Radiometric methods - Key points

- Overview of atomic structure
- Radioactive decay
- Radioactivity of rocks
- Gamma-ray spectra
    - Geological isotopes
    - Measurement
    - Data reduction and corrections
- Presentation of radiometric data

- Reading:
    - Reynolds, Chapter 15
    - Dentith and Mudge, Chapter 4

Overview of atomic structure

- As you may remember from high school and other classes, all matter consists of atoms. An atom consists of a positively (electrically) charged nucleus surrounded by electrons with an equal negative charge
  - The nucleus contains most of the atom's mass and has a dimension of about 10^{-14} m
  - The whole atom has a size of about 10^{-10} m (this unit is called Angström), and so it would seem that the atom mostly consists of empty space. However, this is not exactly so, because electrons are not point-like particles but rather quantum *waves*, which are localized within the mentioned 10^{-10} m wave lengths
  - Electrons can be relatively easily lost or gained by the atom during chemical reactions, ionization, or when the atom is included in a molecule or conductive material (like electrolyte or metal)
- The nucleus further consists of approximately equal-mass nucleons, which are of two types: positively charged protons or neutral neutrons
  - The number of protons gives the atomic number, which equals the total positive charge of the nucleus This number also determines the number of electrons and all chemical and molecular properties of the atom
  - The number of neutrons in the nucleus may be variable for different isotopes.
    - For example, the nucleus of the ordinary hydrogen (chemical symbol H) consists of a single proton, and this isotope is denoted ${}^{1}_{1}\mathrm{H}$ (the subscript is the number of protons and the superscript is the total number of nucleons, or mass). There also exist two other isotopes of hydrogen called deuterium D (with an additional neutron, ${}^{2}_{1}\mathrm{H}$) and tritium T (with two neutrons, ${}^{3}_{1}\mathrm{H}$). The atomic number subscript is often suppressed in the notation: ${}^{1}\mathrm{H}$, ${}^{2}\mathrm{H}$, ${}^{3}\mathrm{H}$.
  - Chemically, all isotopes are equivalent, but they may participate in different nuclear reactions, as discussed below

Radioactive decay

- The nuclei of atoms can be stable (last forever) or unstable. Unstable nuclei undergo nuclear fission and fusion reactions at unpredictable moments of time. This process of random transformation is called radioactive decay and leads to three effects:
  - Emission of various particles and energy
  - Production of different chemical elements and isotopes
  - Exponential reduction of the amount of original isotope as:

$$N(t) = N(0)e^{-\lambda t} = N(0)2^{-\frac{t}{t_{1/2}}}$$

Here, $N(t)$ is the number of nuclei at time t, λ is the decay rate, and $t_{1/2}$ is the half-life time. After time $t = t_{1/2}$, the amount of radioactive material reduces by half.

The meaning of decay-rate parameter λ is seen by taking derivative of this law:

$$\frac{dN}{dt} = -\lambda N$$

By taking logarithm, you can see that the two decay constants are related:

$$\lambda = \frac{\log 2}{t_{1/2}}$$

which means that λ is the fraction of the original mass that will decay in one second

- In the preceding example of hydrogen, its primary isotope and deuterium are stable, but tritium is unstable and decays with half-life of 12.32 years

Common modes of radioactive decay

- The common types of radioactive decay reactions are:
  - α-decay - emission of nuclei of Helium, also called α-particles, plus photons (light, X-rays, called "γ-particles" here):

$$ {}^{p+n}_{p}\mathrm{X} \rightarrow {}^{p+n-4}_{p-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He}^{++} + \gamma $$

  - β-decay – transformation of one neutron into a proton with emission of an electron (β-particle) and light:

$$ {}^{p+n}_{p}\mathrm{X} \rightarrow {}^{p+n}_{p+1}\mathrm{Y} + e^{-} + \gamma $$

  - Inverse reaction to β-decay (transformation of proton into a neutron by absorption of an electron), called electron-capture (EC), or K-capture:

$$ {}^{p+n}_{p}\mathrm{X} + e^{-} \rightarrow {}^{p+n}_{p-1}\mathrm{Y} + \gamma $$

- The specific type of reaction occurring within rock is usually recognized by the energy carried by the emitted photons γ (gamma-ray spectrometry; next slides)
- In some reactions, other particles such as mesons and neutrinos are produced (in particular, neutrinos always result from β-decay). These particles are important for making the energy and momentum balances for these nuclear reactions, but they are insignificant for geophysical observations and are not discussed below

