Radioactivity, Radiation, Radon and Health

Earth 281

Main reference: Chapter 10 from Selinus O., Alloway B., Centeno J.A., Finkelman R.B, Fuge R., Lindh U., and Smedley P., 2005. *Essentials Of Medical Geology: Impacts Of The Natural Environment On Public Health.* p.832. Academic Press.

Radioactivity: Why is it important? What is the problem?

a) Invisible – Fear
b) Natural hazards vs. man made
c) Both scientific issues and regulatory issues (e.g. natural sources and occurrences vs. policing of International Atomic Energy Agency – IAEA – nuclear programs)

Naturally Occurring Sources

1. Many natural sources; the Earth's heat and tectonics function in part due to radiation and radioactive decay (explained shortly) (provides heat – drives cycles)
2. Most abundant ^{40}K, ^{232}Th, ^{238}U, ^{235}U (most activity in the near surface is traceable back to U and Th) (~ 10^{22} Bq)
3. Crustal rocks ~2.7 ppb U; 9.6 ppb Th. Enriched in silica rich rocks, e.g. granite or some groundwaters (< 0.1 (μL^{-1}) in reducing waters; can be > 100 $\mu g L^{-1}$ in oxidizing waters

Naturally Occurring Sources

4. The radiation that you receive each year is about 85% natural (e.g. cosmic, gamma, radon). Mostly geological (Figure 2). Gamma rays from U, Th, K, minerals. Often incorporated into building materials (e.g. concrete).
5. Natural foods: shellfish are the highest (filter feeders, capture fine mineral particulates)
6. Cosmic Rays: Solution; Do not live at high altitude or fly a lot. The poles are higher in radiation as well. (Table VII)
7. 1 Bq = 1 atomic disintegration per second (Table III)

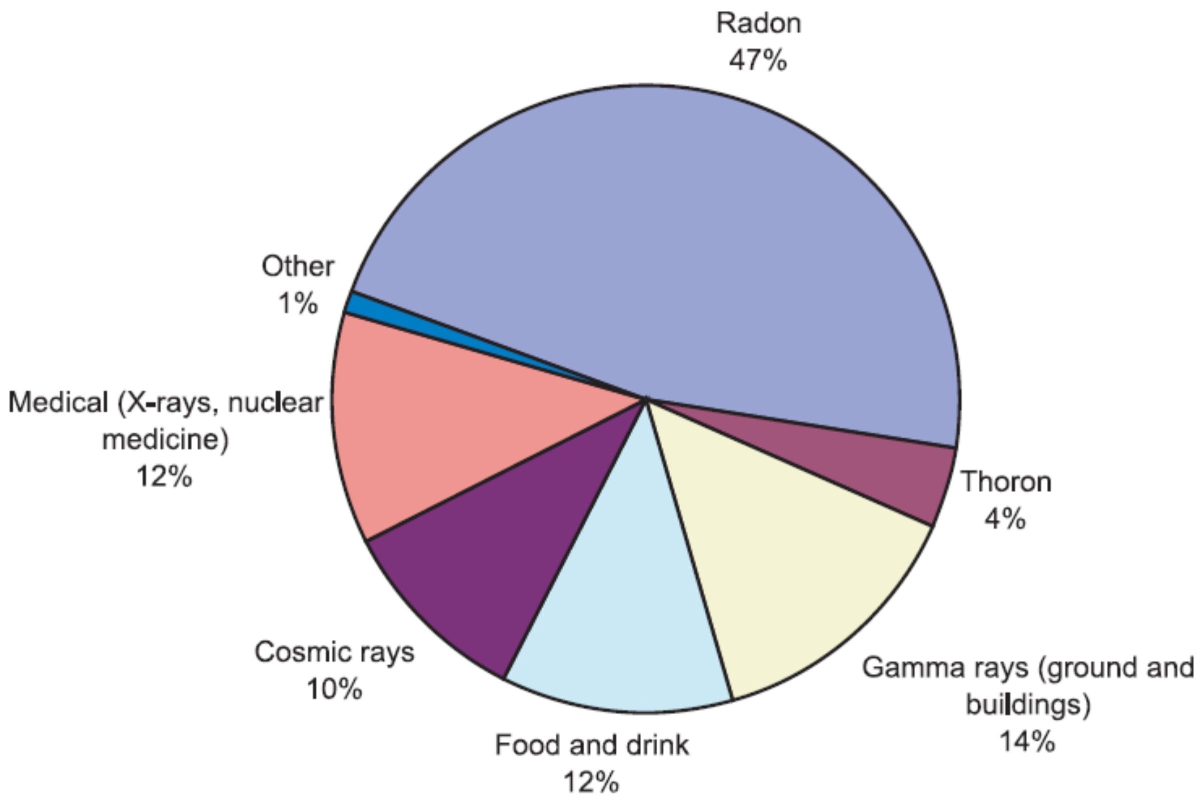

FIGURE 2 Sources of radiation exposure contributing to average effective dose in the UK. Other = occupation 0.3%, fallout 0.2%, nuclear discharges <0.1%, and products <0.1%. (UK NRPB data.)

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TABLE VII. Sources of Radiation for Average Person in the UK

Source	*Annual dose (%)*
Natural sources	87.0
Radon (^{222}Rn) gas from the ground	47.0
Thoron (^{220}Rn) from the ground	4.0
Gamma rays from the ground and building materials	14.0
Food and drink	12.0
Cosmic rays	10.0
Artificial sources	13.0
Medical	12.0
Nuclear discharges	0.1
Work	0.2
Fallout	0.4
Miscellaneous	0.4

From NRPB, 1989.

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TABLE III. Units of Measurement of Radioactivity and Dose

Quantity	*Unit*	*Purpose*	*Comments*
Activity	Becquerel (Bq)	Measure activity of a radioactive material (solid or gas); the International System of Units (SI) definition of activity	1 Bq = 1 atomic disintegration per second
	Curie	In the United States, the activity (rate of decay) of ^{222}Rn is expressed in units called curies	The curie is based on the rate of decay of one gram of ^{226}Ra or 3.7×10^{10} disintegrations per second
	Pico curies (pCi)		1 pCi = one trillionth of a curie; 0.037 disintegrations per second, or 2.22 disintegrations per minute
Radioactivity in air or water	Becquerels/m^{-3} ($Bq\,m^{-3}$)	Measure average concentration of radon gas in building or in soil air Bq/L used to measure radon in water	Average level of radon in houses in Great Britain is 20 $Bq\,m^{-3}$; in Sweden 108 $Bq\,m^{-3}$
	pico curies/L^{-1} ($pCi\,L^{-1}$)	Unit used in the United States	Average level of radon in houses in the United States is 1.24 $pCi\,L^{-1}$ equivalent to 46 $Bq\,m^{-3}$
Absorbed dose	Gray (Gy)	Measure energy per unit mass absorbed by tissue	1 joule of energy absorbed by 1 kg of tissue
	rad	Old unit of absorbed dose	1 rad = 0.01 Gy
Dose equivalent	Sievert (Sv)	Measure of absorbed doses caused by different types of radiation	Absorbed dose weighted for harmfulness of different radiations
	Roentgen equivalent man (rem)	Old measure of absorbed dose	The rem is being replaced by the Sievert, which is equal to 100 rem

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Man-made Radioactivity

1. Nuclear waste (total loads – see Table 2)

a) Spent fuel (SF)

- Fuel bundles – mostly enriched uranium (often called HLW – high level waste) (contains U, fission products, transuranics) as opposed to medium and low level, i.e. material that contacted HLW – e.g. the proposed Ontario Power Generation Facility at Kincardine is a medium to low waste repository to be built Deep Underground .
- Note: Upper 100m lithosphere = all HLW we have

  but dispersed vs concentrated

Man-made Radioactivity

1. Nuclear waste (total loads – see Table 2)

b) Transuranic Waste (TRU)
   - α emitters, longer half lives
   - result from reprocessing of Spent Fuel
   - reprocessed for plutonium can be used as bomb triggers

c) Tailings
   - Just as it sounds – the waste that results due to mining. One of the wealthiest mining companies in Canada is Cameco Corp. in Saskatchewan.

Table 2 Examples of sources of radioactivity in the environment.

Location	*Source of radioactivity*	*Major radionuclides*	*Amount of radioactivity*	*Ref.*
Global	Top 100 m of lithosphere	$^{238,235}U$, ^{232}Th	1.0×10^{22} Bq	1,2
HLW geologic repository	70 kt spent fuel (proposed)	^{137}Cs, ^{90}Sr	1.0×10^{22} Bq	1,2
Atmospheric testing	220 Megaton yield	^{131}I and ^{3}H	2.0×10^{20} Bq	1,2
		$^{239,240}Pu$	1.0×10^{17} Bq	
Mayak, Russia	Nuclear production	Various HLW	3.6×10^{19} Bq	4
		^{90}Sr, ^{137}Cs	2.1×10^{19} Bq	
US weapons complex	High level waste/ 100 million gallons (3.8×10^{5} m^{3})	Short-lived ($t_{1/2} < 50$ yr): ^{137}Cs, ^{90}Sr, ^{90}Y, ^{137m}Ba, ^{241}Pu	3.3×10^{19} Bq	6
		Longer lived ($t_{1/2} = 50$–500 yr): ^{238}Pu, ^{131}Sm, ^{241}Am	1.1×10^{17} Bq	
		Long lived ($t_{1/2} = 500$–$50{,}000$ yr): ^{239}Pu, ^{240}Pu, ^{14}C	3.3×10^{15} Bq	
		Longest lived ($t_{1/2} > 50{,}000$ yr): ^{99}Tc, ^{135}Cs, ^{233}U	2.0×10^{15} Bq	
Chernobyl	Reactor accident in 1986	^{131}I, $^{134,137}Cs$, $^{103,106}Ru$	1.2×10^{19} Bq	1,2,5
US	U mining and milling	^{226}Ra	1.9×10^{15} Bq	1

References: 1. Ewing (1999), 2. Santschi and Honeyman (1989), 3. NRC (2001), 4. Cochran *et al.* (1993), 5. IAEA (1996), and 6. US DOE (1997a).

From Siegel and Bryan (2005) *in* Vol. 9 *Treatise on Geochemistry*

Radioactivity

a) Many atoms (elements) are unstable and can emit 'ionizing radiation' and change into another atom (element).
b) Process is radioactivity: Change is radioactive decay.
c) These atoms are called radionuclides or radio isotopes.
d) The rate at which the change or 'decay' occurs is called the half life – "period of time during which half the original number of atoms will have changed or decayed to the new atom (element)." Old term sometimes used for new element 'daughter product' OR 'progeny'

TABLE I. The Uranium-238 Decay Series

Nuclide	*Principal mode of decay*	*Half-life*
^{238}U	α	4.5×10^9 years
^{234}TH	β	24.1 days
^{234}Pa	β	1.2 minutes
^{234}U	α	2.5×10^5 years
^{234}TH	α	7.5×10^4 years
^{226}Ra	α	1,602 years
^{222}Rn	α	3.8 days
^{218}Po	α	3.1 minutes
^{214}Pb	β	26.8 minutes
^{218}At	α	1.5 seconds
^{214}Bi	α	19.9 minutes
^{214}Po	α	$1.6 - 10^{-4}$ seconds
^{210}Tl	β	1.3 minutes
^{210}Pb	β	22.6 years
^{210}Bi	β	5.0 days
^{210}Po	α	138.4 days
^{206}Tl	β	4.2 minutes
^{206}Pb	Stable	Stable

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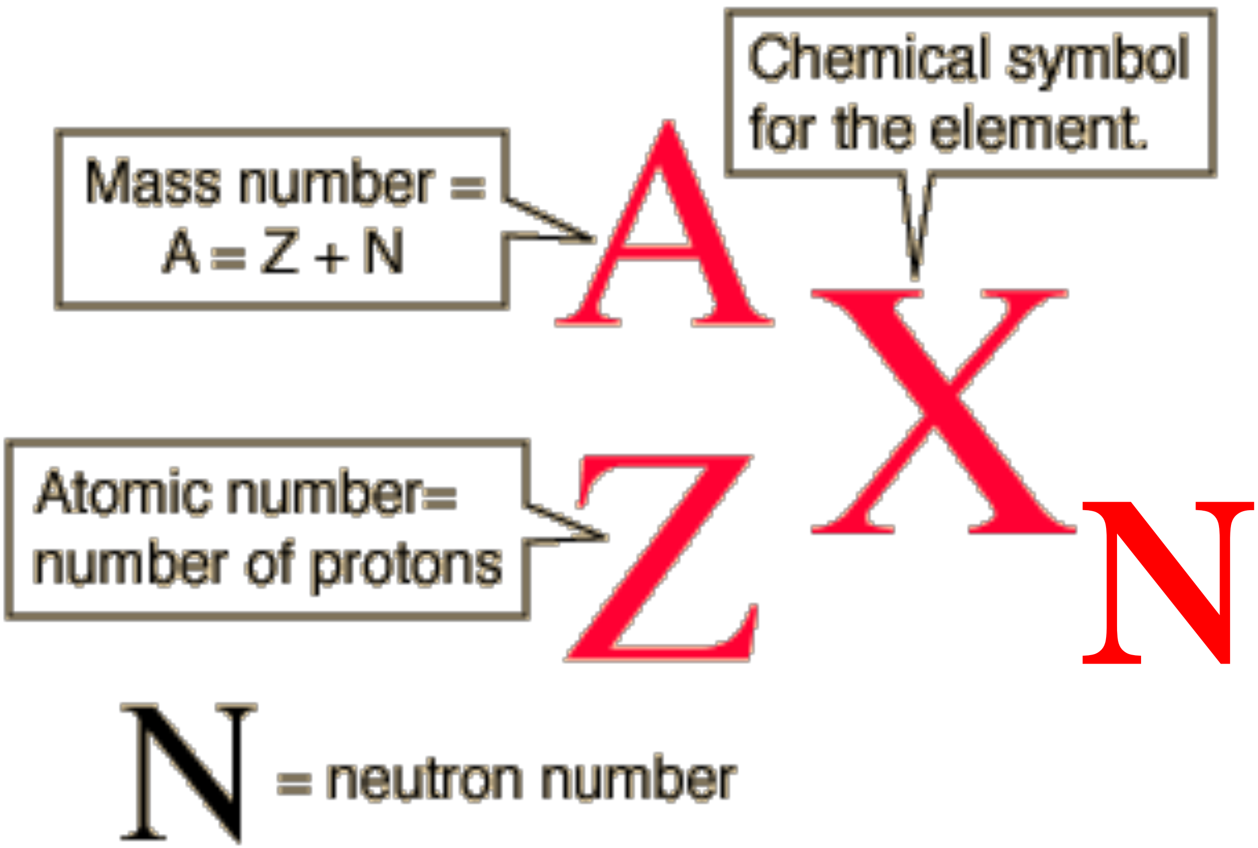
TABLE II. The Thorium-232 Decay Series

Nuclide	*Principal mode of decay*	*Half-life*
^{232}Th	α	1.4×10^{10} years
^{228}Ra	β	5.8 years
^{228}Ac	β	6.1 hours
^{228}TH	α	1.9 years
^{224}Ra	α	3.7 days
^{220}Rn	α	55.6 seconds
^{226}Po	α	0.15 seconds
^{212}Pb	β	10.6 hours
^{212}Bi	α 36%	60.5 minutes
	β 64%	
^{212}Po	α	3.0×10^{-7} seconds
^{208}Tl	β	3.1 minutes
^{207}Pb	Stable	Stable

