Radiometric methods

Radioactivity

- It means the disintegration of an atomic nucleus by emission of energy and particles of mass.

- The disintegrating nucleus ${}^{A}X_{Z}$ is transformed into a nucleus of another element with a change in atomic mass A and atomic number Z .

- The by-product of disintegration being alpha particles (helium nuclei) , beta particles (electrons) and gamma radiation in various combinations.

- The radioactivity decay law expresses the decrease in the number of atoms of a radionuclide with time:

$$N_t = N_0 e^{-\lambda t}$$

where N_t = the number of atoms present after time t (s);
N_0 = the number of atoms present at time $t = 0$;
λ = the decay constant of a radionuclide (s^{-1}),

A related constant, the half-life $T_{1/2}$ (s), is the time taken for half the radionuclides to decay:

$$T_{1/2} = \frac{0.693}{\lambda}$$

Types of radioactive decay

- There are several types of radioactive decay:

- *Alpha decay is accompanied by the release of an* alpha particle consisting of 2 protons and 2 neutrons.
- *Beta⁻ decay is realized by the emission* of a beta particle identical to a negatively charged electron.
- *Beta⁺ decay, which is less* frequent, is accompanied by the emission of a positively charged positron.
- *Electron capture* occurs through the absorption of an orbital electron of an atom by the atomic nucleus. The replacement of the vacant electron position is followed by the emission of characteristic radiation (electromagnetic radiation of low energy).

- Some radionuclides may have more than one mode of decay.

- Radioactive decay also often occurs in a series (or chain) with a number of daughter products, which are also radioactive, and terminates in a stable isotope.
- In a closed system, and starting with a specified amount of a mother element, the number of atoms of daughter elements and their activity grows gradually until radioactive equilibrium of the disintegration series is reached.
- At this point, the activities of all the radionuclides of the series are identical. Thus the measurement of the concentration of any daughter element can be used to estimate the concentration of any other element in the decay series.
- Under equilibrium conditions, this relationship can be expressed as follows: $\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \ldots \lambda_i N_i$

Statistical nature of radioactive decay

- Radioactive decay is a statistical phenomenon.
- Each atomic disintegration during radioactive decay occurs completely independently of every other decay event, and the time interval between disintegrations is not constant.
- For a large number of randomly disintegrating atoms of a particular radionuclide, the frequency of radioactive decay is given by Poisson's distribution: if $\overline{n}$ *is the mean decay rate, the probability, P, that the number of atomic nuclei, n, will decay within a time unit is:*

$$P(n) = \frac{\overline{n}^{n}}{n!}\exp(-\overline{n})$$

For Poisson's distribution it holds that the variance σ^2 of a distribution is equal to its mean value, and σ is the standard deviation. The range of $\pm 1\sigma$ about the mean encompasses 68.3 percent of the distribution, $\pm 2\sigma$ encompasses 95.5 percent of the distribution, and $\pm 3\sigma$ encompasses 99.7 percent of the distribution.

•The emission of particles and gamma rays in radioactive decay is proportional to the number of disintegrating atoms, and the standard deviation may be used to estimate the range of deviations and errors of the radiometric measurements.

•If *N counts are recorded in time t, then* the standard deviation of the recorded counts is:

$$\sigma(N) = \sqrt{\overline{N}}$$

Radiometric Dating

History, Theory, Current Methods, Problems
SRJC, Physics 43, Spring 2011

Aaron Krive, Kevin Chee

History

- Radioactive decay of Uranium was discovered in 1896 by French Scientist Henry Becquere.
- Possibility of dating using radioactivity was proposed by British scientist Lord Rutherford in 1905.
- The first list of geological ages based on radiometric dating published by Yale radiochemist Professor B. B. Boltwood in 1907.

US Geological Survey <http://pubs.usgs.gov/gip/geotime/radiometric.html>

History Cont.

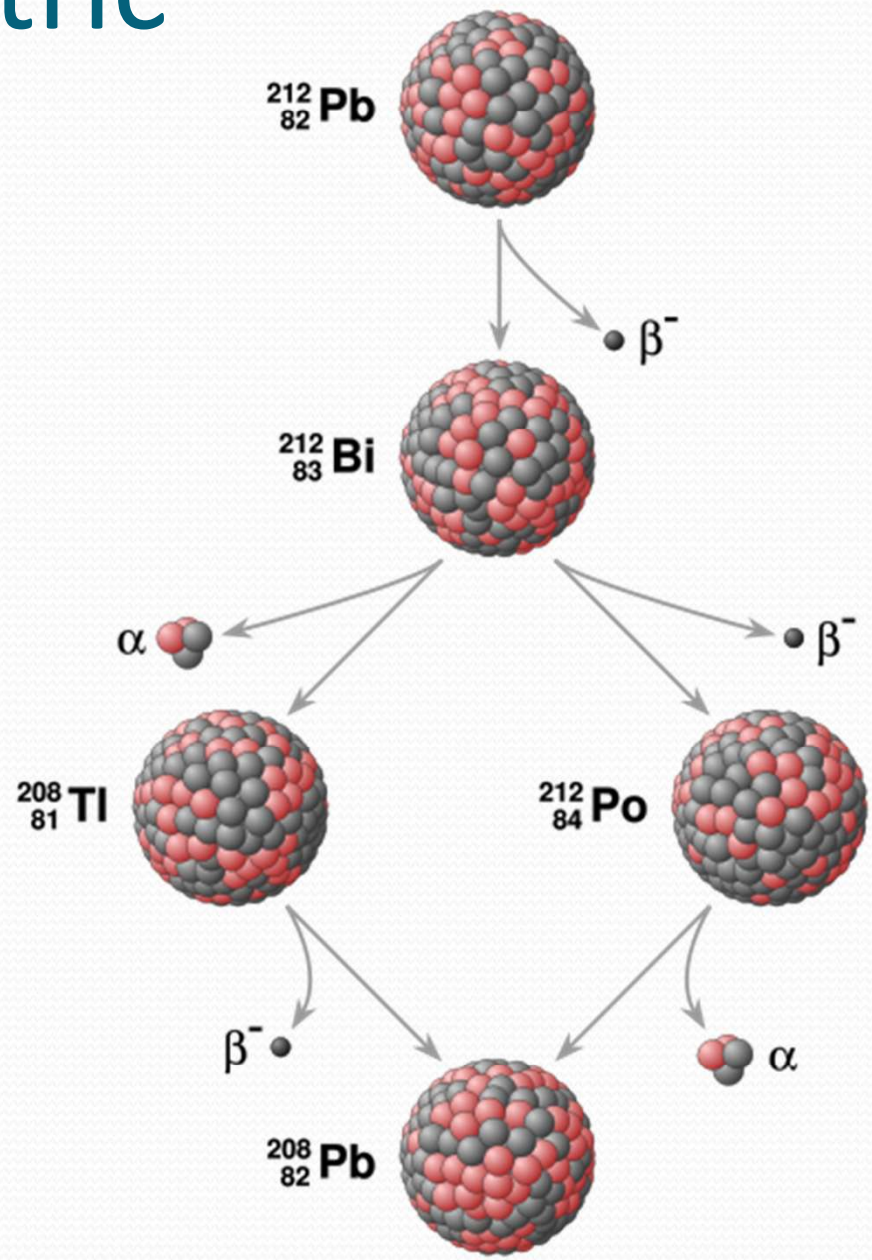
- Precise dating is supposed to have been accomplished from 1950 onward.
- List of the most common parent isotopes and daughter products:

Parent Isotope	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.0 billion years
Rubidium-87	Strontium-87	48.8 billion years
Potassium-40	Argon-40	1.25 billion years
Samarium-147	Neodymium-143	106 billion years

US Geological Survey <http://pubs.usgs.gov/gip/geotime/radiometric.html>

Theory of Radiometric Dating

- Given initial conditions, the decay of a radioactive material into its stable daughter material should be constant.
- Thus, measuring the amounts of both the parent and daughter material should give an accurate date.



Theory Cont.

- The mathematical expression that relates radioactive decay to geologic time is called the age equation and is. This equation assume no initial daughter material

$$t = \frac{1}{\lambda} \ln\left(1 + \frac{D}{P}\right)$$

where t is the age of the rock or mineral specimen,
D is the number of atoms of a daughter product today,
P is the number of atoms of the parent isotope today,
ln is the natural lograithm (logarithm to base e), and
λ is the appropriate decay constant.

(The decay constant for each parent isotope is related to its half-life, $t^{1/2}$ by the following expression: $t^{1/2} = \frac{\ln 2}{\lambda}$

US Geological Survey <http://pubs.usgs.gov/gip/geotime/radiometric.html>

Theory Cont.

This age equation considers the possibility of initial daughter material:

- $D = D_0 + N(e^{\lambda t} - 1)$

t = the age of the sample

D = the number of daughter atoms in the sample

D_0= the initial number of daughter atoms.

N = the number of isotropic atoms at t, $N = N_0 e^{-\lambda t}$

λ = the decay constant $\lambda = ln(2)/t_{1/2}$

Wikipedia
http://en.wikipedia.org/wiki/Radiometric_dating

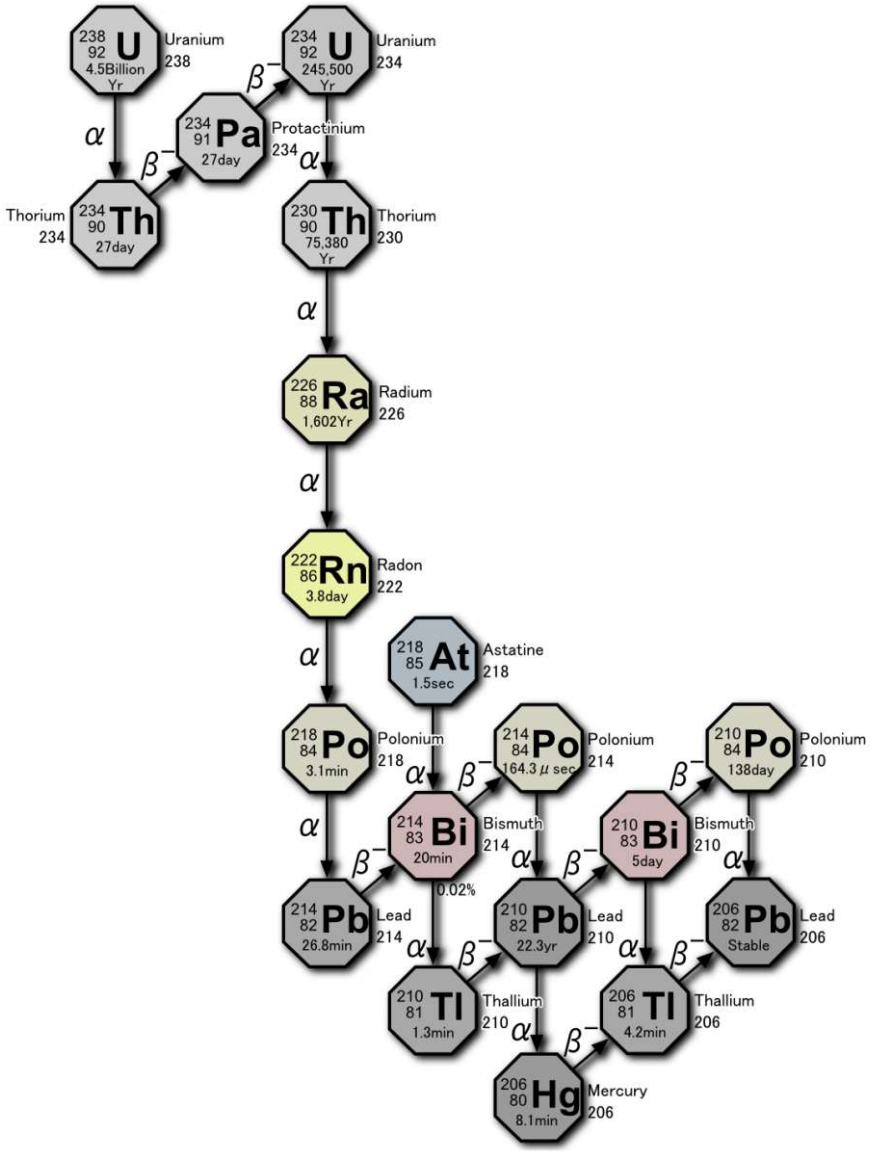
Uranium-Lead Dating

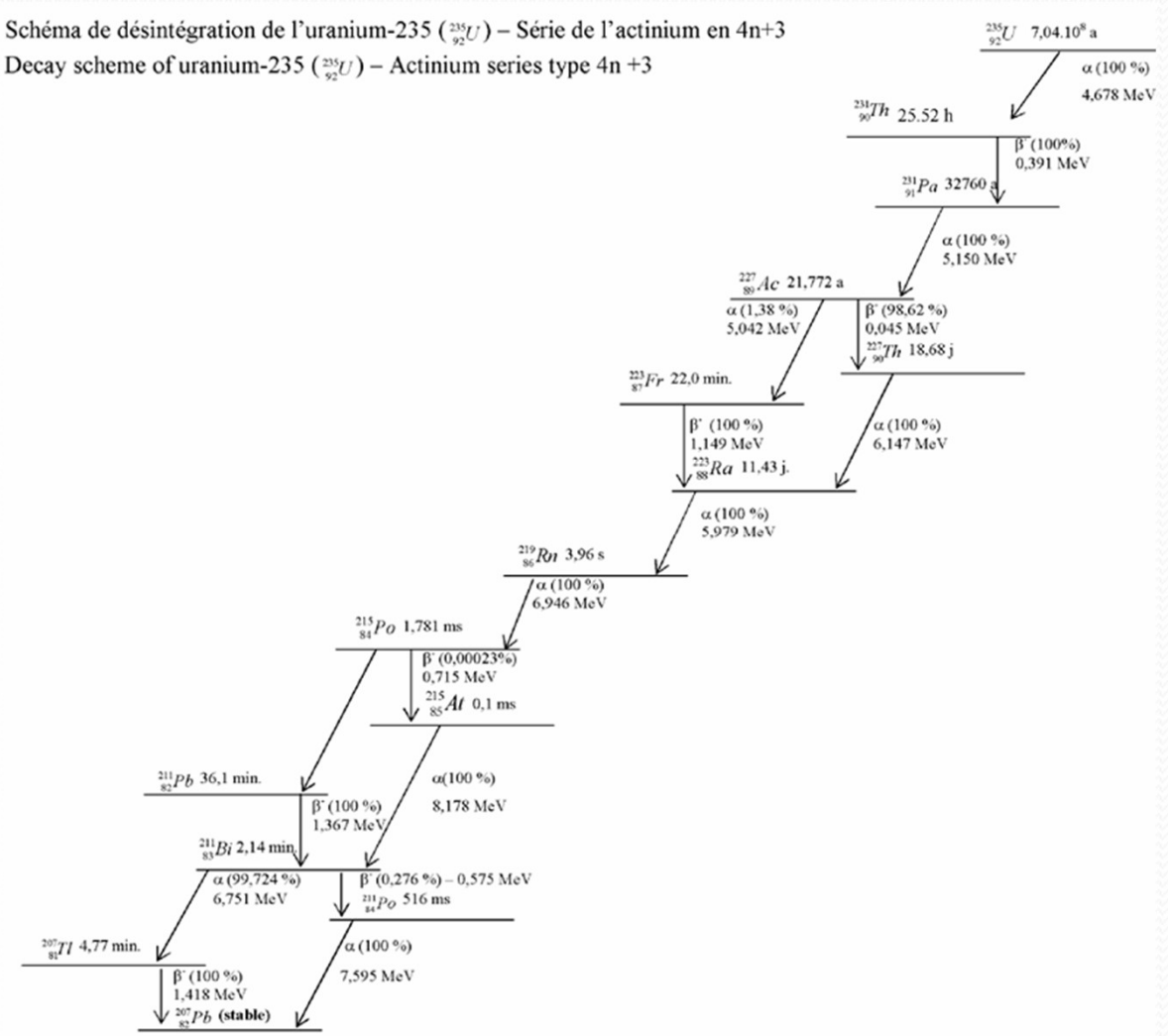
- One of the oldest and most refined of the radiometric dating methods
- Routine age range of ~1 million – 4.5 billion years
- Routine precision in 0.1-1 % range
- Method uses 2 distinct decay chains
  - Uranium series: $^{238}U \rightarrow {}^{206}Pb$
  - Actinium series: $^{235}U \rightarrow {}^{207}Pb$

Boltwood, B.B., 1907, On the ultimate disintegration products of the radio-active elements. Part II. The disintegration products of uranium: American Journal of Science 23: 77-88.

Parrish, Randall R.; Noble, Stephen R., 2003. Zircon U-Th-Pb Geochronology by Isotope Dilution – Thermal Ionization Mass Spectrometry (ID-TIMS). In Zircon (eds. J. Hanchar and P. Hoskin). Reviews in Mineralogy and Geochemistry, Mineralogical Society of America. 183-213.

The 2 U→Pb decay series:





Uranium series: http://en.wikipedia.org/wiki/File:Decay_chain(4n%2B2,_Uranium_series).PNG
Actinium series : http://en.wikipedia.org/wiki/File:Decay_scheme_U235.png

Minerals used for dating:

- Zircon ($ZrSiO_4$), is the preferred mineral analyzed:
  - Zircon incorporates Uranium and Thorium atoms into it's crystalline structure, but strongly rejects lead.
  - Zircon has a high trapping temperature of 900°C. Its clock is not easily disturbed by geologic events—not erosion or consolidation into sedimentary rocks, not even moderate metamorphism.
  - Widespread in igneous rocks, which have no fossils to indicate their age.
  - Tough, so easier to separate Zircon crystals from surrounding environment.

http://geology.about.com/od/geotime_dating/a/uraniumlead.htm

Mineral / radioactive decay interaction (for Zircon)

- Each alpha decay damages the crystal structure of the Zircon
- In the decay steps where Pb is created, Pb is ejected from the crystal lattice, again damaging the minerals structure.
- Thus, areas in mineral with high concentrations of Uranium and Thorium (early elements in decay chain) will have the most damage.
- Damage to the mineral structure can result in leaching of Pb from the Zircon sample, thus effecting the precision of age determination.

Romer, R.L. 2003. Alpha-recoil in U-Pb geochronology: Effective sample size matters. Contributions to Mineralogy and Petrology 145, (4): 481-491.