Radioactive decay series

- Products of the above reactions are often unstable and decay themselves, and therefore radioactive decay occurs in series
- For example, here is the decay series for uranium ^{238}U:
- This causes combinations of radioactive elements being always present in the ground and in gamma-ray spectra

Isotope	Half-life	Decay mode	Decay energy (MeV)
^{238}U	4.47×10^{9} years	α	4.270
^{234}Th	24.1 days	β	0.273
^{234}Pa	1.17 min	β	2.197
^{234}U	2.48×10^{5} years	α	4.859
^{230}Th	7.7×10^{4} years	α	4.770
^{226}Ra	1622 years	α	4.871
^{222}Rn	3.82 days	α	6.681
^{218}Po	3.05 min	α	6.115
^{214}Pb	26.8 min	β	1.024
^{214}Bi	19.8 min	β	3.272
^{214}Po	162 μsec		7.833
^{210}Pb	22.3 years	β	3.792
^{210}Bi	5.01 days	β	5.037
^{210}Po	138.4 days	α	5.407
^{206}Pb	stable		

Radioactivity of rocks

- Radioactive isotopes that are most significant for geological investigations:

Element	Isotope symbol	Natural abundance (%)	Half-life (years)	Primary decay mode	Decay energy (MeV)
Samarium	^{147}Sm	15.00	1.08×10^{11}	α	
Rubidium	^{87}Rb	27.83	4.9×10^{10}	β	
Rhenium	^{187}Re	62.60	4.5×10^{10}	β	
Lutetium	^{176}Lu	2.59	2.2×10^{10}	β	
Thorium	^{232}Th	100.00	1.4×10^{10}	α	4.083
Uranium	^{238}U	99.28	4.47×10^{9}	α	4.270
Potassium	^{40}K	0.01	1.25×10^{9}	β	1.47
Uranium	^{235}U	0.72	7.04×10^{8}	α	4.679

Red highlights elements most commonly measured (due to abundance, faster decay rates, or lower energy)

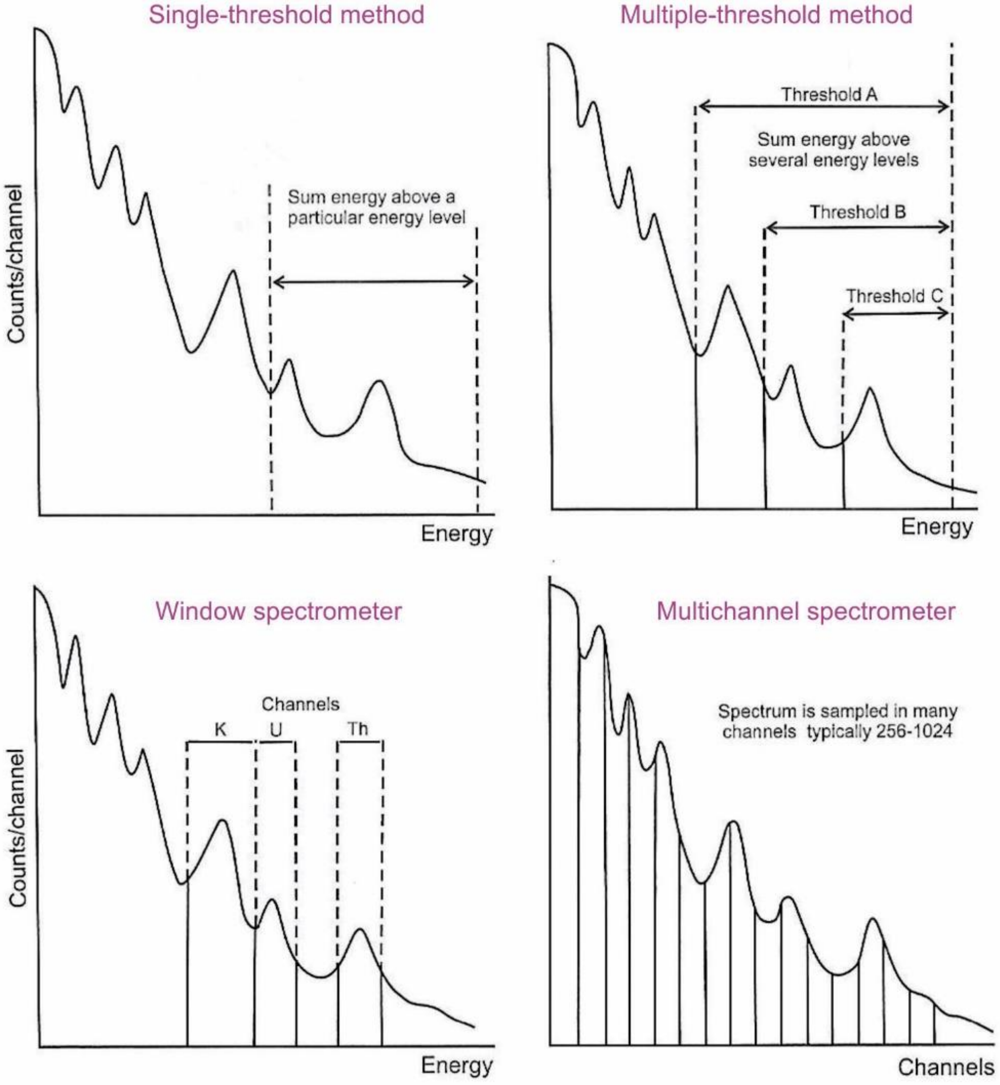
- Potassium-containing minerals are very widespread, and their radioactivity often presents noise in U and Th investigations
- Generally, radiative activity is greater in sedimentary rocks than in igneous and metamorphic rock types, except for potassium-rich granites