Isotopes



nuclearphysicswbi.blogspot.ca/

For example:
<u>Oxygen</u>

$$^{16}_{8}O_{8}$$

$$^{18}_{8}O_{10}$$

Decay

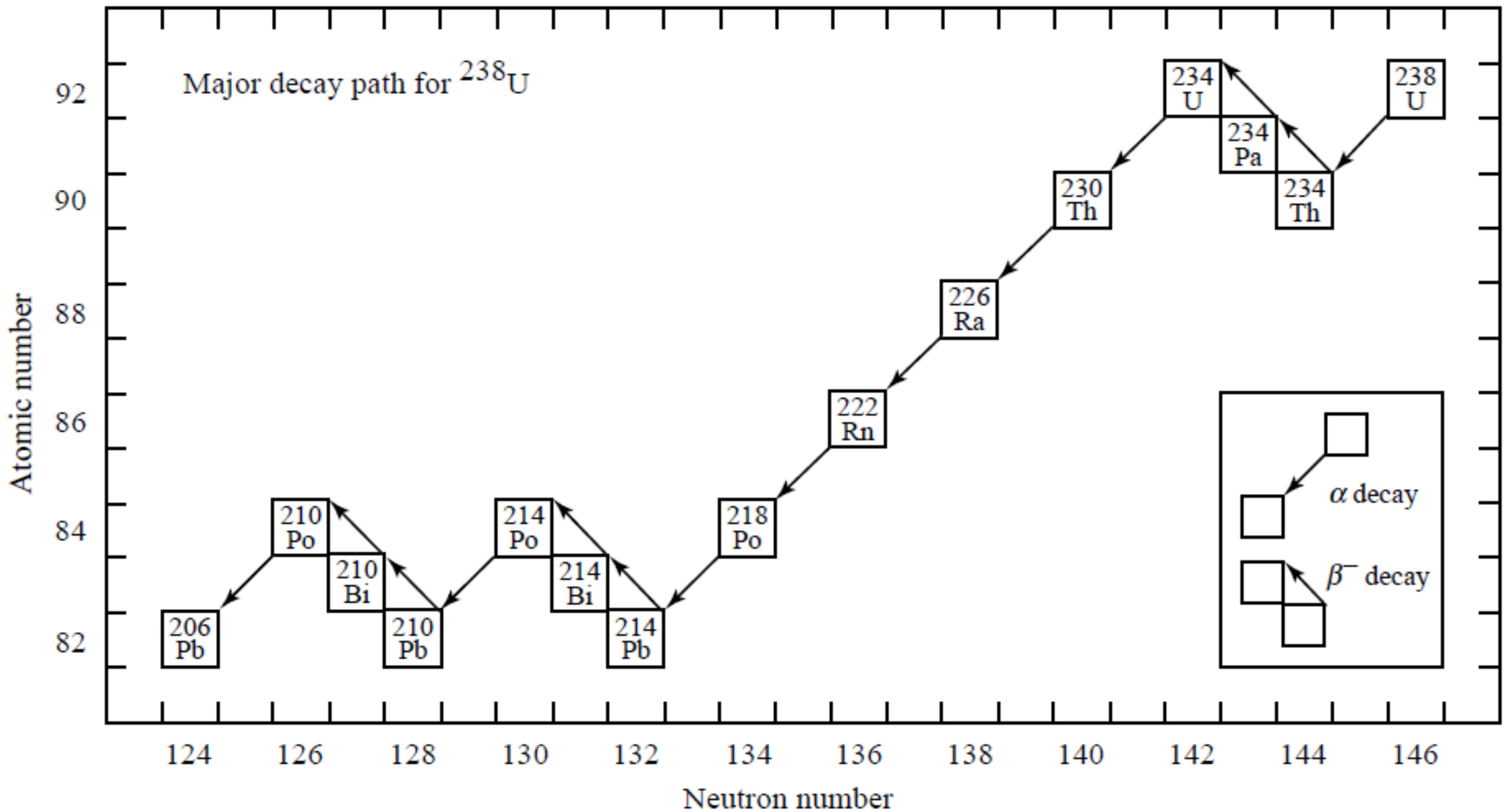


Figure 1 The major decay path for ^{238}U. A small fraction of decays will follow other possible decay paths—for example, decaying by β^- emission from ^{218}Po to ^{218}At, and then by α emission to ^{214}Bi—but ^{206}Pb is the stable end product in all cases.

From Siegel and Bryan (2005) *in* Vol. 9 *Treatise on Geochemistry*

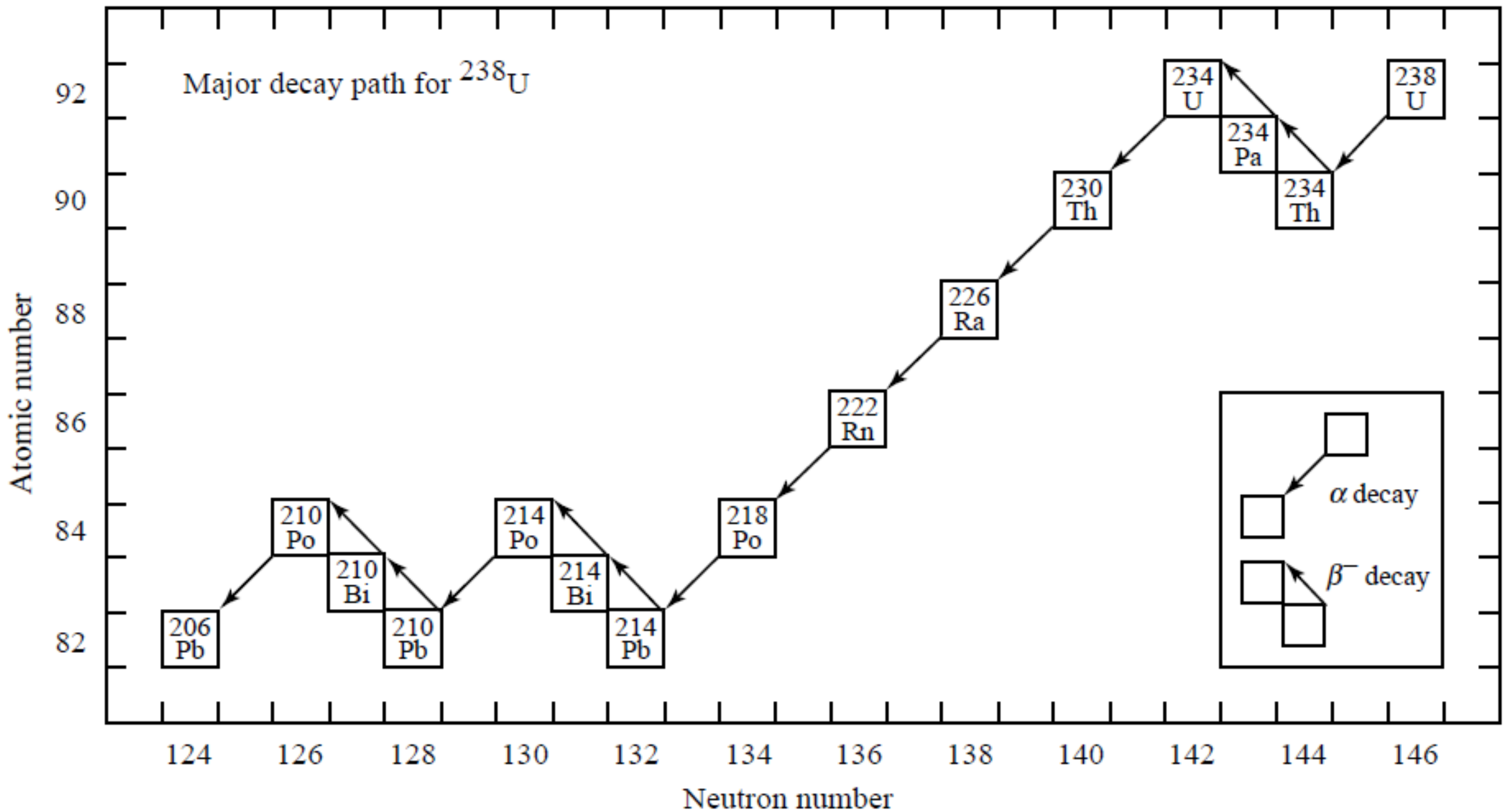
Decay

a) Typical decay chain ^{238}U - Plots Proton number (Z) versus Neutron number (N) (remember the isotope lecture). e.g: Radon 222 – add N(136) + Z (86) = 222

b) At Higher atomic weights you need higher proportion of neutrons to produce stability and therefore transformations or changes occur as the numbers of protons (Z) and/or neutrons (N) change (decay)

c) Back to Figure 1…

Decay



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Decay

- β^- -decay–a negatively charged beta particle (electron) is emitted from the nucleus of the atom, and one of the neutrons is transformed into a proton. Z increases by 1 and N decreases by 1.
- β^+ -decay–a positively charged beta particle (positron) is emitted from the nucleus, and a proton is transformed into a neutron. Z decreases by 1 and N increases by 1.

Decay

- Electron capture–an unstable nucleus may capture an extra nuclear electron, commonly a K-shell electron, resulting in the transformation of a proton to a neutron. This results in the same change in *Z* and *N* as β^+ decay; commonly, nuclides with a deficiency of neutrons can decay by either mechanism.
- α-decay–nuclei of high atomic number (heavier than cerium) and a few light nuclides, may decay by emission of an α-particle, a ^{4}He nucleus consisting of two protons and two neutrons. Z and N both decrease by 2.

Health, Radiation and Radon

1. Radiation leads to particles emitted → particles collide with water and organics in cells (DNA-RNA) and result in "ionization" (e.g. cosmic bombardment creates radionuclides like tritium (^{3}H), ^{36}Cl, etc.)

Health, Radiation and Radon

2. After DNA-RNA
   a) e.g. alpha α little penetration but big energy (cloths stop alphas) – therefore direct impact on the skin – burns with eventual skin cancer. BUT, lungs do not have epidermis like skin so major molecular disruptions are possible (radon progeny)
   b) Gamma rays – X-rays – penetrate – more energetic but fewer… (but not a big issue in Radon problems – greater problems if radiation is severe – ie acute).
   c) Beta intermediate

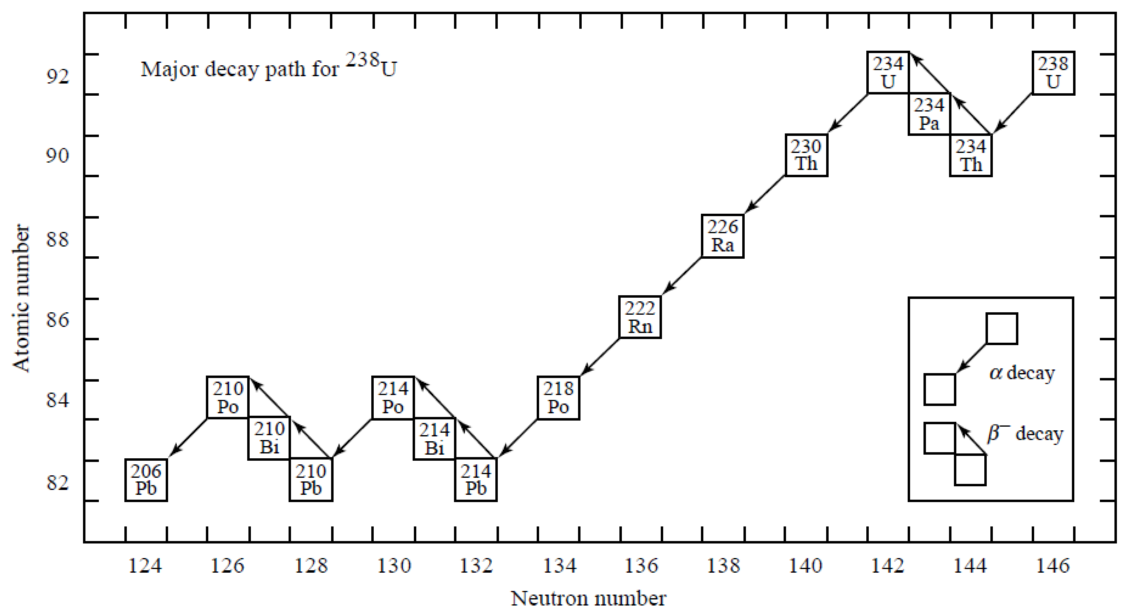
Health, Radiation and Radon

3. Still for radon the "alpha" internal is very bad for health and the by-products (e.g. Po) or progeny can be like dust and be biosoluble in body fluids, etc. This can be a real "long term" problem

Radioactivity and what you receive – Deliverable or Dose

Radon (Rn)

a) Occurs as a gas both in the atmosphere and/or as a dissolved phase in waters (groundwater or surface water). Source is the Uranium decay chain in Figure 1 (Treatise). The parent is radium 226 (Ra half life is 1602 years).



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Radon

b) Three radon isotopes:

Actinon ^{219}Rn (half life 3 seconds)

Thoron ^{220}Rn (half life 55.6 seconds in ^{232}Th chain)

Radon ^{222}Rn (half life of 3.82 days)

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Radon

c) Radon is estimated to be responsible for about 50% of the total radiation a human receives in a year. (Figure 2 in text). Most radon inhaled is exhaled, but you can get polonium 218 (solid) attached to dust particles and other aerosols. The alpha decay is an irritant to bronchi and lungs (high levels can cause cancer – usually a chronic problem).

Radon

a) outdoor air (natural?) 4-8 Bqm^{-3} up to 100 Bqm^{-3} in some valleys (Radon denser than air – sinks)
b) indoors 20 to 110,000 Bqm^{-3} world average (19 Bqm)
c) average 9 in Egypt, 46 US, 108 Sweden (Canada)
d) soils – higher, usually order of magnitude higher than air

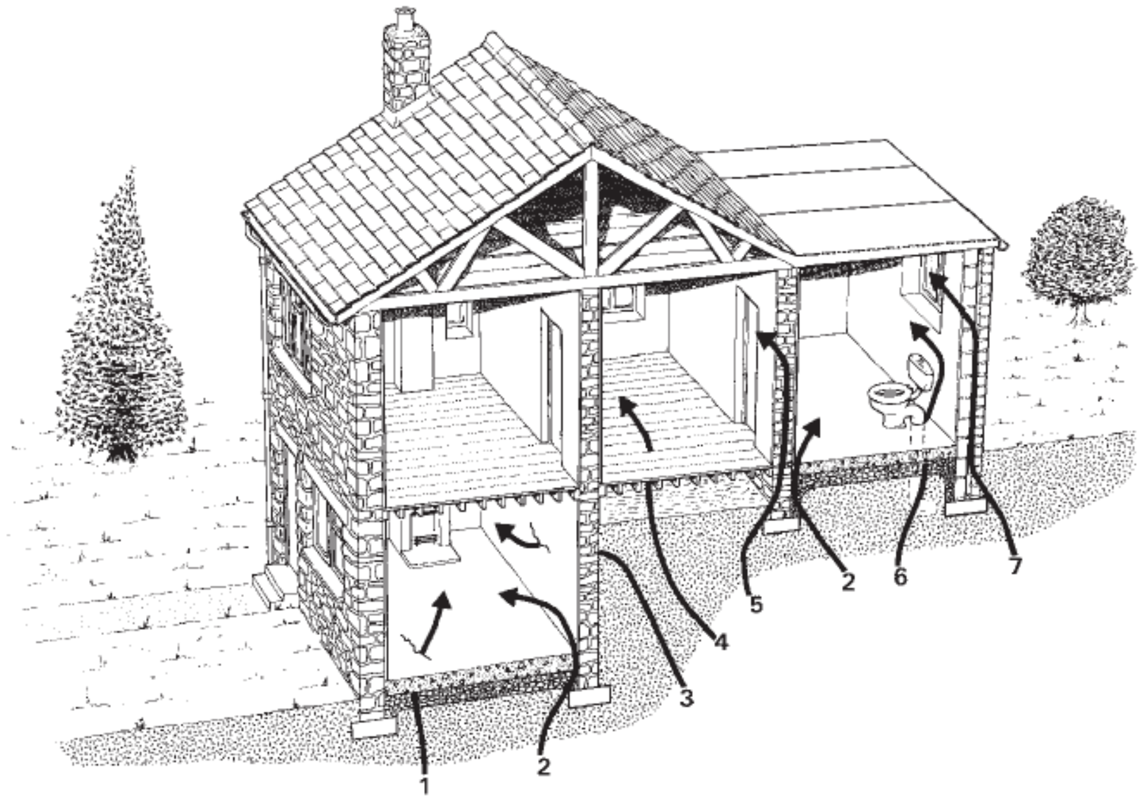

FIGURE 3 Routes by which radon enters a dwelling. (Reproduced with permission from CRC Ltd., publishers of BR211, BRE, 1999.)

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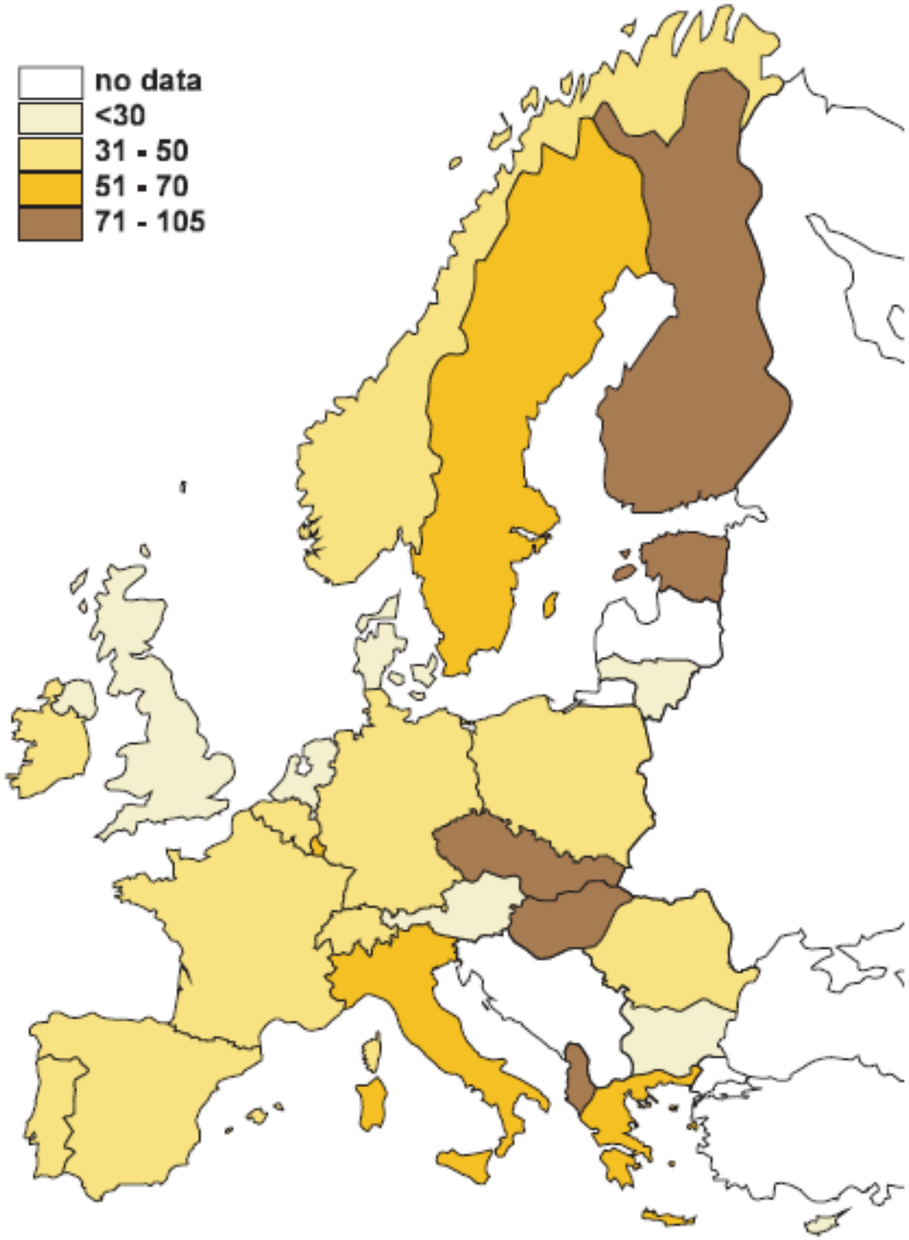

FIGURE 4 Geometric mean radon concentrations ($Bq\,m^{-3}$) indoors in Europe. (Compiled from data in UNSCEAR, 2000.)