Mattinson, J.M., 2005. Zircon U-Pb Chemical abration ("CA-TIMS") method: Combined annealing and multi-step dissolution analysis for Improved precision and accuracy of zircon ages. Chemical Geology. 200, 47-66.

Process details:

- Given conditions where system is closed (no Pb lost)

  Age can be determined from:

$$\frac{^{206}\mathrm{Pb}^*}{^{238}\mathrm{U}} = e^{\lambda_{238} t} - 1 \qquad \frac{^{207}\mathrm{Pb}^*}{^{235}\mathrm{U}} = e^{\lambda_{235} t} - 1$$

  -The Pb/U ratios of each equation are plotted on the axis of the same graph. (Pb206/U238) plotted on the y-axis and (Pb207/U235) plotted on the x-axis. The plot results in a curved line called the concordia. A graph of a concordia can be seen 2 slides later.

  -The concordia represents ideal situations and can be calculated directly from the equations and known half lives of our subject elements.

  -Proof of concept can be demonstrated by taking samples of varying ages from different locations, whos ratios (given closed system conditions) will all fall on the concordia line.

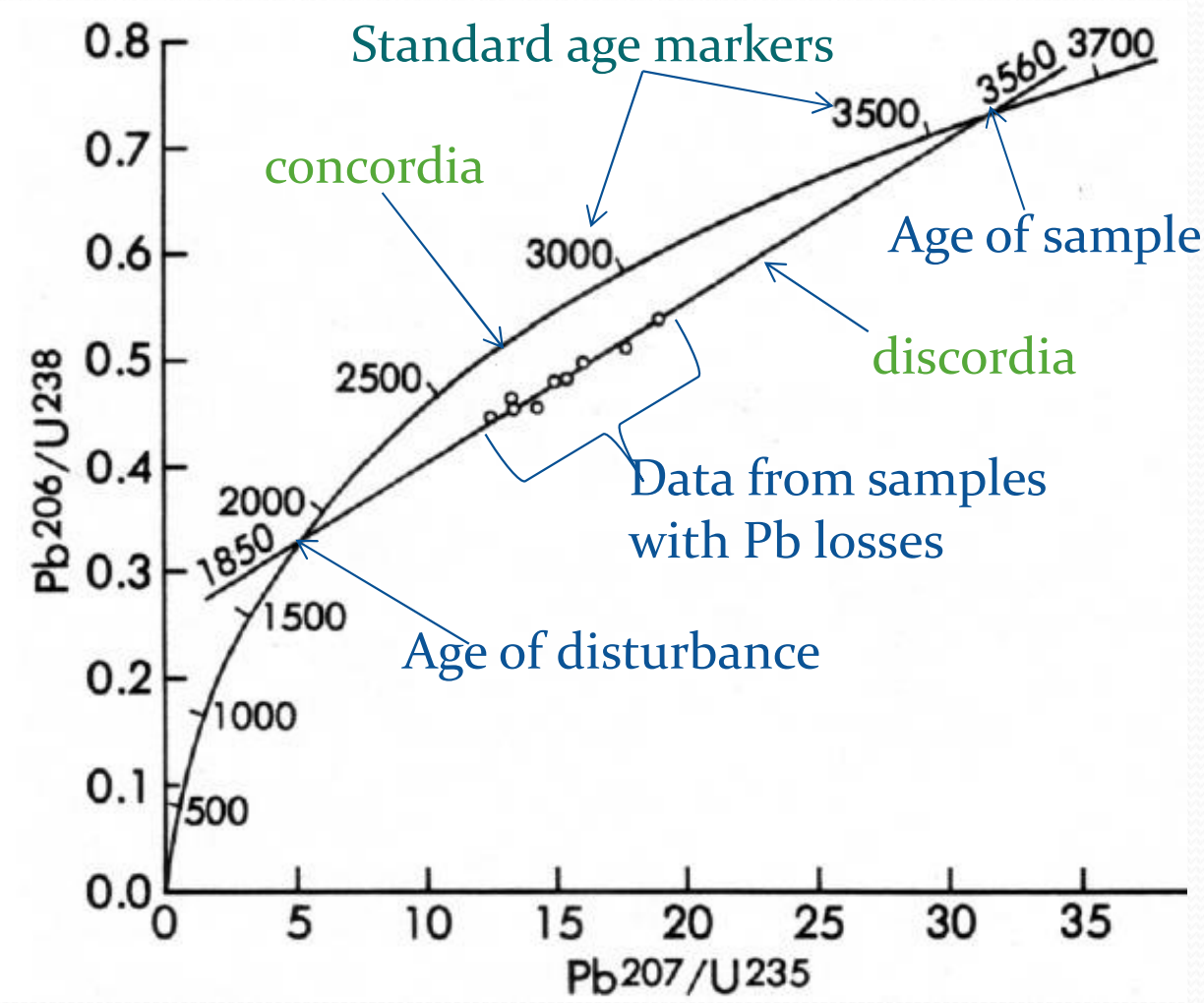
^ Dickin, A.P., 2005. Radiogenic Isotope Geology 2nd ed. Cambridge: Cambridge University Press. pp. 101.

Process details (Pb losses):

- Zircon samples taken from a location are not usually perfect, thus some samples will have no loss while others will have varying degrees of Pb losses.
- Pb losses can be used to determine the time of disturbance events and age of samples.
  - Imagine a 1 billion year old zircon deposit. If there were no losses it would ride up the concordia perfectly to the 1 billion year point. (figure on next slide may be helpful in visualizing)
  - Now imagine, at the 1 billion year birthdate , a strong disturbance (earthquake) which caused Pb losses of varying degrees in different areas of the zircon deposit.
  - Pb loss follows a more linear type loss rate down to the origin. And samples with Pb losses from the same event would fall on a straight line from (1) the point on the concordia at time of disturbance to (2) the origin. This line is called the discordia. (A discordia can be seen in the next slide)
  - After the disturbance, as time went along, the discordia would travel up with the growing concordia.
    - The upper intercept of the two lines would be the current age of the sample
    - The lower intercept would be the age of the disturbance.

^ Dickin, A.P., 2005. Radiogenic Isotope Geology 2nd ed. Cambridge: Cambridge University Press. pp. 101.

Plot of concordia and discordia



http://www.talkorigins.org/faqs/dalrymple/radiometric_dating.html

Problems With Radiometric Dating

- Based on assumptions (Constant decay, initial conditions)
- For many types of dating, there is no way to correct for leeching of the parent or daughter materials
- It is impossible to compare the results to the actual age and determine how accurate these results actually are.

Constant Decay – Daughter Material

- Current decay rates are cannot be verified as constant over millions or billions of years. The decay rates are known to change because of environmental factors.

- Scientists must assume that there is no daughter material in the rock when it is formed. In the case of Uranium-Lead dating, scientists must assume that there was no lead in the rock when it formed.

Radioactivity of rocks

- Measurements of the radioactive properties of naturally occurring substances indicate that a low level of activity is present in almost all rocks and minerals.
- In the beginning this was attributed almost entirely to traces of uranium and thorium and their radioactive decay products.
- Later investigations showed that an isotope of potassium ^{40}K is also radioactive .

Disequilibrium

- Disequilibrium occurs when one or more decay products in a decay series are completely or partially removed or added to the system.

- Thorium rarely occurs out of equilibrium in nature, and there are no disequilibrium problems with potassium.

- However, in the uranium decay series disequilibrium is common, and can occur at several positions in the ^{238}U decay series:^{238}U can be selectively leached relative to ^{234}U; ^{234}U can be selectively leached relative to ^{238}U; ^{230}Th and ^{226}Ra (Radium) can be selectively removed from the decay chain; and finally ^{222}Rn (radon gas) is mobile and can escape from soils and rocks into the atmosphere.

- Depending on the half-lives of the radioisotopes involved, it may take days, weeks or even millions of years for equilibrium to be restored.

- Disequilibrium in the uranium decay series is a serious source of error in gamma ray spectrometry.

- Uranium concentration estimates are based on the measurement of ^{214}Bi and ^{214}Pb isotope abundances. These occur far down in the radioactive decay chain and may not be in equilibrium with uranium.

- Estimates of uranium concentration are therefore usually reported as "equivalent uranium" (eU) as these estimates are based on the assumption of equilibrium conditions. Thorium is also usually reported as "equivalent thorium" (eTh), although the thorium decay series is almost always in equilibrium.

Interaction of gamma rays with matter

- Radiation is comprised of a flux of elementary particles and energy quanta, and can be classified by its physical character and energy.

These determine how the radiation interacts with matter.

- Alpha radiation is a flux of positively charged alpha particles. Alpha particles have an initial energy of several MeV, and an initial velocity of the order 10^7 m/s.
- They exhibit high ionization, and their penetration range in matter is low. Alpha particles are absorbed by about 10^{-2} m of air, and 10^{-5} m of rock.

- Beta radiation is a flux of electrons with a continuous energy spectrum up to a maximum energy, which depends on the particular radionuclide.

- The initial velocity of beta particles can approach the velocity of light.

- The penetration range for beta particles depends on the initial energy of the particle. For E=2 MeV, the penetration range is about 8 m in air and 1 cm in water.

- Beta radiation passing through matter loses its energy by ionization and generates electromagnetic radiation called bremsstrahlung. Positrons passing through matter combine with electrons, and generate two annihilation gamma quanta of energy 511 keV each.

- Gamma radiation is part of the electromagnetic spectrum. Gamma rays travel at the speed of light (*c*), *and have a discreet energy (E), frequency (f), and wave length (λ). These are related* by:

$$E = hf = hc/\lambda$$

where *h* = Planck's constant 6.6261×10^{-34} Js; c = velocity of light.

- Electromagnetic radiation of energy *E < 40 keV is denoted as X-rays*.
- *Gamma rays comprise* that part of the electromagnetic spectrum where *E > 40 keV*.

- Gamma rays interact with atoms of matter by three principal processes (ICRU, 1994). These are the photoelectric effect, Compton scattering and pair production.

- The photoelectric effect is the predominant absorption process at low energies, and results in all the energy of a gamma quantum being absorbed in a collision with an electron of an atom.

- Compton scattering predominates at moderate energies and corresponds to a collision of an incident photon with an electron. The incident photon loses part of its energy to the electron and is "scattered" at an angle to its original direction.

- Pair production occurs at energies greater than 1.02 MeV. It is the process whereby an incident photon is completely absorbed and results in the creation of an electron-positron pair in the electrostatic field of a nucleus.

➢For gamma rays of natural terrestrial origin (*E up to 2.615 MeV) and for matter comprising rock, water and air,* Compton scattering is the dominant interaction process.

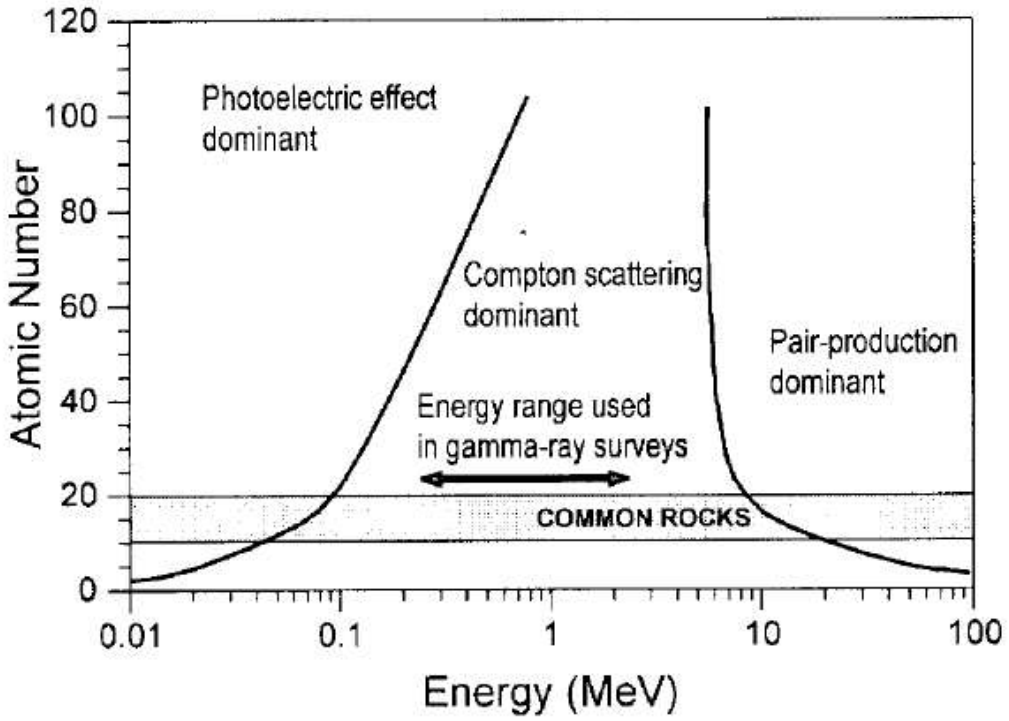


FIG. 2.1. The interaction of gamma rays with matter.

- Typically, gamma ray photons lose energy through successive Compton scattering events, until eventually the resulting low-energy photons are absorbed through the photoelectric effect.
- As a result of the interaction of gamma rays with matter, the intensity of radiation decreases with distance from the source.
- The absorption of gamma rays of a specific energy in matter is described by either a linear attenuation coefficients μ (m^{-1}) or a mass attenuation coefficient μ/ρ (m^2/kg).
- For a narrow beam of gamma rays, the attenuation of the gamma rays can be modelled by an exponential function.
- The range of gamma rays of natural radionuclides is about 700 m in air, up to 0.5 m in rocks and a few cm in lead.
- Gamma rays have a discrete energy that is specific for a particular radionuclide.
- Since gamma rays are the most penetrating component of natural and man-made radiation, they are widely used in the study of the radiation environment.

Detectors and instruments

- Ionizing radiation can be measured through the physical and chemical effects of its interaction with matter.

- Field and laboratory methods are based mainly on the ionizing properties of radiation and the use of instruments that convert the radiation to electrical signals.

- Ionization chambers, proportional counters, Geiger-Muller tubes, scintillation counters, semiconductor detectors, thermoluminiscence detectors and various mechanical and chemical track detectors are used to monitor and quantify the α, β, γ and neutron radiation of the environment.

- The efficiency of a detector is a measure of the probability that an incident photon will be absorbed in the detector. It is usually quoted as the ratio of recorded counts to incident photons.

- The energy resolution of a detector is a measure of its ability to distinguish between two gamma rays of only slightly different energies.

- This is usually defined as the full width of a photopeak at half the maximum amplitude (FWHM) divided by its energy.

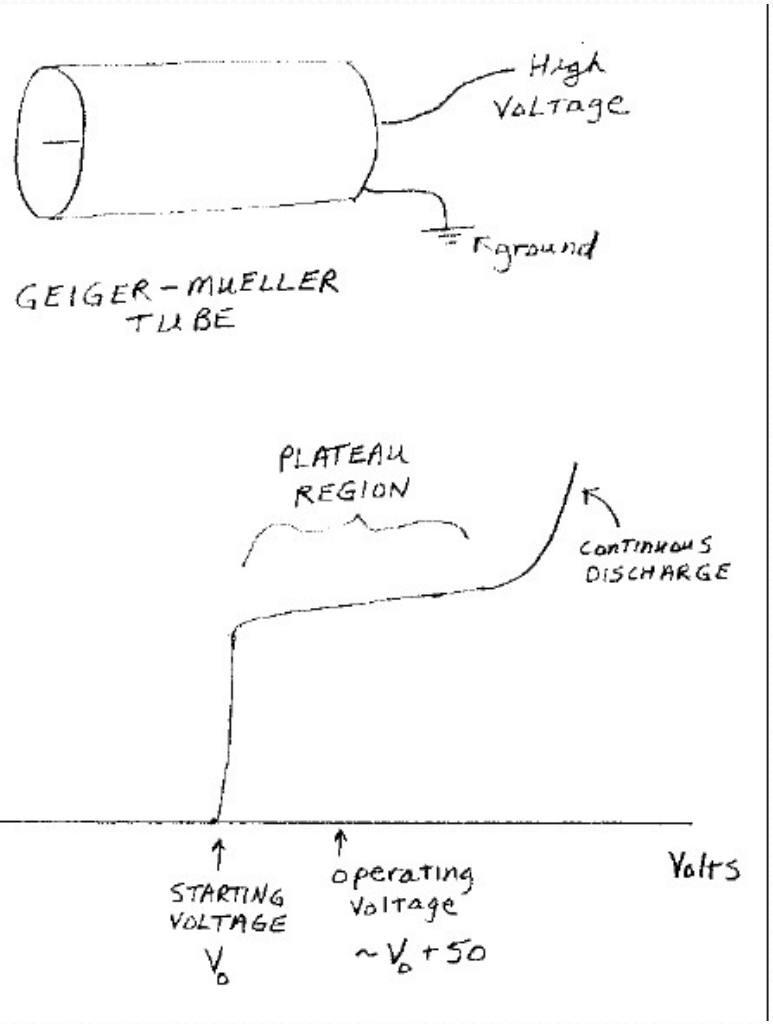
- Instruments used in in-situ gamma ray spectrometry are usually specified by the energy resolution of the ^{137}Cs photopeak at 662 keV.
- Dead time refers to the finite time required for a detector to process an individual particle of radiation. During this time all incoming pulses are ignored. Dead time should thus be as small as possible.

Geiger-Muller counter

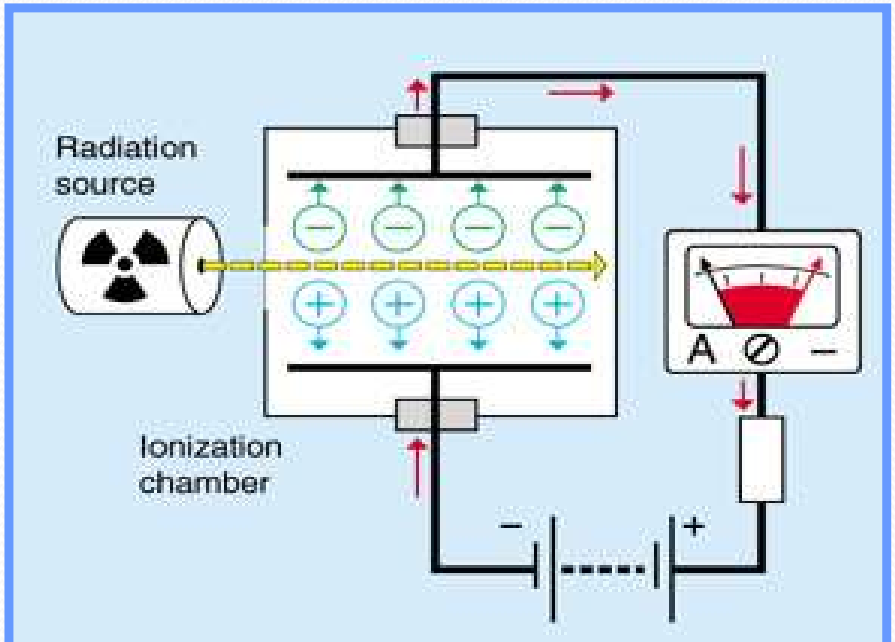
GM counter consists of a gas-filled tube equipped with a metal cylinder (the cathode) and a thin conductive wire (the anode) mounted along the tube axis.

