

**THE USE OF GAMMA RAY DATA
TO DEFINE
THE NATURAL RADIATION ENVIRONMENT**



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FOREWORD

The accident at the nuclear reactor at Chernobyl in the USSR in April 1986, and the confusion in the public mind over the nature and extent of the resulting fallout pointed up the need for more widespread awareness of the natural radiation background in which people live. An examination of the possibilities for acquiring these data led to the recognition of the work of the uranium exploration community over the years as an important source of, as yet unused, natural radiation data. These data have been collected for the purpose of locating uranium deposits in many countries, frequently through the use of public funds or development funds. The most extensive effort was that carried out in the U.S.A. where the whole of country was flown with airborne gamma ray spectrometer surveys during the National Uranium Resources Evaluation (NURE) project. These data have been compiled and issued as background radiation maps that have been of great value in locating areas of potential radon hazard, in addition to their use in geological mapping and mineral exploration for a number of metals. They will be of fundamental importance in the International Geological Correlation Programme (IGCP)/UNESCO project on International Geochemical Mapping which has the ultimate aim of producing Geochemical Maps of the World. The IAEA is playing a coordinating role in the production of the Radioelement Geochemical Maps. This manual is designed to encourage and assist in the use of preexisting gamma ray survey data to produce maps of the natural radiation environment.

The manual is the work of three consultants; Dr. J. S. Duval of the United States Geological Survey, Dr. Anders Linden of the Swedish Geological Company, and Dr. Milan Matolin of Charles University in Prague, Czechoslovakia. These three combine a great many years of experience in natural radiation measurement and in the development of the methods to their high level of sophistication. The Agency wishes to thank most sincerely these three for contributing their time and expertise to the task. The Agency staff member responsible for the project was Arthur Y. Smith of the Division of Nuclear Fuel Cycle.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION	7
2. THE NATURAL RADIATION ENVIRONMENT	8
2.1. Sources of natural radiation	8
2.2. Radiation units and conversion factors	10
2.3. Occurrence of potassium, uranium, thorium and other radiation sources in the environment	11
2.3.1. K, U and Th in rock and soil	11
2.3.2. K, U and Th and their daughter products in the atmosphere, hydrosphere and biosphere	14
2.3.3. Cosmic radiation	15
2.3.4. Natural nuclei concentrated or relocated by man ..	15
2.3.5. Artificial nuclei in nature	15
2.4. Measuring the natural radiation environment	16
2.5. Equivalent dose to man from natural radiation	17
3. GAMMA RAY SURVEYS	18
3.1. Instrumentation	18
3.2. Calibration and reporting units	19
3.3. Geological gamma ray surveys	20
3.4. Suitable data	20
4. STANDARDIZATION TECHNIQUES	22
4.1. General concept of standardization	22
4.1.1. General considerations	22
4.1.2. Conversion of radioelement concentrations to air dose rate	23
4.2. Levelling of data within a survey area	24
4.2.1. Factors causing level differences	24
4.2.2. A mathematical approach to levelling	26
4.2.3. Levelling of data using image techniques	28
4.3. Levelling of data between survey areas	32
4.4. Procedure for standardization of spectrometer surveys	32
4.4.1. Gamma ray spectrometer surveys with calibrated equipment	32
4.4.2. Gamma ray spectrometer surveys with uncalibrated equipment	32
4.5. Procedures for standardizing total count surveys	34
4.5.1. General problems related to the use of total count surveys	34
4.5.2. Total count surveys with calibrated equipment	37
4.5.3. Total count surveys with uncalibrated equipment	38

5. DATA PRESENTATION	38
5.1. Graphical form	38
5.2. Map compilation	39
5.2.1. Manual compilation	39
5.2.2. Digital compilation	41
6. INTERPRETATION AND USE OF THE MAPS	42
REFERENCES	45

1. INTRODUCTION

The natural radiation environment is the major source of radiation exposure to man and consists of both internal and external sources. The most significant internal sources are the radioactive elements ^{40}K and ^{222}Rn which are taken into the body. The external sources are cosmic rays and naturally occurring radioactive isotopes of the ^{40}K , ^{238}U , and ^{232}Th decay series, some or all of which can be found in the ground, in construction materials, and in the air. Both internal and external radiation levels vary as a function of the geological materials, type of dwelling, and elevation above sea level. This report has been prepared to provide a guide for the use of existing gamma ray survey data to define the natural radiation environment, but will only be concerned with the gamma ray exposure resulting from radiation originating in geological materials. Chapter 2, below, discusses the natural radiation environment in greater detail.

Because natural radiation levels represent the minimum exposure attainable, they are used for comparison when judging the significance of exposure from man-made sources such as medical x-rays, nuclear weapons fall-out, and nuclear power plants. The entire issue of man-made radioactivity becomes more important as the number of nuclear power plants, research reactors, medical and industrial isotope sources, etc. increases.

The study of the natural radiation environment has been actively carried out since the discovery of radioactivity. In recent years a series of symposia [1], [2], [3], [4], dedicated to the subject have produced a significant volume of information. However, currently available data provide coverage for a small fraction of the earth's land surface and maps covering much larger areas are needed. Examples of such maps for parts of Canada were presented by A.G. Darnley et al. [5]. The type of data needed to produce similar maps are available as a result of airborne, carborne, and ground gamma ray surveys in many parts of the world. Although most of these data were acquired for uranium and other mineral exploration and geological mapping purposes, they can be used to provide background radioactivity information. The primary criteria for the use of these data is that they must be of good quality and self consistent. Chapter 3 discusses the characteristics of gamma ray surveys.