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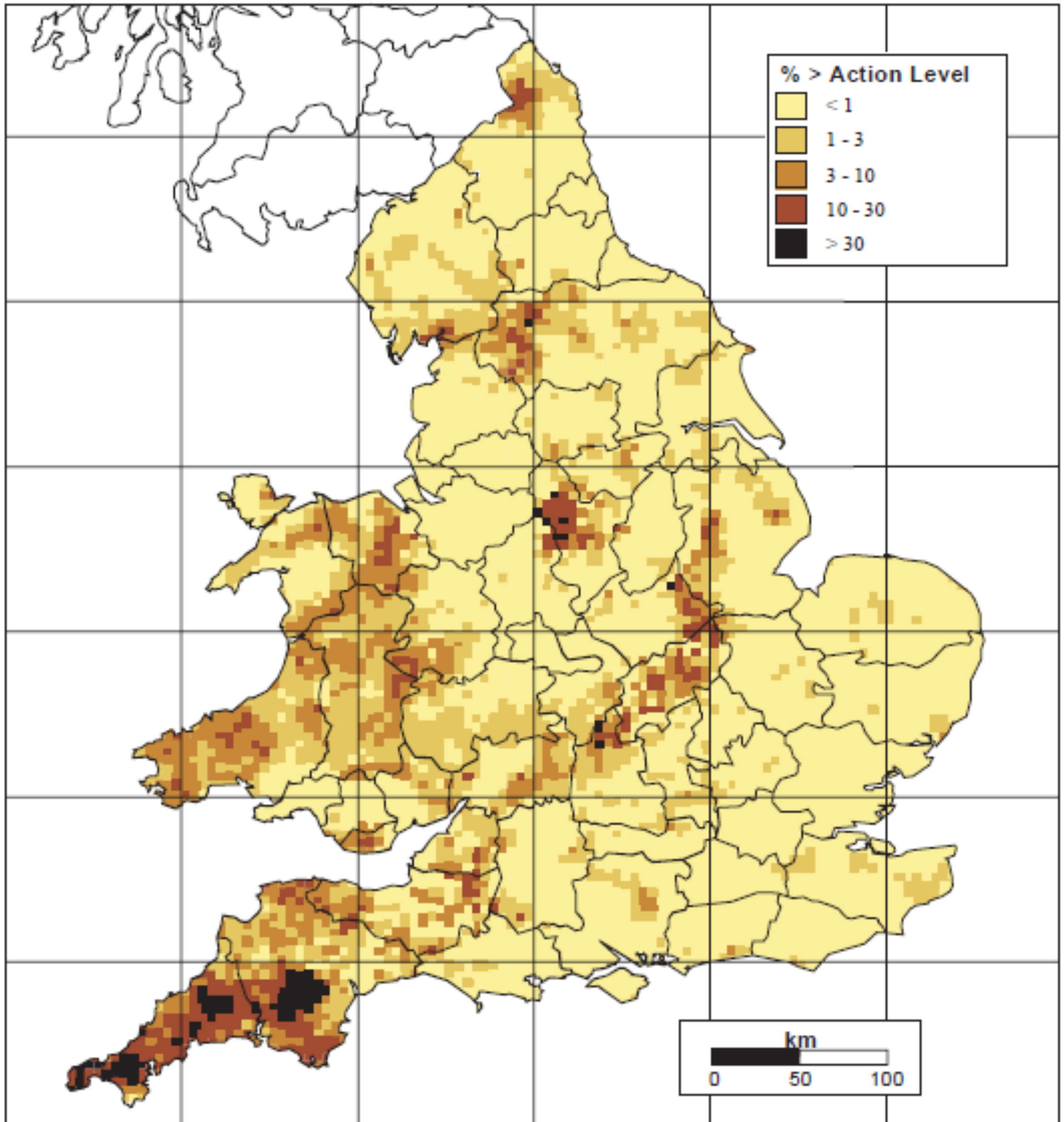

FIGURE 5 Estimated proportion of homes exceeding the action level in each 5-km grid square of England and Wales. (Adapted from Figure 2-2 in Appleton et al., 2000a.)

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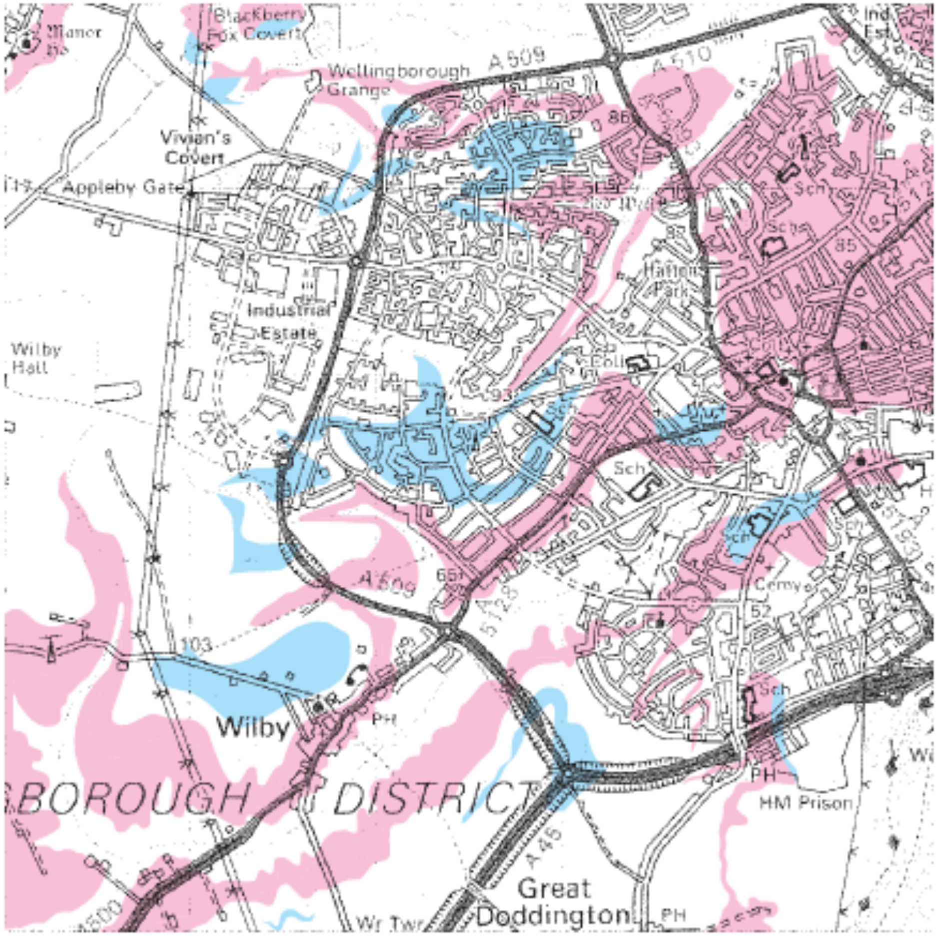

FIGURE 6 Geological radon potential map of the 5-km grid square (485265) that encompasses the western sector of Wellingborough, England. The 1:50,000 scale map illustrates the distribution of geological units with <3% (white), 3–5% (blue), and 10–20% (pink) of dwellings above the UK radon action level. The 5-km grid square has an average radon potential of 3.9% (NRPB 1998 data). (Topography based on Ordnance Survey 1:50,000 Scale Colour Raster data with permission of The Controller of Her Majesty's Stationery Office Crown Copyright. Ordnance Survey Licence number GD272191/2004.)

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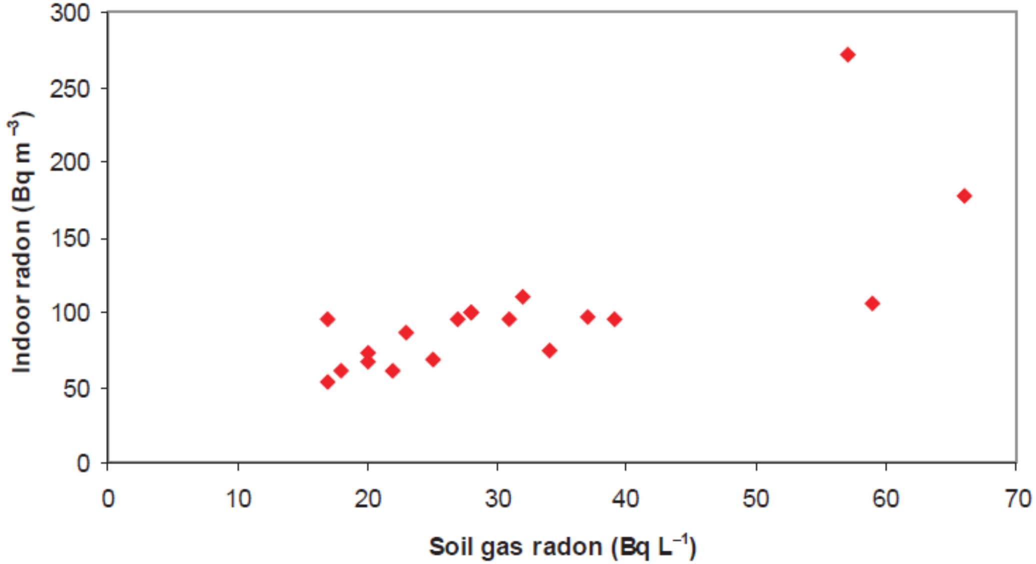

FIGURE 9 Relationship between average soil gas radon (Bq L^{-1}) and average indoor radon (Bq m^{-3}) for major rock types of the Czech Republic. (Based on data in Table 1, Barnet et al., 2002.)

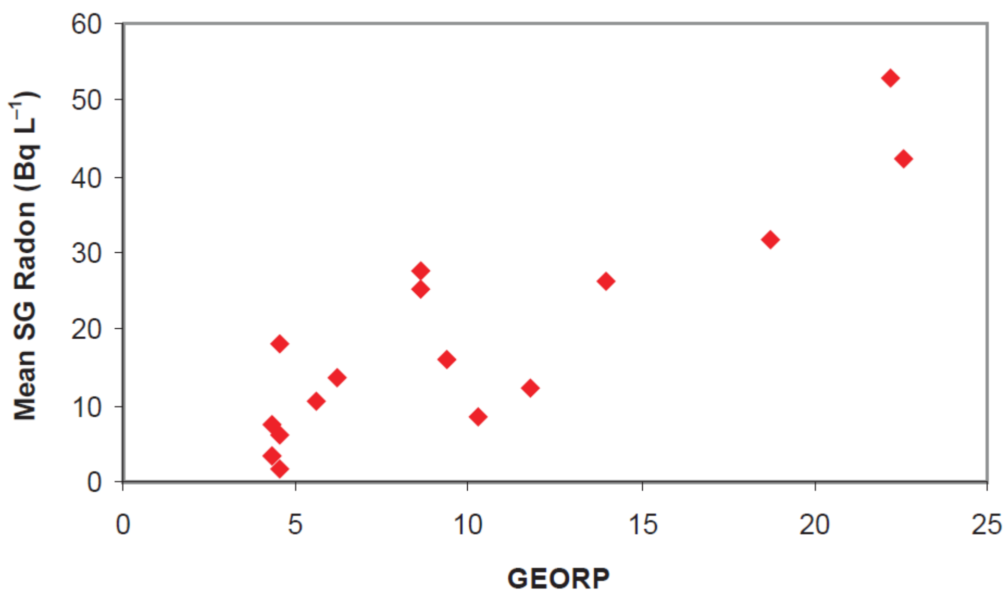

FIGURE 10 Relationship between average soil gas radon concentration (Bq L^{-1}) and the geological radon potential (GEORP = estimated proportion of dwellings exceeding the UK radon action level, 200 Bq m^{-3}. Data for dwellings sited on the Jurassic Northampton Sand Formation grouped by 5-km grid square). (Reproduced from Appleton et al, 2000a.)

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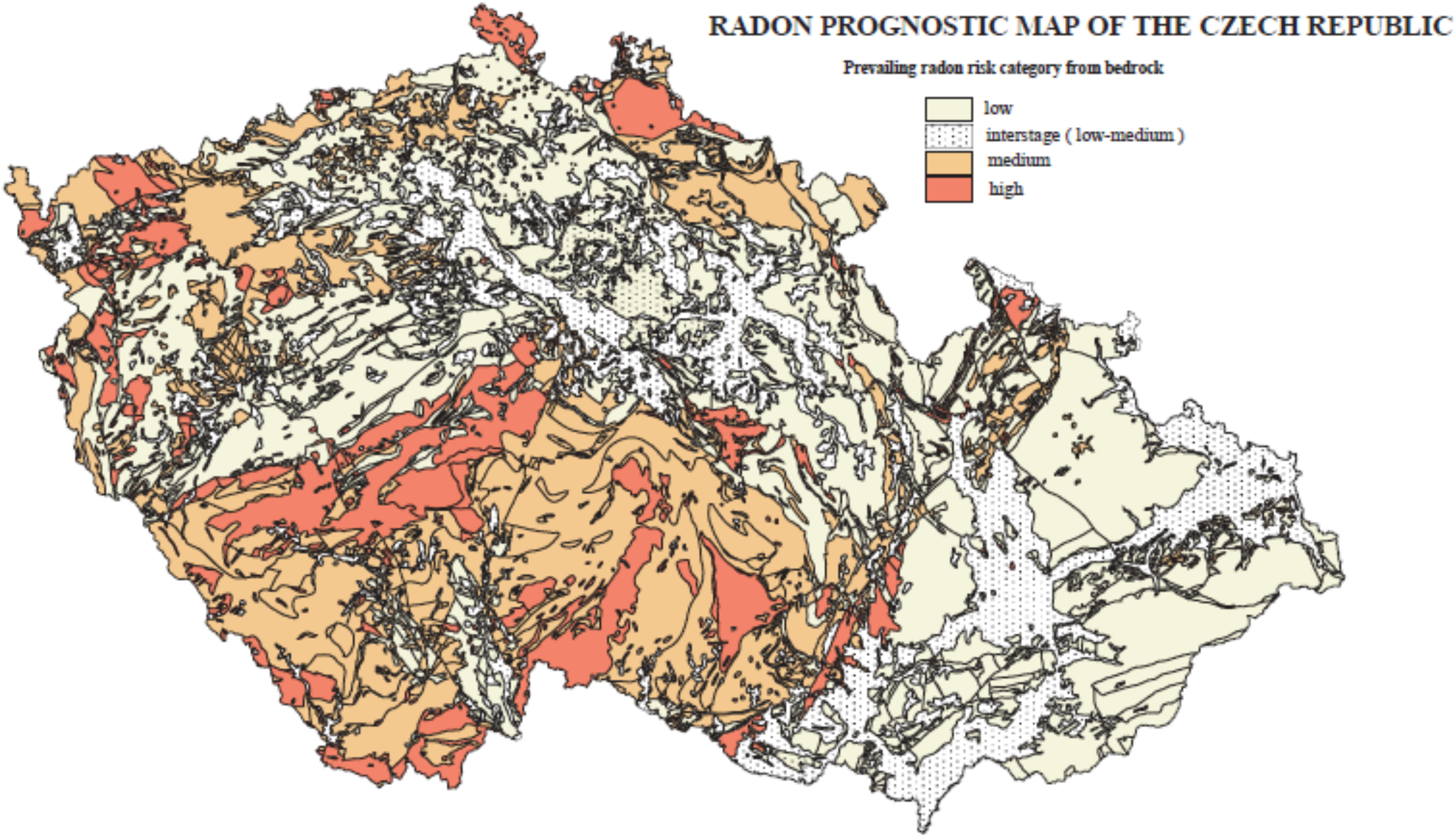

FIGURE 7 Radon prognostic (risk) map of the Czech Republic. (Reproduced with permission from the Czech Geological Survey.)