Radiation detectors

- Radiation detectors are based on counting the occurrences of reactions in the preceding slides by using the α-, β- and γ- radiations produced by them
  - α- and β-particles are charged, and they can be easily detected by electrical effects (ionization of gas in a Geiger-Müller counter or vapor in a cloud chamber). However, charged particles do not travel far in materials or air
  - In geophysical applications, natural γ radiation (photons of approximately X-ray wavelengths) is typically used. These photons are effectively counted by scintillation detectors and gamma-ray spectrometers, which can be placed at some distance from the sample
    - The scintillation detector consists of a crystal, usually thallium-activated sodium iodide (denoted NaI(Tl)), which emits photons of visible light when a γ-ray photon hits it. The intensity of light (energy of emitted photons) is proportional to the energy of the γ ray
    - The intensity of scintillations is multiplied by photo-multiplier tubes and counted electronically by a fast digitizer (~60 MHz). The count of γ-ray photons indicates how much of the radioactive material is present, and the distribution of their energies indicates the type of radioactive material
- Another popular active-source radiometric technique is neutron logging:
  - An artificial, sealed source (such as americium/beryllium (AmBe)) emits fast neutrons that are slowed down by hydrogen atoms until they are captured. The capture results in emission of γ-rays, which are measured as above. This technique allows evaluation of formation porosity
  - Other techniques use lower-energy ("thermal" or "epithermal" neutrons). These are useful to correlate between different boreholes and to detect gas in some circumstances