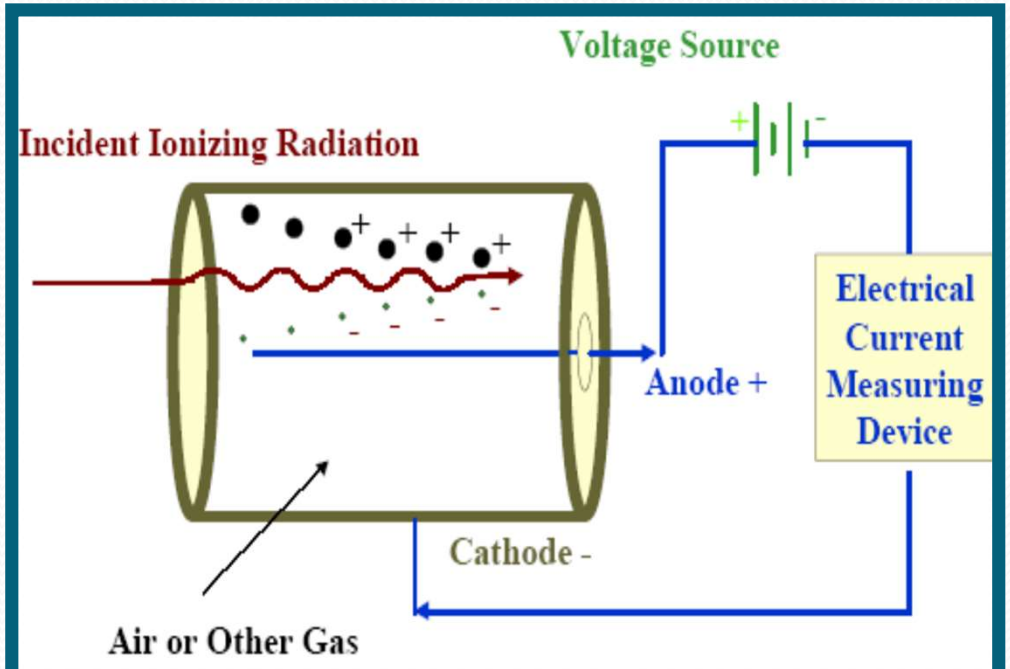
Normally argon, with an admixture of halogen vapour, is used as gas filling.

GM counters are 2 to 30 cm long and 1 to 4 cm in diameter, and they operate with applied voltage of several hundred volts.



- GM counters make use of the **progressive growth of ionization** in a strong electric field between the anode and the cathode.
- An incident photon interacts with the cathode and **releases an electron** that may be directed into the GM tube.
- The growth of ionization between the anode and the cathode amplifies the signal and generates **an electric current** between the electrodes.
- This results in **a voltage pulse** at the anode output of the GM counter.
- The multiplication coefficient of the gas ionizing chain reaction is of the order of 10^6, and the output pulse is not proportional to the absorbed gamma ray energy. The detection efficiency of GM counters is very low (less than 2%) and the dead time is of the order 10^{-4} s.





Scintillation counters

- Scintillation counters consist of a scintillator and a photomultiplier.
- An incident gamma ray photon interacts with the material of the scintillation crystal to produce scintillations.
- These photons of visible light induce the ejection of electrons from the photocathode of the attached photomultiplier.
- Their number multiplies progressively at dynodes of the photomultiplier, and an electron cloud strikes the anode.
- This induces a negative voltage pulse as output, with amplitude proportional to the energy of the incident photon.
- Scintillation counters are widely used in gamma ray spectrometry.
- Thallium-activated sodium iodide NaI(Tl) crystals are mainly used as detectors in field gamma ray surveys.
- They have a detection efficiency of up to 100% for low-energy gamma rays but somewhat less for high-energy gamma rays. The dead time is of the order 10^{-7} s.

- NaI(Tl) detectors are hygroscopic, they age, they are fragile, and the photomultiplier tube function is dependent on temperature.
- Their large crystal volumes are an advantage in applications such as airborne surveying where measurement times are necessarily short.
- Thallium-activated cesium-iodide CsI(Tl) crystals are neither hygroscopic nor particularly fragile.
- They have a dead time of the order 10^{-9} s.
- But they are too expensive for widespread use.

- Plastic scintillators are an admixture of a scintillator and a plastic transparent material.
- They can be produced in large volumes, but have poor energy resolution and are not suitable for gamma ray spectrometry.
- Bismuth-germanium-oxygen $Bi_4Ge_3O_{12}$ scintillation crystals have been applied to field gamma ray spectrometry in boreholes. Due to their high density (7.13 g/cm^3) they are efficient at high gamma ray energies.

Germanium semiconductor detectors

- Germanium semiconductor detectors use the electronic carriers (electron-ion and electron-hole pairs) created by the absorption of gamma ray photons in the germanium detector.

- These collect directly on the detector electrodes, causing a flow of electric current through the semiconductor and produce an output voltage pulse of amplitude proportional to the energy of the incident gamma ray photon.

- The detector consists of a germanium crystal mounted in a vacuum cryostat cooled to -196 °C.
- Cooling is by insertion of the cryostat in a dewar vessel filled with liquid nitrogen, or by electrically powered cryogenic refrigerators.
- The detectors are generally of small volume and used in in-situ gamma ray spectrometry.
- The energy resolution of these detectors is very high, but because of their small volume, their sensitivity is low and it may take tens of minutes to record a spectrum.

Gamma ray spectrometers

- Gamma ray spectrometers use the direct proportionality between the energy of an incoming gamma ray and the pulse amplitude at the output of the detector.
- The output of the spectrometer is an energy spectrum of detected radiation.
- Since individual radionuclides emit specific gamma ray energies, gamma ray spectra can be used to diagnose the source of the radiation.

- Gamma ray spectrometers are either “integral” or “differential”.
- Integral spectrometers record only those pulses with amplitudes exceeding a discrimination threshold.
- This threshold can be changed to allow the discrimination of individual radionuclides.
- Differential gamma ray spectrometers record pulses whose amplitudes fall within a given amplitude interval (or channel), corresponding to a discrete range of gamma ray energy.
- Wider energy intervals (comprising several channels) are called energy windows.
- Modern analyzers use as many as 256 or 512 channels, with a width of several keV per channel.
- Older systems are limited to recording several distinct energy windows.
-

Quantities and units

- ***Activity,*** *A, becquerel, Bq, (s^{-1}). The mean number of spontaneous nuclear transitions per unit* time interval. 1 Bq = 1 disintegration per second. 1 Ci (curie) = 3.7×10^{10} Bq. 1 g of 226Ra has an activity of 3.7×10^{10} Bq.

- ***Exposure****, X, coulomb per kilogram, C/kg, (kg^{-1} s A). The ionizing power of electromagnetic* radiation in air - defined by the ratio of the sum of electrical charges, dQ, of one sign of ions liberated indirectly by photons of gamma or X-radiation in air, and the mass, dm, of the air, X= dQ/dm. 1 R = 2.58×10^{-4} C/kg.

- ***Exposure rate***, *X′, coulomb per kilogram and second (ampere per kilogram) C/(kg s) (A kg^{-1}).* The ratio of an incremental exposure, dX, in a time interval, dt, to the time interval, X′ = dX/dt. Exposure rate was used for the description of terrestrial gamma radiation in μR/h, 1 μR/h = 7.17×10-14 A/kg. Terrestrial gamma radiation be expressed as dose rate.

- ***Dose***, *absorbed dose, D, gray, Gy, (m^2 s^{-2}). Absorbed dose is defined as the energy imparted* by radiation to a unit mass of irradiated matter. 1 Gy = 1 J/kg. The matter (air, tissue) is specified. 1 rad = 10^{-2} Gy. Conversion: 1 R = 8.69×10^{-3} Gy (in air), 1 R = 9.57×10^{-3} Gy (in tissue).رونتجن

- ***Dose rate***, *absorbed dose rate, D′, gray per second, Gy/s, (m2 s-3). Dose rate is defined as the* ratio of an incremental dose, dD, in a time interval, dt, to the time interval, D′ = dD/dt. Gamma dose rate in air is used for the description of terrestrial radiation, and is usually expressed in nGy/h. For conversion of terrestrial exposure rate to terrestrial dose rate in air it holds: 1 μR/h = 8.69 nGy/h.

Ground radioelement concentration units

- In geology and nuclear geophysics, radioelement concentrations in rocks, air and water are expressed in the following units:

- mass concentration of K: % K (percent potassium)
- mass concentration of U: ppm U (parts per million of uranium)
- mass concentration of Th: ppm Th (parts per million of thorium)

Conventional ground reporting units

- **The estimation of the potassium concentration in rocks and soils by gamma ray spectrometry is through the detection of 1461 keV gamma rays emitted by ^{40}K. ^{40}K occurs in nature as a fixed ratio to other, non-radioactive, isotopes of potassium. Thus, the estimation of K is direct, and results are reported in % K (percent potassium).**

- **The estimation of uranium is through detection of 1765 keV gamma rays of ^{214}Bi, a daughter product in the ^{238}U disintegration series. The estimation of U by gamma ray spectrometry is thus indirect, and the results are reported in ppm eU (parts per million of equivalent uranium). The 'equivalent' serves as a reminder that the estimate is based on the assumption of radioactive equilibrium in the ^{238}U decay series.**

- **The estimation of thorium is through detection of 2615 keV gamma rays of ^{208}Tl, a daughter product of ^{232}Th decay series, and estimates are reported in ppm eTh (parts per million of equivalent thorium).**

- The response of total count gamma ray instruments to radiation from K, U or Th sources depends on the concentration of the source, the detector volume and efficiency, and the energy threshold of the instrument.

- In 1976, the IAEA introduced the unit of radioelement concentration, denoted "ur" (IAEA, 1976), to allow the reporting of total count measurements that are independent of the source and source/detector geometry. This unit of measurement does not entirely eliminate the instrument response and should be considered as a compromise.

- More recently, total count measurements are converted to gamma dose rate or exposure rate. However, these conversions are also approximations.

FUNDAMENTALS OF GAMMA RAY SPECTROMETRY

- **1. Sources of gamma radiation**
- Each gamma ray photon has a discrete energy, and this energy is characteristic of the source isotope. By measuring the energies of gamma ray photons, we can determine the source of the radiation.
- Radiation not originating from the earth's surface is usually regarded as "background", and is removed during data processing.
- There are three main sources of background radiation: atmospheric radon, cosmic background, and instrument background.

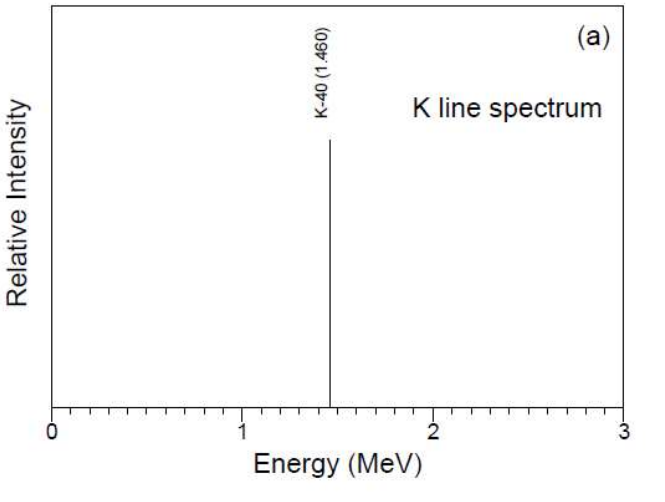
- Atmospheric radon (^{222}Rn) and its daughter products are the main source of background radiation. ^{222}Rn (radon gas) is mobile, and can escape from rocks and soils and accumulate in the lower atmosphere. Its daughter products (^{214}Bi and ^{214}Pb) attach to airborne aerosols and dust particles and emit gamma rays on decay.

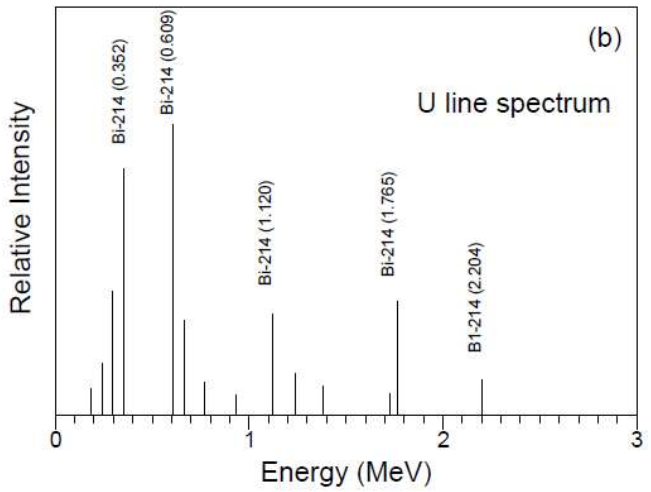
- High energy gamma rays and atomic particles of cosmic origin react with atoms and molecules in the upper atmosphere and generate a complex secondary radiation. This secondary radiation reacts with surrounding matter to produce a "cosmic" gamma ray background.

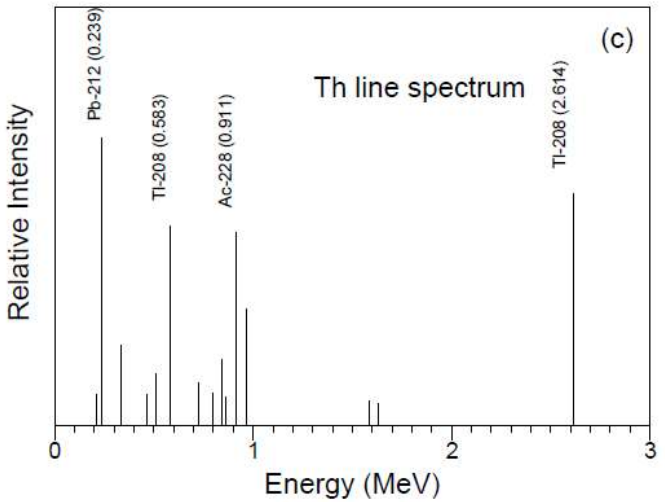
- Instrument background refers to radiation due to trace amounts of K, U and Th in the detector and surrounding equipment. This component of background is constant

2. Properties of gamma ray spectra

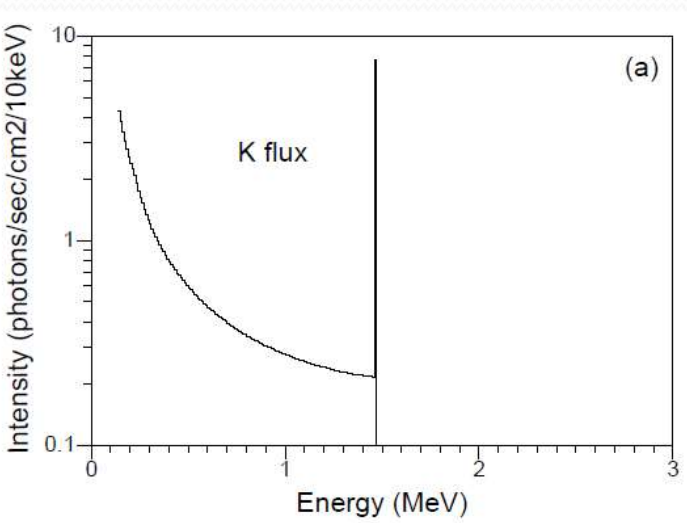
- Potassium and the uranium and thorium equilibrium decay series each have characteristic line spectra.
- Each line spectrum (or "emission" spectrum) shows the energy and relative intensity of gamma ray emissions in the decay series.
- However, the energies of these original photons are reduced by Compton scattering in the source, in the detector, and in matter between the source and the detector.

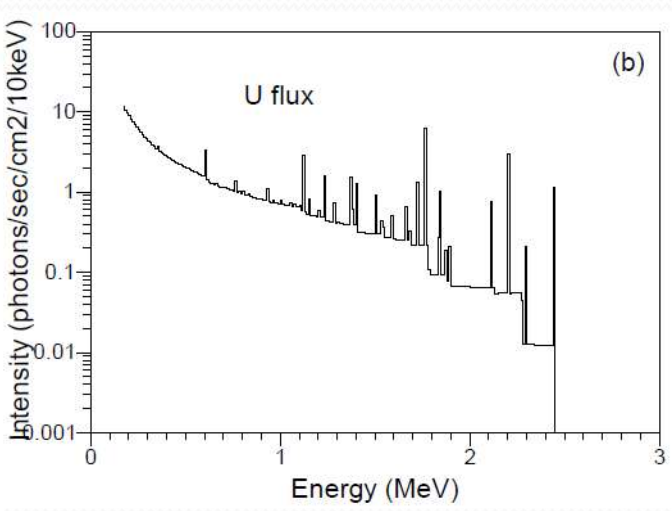


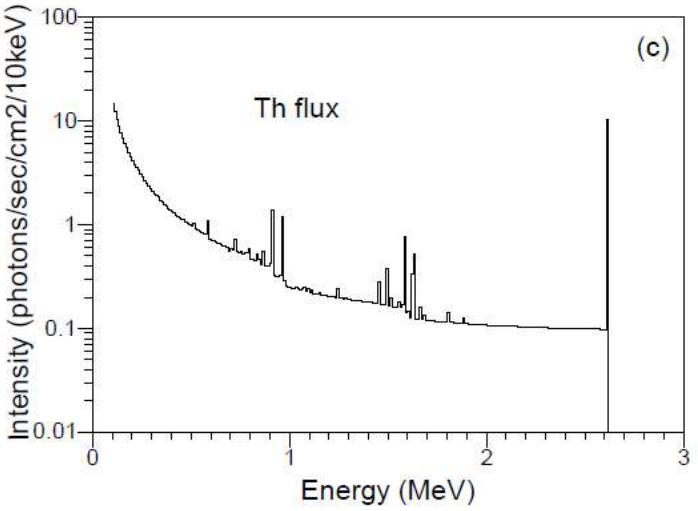




- Figure 3.2 shows the simulated gamma ray flux due to each of K, U, and Th at 300 m height (Kirkegaard and Lovborg, 1974).
- Each radioelement generates a sharp peak representing the energy of directly transmitted photons.
- This is superimposed on the spectrum of Compton scattered photons which show a continuum of energies up to the maximum energy of the photons emitted by the isotope.