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TABLE VIII. Criteria Used in Sweden for Classifying High- and Low-Radon Ground

Bedrock or overburden	^{226}Ra *(Bq kg^{-1})*	^{222}Rn *in soil gas (Bq L^{-1})*
High radon ground		
Bare rock	>200	Not relevant
Gravel, sand, coarse till	>50	>50
Sand, coarse silt	>50	>50
Silt	>70	>60
Clay, fine till	>110	>120
Low radon ground		
Bare rock	<60	
Gravel, sand, till	<25	<20
Silt	<50	<20
Clay, fine till	<80	<60

After Clavensjö and Åkerblom, 1994.

TABLE IX. Czech Republic Radon Risk Classes Based on Radon in Soil Gas and Rock-Overburden Permeability

	Rock-overburden permeability		
	High	*Medium*	*Low*
Radon risk	*Radon concentration in soil gas (Bq L^{-1})*		
High	>30	>70	>100
Medium	10–30	20–70	30–100
Low	<10	<20	<30

After Barnett, 1994.

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Radon

Dose: Energy absorbed by a unit mass of tissue. Dose equivalent takes in potential damage to tissue (remember here that sunburn as an example can change your radon/other radioactive dose).

Absorbed Dose: unit tissue absorption

- Dose equivalent: absorbed dose multiplied by "quality factor"
- 1 for beta and gamma
- 20 for alpha

- Alpha more dense – hits harder so more energy transfer
- Some go through – genetic damage, others hit harder and disperse – more damage

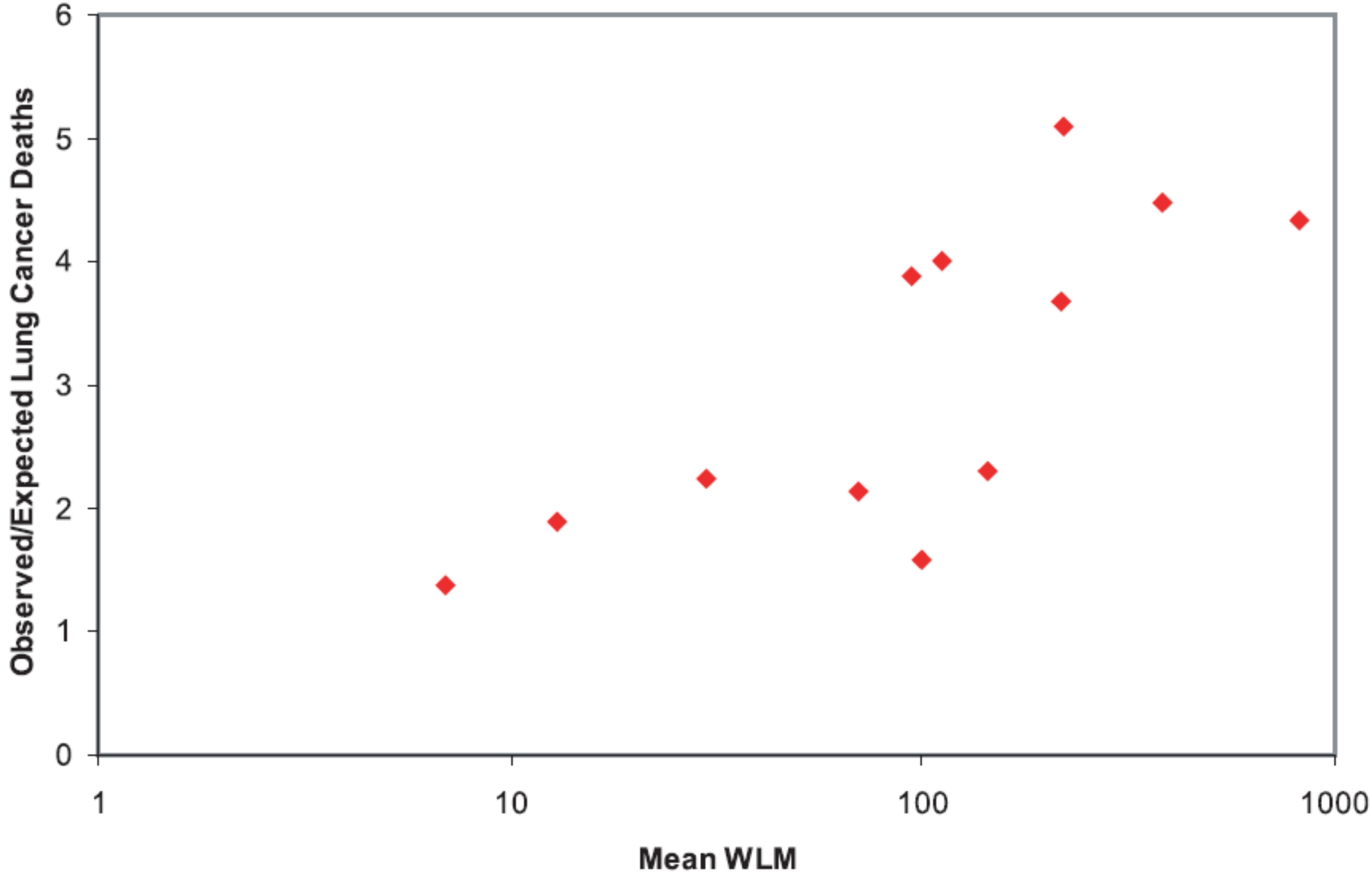

FIGURE 1 Excess mortality from lung cancer among miners exposed to high levels of radon. WLM = Working Level Month, a unit of exposure to radon. (Data from NRPB, 2000.)

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Epidemiology: Evidence Radon is Harmful

1. Miners (Figure 1) - longer you work more likely you get cancer (risk 2% at 250 WLM to 10% at 2500 WLM; WLM = working level month)
   - historically lung cancer and the German – Czech miners 1500-1600
   - modern studies – long low exposures (chronic), greater chance of lung cancer than high exposure over very short time (acute)
   - lung cancer risk higher in miners that had worked in other exposures such as asbestos – As – Cr, etc. Chronic (COPD)
   - non-smoking miners in Rn exposed situations at "greater risk"
   - studies based on 10,000 miners worldwide (68000 men – 2700 died of lung cancer)
   - in mines vs. home – more dust and other pollutants (e.g. organics like diesel), but miners more active? and shorter exposures compared to bad house

Epidemiology: Evidence Radon is Harmful

2. Domestic
   - you move often - that may be a good thing (random chance of exposure over long times in a bad house or geologic area)
   - location: a) geographic – lowlands ; b) geologic –granites vs others; c) where are you in the house – eg. basement
   - other factors: your a smoker, dust or other irritants

Epidemiology: Evidence Radon is Harmful

- many more factors in radon transfer
  - soil (higher release) than rock (more porosity)
  - rock type (felsic favoured) – pathways eg. fractures; bedding; openings; saturated vs. unsaturated; oxidized vs. reduced; e.g. Palmottu, Finland (transfer from deep to surface)
  - uranium – radium content of geological material
  - porosity (holes) – permeability (level of connected holes)
  - carrier, e.g. other gases He or CO_2, CO_2 collects radon (volcanoes), or water, etc.
  - weather (barometric pumping – saturated porous media Rn stays, but if rock or soil is unsaturated Rn pumped out
  - house construction (porosity)
  - occupant's habits – basement dwellers

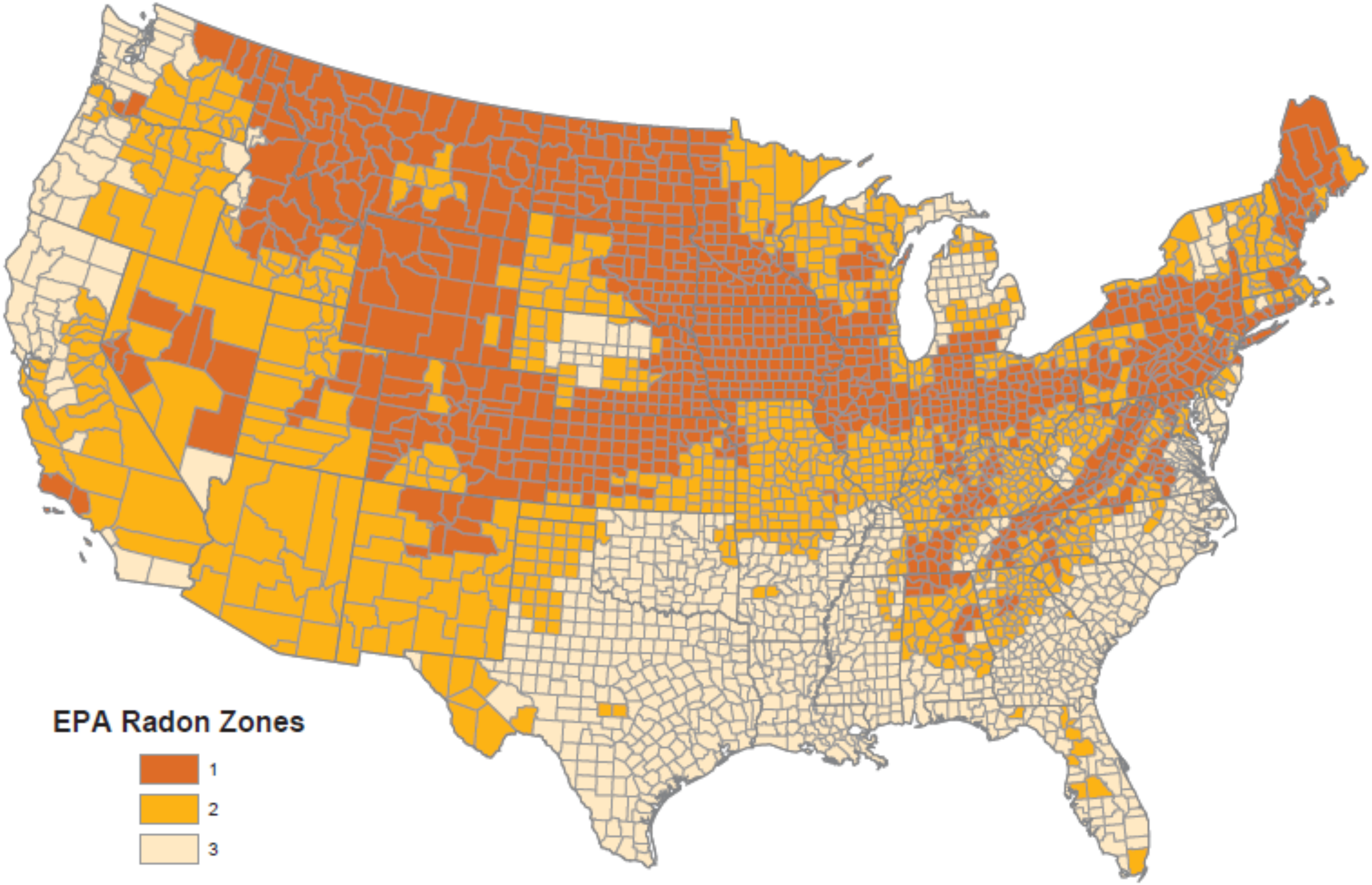

FIGURE 8 U. S. EPA Map of Radon Zones (excluding Alaska and Hawaii). Zone 1, 2, and 3 counties have a predicted average indoor radon screening concentration of >148, 74–148, and <74 Bq m^{-3}, respectively. (Map based on state radon potential maps available at http://www.epa.gov/radon/zonemap.html; state and county boundaries SRI ArcUSA 1:2M.)

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Radon and Health

1. Cases of cancer from Radon: 15 – 20,000 in USA; ~ 10-15% lung cancer cases
2. Factors: Exposure
   - eg. The miners
   - low Rn – smoker, dust or other intake to lungs
   - higher radon non-smoker, etc.

Remediation of Radon

- seal lower floors – basement
- install subfloor ventilation – collection cavity
- depressurize subfloor if possible
- positive pressure in the house – keep Rn out
- ventilation – intake above ground

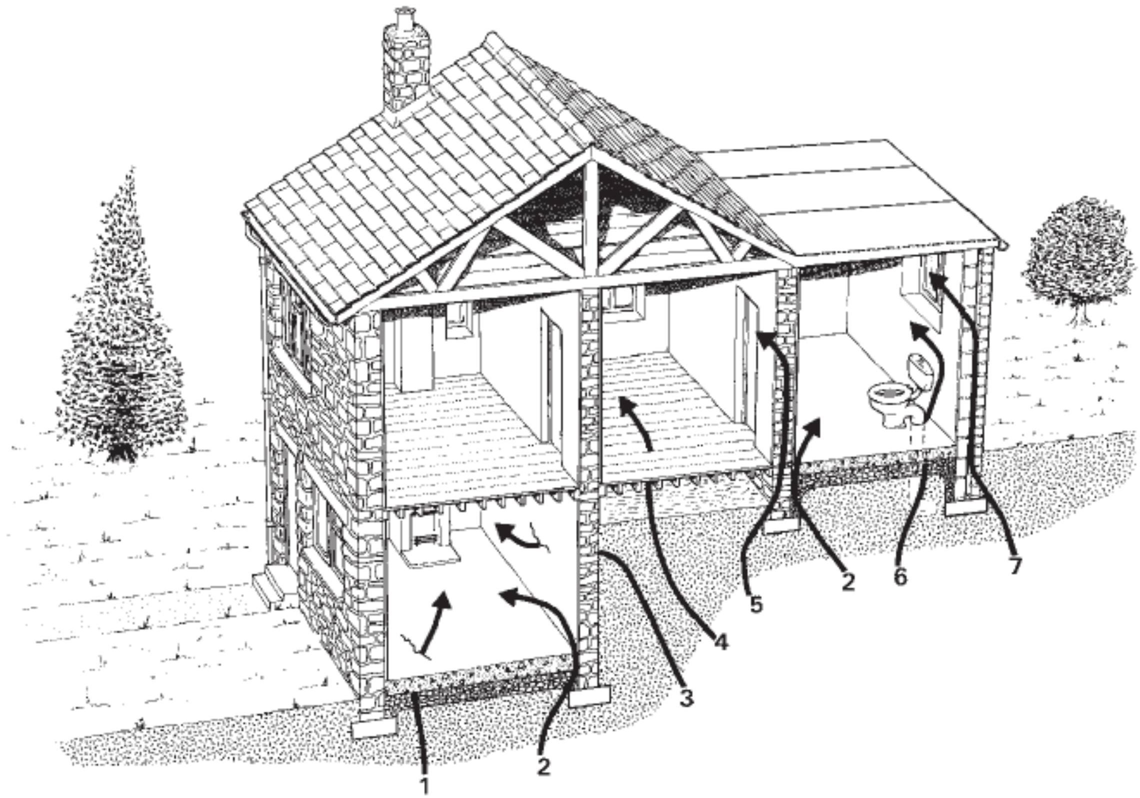

FIGURE 3 Routes by which radon enters a dwelling. (Reproduced with permission from CRC Ltd., publishers of BR211, BRE, 1999.)

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TABLE V. Estimated Annual Absorbed Doses to Adult Tissues From ^{222}Rn and Its Short-Lived Progeny for Domestic ^{222}Rn Concentration of $20\,Bq\,m^{-3}$

Tissue	*Annual dose* ($\mu Gy\,y^{-1}$)
Lung	500
Skin[a]	50–1000
Red bone marrow	0.5–6
Bone surface	0.4–4.4
Breast	1.2–1.5
Blood	1.1
Liver	2.5
Kidney	14.4

[a] Basal cells at 50 µm in exposed skin.
From NAS, 1998.

TABLE VI. Fatal Lifetime Lung Cancer Risks for Lifetime Radon Exposure at 200 $Bq\,m^{-3}$ Based on BEIR VI Models

	Risk (%)
General population	3–5
Smokers	10–15
Non-smokers	1–3

From NRPB, 2000.