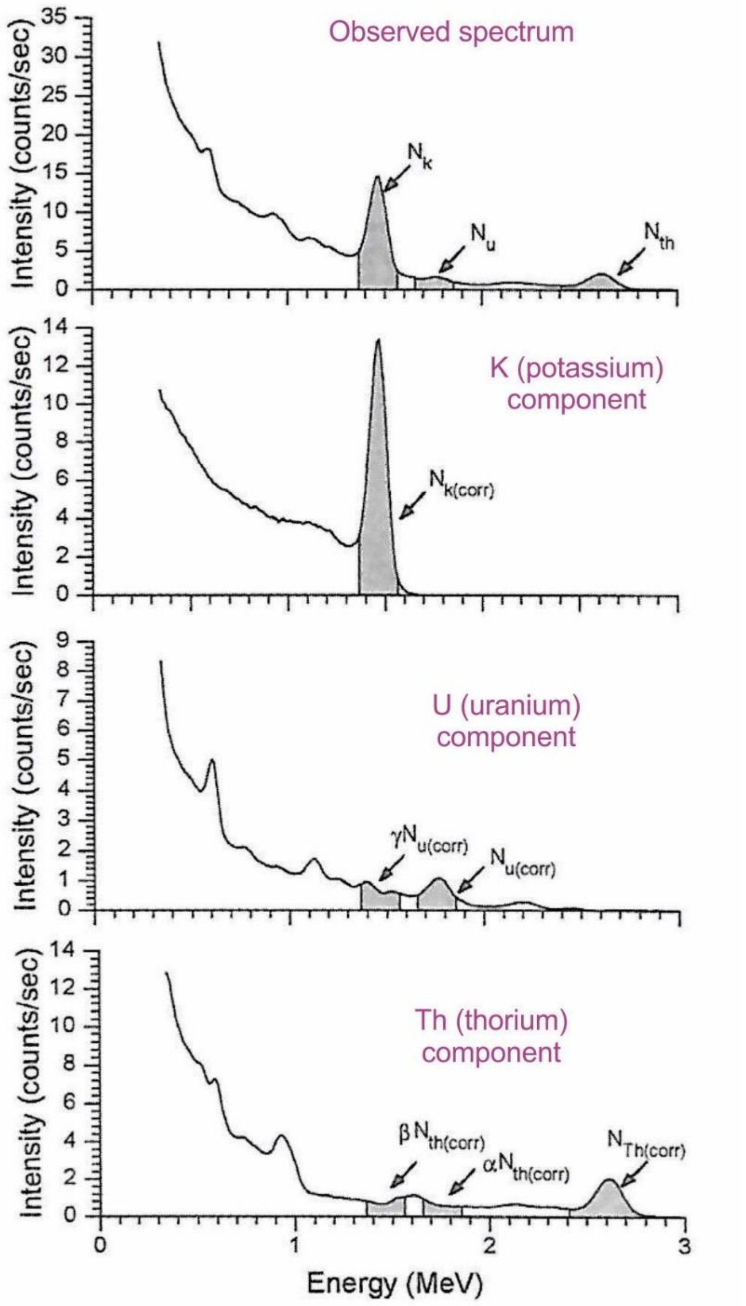
Gamma-ray spectrum

- The γ-ray spectrum is a histogram of the number of detected γ-ray photons with a given energy
- The energies of γ rays are measured in Mega electron-Volts (MeV). One eV is the energy attained by one electron after moving through a potential difference of 1 Volt: $1\ \text{eV} = 1.6\cdot10^{-19}\ \text{J}$
- Gamma-ray spectrometry gives a relatively rapid way to evaluate the chemical composition of the near-surface rocks
  - Presence of certain elements is established by comparing energies above one or several thresholds, within windows, or by matching the complete spectra (figure on the right)
- The general rise of the spectra toward lower energies is caused by scattering of γ-rays prior their detection. By scattering, the energy of the rays reduces, producing an exponential trend



Geological isotopes

- In geological applications, the γ-ray spectrum is used to evaluate the concentrations of potassium (K), uranium (U) and thorium (Th) in the sample
  - Note that for potassium, we only measure the concentration of the radioactive isotope ^{40}K. However, the ratio of concentrations of $^{40}\text{K}/^{39}\text{K} = 0.00012$ is nearly constant, and so we can estimate the total concentration of potassium from a γ spectral analysis
- Figure on the right shows how spectral peaks are inverted for concentrations of elements
  - The highest-energy peak at 2.62 MeV can only come from thorium. If we have a calibration sample with known amount of Th at the same distance from the detector, we can estimate the amount of Th in our target.
    - The thorium peak will also give some amounts of energy in the lower-energy spectra (gray), which we will account for
  - Next, we will proceed to the uranium peak at 2.4 MeV and potassium peak at 1.46 MeV to match the observed spectrum (figure)