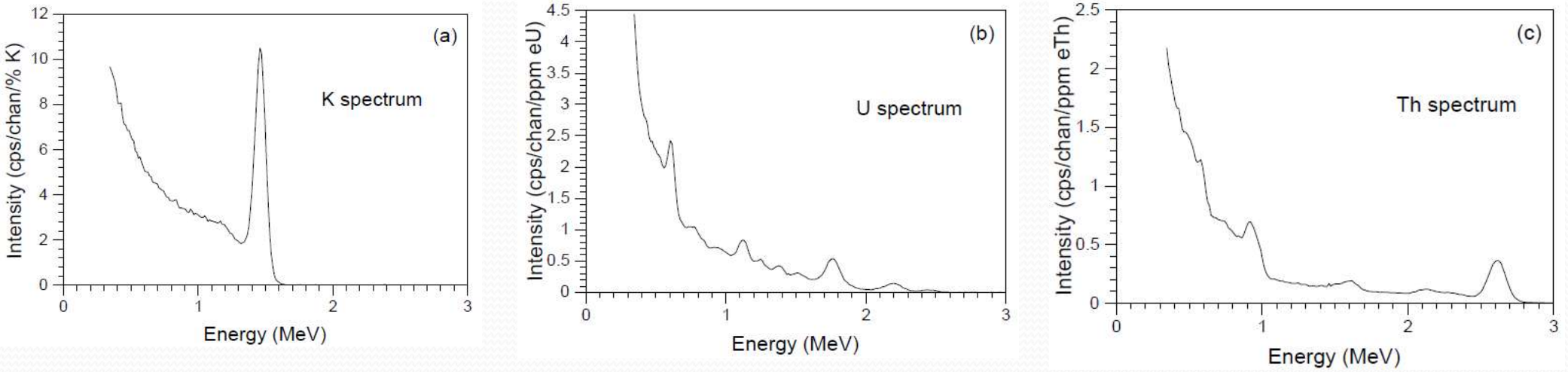






- Measured spectra are functions of the concentration and geometry of the source, the height of the detector above the ground, the thickness of any non-radioactive overburden, and the response function of the detector.

- The spectra shown in the figure were recorded on the ground using specially constructed radioactive sources.



3. Measurement of gamma radiation

- Modern gamma ray spectrometers typically record 256 (or 512) channels of information in the energy range 0-3.0 MeV. Each channel thus records all gamma rays absorbed by the detector that have energy within a 11.7 keV range.

- The conventional approach to the acquisition and processing of gamma ray spectrometric data is to monitor three or four relatively broad spectral windows.
- The K energy window monitors the 1.46 MeV gamma rays emitted by ^{40}K.
- The U and Th energy windows monitor gamma ray emissions of decay products in the U and Th decay series.
- The total-count window gives a measure of total radioactivity.

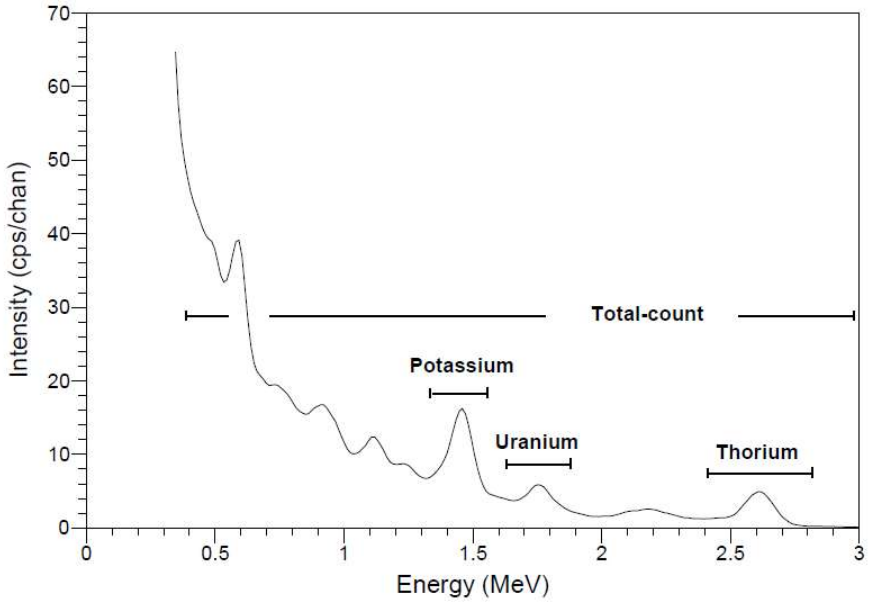


FIG 3.4. Typical airborne gamma ray spectrum showing the positions of the conventional energy windows.

4. Physical models

- The simplest approach to the modelling of gamma ray fields is a semi-empirical one based on mono-energetic (unscattered) radiation.

- Clark et al. (1972) used a two-layer model with the earth as an infinite half-space with a constant density and radioelement concentration overlain by non-radioactive air of constant density .
- They showed that the mono-energetic radiation intensity, dI, *due to a photopeak of intensity* E_0 *from gamma ray emissions by a* volume element dV *within the earth is given by*

Environmental effects

1. The amount of attenuating material between the radioactive source and the gamma ray detector,

2. the height of the detector above the ground has a large effect.

3. Topographic effects can be severe for both airborne and ground surveying. Both airborne and portable gamma ray spectrometers are calibrated for a 2π surface geometry.

GROUND RADIOMETRIC METHODS

- Most modern portable gamma ray spectrometers are differential spectrometers.
- These typically have at least 350 cm^3 of NaI(Tl) detectors, and record either 256 or 512 channel of data in the energy range 0-3 MeV.
- The instruments can record the full gamma ray spectrum as well as sum channels over broad energy windows for the in situ estimation of K, U and Th radioelement concentrations.
- Calibration constants are stored in the instrument memory.

Field measurement

- Portable gamma ray spectrometers used for natural radionuclide mapping monitor energy windows centred on the 1461 keV (^{40}K), 1765 keV (^{214}Bi) and 2615 keV (^{208}Tl) photopeaks for the estimation of K, U, and Th concentrations, respectively .

- Meaningful measurements along a traverse can only be obtained if the source-detector geometry is constant for all observations.

- The detector should either be placed directly on the earth surface or be kept at a low but constant height. This minimizes the effects of local variation in relief and radioelement distribution.

Instrument calibration

- The calibration of gamma ray spectrometers is the estimation of those constants that relate instrument count rates to either radionuclide concentration or environmental dose rate.

- This includes the estimation of background radiation, stripping ratios and sensitivity constants.

Instrument calibration:

Background radiation

- Background radiation is due to the internal radioactivity of the instrument, cosmic radiation, and atmospheric radon.
- The background is estimated by taking measurements from a small boat (preferably fibreglass) over a river or lake, and at least 200 m from the shore. The shoreline should be flat.
- Background count rates are recorded in all energy channels.

- Portable gamma ray spectrometers used for assaying K, U and Th in rocks are calibrated by means of calibration pads.
- A calibration pad is a slab of concrete containing known concentrations of the radioelements.
- Each of the pads is enriched in either K, U or Th.

- The fourth pad serves as a background pad.

- The K, U and Th window count rates obtained over the pads are linearly related to the K, U and Th concentrations in the pads.

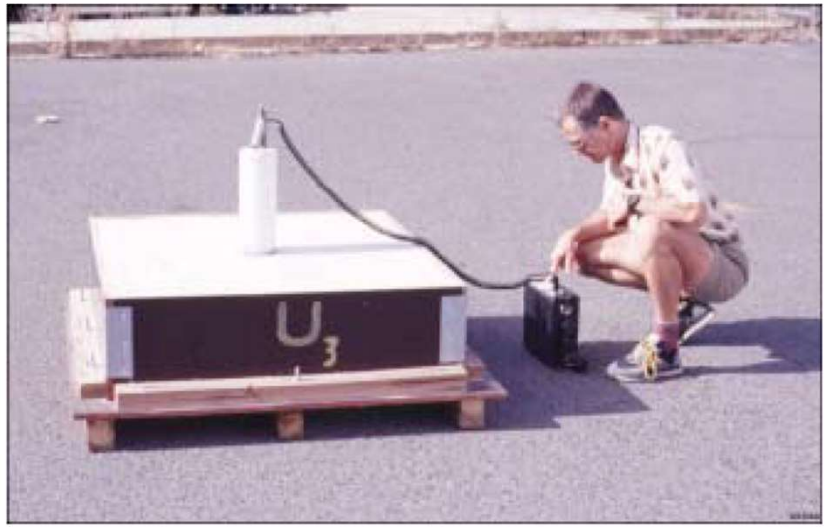


FIG. 4.4. Calibration of a portable spectrometer on a transportable calibration pad.

- Let n_i $(i = 1, 3)$ *be the count rate in the i-th energy window* (either K, U or Th), and let s_{ij} $(i = 1, 3; j = 1, 3)$ *be the sensitivity of the i-th elemental count* rate to the concentration of the *j-th element (either K, U or Th), then*

$$n_i = s_{iK} c_K + s_{iU} c_U + s_{iTh} c_{Th} + n_{iBG} \qquad (4.1)$$

where n_i = count rate in the i-th energy window (i = 1, 2, 3), (c/s);
s_{ij} = sensitivity of the spectrometer for the detection of the j-th element in the i-th energy window, (c/s per unit concentration of the j-th element);
c_j = concentration of the j-th element, (% K, ppm U, ppm Th);
n_{iBG} = background count rate in the i-th energy window, (c/s).

- Since the estimation of K, U, and Th is based on measurements in 3 energy windows, and the background count rates n_{iBG} *can be subtracted, equation (4.1) may be written in matrix* notation as follows:

$$\mathbf{N} = \mathbf{SC} \qquad (4.2)$$

where $\mathbf{N}$ = column vector of background-corrected count rates (n_i-n_{iBG});
$\mathbf{S}$ = 3×3 matrix of sensitivities (s_{ij});
$\mathbf{C}$ = column vector of concentrations (c_K, c_U, c_{Th}).

- The sensitivity constants, s_{ij}, *are estimated from measurements on the four calibration pads.*
- The detector is placed on the centre of a calibration pad and count rates, n_i, *are measured in* three energy windows ($i = 1, 2, 3$).
- *Backgrounds are removed by subtracting the counts* measured on the background pad, n_{iBG}, *and subtracting the concentration of the background* pad from the concentrations of the other three pads.
- Equation (4.1) is thus modified as follows:

$$n_i - n_{iBG} = s_{iK}\Delta c_K + s_{iU}\Delta c_U + s_{iTh}\Delta c_{Th} \qquad (4.3)$$

where Δc_j = the difference between the concentrations of the j-th element in a calibration pad and the concentration of the j-th element in the background pad.

- Or, in matrix notation

$$\mathbf{N} = \mathbf{S}\Delta\mathbf{C} \qquad (4.4)$$

where $\mathbf{N}$ = 3×3 matrix of background-corrected count rates, $(n_i - n_{iBG})$;
$\mathbf{S}$ = a 3×3 matrix of sensitivities (s_{ij});
$\Delta\mathbf{C}$ = 3×3 matrix of differential concentrations of K, U, and Th in the K, U, and Th pads minus the K, U, and Th in the background pad.

- The sensitivity matrix may then be estimated as

$$\mathbf{S} = \mathbf{N}\Delta\mathbf{C}^{-1} \qquad (4.5)$$

where $\Delta\mathbf{C}^{-1}$ is the inverse of $\Delta\mathbf{C}$. The sensitivities s_{ij} are in units of count rate (in a specific energy window) per unit concentration (1% K, 1 ppm U, 1 ppm Th) of the radioelements.

For the K, U and Th energy windows (i=1, 2 and 3), the "stripping ratios" α, β, γ, *a*, *b* and *g* (see §4.1.4) are defined by the ratios of sensitivities as follows

$$\alpha = \frac{s_{2Th}}{s_{3Th}} \qquad \beta = \frac{s_{1Th}}{s_{3Th}} \qquad \gamma = \frac{s_{1U}}{s_{2U}} \tag{4.6}$$

$$a = \frac{s_{3U}}{s_{2U}} \qquad b = \frac{s_{3K}}{s_{1K}} \qquad g = \frac{s_{2K}}{s_{1K}} \tag{4.6}$$

- The stripping ratios define the ratios of count rates, caused by a single element in an energy window, to the count rate of the same element in its principal energy window.
- They are used during data processing to estimate the net count rate of a single element in an energy window.

The stripping ratios α, β, γ, and *a* also give an indirect measure of the energy resolution of a detector system – the smaller their values, the better the energy resolution of the detector.

- Due to the finite dimensions of calibration pads, a geometrical correction, *G, must be applied to the derived sensitivities.*
- *The correction depends* on the pad dimensions, pad density, and the height of the centre of the scintillation crystal above the pad surface.
- The ratio, *R, of gamma radiation from a cylindrical pad 0.5 m thick to* that from an infinite source, with the detector placed on the centre of the pad, and $h/r < 0.2$, *is*

$$R = 1 - \frac{h}{r} \qquad (4.8)$$

where h = height of the scintillation crystal centre above the surface of the pad (m);
r = radius of a cylindrical pad (m).

- The geometrical correction can be applied by multiplying the derived sensitivities by $G = 1/R$.

Data processing procedure

- Gamma ray field measurements yield a number of counts, *N*, *registered in a particular energy* window for a counting time, *t*.

- *These can be converted to a count rate,* $n = N/t$ *(c/s).*

- The observed count rates, n_i, *are corrected for background and the elemental* concentrations can be estimated using either the matrix method or the stripping method.

- The matrix method :The concentrations of K, U, Th are estimated as follows:

$$\mathbf{C} = \mathbf{N}\mathbf{S}^{-1}$$

- The stripping method uses the “stripping ratios” to estimate elemental count rates in each window before converting these to concentrations.

- Assuming that stripping ratios $b = g = 0$, the net count rates, n_{ij}, *of the j-th radioelement in a specific* energy window, *i, are given by*

$$n_{3Th} = \frac{n_3 - n_{3BG} - a(n_2 - n_{2BG})}{1 - \alpha a}$$

$$n_{2U} = n_2 - n_{2BG} - \alpha n_{3Th}$$

$$n_{1K} = n_1 - n_{1BG} - \beta n_{3Th} - \gamma n_{2U}$$

- and the concentrations are given by

$$c_K = \frac{n_{1K}}{s_{1K}}$$

$$c_U = \frac{n_{2U}}{s_{2U}}$$

$$c_{Th} = \frac{n_{3Th}}{s_{3Th}}$$

where s_{ij} *are the instrument sensitivities. The concentration are in % K, ppm eU and ppm eTh.*

- Ratios between radioelement concentrations (Th/U, Th/K, U/K) are often used to reduce the effect of terrain geometry on the concentration estimates.

- Anomalous ratios are often indicative of mineralization and rock alteration.

- Estimates of the radioelement concentrations may be converted to either the dose rate in air or the exposure rate.

- Erdi-Krausz, G., Matolin, M., Minty, B., Nicolet, J.P., Reford, W.S. and Schetselaar, E.M., 2003. *Guidelines for radioelement mapping using gamma ray spectrometry data: also as open access e-book*. International Atomic Energy Agency (IAEA).

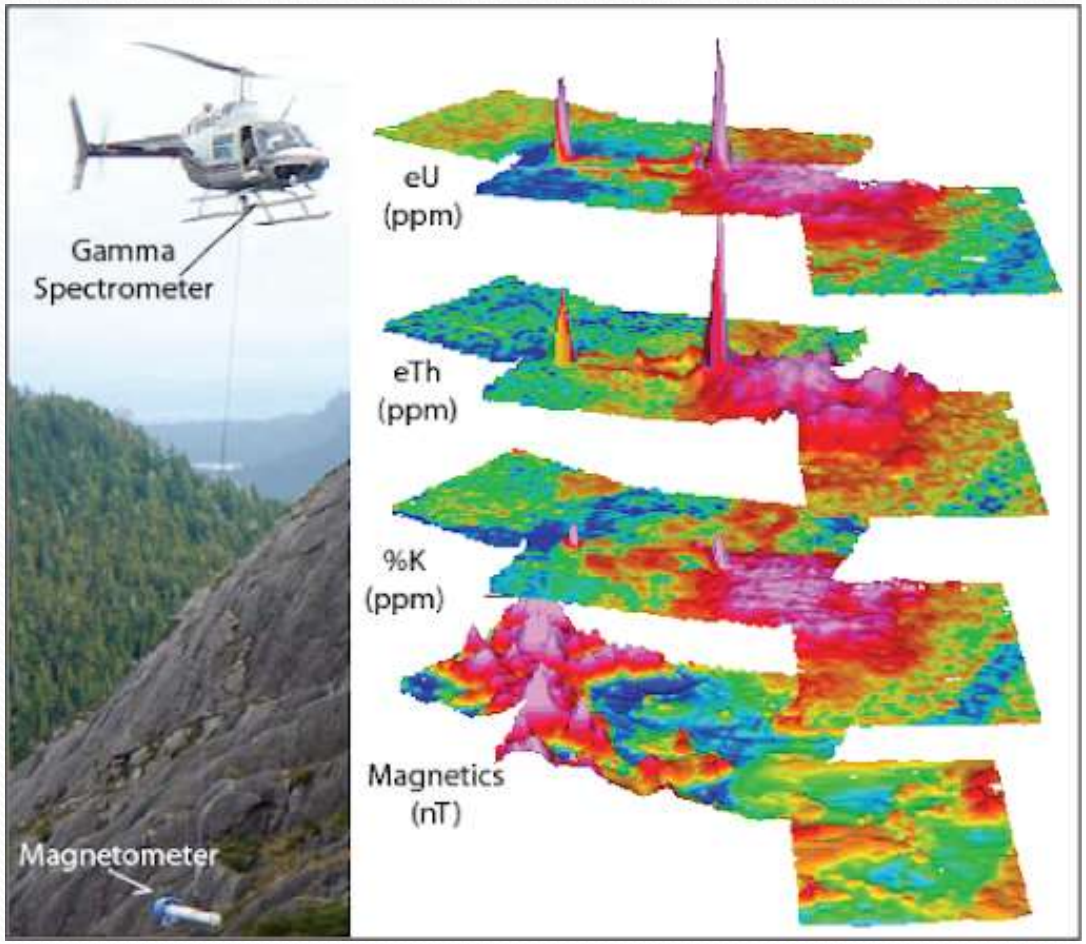
AIRBORNE GAMMA RAY SPECTROMETRY

Airborne gamma ray spectrometry has been used for :

- the direct detection of ore bodies
- as a lithological mapping tool.
- Environmental applications such as health risks associated with radon in houses,
- the mapping of fallout from nuclear accidents.
- soil mapping,
- ground water discharge and salinity studies.