Selinus *et al.* 2005

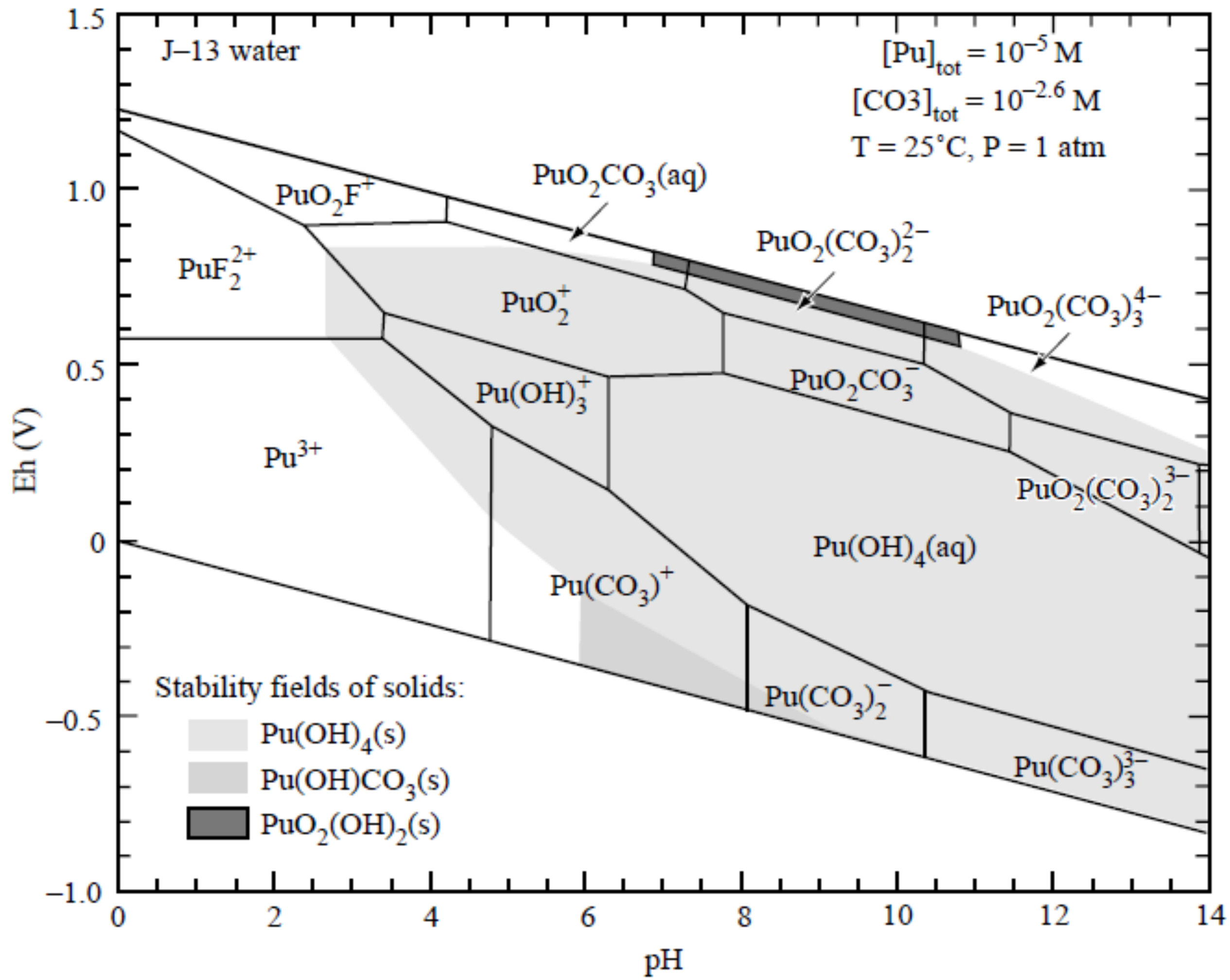


Figure 8 Eh−pH diagram showing dominant plutonium solid phases and species for J-13 water variants at 25 °C as calculated by Runde *et al.* (2002a). Solid lines indicate dominant solution species and shaded areas indicate solids supersaturated in 10^{-5} M Pu solutions. Precipitation of PuO_2 was suppressed in the calculations; see Runde *et al.* (2002a) for details. (reproduced by permission of Elsevier from *Appl. Geochem.*, **2002**, *17*, 844).

Radioactive Waste

Radioactivity

- Many atoms (elements) are unstable and can emit ‘ionizing radiation’ and change into another atom (element).
- Process is radioactivity: Change is radioactive decay.
- These atoms are called radionuclides or radio isotopes.
- The rate at which the change or ‘decay’ occurs is called the half life – “period of time during which half the original number of atoms will have changed or decayed to the new atom (element).”

Materials Involved
Tailings

- Waste that results from mining.
- Uranium content in rock often only 0.1 – 0.2% but higher in some Canadian mines.
- It takes about 20,000 kg of rock to produce 1 kg of useful U.

Atlas Site, USA

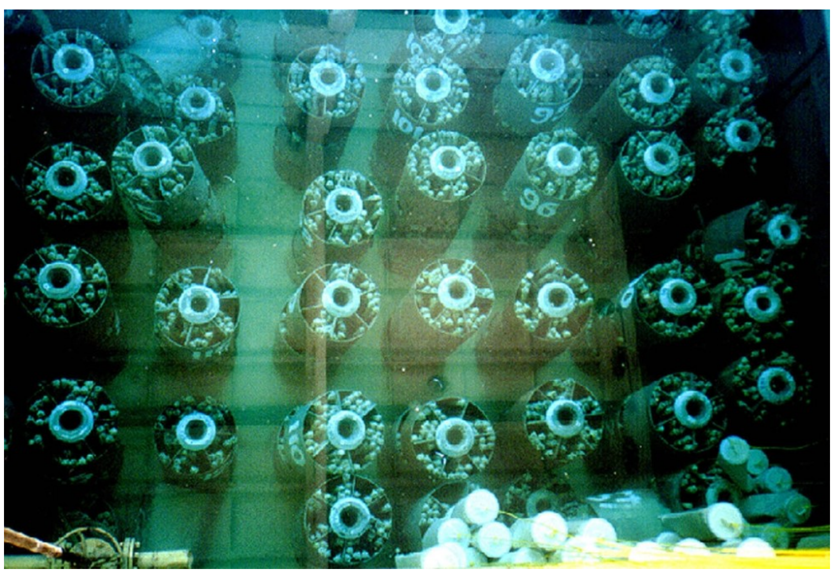
Ronneburg, Germany

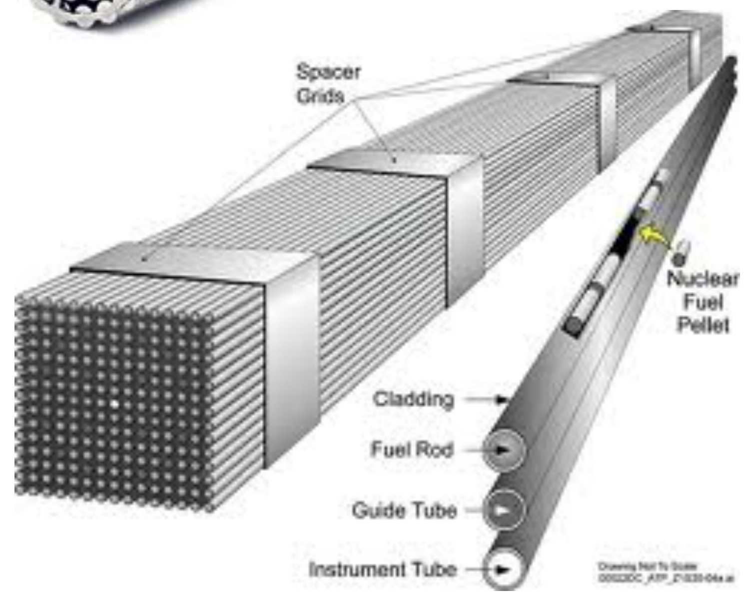
Materials Involved
Low-Intermediate Level Waste

- Used rags, tool, resins, etc.
- In Canada considered all forms of radioactive waste except spent fuel and mining/milling waste.
- Most stored at Bruce Nuclear Power Development.

Materials Involved
High Level Waste

- Spent fuel nuclear fuel.
- Usually stored in "swimming pools".





Materials Involved
Transuranic Waste (TRU waste)

- Transuranic elements: elements with atomic numbers greater than uranium
- Transuranic waste: contaminated with transuranic radionuclides.
- Mainly a by-product of weapons production.

Geochemistry

- Decay chains - multiple elements, multiple isotopes

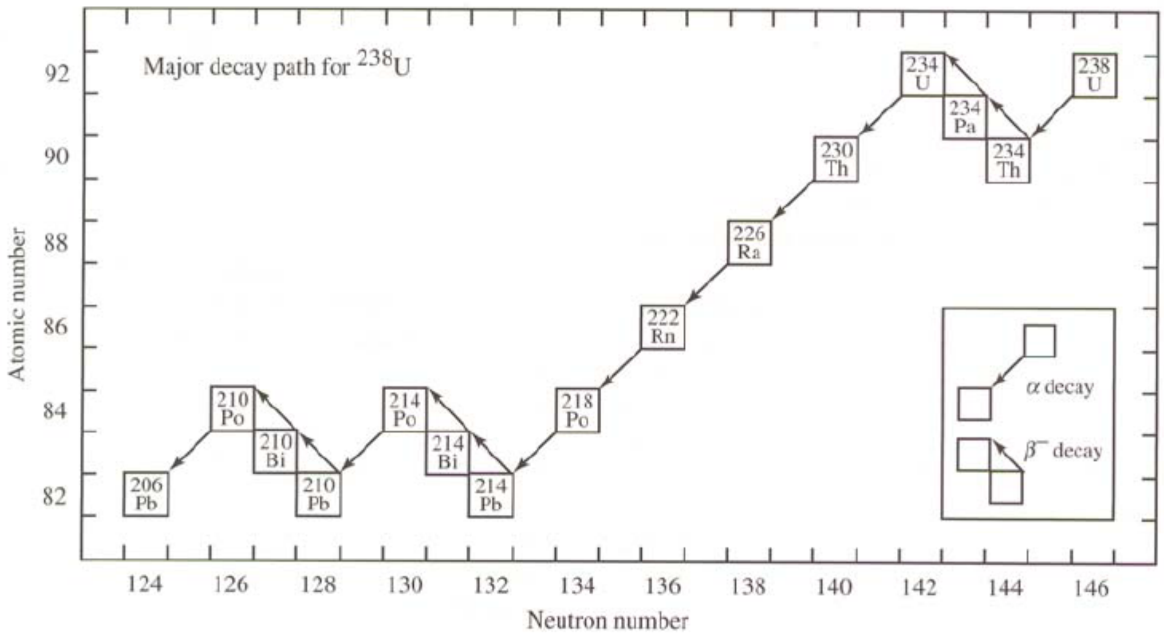


Figure 1 The major decay path for ^{238}U. A small fraction of decays will follow other possible decay paths—for example, decaying by β^- emission from ^{218}Po to ^{218}At, and then by α emission to ^{214}Bi—but ^{206}Pb is the stable end product in all cases.

From Siegel and Bryan (2005) *in* Treatise on Geochemistry, Vol 8, *Environmental Geochemistry*

Geochemistry

TABLE I. The Uranium-238 Decay Series

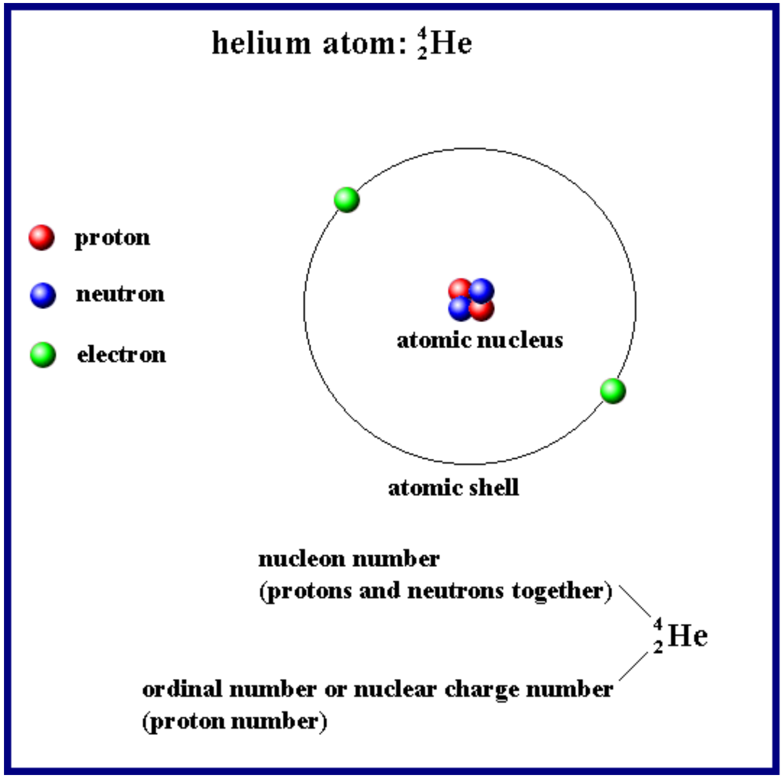
Nuclide	*Principal mode of decay*	*Half-life*
^{238}U	α	4.5×10^{9} years
^{234}TH	β	24.1 days
^{234}Pa	β	1.2 minutes
^{234}U	α	2.5×10^{5} years
^{234}TH	α	7.5×10^{4} years
^{226}Ra	α	1,602 years
^{222}Rn	α	3.8 days
^{218}Po	α	3.1 minutes
^{214}Pb	β	26.8 minutes
^{218}At	α	1.5 seconds
^{214}Bi	α	19.9 minutes
^{214}Po	α	$1.6 - 10^{-4}$ seconds
^{210}Tl	β	1.3 minutes
^{210}Pb	β	22.6 years
^{210}Bi	β	5.0 days
^{210}Po	α	138.4 days
^{206}Tl	β	4.2 minutes
^{206}Pb	Stable	Stable

TABLE II. The Thorium-232 Decay Series

Nuclide	*Principal mode of decay*	*Half-life*
^{232}Th	α	1.4×10^{10} years
^{228}Ra	β	5.8 years
^{228}Ac	β	6.1 hours
^{228}TH	α	1.9 years
^{224}Ra	α	3.7 days
^{220}Rn	α	55.6 seconds
^{226}Po	α	0.15 seconds
^{212}Pb	β	10.6 hours
^{212}Bi	α 36%	60.5 minutes
	β 64%	
^{212}Po	α	3.0×10^{-7} seconds
^{208}Tl	β	3.1 minutes
^{207}Pb	Stable	Stable

Geochemistry - Decay

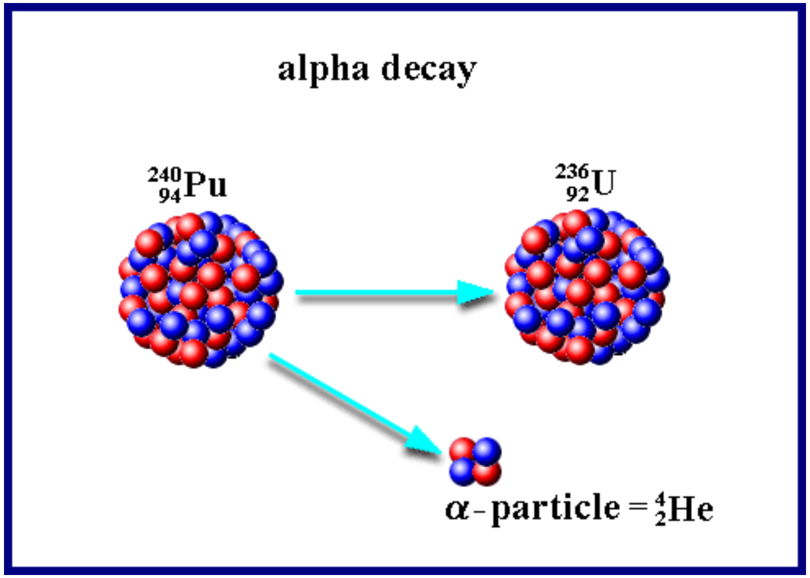
- Parent radionuclide -> daughter nuclide.
- Change in number of protons and neutrons or energy state of nucleus of atom.
- Usually change in chemical element except for in the case of gamma decay and internal conversion decay.



Images from:
http://www.hpwt.de/
Kern2e.htm

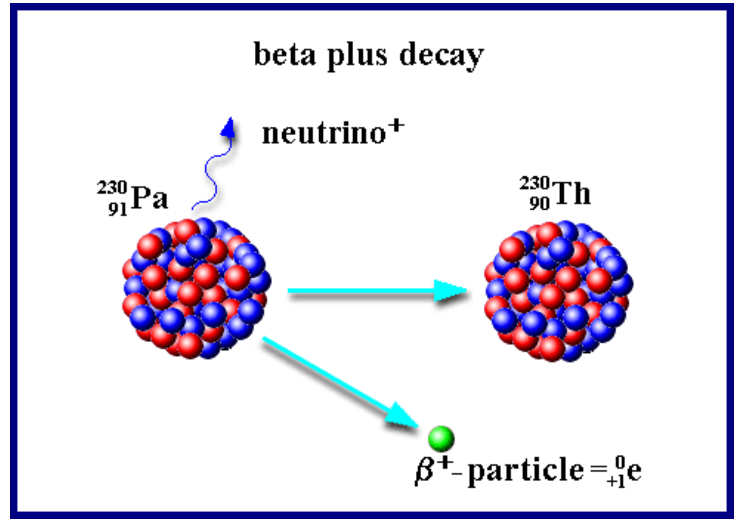
Geochemistry - Decay

- Several types of radioactive decay:
  - α decay: alpha particle emitted (^{4}He nuclei).