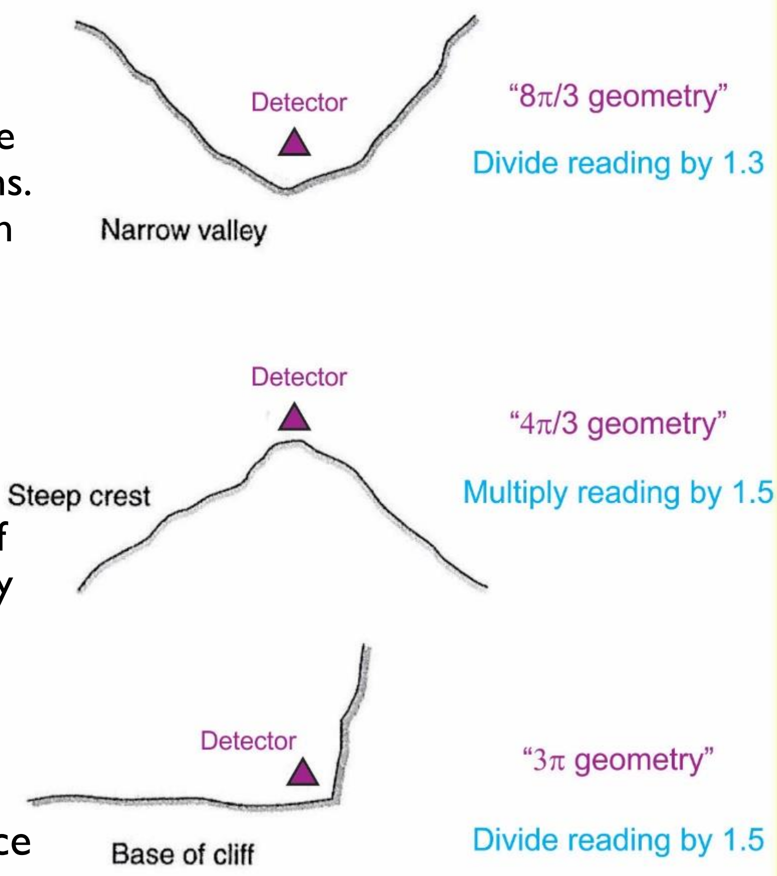


Extra note for GEOL334

Data reduction and corrections

- Radiometric surveys (sometimes) may also require some data reduction and corrections
- For some time following each detected scintillation, the instrument does not count any other incoming photons. This time is called the instrument dead time (T_d), which is typically $T_d = 5$ to $15\ \mu$s/pulse
  - Where essential, the dead time is corrected for by increasing the counts: $N_{\text{true}} = \dfrac{N_{\text{measured}}}{1 - T_d c}$
  - where c is the total count rate over all channels
- Geometric corrections may also be needed because of variable illumination of the detector due to topography (Figure on the right)
  - Recording over a plane is called "2π geometry" (name by the solid angle to the sources of radiation)
  - These corrections can be made as shown here
- In airborne surveys, corrections for terrain clearance (elevation) are also needed:

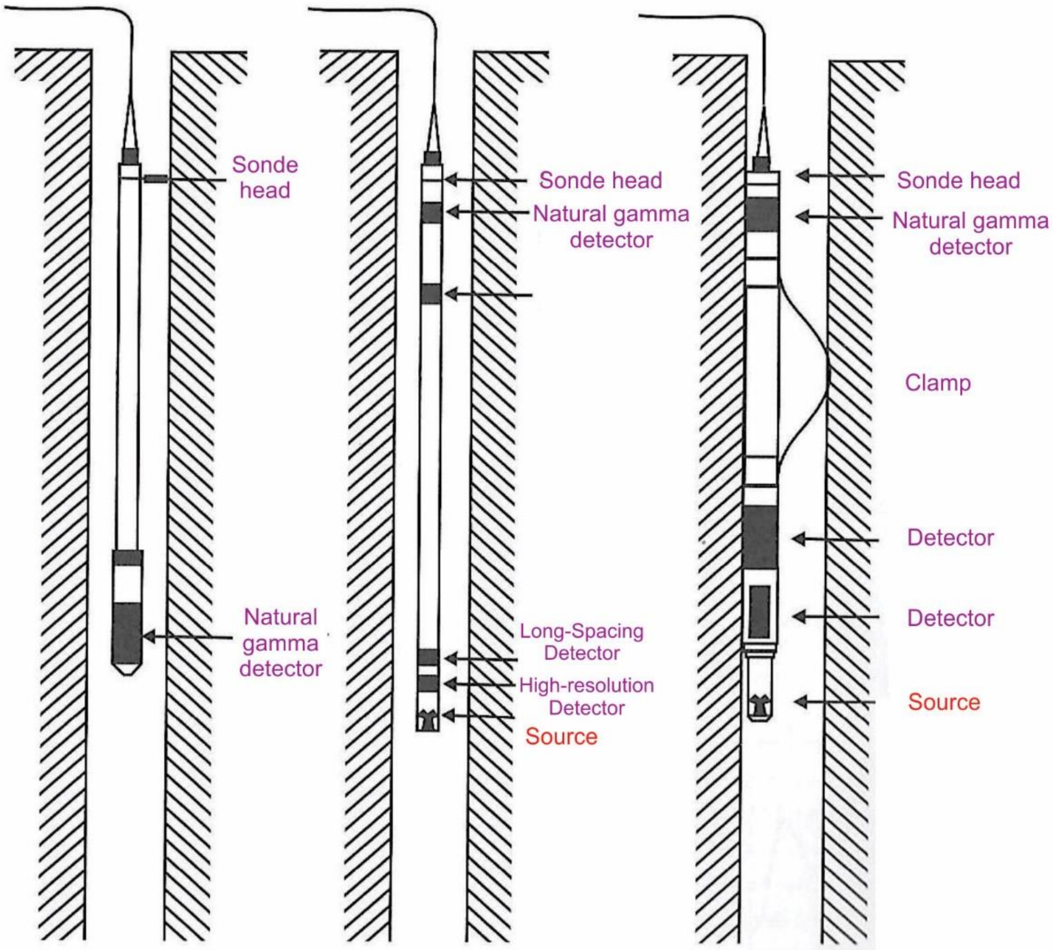
$$N(H) = N_{\text{measured}}(h)\,e^{-\mu(H-h)}$$