Recent developments include

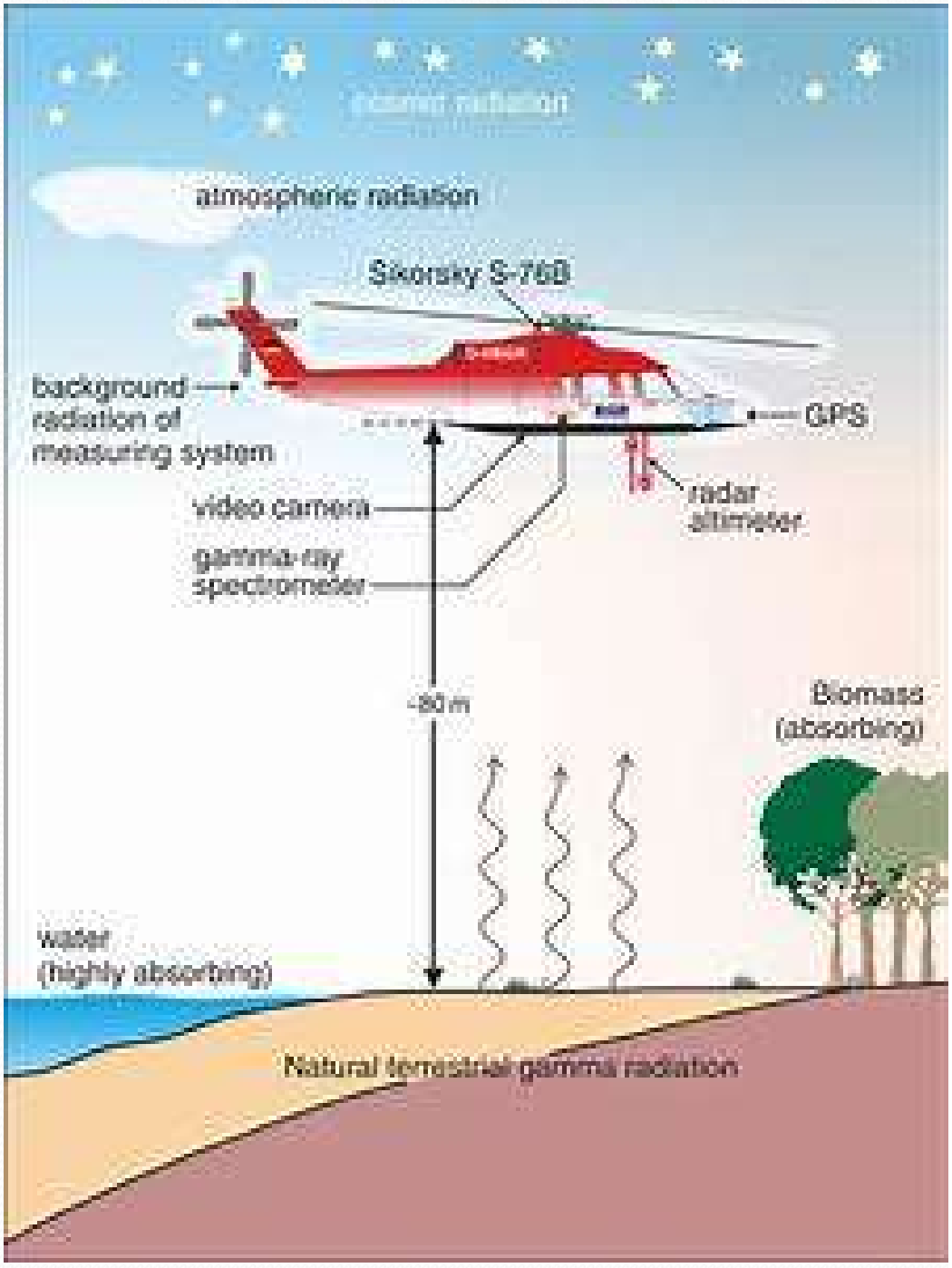
- multichannel processing methods
- the use of statistical methods to reduce noise in multichannel spectra.



Instrumentation

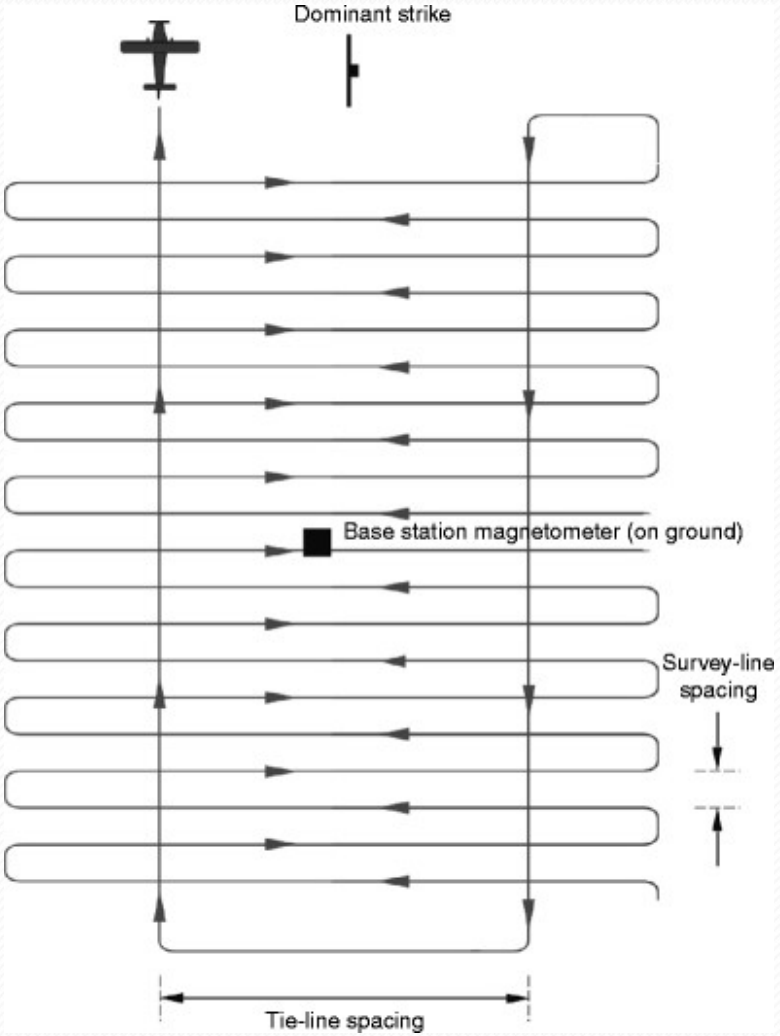
- Airborne spectrometer systems
- GPS navigation (real-time differential),
- radar altimeter,
- Barometer
- thermometer.

- The radar altimeter, temperature and pressure are used to correct gamma ray data for the height of the detector above the ground.



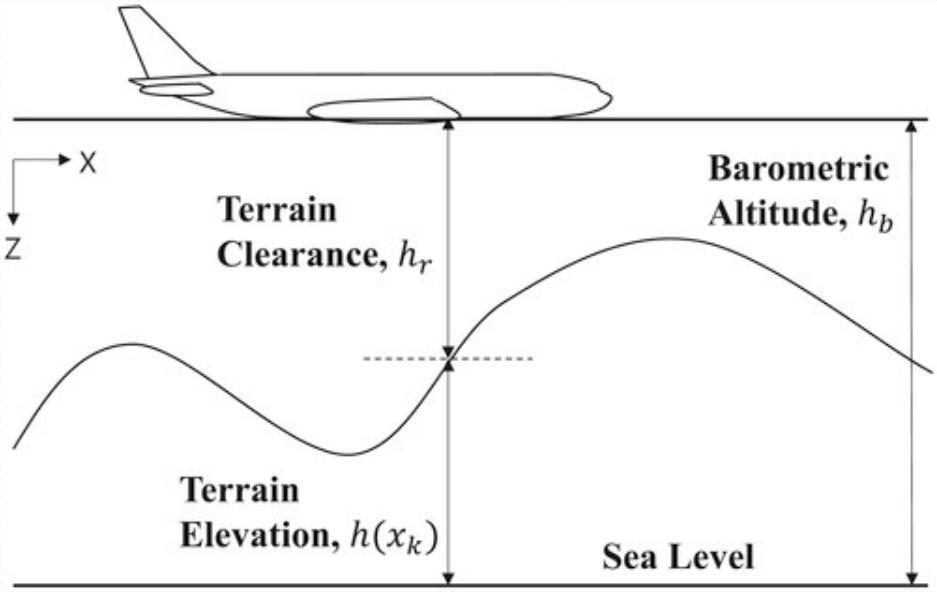
Survey methodology

- Airborne geophysical surveys are normally flown on a regular grid along parallel lines ("flight lines").
- The flight line spacing depends on the survey application.
  - For detailed surveys, used for geological and environmental mapping, flight lines are usually between 50 m and 400 m apart.
  - Regional geochemical baseline surveys may be flown with a flight line spacing of 1 km or greater.
- A complementary set of lines ("tie lines") are often flown perpendicular to the flight lines, and with a line spacing about 5 times that of the flight line spacing.



Survey methodology

- Surveys are typically flown at a constant height above the ground of between **40 m** and **100 m**, with helicopters able to fly considerably lower than most fixed-wing aircraft.



- This is the “nominal ” height of the aircraft above the ground, اسمی، صوری شکلی، بالاسم فقط

- the extent to which the aircraft deviates from this height depends on both the topography and the skill of the pilot.

Survey methodology

- Airborne gamma ray spectrometric data are almost always collected along with other remotely sensed data - such as measurements of the earth's magnetic field.

- Gamma ray spectrometric data are usually acquired over a sample interval of 1 s.

- During this interval, a fixed-wing aircraft traverses about 55 m along the line.

- This dense sampling along lines, with a complete absence of data between lines, is typical of airborne surveying.

Airborne gamma ray spectrometric data can be severely distorted in rough terrain as follows:

1. the radiation signal decays at an approximately **exponential rate** with **increasing distance to the source**, thereby reducing the signal-to-noise ratio of the data;

   the rate of decay with distance depends on the source geometry – eg. **the signal from narrow sources attenuates more quickly than from broad sources.**

   This limits the accuracy of the height correction of airborne data;

2. the field of view of an airborne spectrometer increases with aircraft height, thus **reducing the resolution of discrete sources**;

4. terrain clearance will vary from line to line depending on the direction of flight

   (i.e. climbs occur at a greater height above a slope than a descent);

5. the necessity for flight lines and control lines (tie lines) to intersect at the **same height** for magnetic levelling purposes, will result in a "**loose drape**" flight surface;
6. the source geometry varies from **the 2π surface**, depending on the aircraft height and the severity of the topography

   – e.g. increased signal in a narrow valley due to contributions from the valley sides; and

7. the geometry of the detector may have a directional bias – e.g. rectangular pad detectors are less sensitive to lateral sources than a spherical detector.

These problems can be mitigated by:

1. flying the survey in "**drape mode**" - i.e. tracking the topography at a constant height above the terrain;

2. using a helicopter rather than fixed wing platform, to improve obedience to a tight drape surface;

3. where valleys have steep walls, flying additional lines parallel to the valleys to allow lower terrain clearance;

4. increasing the spectrometer crystal volume (e.g. from 33 litre to 49 litre) to improve the signal-to-noise ratio;

5. using **256-channel data processing techniques** to improve the signal-to-noise ratio;

6. applying **deconvolution** and **height correction** techniques to minimize the effect of topography.

Data Corrections:

- The main corrections are:

1. **background correction**,
2. **stripping correction**,
3. **height correction**, and
4. **sensitivity correction** (reduction to elemental concentrations).

Calibration data requirements

- There are **four main procedures** for acquiring calibration data:

1. high altitude background calibration flights,
2. ground calibrations over radioactive sources to determine stripping ratios,
3. calibration flights over a calibration range to determine height attenuation coefficients and sensitivity coefficients, and
4. flights to measure the radon spectrum.

1- High-altitude aircraft/cosmic background flights

- These are usually **flown offshore** in an area where there is low atmospheric radon.
- Spectra are measured at **a range of heights** – typically **1.0, 1.5, 2.0, 2.5, 3.0** and **3.5 km above the water**.
- **Fifteen minutes** accumulation time at each height is sufficient for a 33 litre detector.
- The data are processed to estimate aircraft and cosmic background.

2-Ground calibration using radioactive pads

- Since K, U and Th spectra overlap, stripping ratios are used to correct each elemental window count rate for the effects of the other elements.
- Measurements over concrete calibration pads with known concentrations of the radioelements are used to calculate the stripping ratios.
- Four pads are required.
- Three of the pads have anomalous concentrations of K, U and Th respectively.
- The fourth pad acts as a background pad.

3-Calibration range flights

- A calibration range is an easily navigated strip of land that is used to measure the response of an airborne gamma ray spectrometer
  - to changes in detector height (**height attenuation coefficients**)
  - to sources of known elemental concentrations (**sensitivity coefficients**).

- The calibration range is flown at different heights – typically in the range 60 m to 240 m at 30 m intervals.

- Flights over a nearby body of water at the same height serve as estimates of background.
- The background-corrected and stripped window count rates are used to estimate the elemental attenuation coefficients.

- The ground concentrations on the calibration range are measured using a portable gamma ray spectrometer at the same time as the airborne calibrations are flown.

- This enables the system "sensitivity coefficients", which are used to convert airborne count rates to elemental concentrations on the ground, to be estimated

4-Radon background calibration flights

- a radon spectrum can be measured by
  - flying over water in the presence of radon
  - subtracting the aircraft and cosmic components.

Calibration frequency

- Airborne gamma ray spectrometers should be fully calibrated every twelve months.

Daily thorium source tests

- During the course of a survey, the Th sensitivity tests are conducted daily - both before and after each day's flying.
- These tests are used to ensure that the system sensitivity does not change significantly during the course of the survey.
- The background-corrected Th window count rates from these tests must be within 5% of the average of all recent Th source tests.
- If this is not the case, flying is suspended until the source of the problem is diagnosed and corrected.

Processing and calibration procedures

- The role of data processing is
  - to correct the observed data for those influences that are not related to the geology, and then
  - to reduce the airborne count rates to estimates of the ground concentrations of the radioelements.

1-*Pre-processing*

- Pre-processing is essentially part of the quality control procedure and should be carried out in the field.
- This usually includes such procedures as:
  - the merging of data from different sources
  - validating the recorded data (i.e. establishing that the recorded values are reasonable),
  - and checking the data for missing or spurious values (spikes).

2-Spectral smoothing techniques

- Spectral methods for reducing noise in gamma ray spectra are a recent development in the processing of multichannel spectra.
- The methods remove noise from raw gamma ray spectra, and the noise-reduced spectra are then processed in the normal way.
- There are two methods currently being used –
  - the NASVD method (Noise Adjusted Singular Value Decomposition)
  - and the MNF method (Maximum Noise Fraction).
- Both methods use a principal component (PC) type analysis to extract the dominant spectral shapes ("PC's" or "components") present in the raw spectra.
- The PC's are then used to reconstruct spectra that have most of the original signal but little of the noise.

3-*Live time (or dead time) correction*

- Spectrometers require a finite time to process each pulse from the detector.
- While one pulse is being processed, all other incoming pulses are automatically rejected.
- The total counting time available is thus reduced by the time taken to process all pulses (the "dead time").
- The time during which the spectrometer is receptive to incoming pulses is the "live time".
- The dead time is therefore the difference between the sample accumulation time and the live time.

- The correction is usually small but can be significant in areas of high radioactivity.

- Most modern spectrometers automatically record the system dead time (or live time).

- A typical dead time would be of the order of 5-15 μs/pulse, and can be corrected for as follows:

$$N = \frac{n}{1 - Ct}$$

where N = corrected count rate (counts/sec);
n = observed count rate (counts/sec);
C = total count rate over all channels(counts/sec);
t = the equipment dead time per pulse.

4-Energy calibration

- Spectrometers are affected by energy drift in the measured spectra. This drift is caused by
  - changes in the gains of the photomultiplier tubes as a result of drift in the high-voltage supply and changes in temperature.

- Modern spectrometers have in-built self-stabilizing features.

- The total drift with these instruments is less than one channel.

5-*Aircraft and cosmic background corrections*

- The calibration procedure for estimating the aircraft spectrum and the normalized cosmic spectrum requires:
  - the acquisition of spectra over water at a number of different heights
  - (say 1.0, 1.5, 2.0, … 3.5 km above sea level)
  - in an area where atmospheric radon is at a minimum.

- The measured spectra are each the sum of the aircraft component (constant) and the cosmic component.

- The aircraft spectrum is constant.
- The cosmic spectrum at each observation point is estimated by
  - scaling a normalized cosmic spectrum by the cosmic window count rate.

- The aircraft and cosmic background spectra are then subtracted from the live time and energy-calibrated observed spectra.

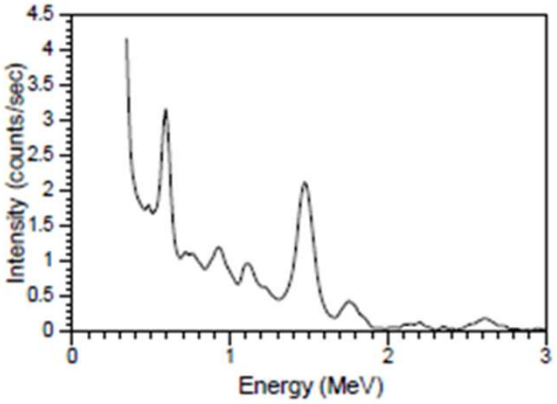


FIG. 5.1. The aircraft gamma-energy spectrum.