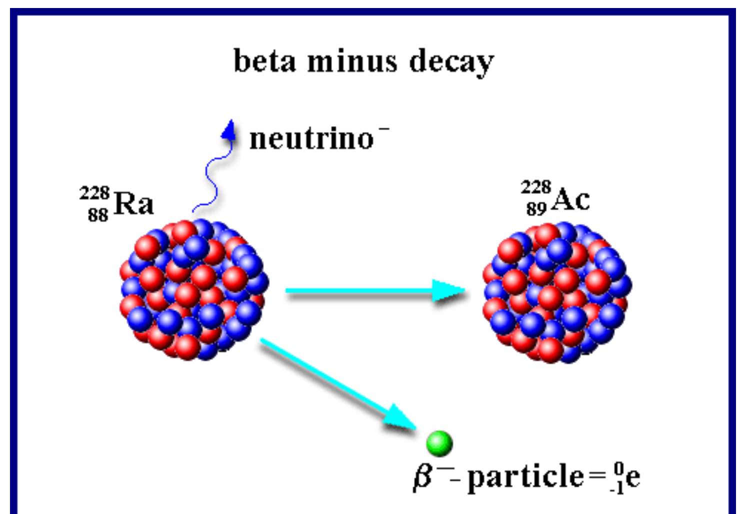


Geochemistry - Decay

- β^+ decay: positively charged beta particle (positron) is emitted from the nucleus of the atom and a proton is transformed into a neutron.

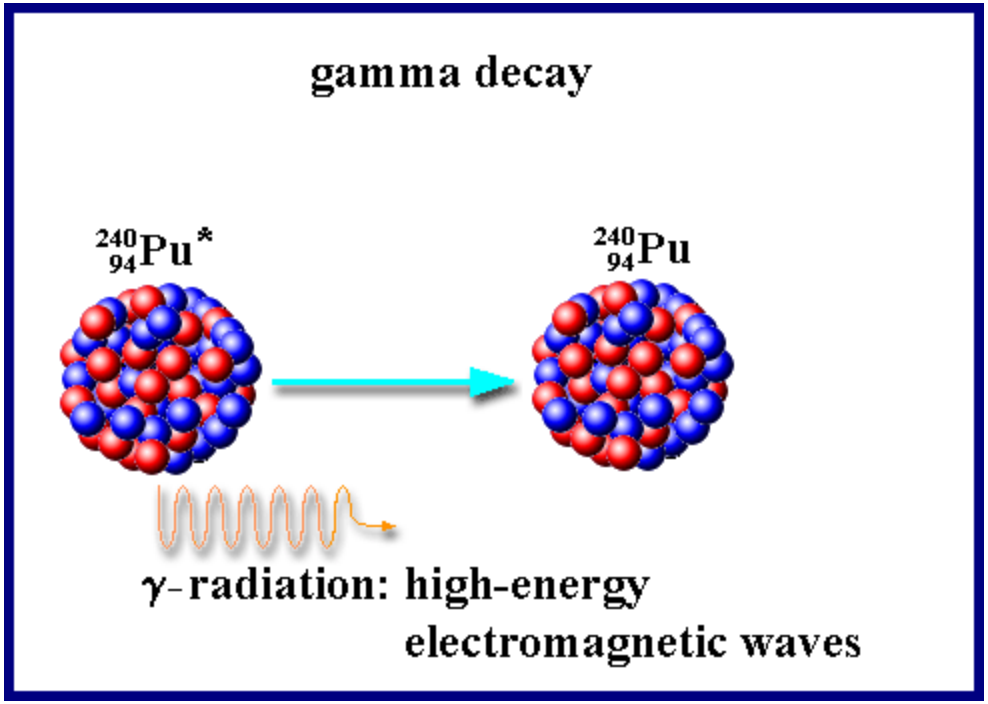


- β- decay: a negatively charged beta particle (electron) is emitted from the nucleus and a neutron is transformed into a proton.



Geochemistry - Decay

- Gamma decay: can occur after alpha or beta decay.



Geochemistry - Decay

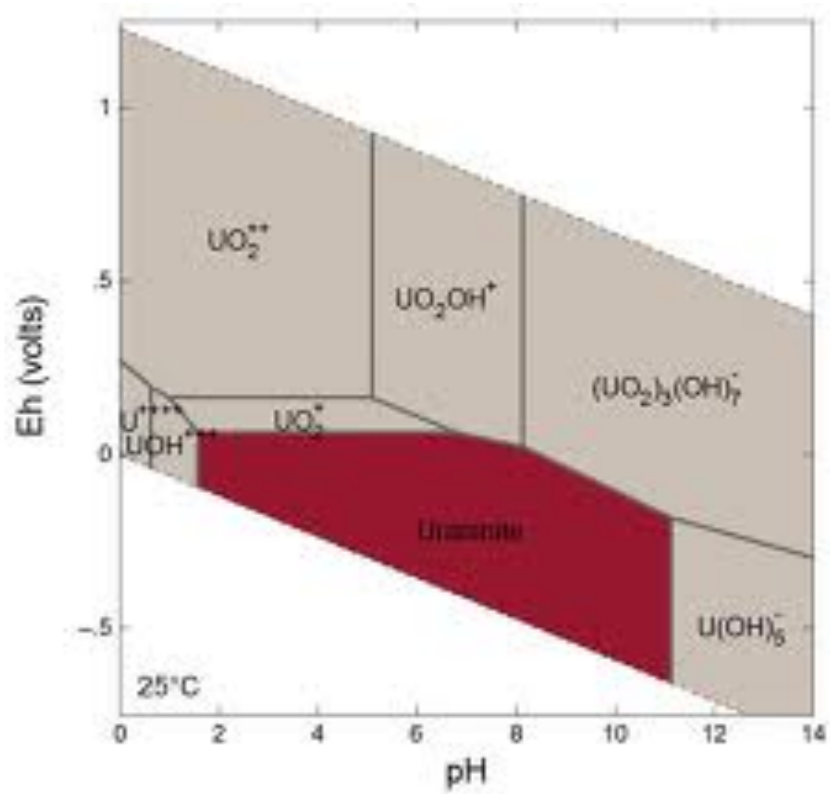
- Impact on human body
  - α decay: little penetration but big energy
    - Clothes stop α
    - On skin – burns and eventual skin cancer
    - In lungs – no epidermis so major molecular disruptions are possible
  - γ decay – penetrates and more energetic
    - Lead protection
  - β decay – intermediate between α and γ.

Geochemistry

- Reservoirs in body
  - Sr in bones
    - ^{90}Sr in milk (1960s – during bomb testing)
  - I in thyroid
    - For example Fukushima and iodine pills
  - Carbon
    - Carbon-14
  - Others

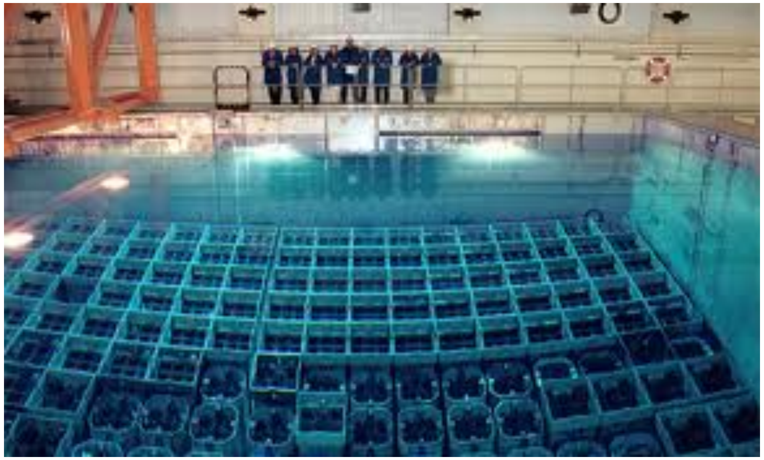
Uranium Solubility

- Uranium solubility in water is dependent on pH and redox conditions.
- Mobile in oxidizing conditions.



Radioactive Waste Disposal

- Interim storage:
  - Swimming pools
  - Silos



Proposed Long Term Storage

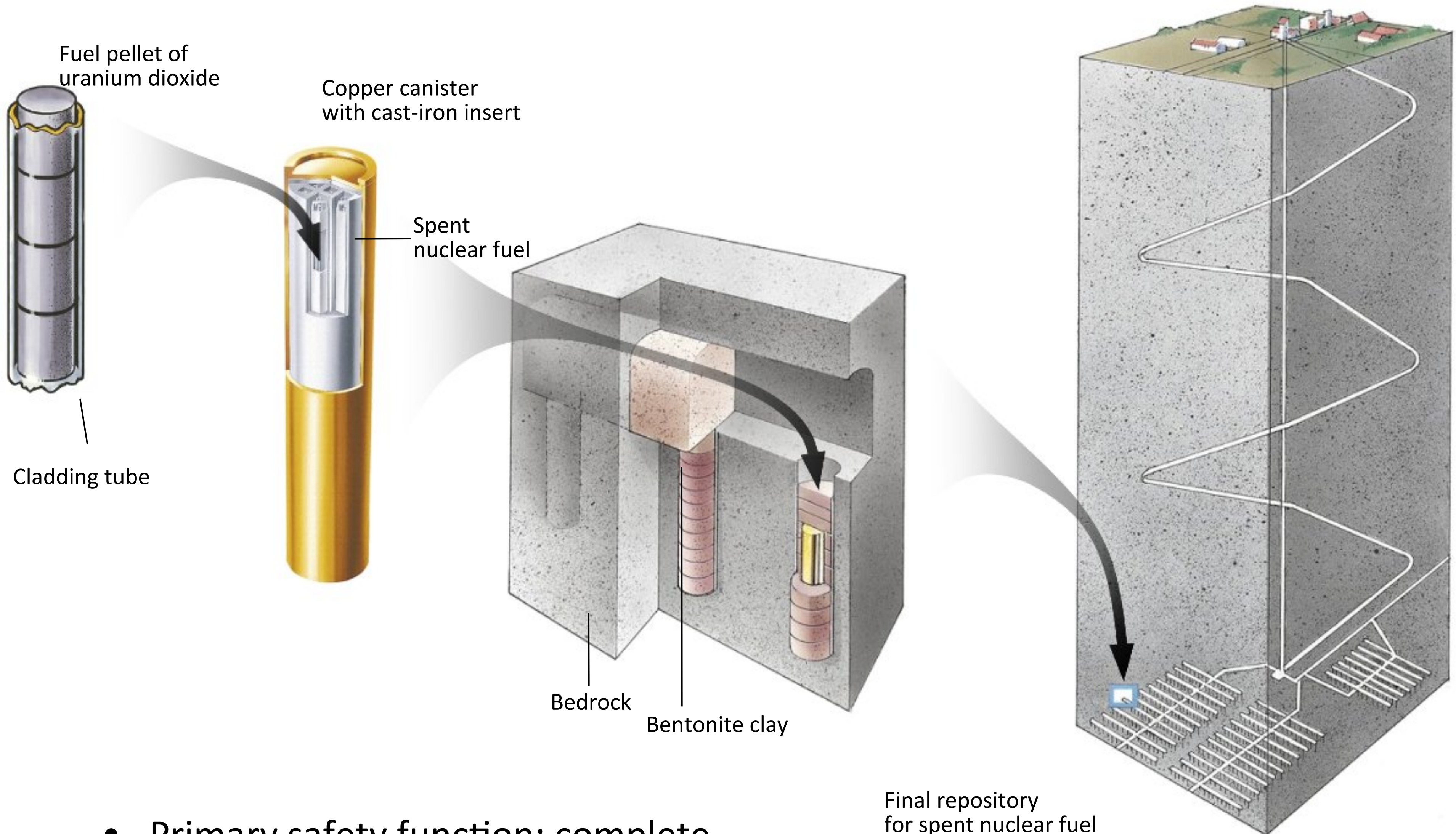
- Geologic:
  - Rock – both crystalline and sedimentary locations
  - Clay – consolidated, unconsolidated
- Creative (probably bad) ideas:
  - Space
  - Glaciers
  - Ocean bottom
  - Subduction zones

Deep Geological Repository

- Safety for a geological disposal site is divided into two areas:
  - Near Field – includes engineered barriers Backfill or waste rock ,buffer –clay , canister design – copper , repository design (Deep Geologic Repository –DGR)
  - Far Field – environment and geology around the DGR. Tectonics, hydrogeology, geology –rock type, long term stability.

Deep Geological Repository

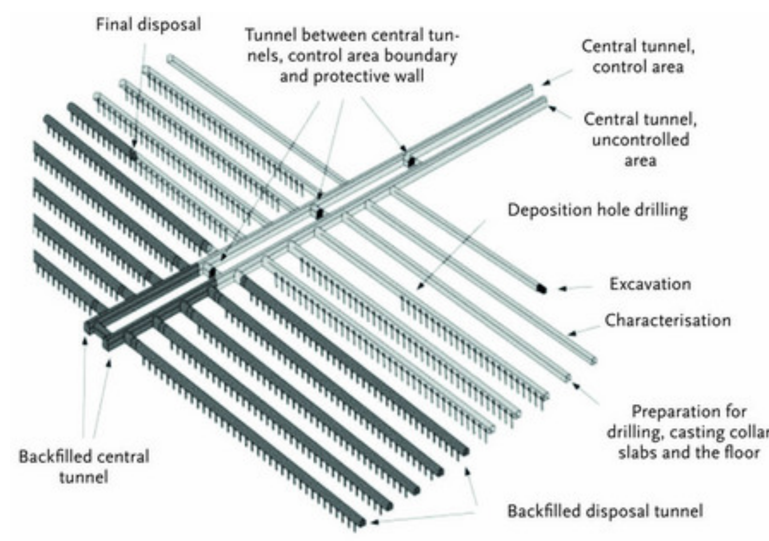
- Typical site – crystalline rock
  - Fuel bundles – Zr steel / U-byproducts
  - Cannisters – Cu
    - Cu → Cu oxides – consume O_2 and form malachite/azurite.
    - Also contains low-grade steel inserts
      - steel/iron + H_2O → H_2 gas and redox ↓
  - Buffer - bentonite (swelling clay)
    - Adsorption → diffusion
    - Lower permeability
    - Buffer chemistry



- Primary safety function: complete isolation
- Secondary safety function: retardation

Deep Geological Repository Near Field

- Backfill – country rock and slurry
- Canisters and buffer
  - in-floor vs in-room (find pictures)
- Bentonite buffer
- Seals – many kinds
  - mostly $CaOH_2$ (portlandite)
  - additives to bring pH up or down

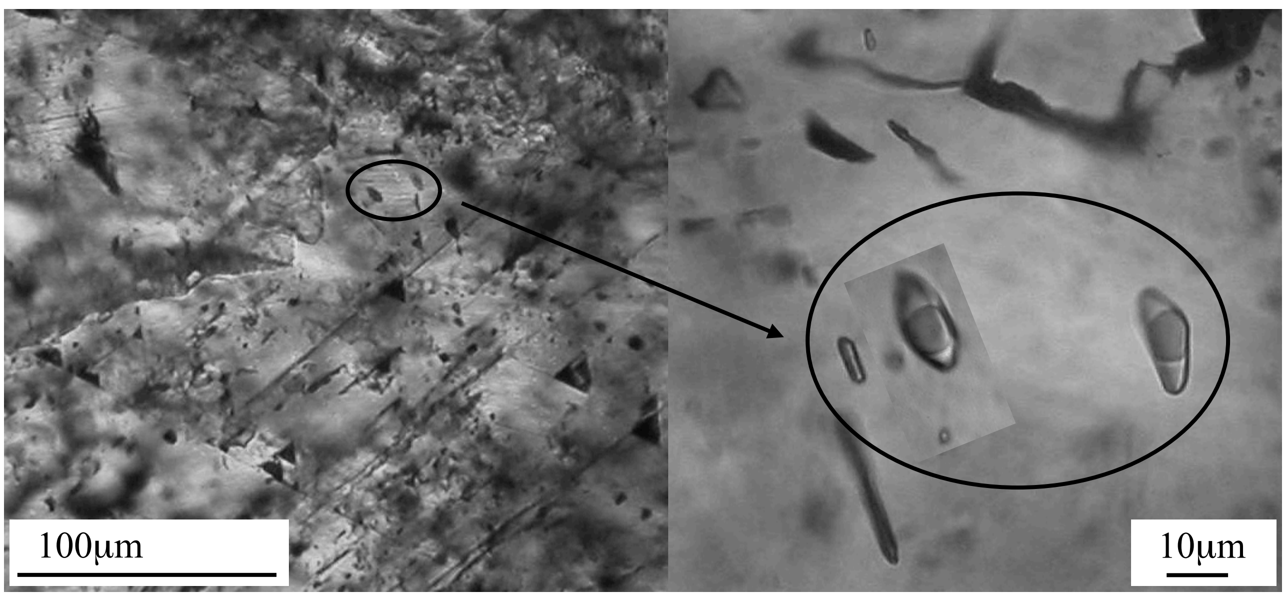


Deep Geological Repository
Far Field

- Rock – intact? matrix
- Granite:
  - Quartz (SiO_2)
  - Feldspars (K-Na-Ca-Si-O)
  - Mica (Fe-Si-OH)
  - Others (Fe-Mg-Si)