Here, h is the actual (variable) survey height, H is the nominal height to which the survey is being leveled, and μ is the "window attenuation coefficient"

Radiometric borehole logging

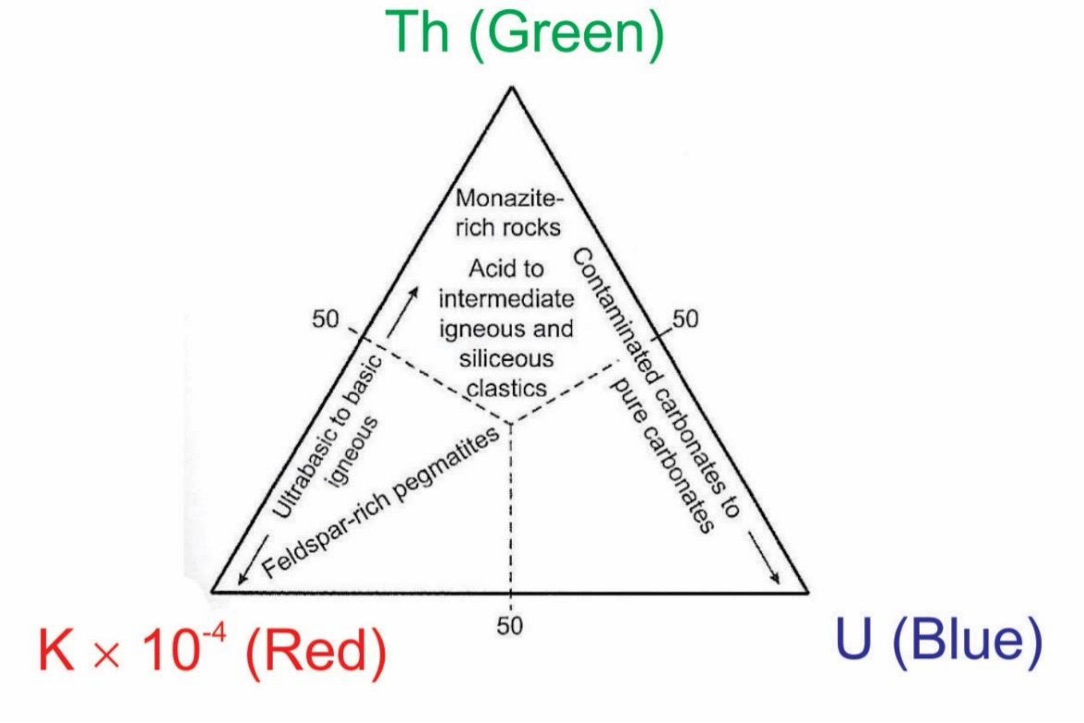
- Boreholes present good environment for radiometric logging
  - Rock is little disturbed and in close proximity to the probe
  - Both natural and active-source (neutron) methods can be used
- Multiple detectors are usually combined in one probe
- Gamma-ray logging is usually conducted while moving the probe at a rate of 6 to 9 m/minute
  - Faster rates may be used in deeper boreholes