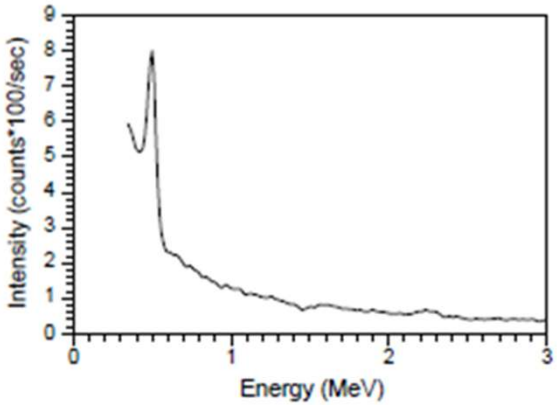


FIG. 5.2. The normalized cosmic gamma-energy spectrum.

- the count rate in the 3-6 MeV cosmic window is linearly related to the count rate in the *i'th* energy channel.

- a linear regression of the cosmic window count rate on any other particular channel yields:
  - the cosmic sensitivity (slope of regression line) and
  - aircraft background (zero intercept) for that channel as follows.

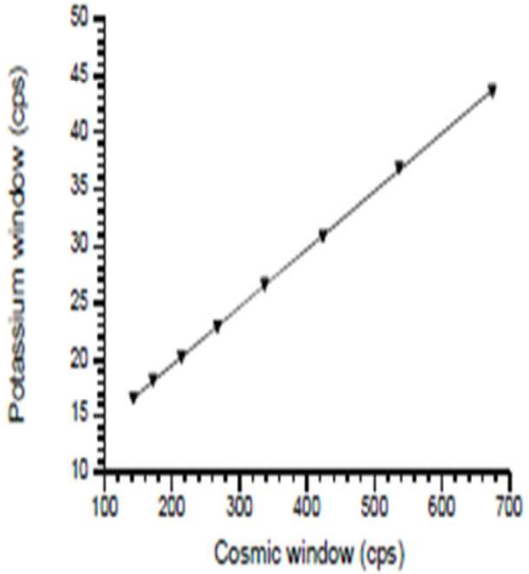


FIG. 5.3. High altitude regression plot for aircraft and cosmic background in the potassium window.

$$n_i = a_i + b_i n_{cos} \qquad (5.4)$$

where n_i = aircraft + cosmic background count rate in the i'th channel;
n_{cos} = cosmic window count rate;
a_i = aircraft background in the i'th channel;
b_i = cosmic background in the i'th channel normalized to unit counts in the cosmic window.

6-Radon background correction

- There are three procedures that can be used for removing atmospheric radon background.

1. The "spectral-ratio method" and the "full-spectrum" method use the shape of the gamma ray spectrum to estimate the atmospheric radon concentration.
   - These methods cannot be used in the northern hemisphere where there is significant ^{137}Cs contamination.

2. The alternative approach is through the use of upward-looking detectors.
   - These detectors give the spectrometer a directional sensitivity capable of distinguishing between atmospheric radon and terrestrial sources of radiation.

- The spectral-ratio and full-spectrum methods operate on multichannel spectra.

- The upward-looking detector method requires window data.

Spectral-Ratio Method

- The low energy ^{214}Bi photopeak at 0.609 MeV from atmospheric radon suffers far less attenuation relative to the ^{214}Bi peak at 1.76 MeV that is the case for radiation from the ground.

- The spectral ratio method uses this fact to estimate the contributions of atmospheric radon to the observed spectrum.

- The method calls for the monitoring of four windows which are denoted by *L* (low energy), *K (potassium), U (uranium) and Th (thorium). L represents counts above the* Compton continuum in the 0.609 MeV photopeak, and *K, U, and Th represent counts in the* conventional K, U and Th windows respectively, after correcting the spectrum for aircraft and cosmic background.

-

Then it can be shown that the radon contribution to the low energy photopeak (L_r) *is given by*

$$L_r = \frac{\left(L_{ob} - U_{ob}(c_2 - c_4\gamma) - Th(c_3 - c_2\alpha - c_4(\beta - \alpha\gamma)) - c_4 K_{ob}\right)}{(1 - c_2/c_1)} \qquad (5.5)$$

where α, β, and γ are the conventional stripping ratios, and c_1, c_2, c_3 and c_4 are calibration constants. L_r is used to scale a standard radon spectrum for multichannel background removal. At this stage of the processing the spectra are summed over the conventional energy windows.

- The radon spectrum can be derived from calibration flights at survey height over water and in the presence of radon.
- The aircraft and cosmic contributions are subtracted from the observed spectrum to give the radon spectrum.
- *c1* is measured directly from the radon spectrum.
- *The* factors required to calculate the radon contributions to the K and Th windows for a fixed number of radon counts in the U window are also determined directly from the radon spectrum.
- The *c2, c3, and c4 coefficients can be estimated from simulated K, U and Th* component spectra.

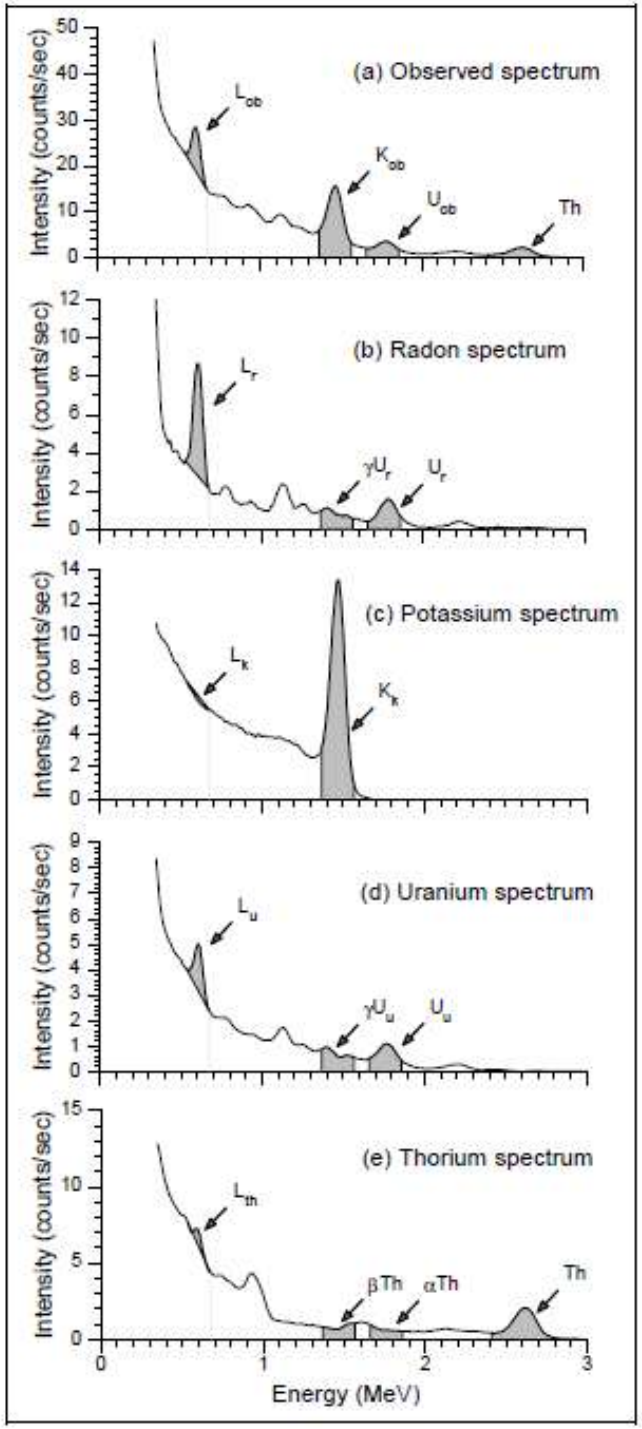


FIG. 5.4. Potassium, uranium, thorium and radon spectra relative to the windows used for the spectral-ratio method for estimating radon background.

Full-Spectrum Method

- After removing aircraft and cosmic background, the observed spectrum can be expressed as a linear sum of four components due to each of K, U, Th and atmospheric radon as follows:

$$I_{obs} = |K| f_K + |U| f_U + |Th| f_{Th} + |R| f_{radon} \qquad (5.6)$$

where I_{obs} is the observed spectrum, $|K|$, $|U|$, $|Th|$ and $|R|$ are the elemental count rates due to K, U, Th and atmospheric radon, respectively, and f_K, f_U, f_{Th}, and f_{radon} are the normalized component spectra due to each of K, U, Th and atmospheric radon. The elemental count rates in equation 5.6 can be estimated using the least-squares method. The K, U and Th component spectra can be simulated during calibration experiments on the ground (Minty, 1998a).

Upward-looking Detector Method

- The upward-looking detector method uses an additional crystal pack that is partially shielded from radiation from below to give the system a directional sensitivity and the ability to discriminate between radiation from the atmosphere and from the ground.

The radon contribution to the uranium window of the main detector package (i.e. the "downward" U window) is given by (IAEA, 1991)

$$U_r = \frac{u - a_1 U - a_2 T + a_2 b_t - b_u}{a_u - a_1 - a_2 a_t} \qquad (5.7)$$

where U_r = radon background in the "downward" U window;
u = count rate in the "upward" U window;
U = count rate in the "downward" U window;
T = count rate in the "downward" Th window;

and a_1, a_2, a_u, a_t, b_u and b_t are constants derived by suitable calibration.

- the total-count and potassium backgrounds are linearly related to the uranium background, and the background in these channels can be derived from the background in the uranium channel by suitable calibration.

- There are several ways of affecting the calibration. a_u, a_t, b_u *and* b_t are regression coefficients that relate radon background in the upward uranium window to radon background in the downward uranium window $(u_r = a_u U_r + b_u)$, and radon background in the downward thorium window to radon background in the downward uranium window $(T_r = a_t U_r + b_t)$.

- These are determined by subtracting aircraft and cosmic background from over-water flights showing a range of radon concentrations.
- Linear regressions yield the calibration coefficients a_u, a_t, b_u *and* b_t.

- Similar regressions on this data yield the required constants for determining the radon contribution to the total-count and potassium windows from the radon background in the uranium window.

- The second stage of the calibration is to relate measured count rates in the upward uranium window to those in the downward uranium window for radiation due to uranium in the ground. These components are related by the equation

$$u_g = a_1 U_g + a_2 T_g \qquad (5.8)$$

where u_g, U_g and T_g are the ground components, and a_1 and a_2 are the calibration coefficients

- The easiest way to determine a_1 *and* a_2 is from background corrected data acquired from lines that both traverse and are adjacent to a large body of water. The over-water sections of the lines are used to remove the total background to yield a number of estimates of u_g, U_g, *and* T_g *over a range of source concentrations.*

7-Stripping corrections

- The stripping correction is used to correct each of the K, U and Th window count rates for those gamma rays not originating from their particular radioelement or decay series.
- For example, thorium series gamma rays appear in both the uranium and potassium windows, and uranium series gamma rays appear in the potassium window.

- The corrections are applied as follows:

$$n_{th(corr)} = \frac{n_{th} - a n_u}{1 - a\alpha}$$

$$n_{u(corr)} = \frac{n_u - \alpha n_{th}}{1 - a\alpha} \qquad (5.11)$$

$$n_{k(corr)} = n_k - \beta n_{th(corr)} - \gamma n_{u(corr)}$$

α, β, γ and a are called "stripping ratios". α are the counts in the U window per unit count in the Th window for a pure Th source, β are the counts in the K window per unit count in the Th window for a pure Th source, γ are the counts in the K window per unit count in the U window for a pure U source, and a are the counts in the Th window per unit count in the U window for a pure U source (Figure 5.5).

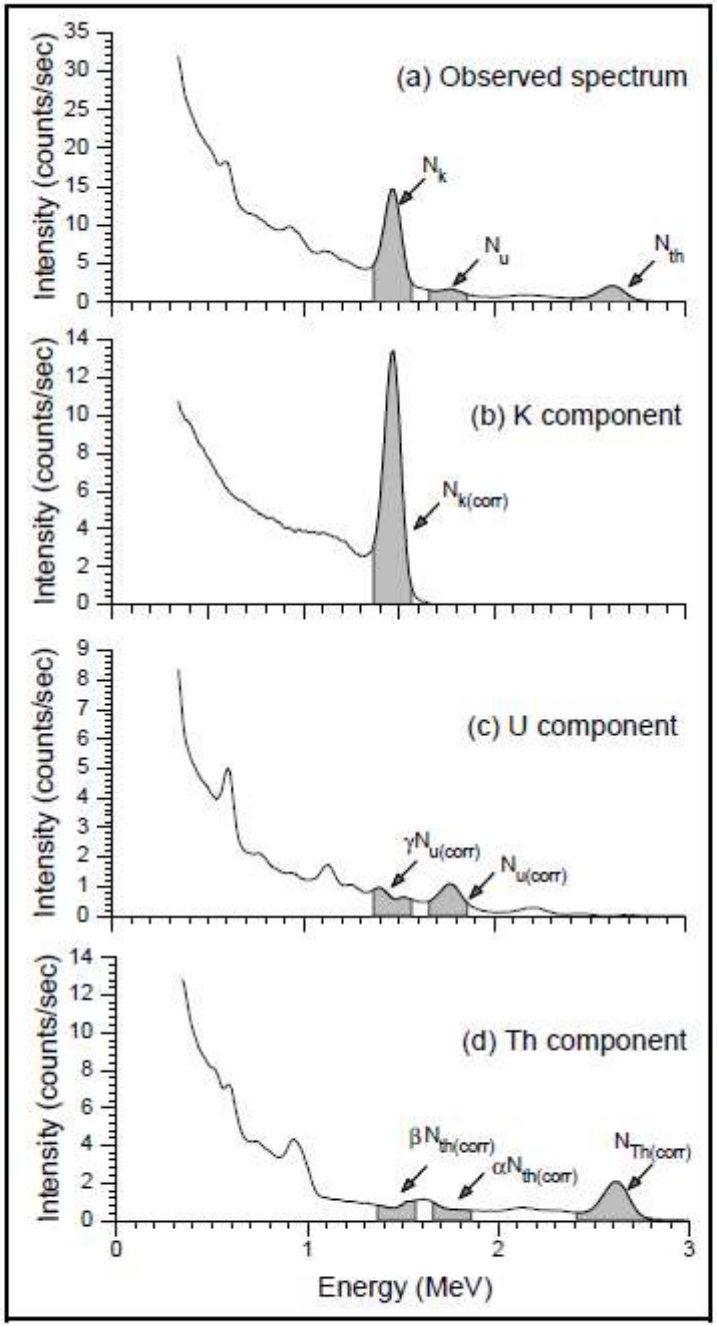


FIG. 5.5. Potassium, uranium, thorium spectra showing the positions of the conventional potassium, uranium and thorium windows and the parameters used for stripping.

- The stripping ratios are calculated from calibration experiments over specially constructed radioactive pad sources .
- The processing of the calibration data to estimate system stripping ratios is the same as for portable spectrometers . However, for airborne surveying a correction must be applied to the stripping ratios for the survey height. Correction factors are given in Table 5.1.

TABLE 5.1. INCREASE IN STRIPPING RATIOS WITH ALTITUDE (after IAEA, 1991)

Stripping ratio	Increase per metre
α	0.00049
β	0.00065
γ	0.00069

8-Height correction

- In airborne surveying the height of the detector changes continuously as the aircraft proceeds along a flight line, and the window data must be corrected to a nominal survey height.
- Window count rates vary approximately exponentially with height for the range of heights normally encountered in airborne surveying.
- An estimate of the count rate at the nominal survey height is given by

$$n = n_0 e^{-\mu(H-h)} \qquad (5.12)$$

where μ = the window attenuation coefficient (per metre);
n_0 = the observed count rate at the STP height, h; and
n = the corrected count rate for the nominal survey terrain clearance H.

- The height used in equation 5.12 must be corrected for the ambient temperature and pressure, since both affect the density and thus the attenuating properties of the air.
- The equivalent height at standard temperature (273.15 °K) and pressure (101.325 kPa) - i.e. the STP height, is given by :

$$h_{STP} = \frac{273.15 \times P \times h_{obs}}{(T + 273.15) \times (101.325)} \qquad (5.13)$$

where h_{obs} = observed height above ground level (metres);
h_{STP} = equivalent height at STP (metres);
T = air temperature (°C);
P = barometric pressure (kPa).

9-Reduction to elemental concentrations

- The simplest means of achieving this is to divide each of the corrected window count rates by a “sensitivity” coefficient.
- The coefficients for each window are estimated from data acquired from airborne flights over a calibration range.
- The concentrations of the radioelements along the calibration range are measured using a well calibrated portable spectrometer at the same time as the airborne data are acquired.

- The coefficients are estimated by dividing the average background-corrected and stripped window count rates at the nominal survey height by the appropriate average ground concentration for the calibration range, i.e.

$$S = \frac{N}{C}$$

where N = average background-corrected and stripped count rate at the nominal survey height (c/s);
C = average ground concentration;
S = sensitivity coefficient.

(Geothermal Method)

(Geothermal Method)

Course Outline

I- Thermal Properties of Rocks

1- Introduction

2- Thermal Properties of Rocks

II- Terrestrial Heat Flow

1- Equality of Continental and Oceanic Heat Flow

2- Regions of Anomalous Heat Flow

3- Temperatures Within the Earth

III-Thermal Prospecting Techniques

1- Heat Flow Measurements

2- Measuring Techniques

3- Gysers

4- Examples of Geothermal Surveys

I-THERMAL PROPERTIES OF ROCKS

1- INTRODUCTION

- **The source of heat energy within the earth is presently believed to be the radioactive decay of long-lived isotopes.**
- **Heat is gradually and sometimes dramatically transferred from the earth's interior to the surface**
- **The heat escaping through the earth sets off various geological processes that are related to tectonic movements and igneous and metamorphic activity.**

- **Below a depth of 100 km, the temperature distribution is highly uncertain, and the distribution of heat sources and the mechanisms of heat transfer are unknown.**

- **Thermal measurements have provided regional and local information on:**

- The theory of convection on the mantle

- The position of structures such as salt domes, anticlines, faults, etc.

- Stratigraphic correlation from borehole measurements

2- THERMAL PROPERTIES OF ROCKS

- **Boreholes and mines measurements showed that the temperature increases with depth.**

$$Q = - K \text{ grad } T = - K \frac{\partial T}{\partial Z}$$

Where,

- Grad T ($\partial T/\partial Z$): is the rate of increase in temperature with depth (energy per unit area per unit time (SI, W/m^2, c.g.s., $\mu cal/cm^2 s$)

- K: is the thermal conductivity and it is a measure of how easily heat flows through material.