Deep Geological Repository
Far Field

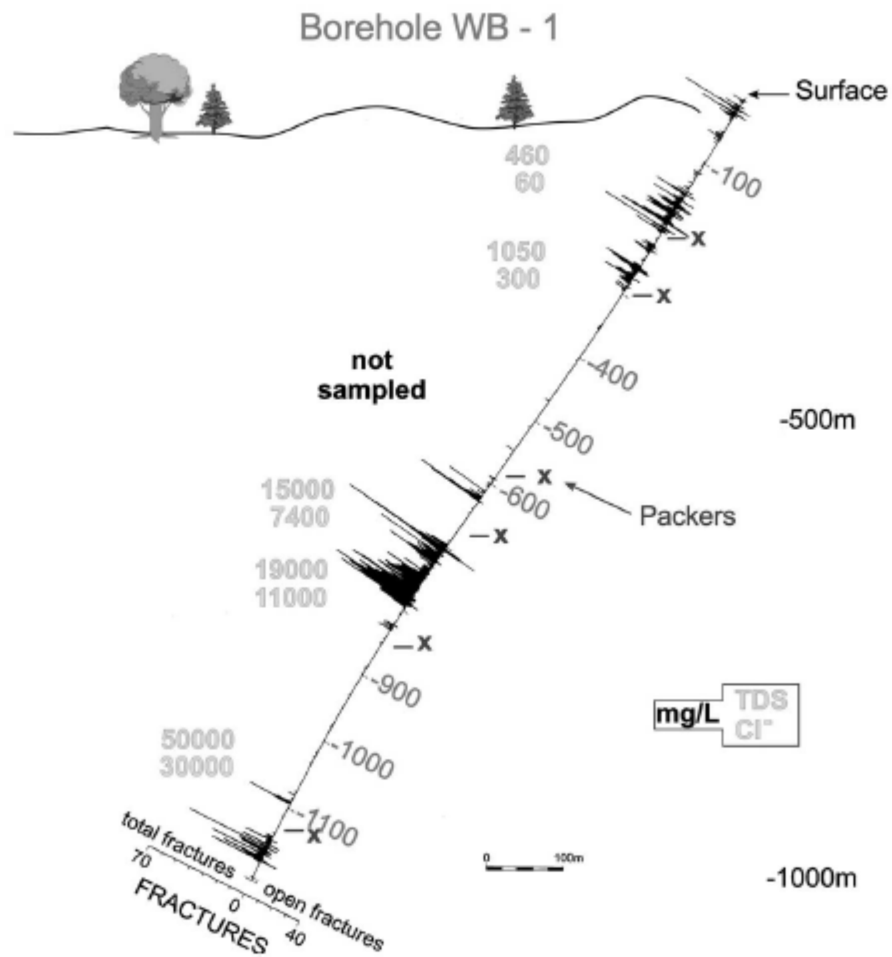
- Reactive – slow and consumes oxygen
- Sorptive – low
- Microfractures – can have high salinity (g/L)



Deep Geological Repository Far Field

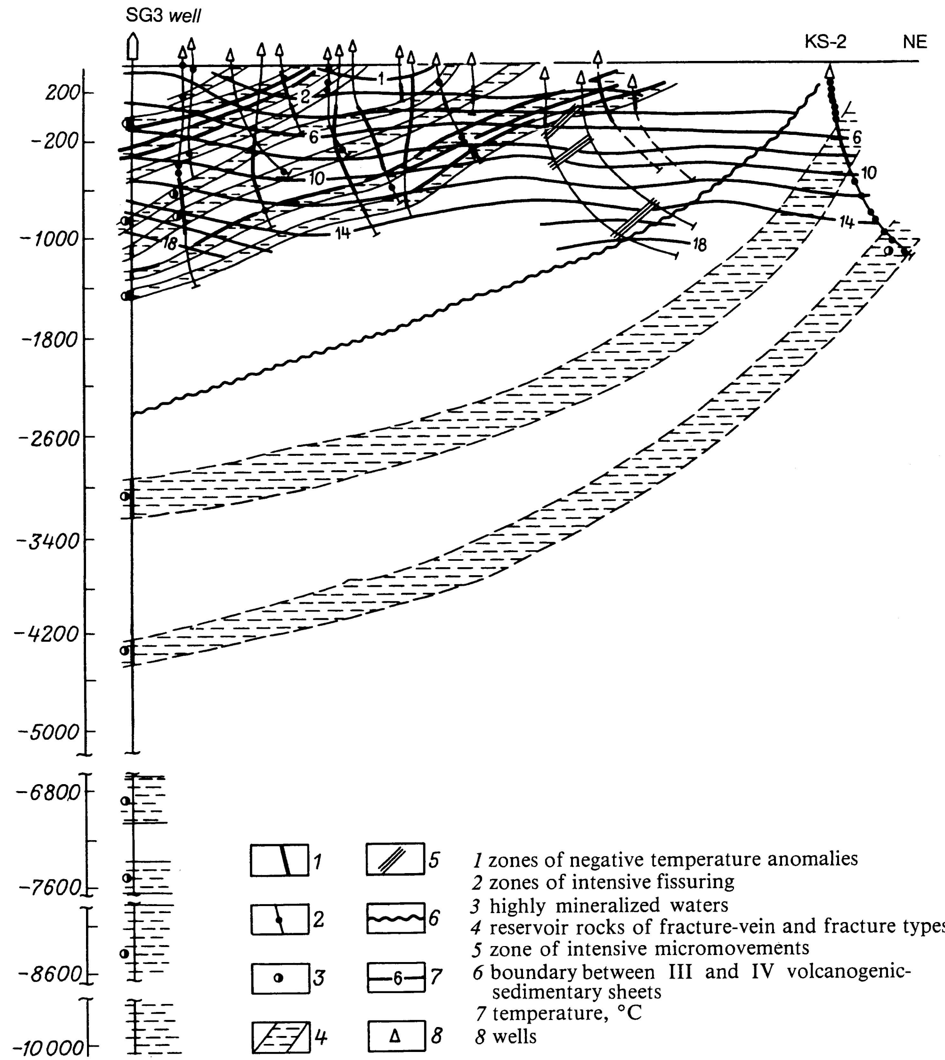
- Rock – fractures
  - Frequency, size, conductivity
  - Fracture frequency tends to decrease with depth

M. Gascoyne / Applied Geochemistry 19 (2004) 519–560



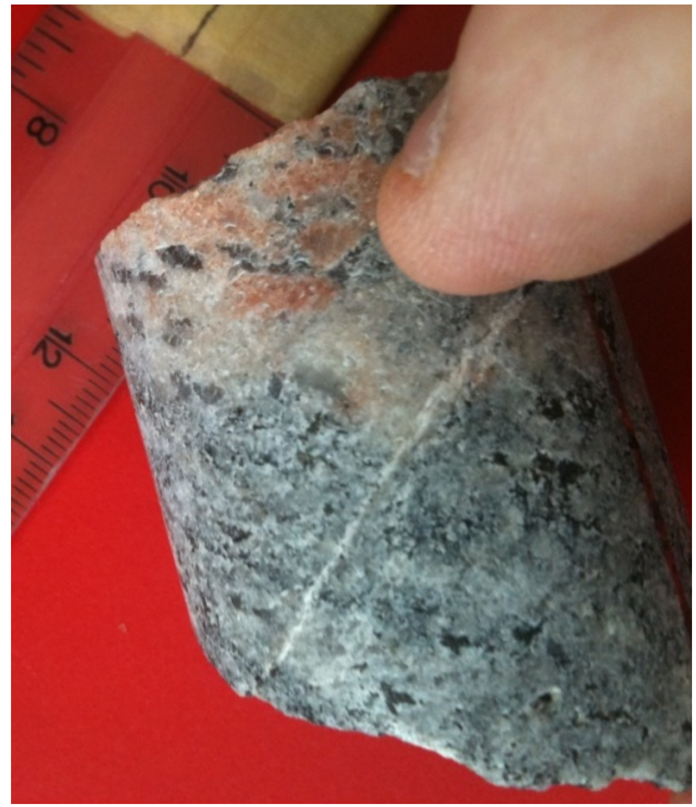
Far Field - Fractures

- Kola superdeep hole.
- Borevsky et al., 1984



Deep Geological Repository
Far Field

- Fracture fillings
  - Fe-OH
  - Calcite ($CaCO_3$)
  - Mica – clays
    - eg. Chlorite (OH)
  - Zeolites (H_2O)
- Sorption
- Consume O_2

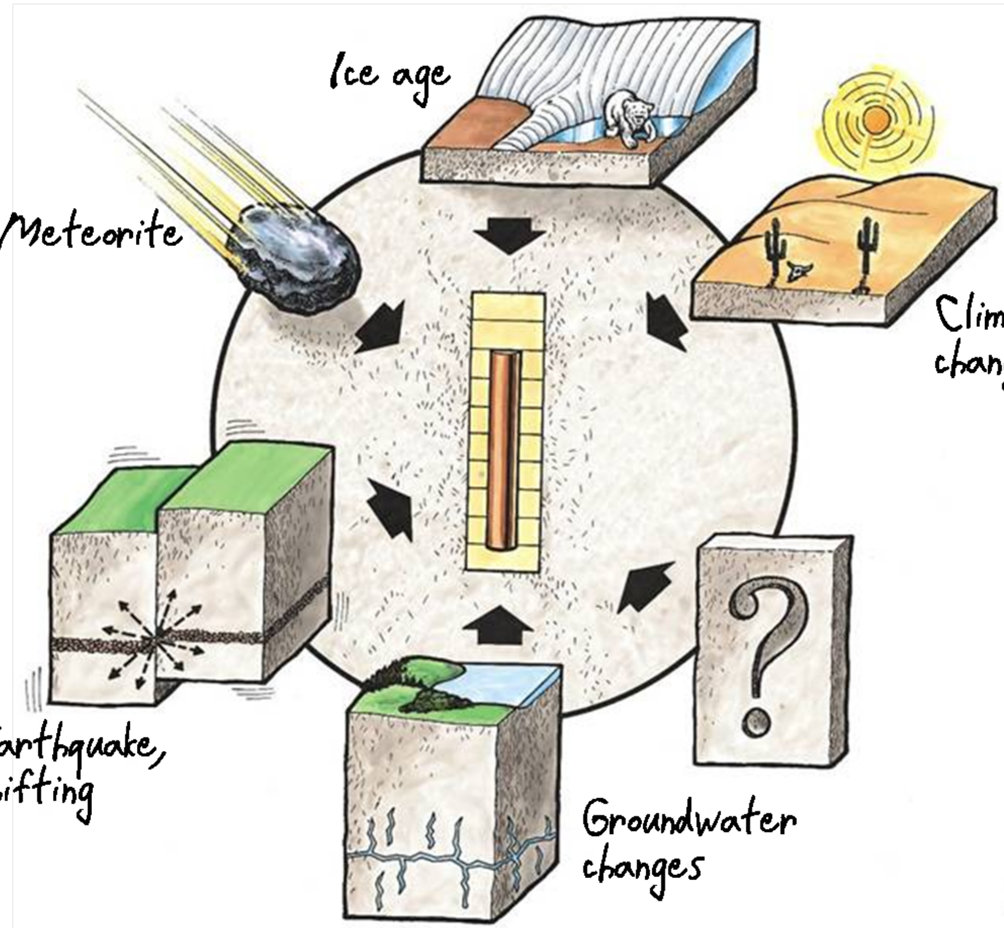


Deep Geological Repository

- Both crystalline and sedimentary rock types have been proposed
- Type is dependent on country
  - Sweden and Finland are investigating crystalline sites
  - Canada is investigating both crystalline and sedimentary sites

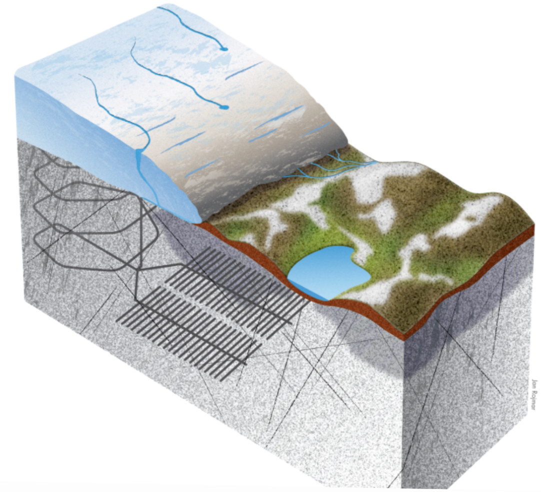
Safety Assesment

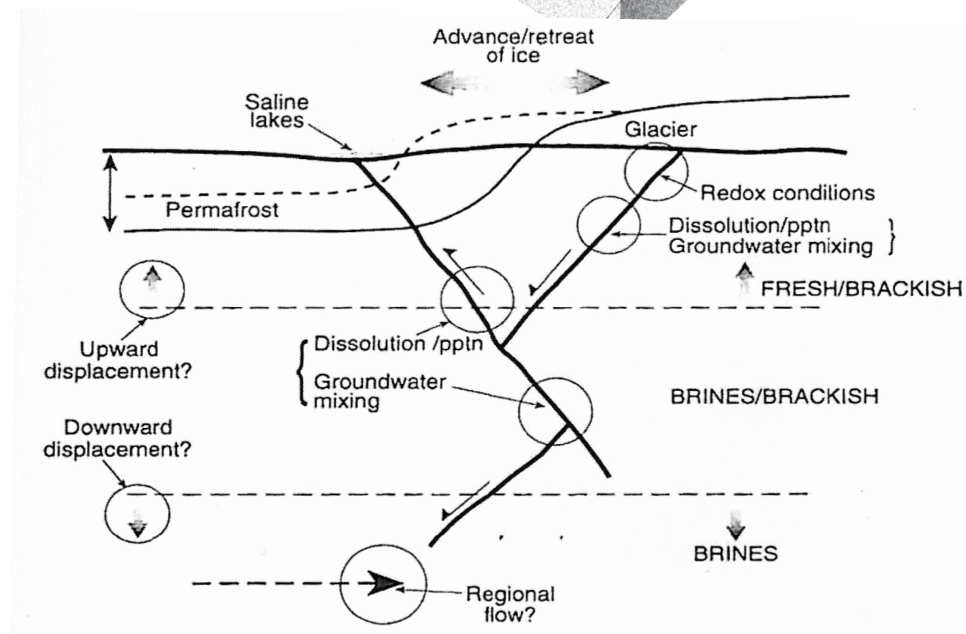
- Safety cases for deep geological repositories must be proven on time scales of 100,000 to a million years.
- Large scale environmental and geological changes over such time scales must be accounted for.