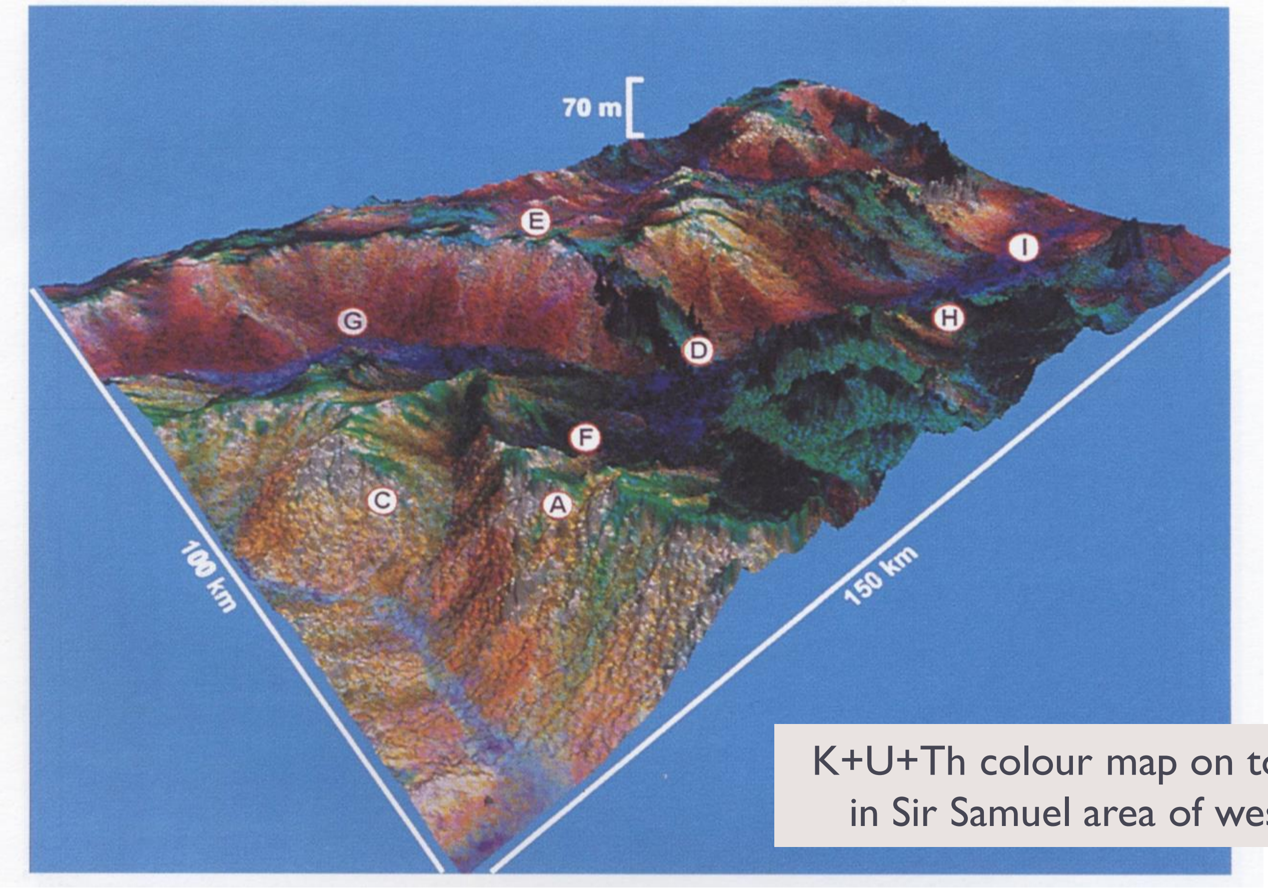
Natural gamma spectroscopy probe | **Density gamma probe (Trisonde)** | **Dual neutron probe**

Presentation of radiometric data

- Relative abundances of the three geologic radioactive isotopes are often shown by ternary (triangular) diagrams
- By mixing the red, green, and blue colors (RGB), these relative abundances are shown on maps (next slide)



Airborne gamma-ray spectrometry



K+U+Th colour map on topographic relief in Sir Samuel area of western Australia

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