- **Lingering (remaining) effects of temperature with time depends on thermal conductivity**

$$\alpha = K/\rho C_p$$

α (Thermal diffusivity) in SI units is m^2 s, ρ the density, C_p is the specific heat at constant pressure

- **Thermal conductivity and diffusivity for most rocks are very low (α = 0.5-2 * 10^{-6} m^2/s.**
- **Thermal conductivity controlled by the porosity and minerals present in a rock.**
- **Thermal conductivity is about 2.5 W/m ^oC down to about 50 Km.**

Thermal conductivity of rocks and minerals

Thermal conductivities of rocks and minerals at normal temperature and pressure (data from Clark, 1966, and Parasnis, 1971)

Material	*Conductivity in SI units* (W/m °C)*
Granite	1·9–3·2 (2·7)
Granodiorite	2·6–3·5 (3·0)
Gneiss	
// to foliation	2·5–3·7 (3·1)
⊥ to foliation	1·9–3·2 (2·7)
Basalt	1·5–2·2
Diabase	2·1–2·3 (2·2)
Gabbro	2·0–2·3 (2·15)
Serpentinite	2·0–3·8 (2·3)
Dunite	3·7–5·2
Sandstone	2·5–3·2
Shales	1·3–1·8 (1.4)
Limestone	2·0–3·0 (2.5)
Rock salt	5·3–7·2 (5.7)
Haematite ore	10·5
Haematite crystal	
// c	12·1
⊥ c	14·8
Magnetite (polycrystalline)	5·3
Water	0·59 (25°C)
Ice	2·2 (0°C)

II- TERRESTRIAL HEAT FLOW

- **The heat that flows from the earth's interior to its surface and escape into space**

- **This is the quantity of thermal energy that the earth is losing (10^{21} joules/year)**

Tectonic region	*No. of data*	*q* (mW/m^2)*2	*Standard deviation*
*All continents**3	597	61·0	19
Precambrian shields	214	41	10
Post-Precambrian non-orogenic areas	96	62	17
Palaeozoic orogenic areas	88	60	17
Mesozoic-Cenozoic orogenic areas	159	74	24
*All oceans**3	2530	61·4	33
Ocean basins	683	53	22
Mid-oceanic ridges	1065	80	62
Ocean trenches	78	49	29
Continental margins	642	75	39
*World**3	3127	61·4	31

- **Characteristics variation in the heat flow of different geologic provinces.**

1- Equality of Continental and Oceanic Heat Flow

- The mean heat-flow values of continents and oceans are nearly equal
- The oceanic crust (5 km) is mafic and has lower concentration of radioactive elements
- The continental crust (30-35 km) is silicic and has higher concentration of radioactive elements

- The near equality of continental and oceanic heat flow indicates a fundamental difference between the mantles underlying these topographic units
- The oceanic mantle has higher temperature and a higher concentration of radioactive elements than the continental mantle
- The alternative explanation is based on the transfer of heat in the upper mantle by convection

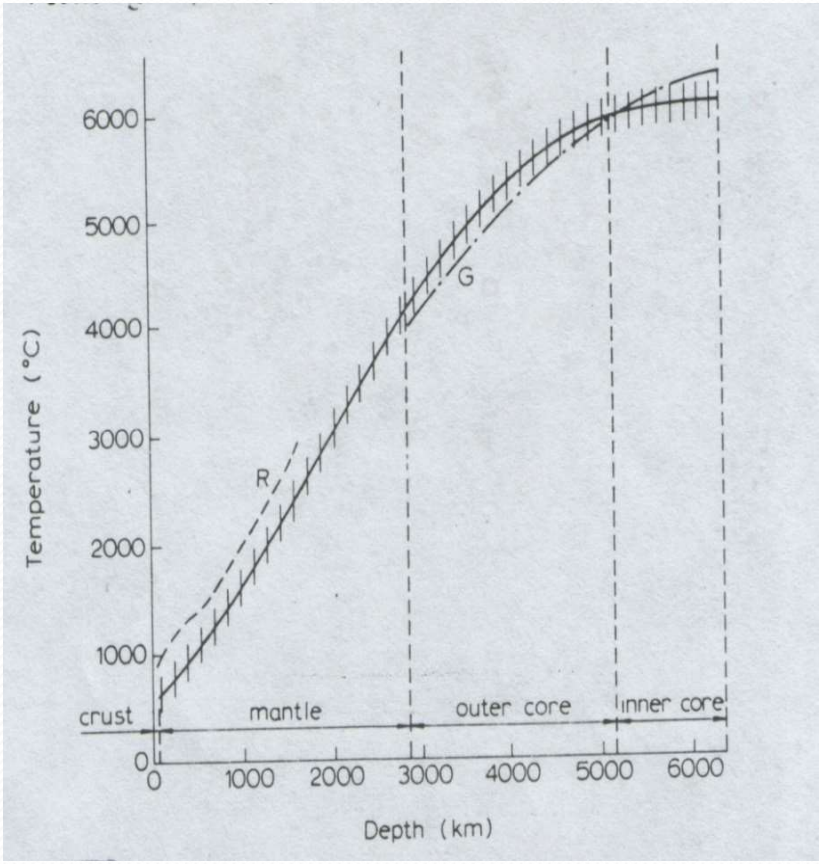
2- REGIONS OF ANOMALOUS HEAT FLOW

- Regions located near the principal ocean ridges which are equivalent to volcanic or geothermal areas on land
- On the continents the most active regions show the highest and most stable regions (shields) show the lowest values
- The regional anomaly could be caused by unusually high concentration of radioactive heat sources in the crust or the upper mantel or due to the effect of convection current in the underlying mantel

3- TEMPERATURES WITHIN THE EARTH

- **Boreholes (few kilometers deep) and mines measurements showed that the temperature increases with depth (3°C per 100m for non-volcanic areas).**

- **The greater the depth the greatest the thermal gradient and the lowest the thermal conductivity.**



- **The temperature at the base of the continental crust (33 km) is estimated at 600°~800°C.**
- **At sea (6 km crustal thickness) the temperature is thought to be 150°~200°C.**
- **Temperatures in the mantel are based on the observed seismic velocities and the variations in electrical conductivity.**
- **Seismological data suggest that the mantle is essentially crystalline and that the outer core is liquid.**

III-THERMAL PROSPECTING METHODS
Introduction

- **Geothermal measurements for the investigation of near-surface and subsurface thermal sources**

- **Causes of local variations in temperature beneath the ground:**
  - **Chemical action resulting in exothermic reactions**
  - **Presence of local radioactive heat source**
  - **The difference in conductivity of rocks**
  - **Presence of volcanic and hydrothermal sources**

- At great depth the usual method involves heat-flow measurements over the area of interest
- The technique is relatively simple, measurements require little correction It used in conjunction with seismic and resistivity method.
- Interpretation of temperature anomalies is relatively straightforward
- Thermal measurements being used in prospecting for groundwater, glacial and alluvial aquifers, thermal reservoirs, shallow salt domes, faults, and fissures, etc

III- THERMAL PROSPECTING METHODS
1- HEAT FLOW MEASUREMENTS

- Two separate measurements (thermal gradient and thermal conductivity)

$$Q = K \ \partial T/\partial Z$$

- A probe device for measuring the heat flow in soft sediments on the ocean floor
- On land, mines and boreholes are used to find the temperature gradient.
- Direct laboratory determinations are made of the thermal conductivity of collected rock samples

- **Measurements are much simpler to take at sea than on land**
- **At sea bottom the water temperature is usually stable through the entire year and there is no need to drill holes**
- **The measurements confirm that the heat flow is indeed small (61W/m^2) both for contents and oceans**
- **The geothermal heat is very small compared to the energy arriving from the sun, too small to have direct effect on the climate**

2- MEASURING TECHNIQUES

- **Precise thermistor units for field use (0 to 70°C) with accuracy better than 0.01°C**
- **Correction is needed due to the diurnal variations of temperature caused by solar radiation (to a depth of 1.5 m)**
- **To eliminate the diurnal effect, measurements are made in shallow boreholes**
- **During the winter, satisfactory results my be achieved by measuring beneath the snow cover**

- A good contact between the soil and sensor probe is required (5 cm into the bottom of the hole)
- Base station with fixed sensor was used to make correction for the small regular shift in the annual temperature level
- Airborne infrared radiometers (IR) is used to map the infrared imagery of large geothermal area (e.g., Iceland)
- Meteorological satellite equipped with high resolution devices (HRIR) have been used to record observations of infrared emission

3- Geysers

- A **geyser** is a spring characterized by intermittent discharge of water ejected turbulently and accompanied by a vapour phase (steam) .
- The formation of geysers is due to particular hydrogeological conditions, which exist in only a few places on Earth. Generally all geyser field sites are located near active volcanic areas,

Steamboat Geyser in Yellowstone

Strokkur geyser, Iceland

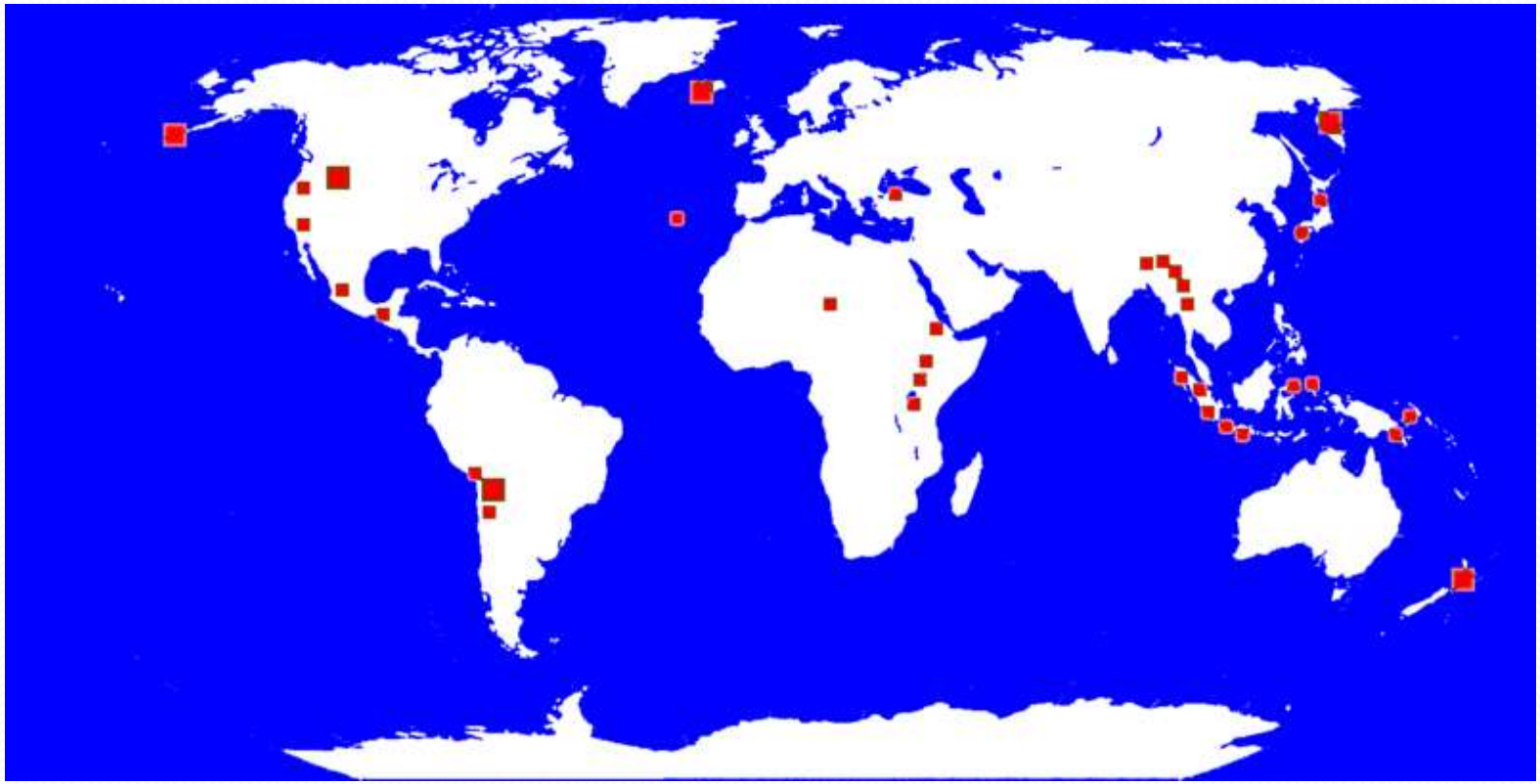
- Generally, surface water works its way down to an average depth of around 2,000 meters where it contacts hot rocks.
- As the water boils, the resulting pressure forces a superheated column of steam and water to the surface through the geyser's internal plumbing

Steam phase eruption of Castle Geyser

Major geyser fields and their distribution

- Geysers are quite rare, requiring a combination of water, heat, and fortuitous plumbing. The combination exists in few places on Earth as:

Yellowstone National Park, U.S; Valley of Geysers, Russia;
El Tatio, Chile; Taupo Volcanic Zone, New Zealand and Iceland



World geyser distribution

The formation of geysers specifically requires the combination of three geologic conditions that are usually found in volcanic terrain:

- The heat needed for geyser formation comes from magma that needs to be near the surface of the earth.
- The water that is ejected from a geyser must travel underground through deep, pressurized fissures in the Earth's crust.
- A plumbing system is required. This includes a reservoir to hold the water while it is being heated.

Geysers are generally aligned along faults. The plumbing system is made up of a system of fractures, fissures, porous spaces and sometimes cavities.

There are two types of geysers:

- fountain geysers which erupt from pools of water, typically in a series of intense, even violent, bursts
- cone geysers which erupt from cones or mounds of siliceous sinter (products of natural fusing processes)

Fountain geyser
(erupting from the pool)

Cone geyser having mound of siliceous sinter

Commercial uses of geysers

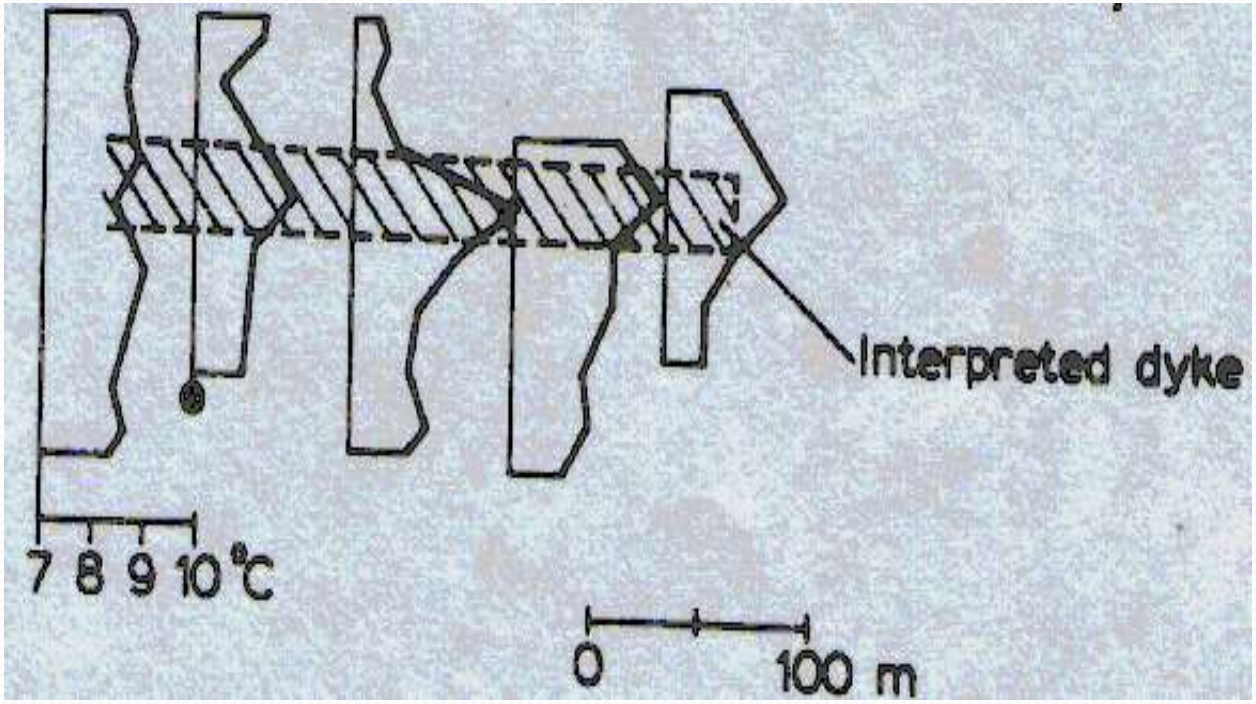
- Geysers are used for various activities such as electricity generation, heating and tourism.

- Many geothermal reserves are found all around the world. The geyser fields in Iceland are some of the most commercially viable geyser locations in the world.