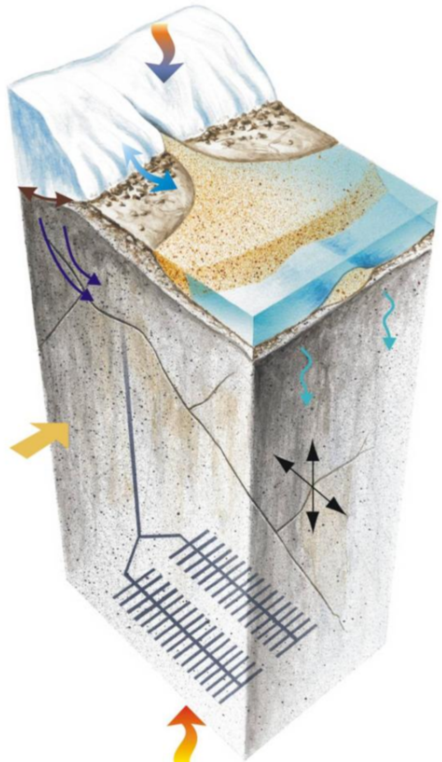
Safety Assesment

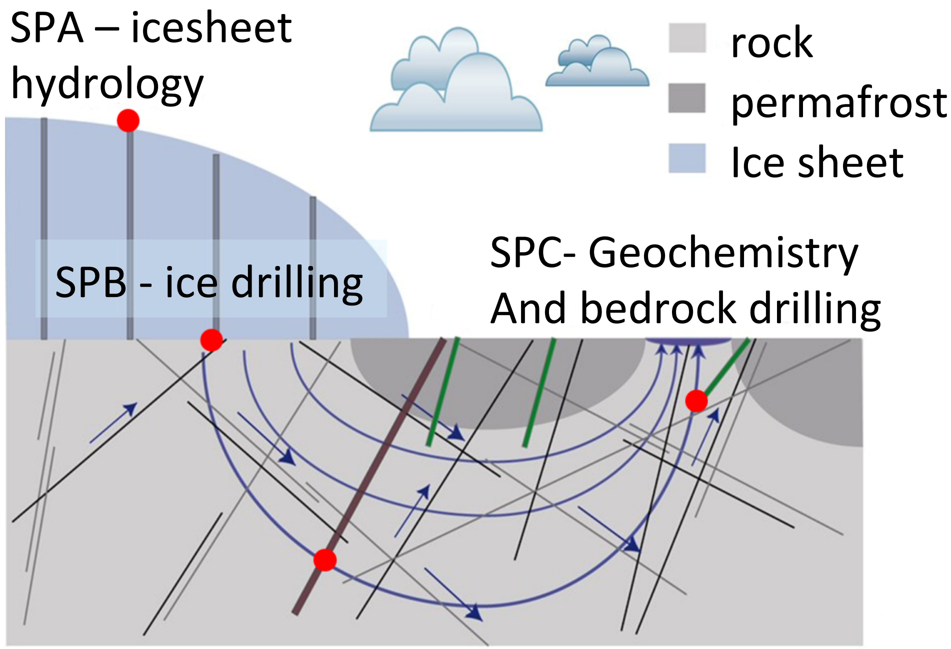
- Glaciation is a major perturbation that is likely to occur over the safety case time scale.
  - Stresses for glaciation
  - Glacial water – dilute and O_2 rich
  - Impact of permafrost
    - Study sites in Canada and Greenland





Greenland Analogue Project

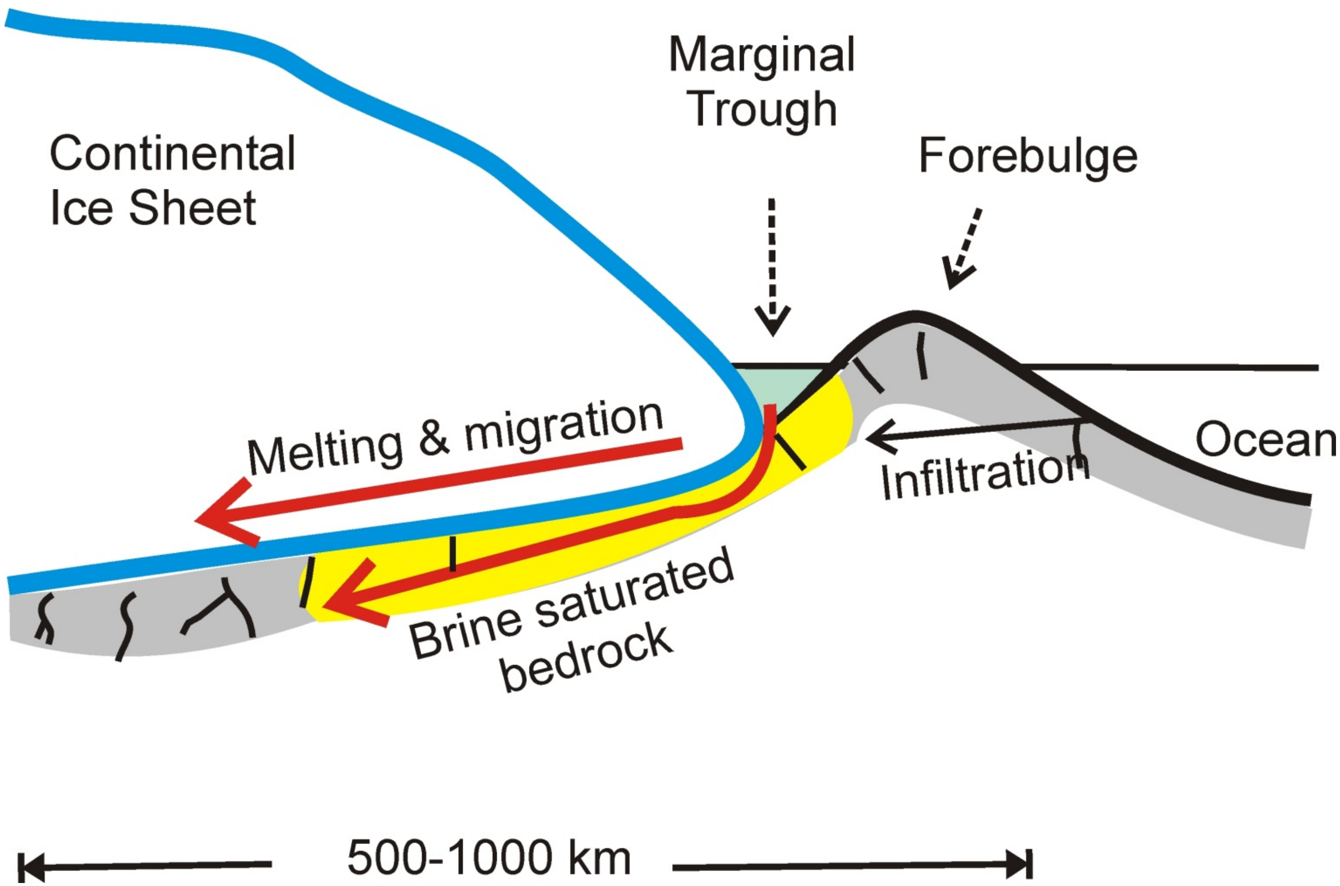


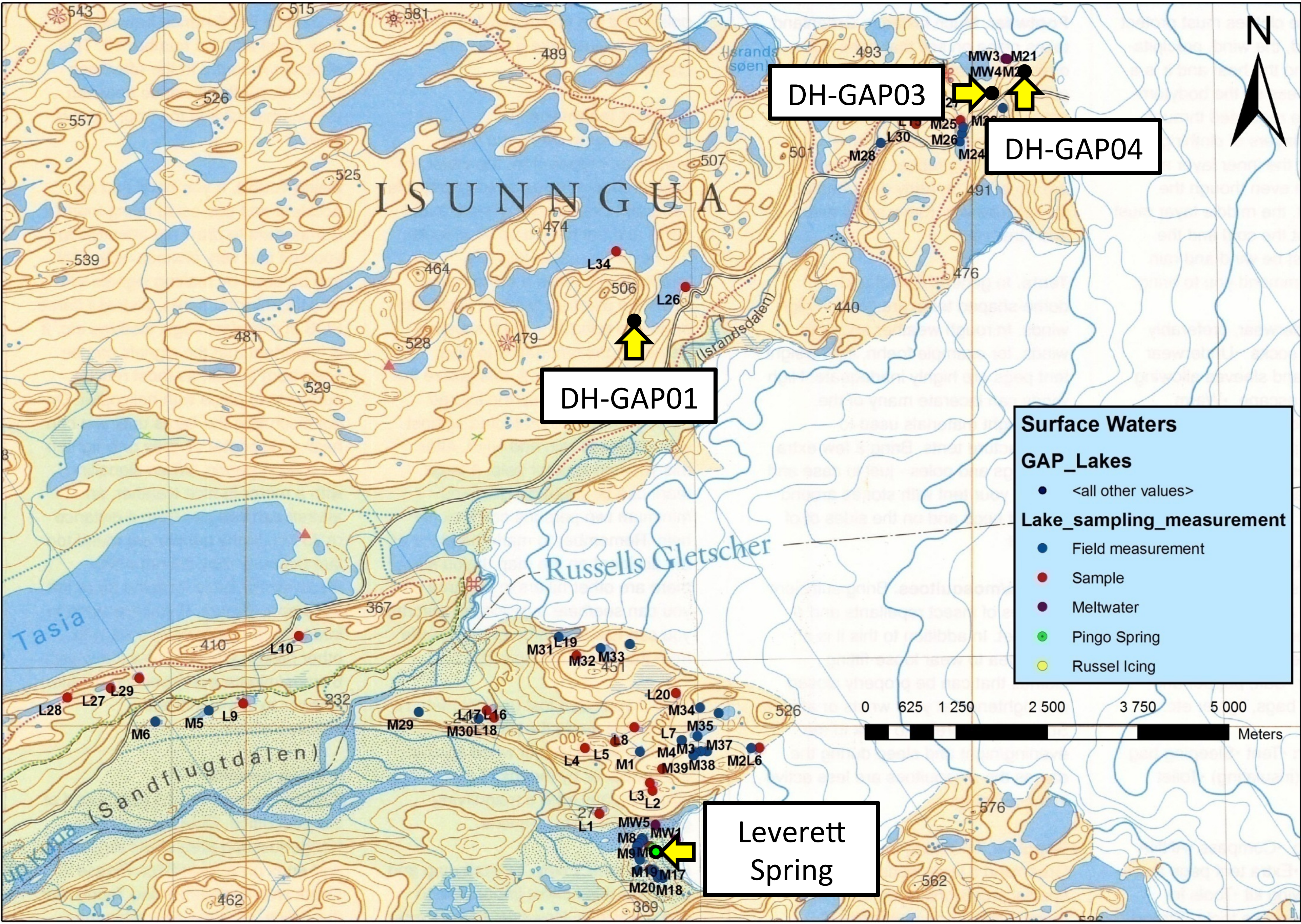


- Glacial periods have high potential risk for deep Nuclear Waste Repositories
- Reduce uncertainties in models

Greenland Analogue Project

- Starinsky and Katz (2003) – glaciations bad news for DGRs




N
DH-GAP03
DH-GAP04
DH-GAP01
Leverett Spring
ISUNNGUA
Russells Gletscher
(Israndsdalen)
(Sandflugtdalen)
Tasia
Surface Waters
GAP_Lakes
<all other values>
Lake_sampling_measurement
Field measurement
Sample
Meltwater
Pingo Spring
Russel Icing
0 625 1 250 2 500 3 750 5 000
Meters
MW3 M21
MW4
L30
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M24
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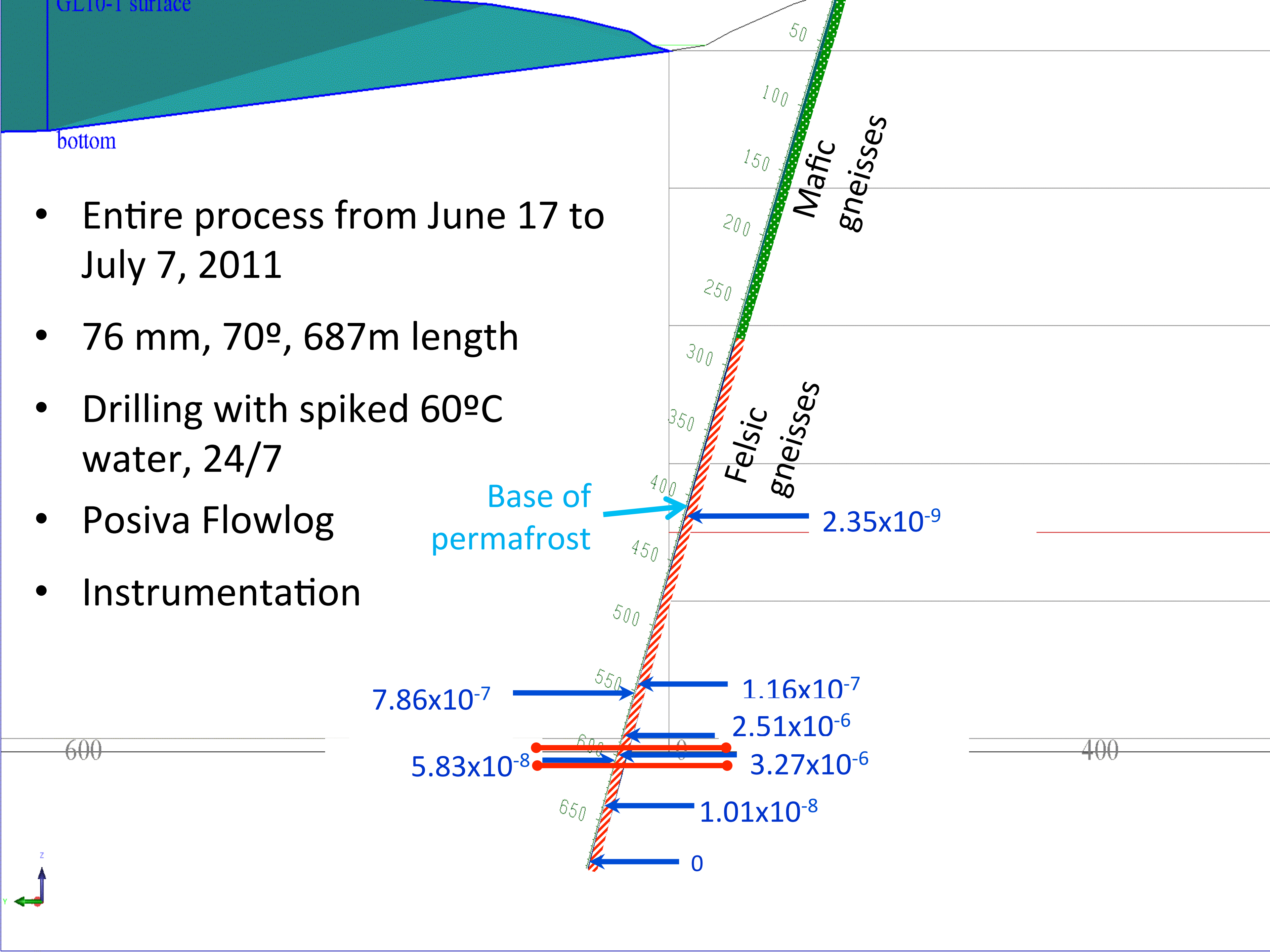
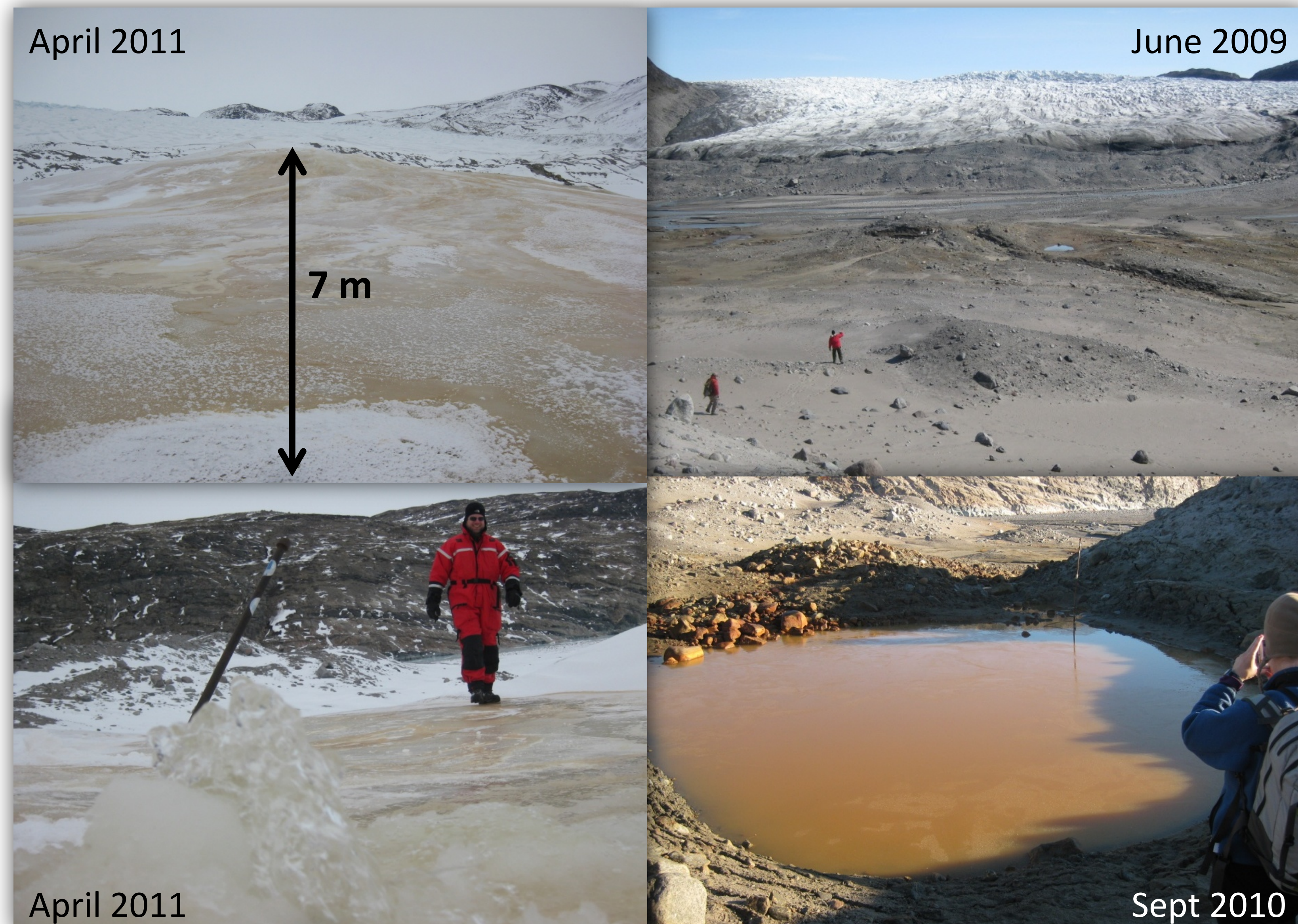
M18

DH-GAP04

- Entire process from June 17 to July 7, 2011
- 76 mm, 70º, 687m length
- Drilling with spiked 60ºC water, 24/7
- Posiva Flowlog
- Instrumentation



Leverett Spring



Pingo and till from north ridge