

Rodinia 1000 Ma

Gondwana 100 Ma
Rift is driven by ascending magma that drives the continents apart with a velocity of ~2cm/year.
Volcano Eruptions

Volcano eruptions eject dust and lava from the earth interior into the atmosphere and the surrounding environment, what is the radioactivity component?

Dimensions of the lava dome
- Lava density: $\rho \approx 2.6 \text{ g/m}^3$
- Lava mass: $m \approx 6.5 \times 10^8 \text{ g}$

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

Annual dust output on average 20 Tg/y = $2 \cdot 10^{13}$/y with a density of $\rho \approx 2500 \text{ kg/m}^3 \Rightarrow 8 \cdot 10^6 \text{ m}^3$/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 (2.6·10$^5$ Bq) to 6,640,000 Bq (6.6·10$^6$ 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 crystallized 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
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 $\gamma$ Radiation

In South Bend area:
$D = 2.5 \, \mu\text{Rem/h} = 2.5 \cdot 10^{-8} \, \text{Sv/h} = 0.2 \, \text{mSv/y}$

In US South West:
$D = 8.5 \, \mu\text{Rem/h} = 8.5 \cdot 10^{-8} \, \text{Sv/h} = 0.74 \, \text{mSv/y}$

Total Dose in the US:
$D = 620 \, \text{mRem/y} = 6.2 \, \text{mSv/year (3%-10%)}$

Total natural Dose in US:
$D = 310 \, \text{mRem/y} = 3.1 \, \text{mSv/year (6%-20%)}$
## Radioactivities in Rocks

### Ranges and Averages of the Concentrations of $^{40}$K, $^{232}$Th, and $^{238}$U in Typical Rocks and Soils

<table>
<thead>
<tr>
<th>Material</th>
<th>Potassium-40</th>
<th>Thorium-232</th>
<th>Uranium-238</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% total K</td>
<td>Bq kg$^{-1}$</td>
<td>ppm</td>
</tr>
<tr>
<td>Igneous rocks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt (crustal ave.)</td>
<td>0.8</td>
<td>300</td>
<td>3–4</td>
</tr>
<tr>
<td>Mafic</td>
<td>0.3–1.1</td>
<td>70–400</td>
<td>1.6, 2.7$^d$</td>
</tr>
<tr>
<td>Salic</td>
<td>4.5</td>
<td>1100–1500</td>
<td>16, 20$^d$</td>
</tr>
<tr>
<td>Granite (crustal ave.)</td>
<td>&gt;4</td>
<td>&gt;1000</td>
<td>17</td>
</tr>
<tr>
<td>Sedimentary rocks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale sandstones</td>
<td>2.7</td>
<td>800</td>
<td>12</td>
</tr>
<tr>
<td>Clean quartz</td>
<td>&lt;1</td>
<td>&lt;300</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Arkose</td>
<td>2–3</td>
<td>600–900</td>
<td>2?</td>
</tr>
<tr>
<td>Beach sands</td>
<td>&lt;1</td>
<td>&lt;300</td>
<td>6</td>
</tr>
<tr>
<td>Carbonate rocks</td>
<td>0.3</td>
<td>70</td>
<td>2</td>
</tr>
<tr>
<td>All rock (range)$^a$</td>
<td>0.3–4.5</td>
<td>70–1500</td>
<td>1.6–20</td>
</tr>
<tr>
<td>Continental crust (ave.)</td>
<td>2.8</td>
<td>850</td>
<td>10.7</td>
</tr>
<tr>
<td>Soil (ave.)</td>
<td>1.5</td>
<td>400</td>
<td>9</td>
</tr>
</tbody>
</table>
Natural Reactors, Oklo in Gabun
Observational Evidence

Near provincial capital Franceville, 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 $^{235}\text{U}$ content. Fission products remained local, there was no diffusion into environment.

$^{235}\text{U}/^{238}\text{U}$ 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 $^{235}\text{U}$. 
High Dose Areas from Ramsar to Guarapari

Ramsar Springs, Iran
Radium solutions up to 250 mSv/y

Guarapari Beach, Brazil
Annual dose: 35 mSv/y

From Thorium deposition in sand reaching activity up to 41200 Bq/kg

Kerala, India
up to 35 mSv/y

Activities of $^{238}$U, $^{232}$Th, $^{40}$K up to 3100 Bq/kg, 12000 Bq/kg, 220 Bq/kg

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?

142-143 $\mu$Sv/h = 1.22 Sv/y

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

Legend:
- Zone 1: > 0.15 Bq/l
- Zone 2: 0.07 - 0.15 Bq/l
- Zone 3: < 0.07 Bq/l
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 $\alpha$ 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?

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

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

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, .....