- Since the 1920s hot water directed from the geysers has been used to heat greenhouses and to grow food that otherwise could not have been cultivated in Iceland's inhospitable climate
- Steam and hot water from the geysers has also been used for heating homes since 1943 in Iceland
- In 1979 the U.S. Department of Energy actively promoted development of geothermal energy in the Known geysers geothermal resource area near California

4- EXAMPLES OF GEOTHERMAL SURVEYS
a. Sulphide Ore Deposits in Slovakia

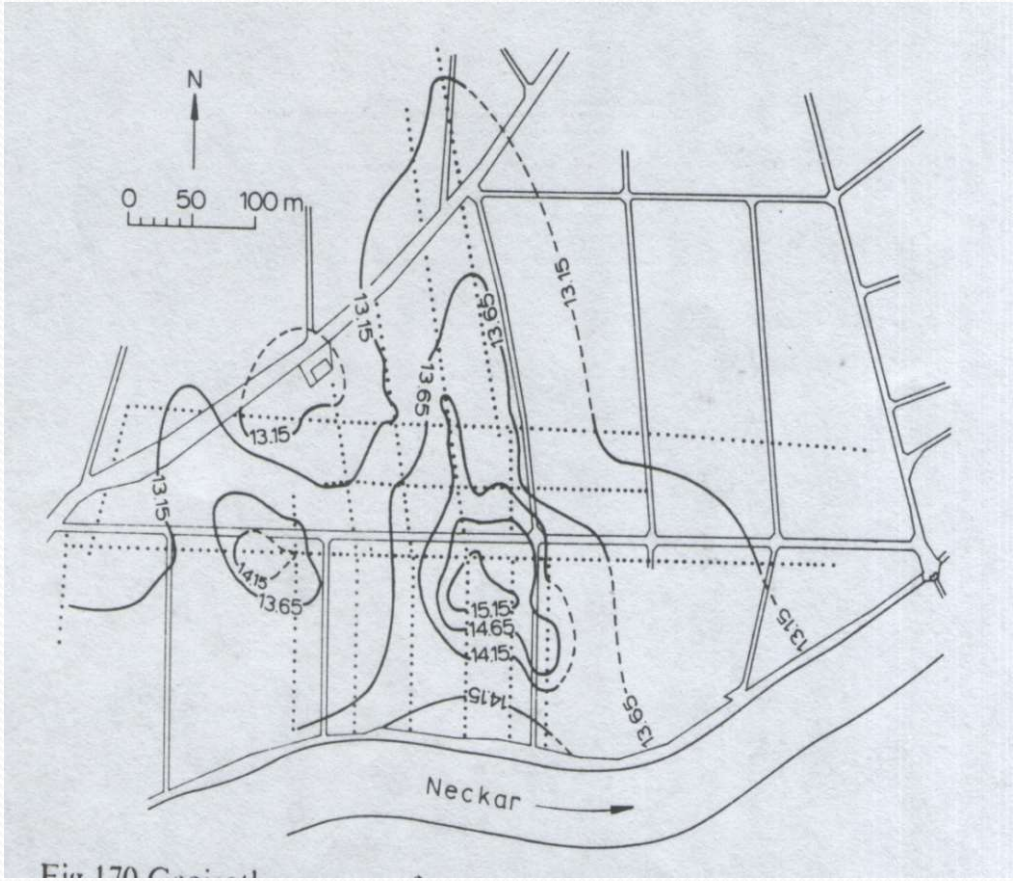
- **Sideretic - sulphide ores together with graphite beds occur in crystalline schists of Paleozoic age in the Spis- Gemer of Slovakia**



Temperature anomaly profiles over a part of the studied area (Krcker & Masin, 1970).

b. Thermal water and hot vapor zones

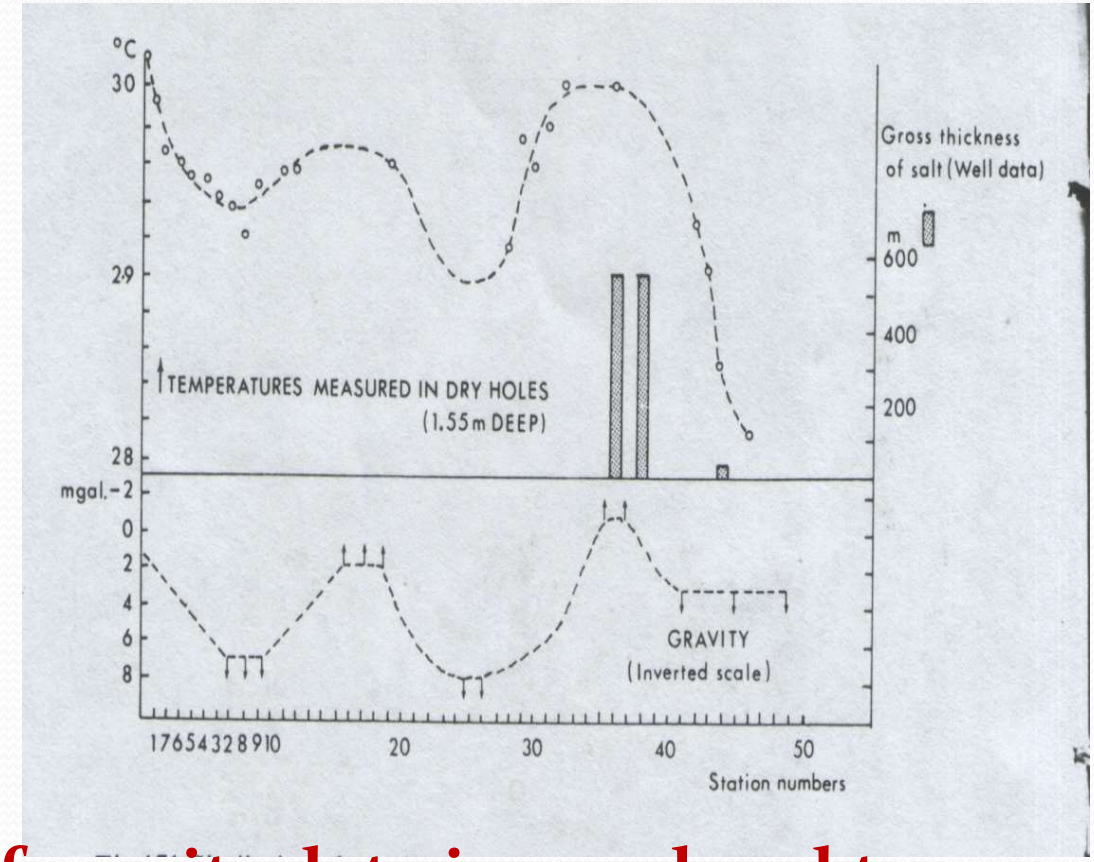
- Thermal water pockets in limestone cavities, where thermal water from depth of 100-150 m seeps up through fissures and cracks and disturbs the local temperature distributions



Geoisotherm map in an area of Neckertal, South Germany (Kappelmeyer & Haenel,1974)

Salt Structure

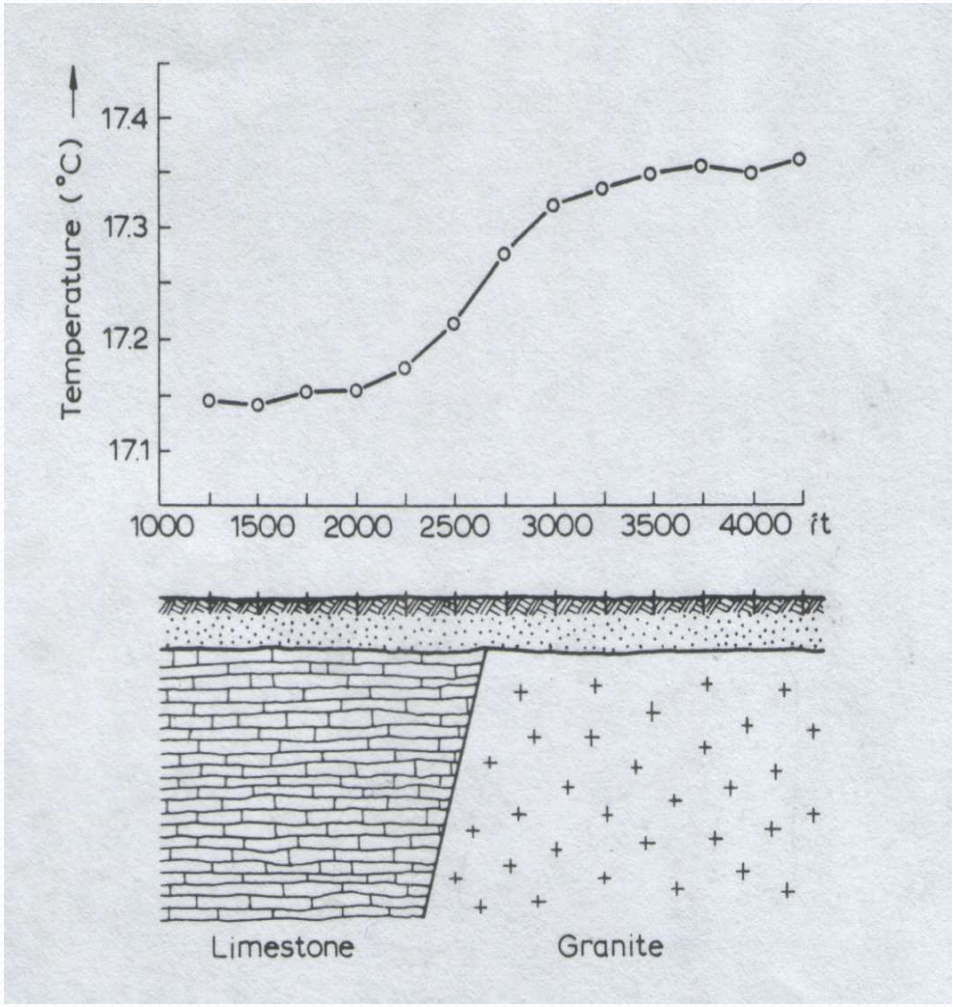
- Temperature profile along a line about 10 km long with gravity data along the same line as well as the salt layer thickness as reported from deep wells
- Correlation between thermal high (maximum salt) and a gravity low were observed



Similarity of gravity data in mgal and tempreture profile over shallow salt structure (Poley &Van Steveninch,1970)

Granite Structure

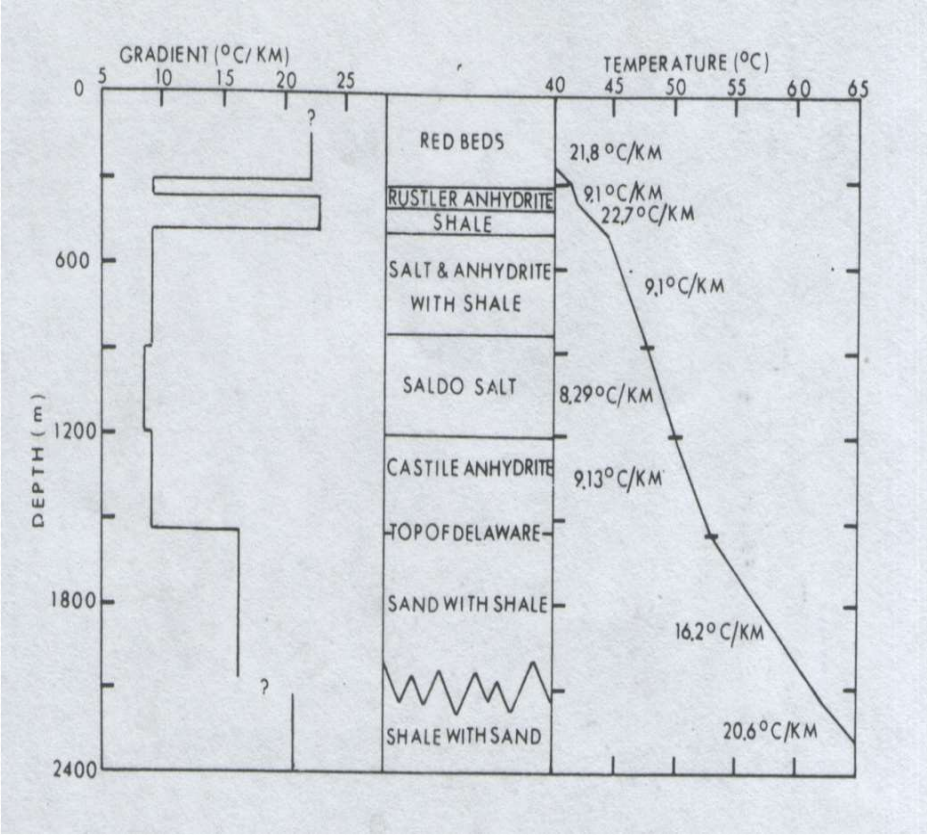
- The anomaly curve resembles in shape that of gravity profile expected over a fault structure.
- The temperature anomaly is attributed to the higher radioactive heat generated in the granite rather than to its conductivity



Temperature anomaly over a granite intrusion in contact with limestone at shallow depths

d. Lithology Information - Temperature Logs

- **Significant variations in the temperature gradient are clearly indicated with lithology**
- **The greatest temperature gradient occurs in shales and the lowest in salt and anhydrite horizons?**



Temperature, geothermal gradients and the lithology of the Northrup well, west Texas.

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Geothermal classification

- In term of temperature, geothermal resources can be classified as:

i. High: temperature ranges of higher than 150 ℃ ,
ii. moderate : 90~150 ℃
iii. low : lower than 90 ℃ ,

- and existence forms of

i. steam,
ii. mixture of water and steam
iii. and water.

Geothermal classification

- Furthermore, the low temperature geothermal resources can be further divided into 3 types:

i. Warm water (25~40 ℃),

ii. warm-hot water (40~60 ℃),

iii. hot water (60~90 ℃).

Geothermal classification

- According to storage modes, geothermal energy can be classified as 5 types:

i. hot water,
ii. steam,
iii. geopressure,
iv. dry hot rock,
v. magma.

- Due to technology, cost and other reasons, the current geothermal resources that have been developed and utilized mainly refer to the first 2 types,

Geothermal classification

i. Most hot water geothermal resources are in areas of volcanic activity and sedimentary basins, with the temperature of 80~180 ℃ , salinity of about 1~400 g/l, often containing sodium chloride, sodium carbonate, sodium sulfate, calcium carbonate, carbon dioxide, hydrogen sulfide, etc.

ii. Steam geothermal resource features with wet and superheated steam, with the temperature of above 200℃ . One of the genetic conditions requires a certain type of geological structure, namely, the steam must be surrounded by impermeable rocks. This kind of geothermal resource is relatively scare, accounting for about 0.5% of total.

iii. Geopressure geothermal resource refers to the high pressure salt water buried in 2~3 km deep sedimentary rocks. Because of being sealed by the outside impermeable rocks, the pressure can reach up to several tens of MPa, with the temperature of 150~260, and is often dissolved with hydrocarbons, thus, its actual exploitable types of energy include heat,

iv. pressure and chemical energy.

Geothermal classification

iv. The thermal energy contained in high temperature rocks where there are no fluid mediums and channels is called dry hot rock geothermal resource, whose temperature reaches 200~650 ℃ and depth reaches 2~12 km. The exploitation of dry hot rock geothermal resource needs to drill permeability channels in the rocks, so as to the heat can be brought to the surface through the fluid loop.

v. Magma geothermal resource is occurred inside the high temperature plastic or molten magma which is located deeply in the ground, with the temperature of above 1,000 ℃ and the pressure of up to several hundreds of MPa. At present, this kind of geothermal resource is hard to exploit for lack of mature technologies.

Resource extent and distribution

- The distribution of geothermal resources is closely associated with plate tectonics whose movements play a significant role in the formation and activity of global geothermal belts.
- High temperature geothermal resources are generally distributed in the plate edges,
- while the low temperature ones are generally distributed in the plate interior.

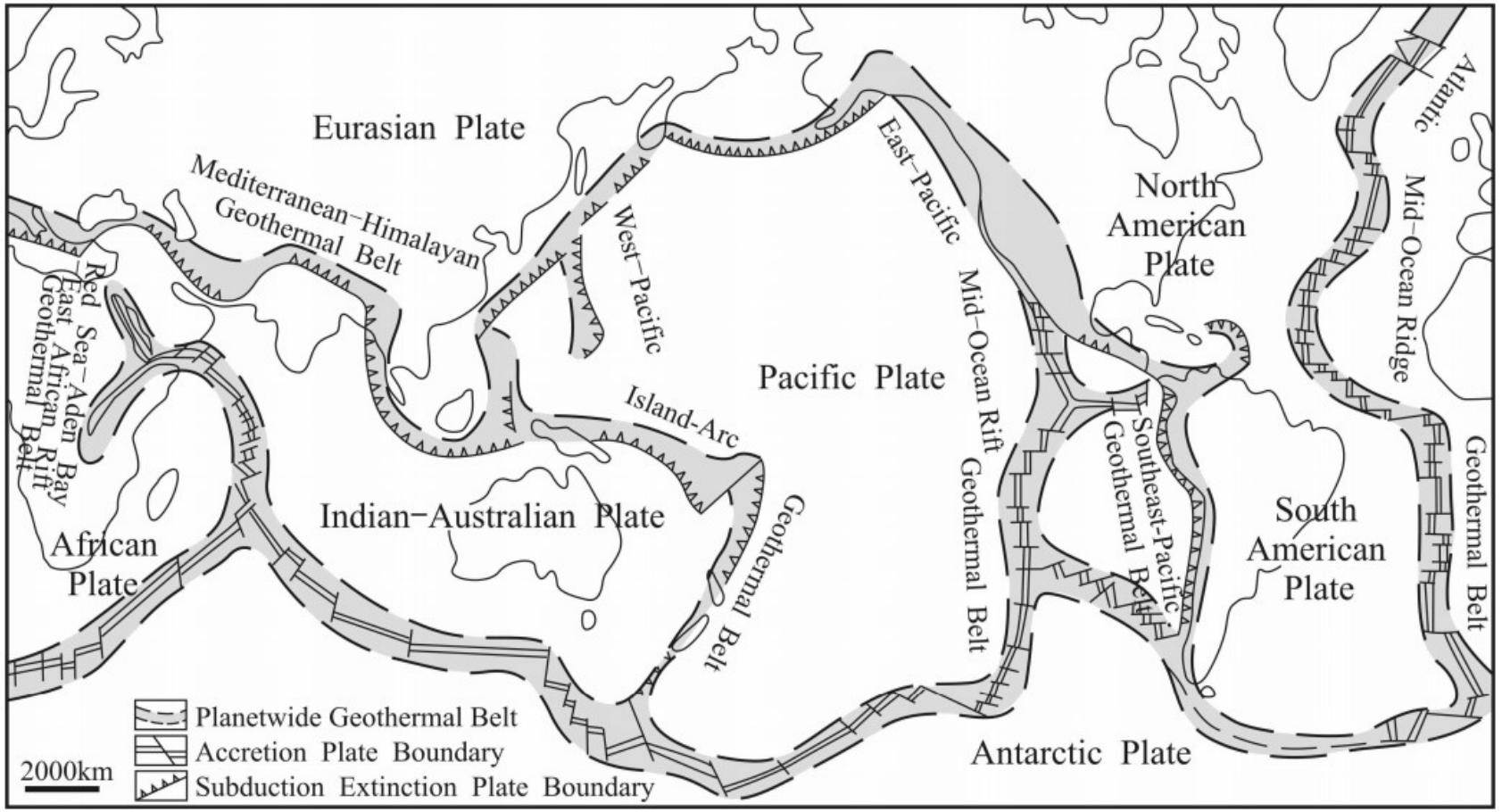

Figure 1. Distribution of planetwide geothermal belt [4-5]

Thank you