Because the relationship between the quantities of natural gamma ray sources and air dose rate is known, existing data can be standardized in terms of the gamma ray exposure resulting from the radioactivity of geological materials. The process of standardization involves the use of conversion factors and, where necessary, back calibration. Chapter 4 discusses standardization procedures.

Standardized survey data can be compiled to produce regional maps of gamma ray air dose rates as well as single radioelement maps. Compilation procedures may use either manual or computer techniques. Chapter 5 discusses these compilation techniques.

Regional maps of air dose rates provide a broad view of the terrestrial part of the natural radiation environment. These maps can be used to estimate the terrestrial radiation dose to the population, and to identify areas of potential natural radiation hazards. They also provide a base against which man made contamination can be estimated. Chapter 6 discusses the interpretation and use of these maps.

Finally, it must be stressed that these maps retain their geological and geophysical information. More importantly, the diverse primary data will have been brought to a common datum enabling the comparison of geological features over large regions. Although this work will primarily be done as national compilations, it will open the possibility of the compilation of radioelement geochemical maps on a regional and global scale.

2. THE NATURAL RADIATION ENVIRONMENT

Natural radiation arises from sources which always have been a part of man's environment. Natural radiation is of three types, alpha, beta and gamma. In the ground the main sources are potassium, the uranium decay series and the thorium decay series. Cosmic radiation coming from outer space, radon in the air and internal radiation in the human body are also contributors to the natural radiation environment. In addition to natural radiation, different sources of man made radiation exist as well. Descriptions of the natural radiation environment are given in Adams and Gasparini [6] and Kogan et al. [7].

2.1 Sources of Natural Radiation

Natural radiation external to man includes terrestrial gamma rays, gamma rays from building material and cosmic radiation. Internal exposure results from radionuclides entering the body through ingestion and inhalation of naturally occurring radioactive substances in food, water and air. The natural radionuclides in the environment are of two general classes; cosmogenic and primordial. Cosmogenic radionuclides are produced through the interaction of cosmic rays with atoms in the atmosphere, and do not contribute significantly to external gamma radiation doses.

The terrestrial component of natural radiation arises from the primordial radionuclides potassium, uranium and thorium and their decay products. Naturally occurring potassium contains 0.0119 % of the isotope ^{40}K . The decay of uranium and thorium to stable isotopes gives decay series comprising several tens of radionuclides. Natural uranium is a mixture of the isotopes ^{235}U and ^{238}U with ^{235}U comprising 0.72 % of natural uranium. Natural thorium, the parent element of the thorium decay series, is made up of the isotope ^{232}Th . The decay of ^{40}K , ^{238}U and ^{232}Th , daughter products and

half-lives are shown in figures 2.1 - 2.3 [1]. There are two gaseous isotopes, ^{222}Rn and ^{220}Rn , in the uranium and thorium decay series. These radionuclides and their decay products contribute significantly to internal alpha exposure.

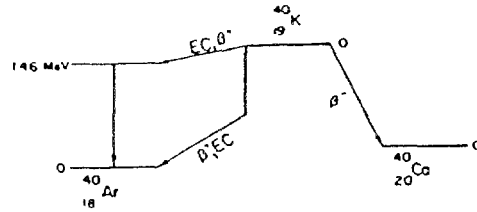


Figure 2.1: The decay of potassium-40.

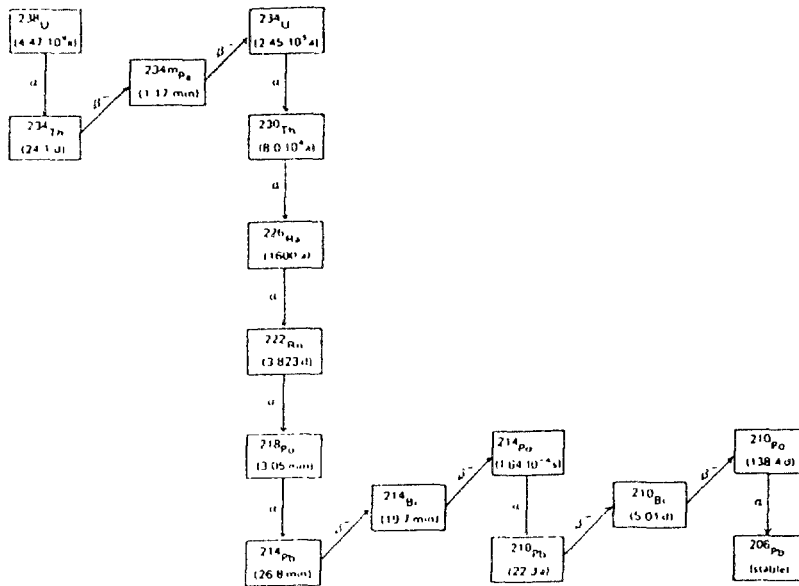


Figure 2.2: The uranium-238 series. Radionuclides produced in quantities of less than 1% are not shown.

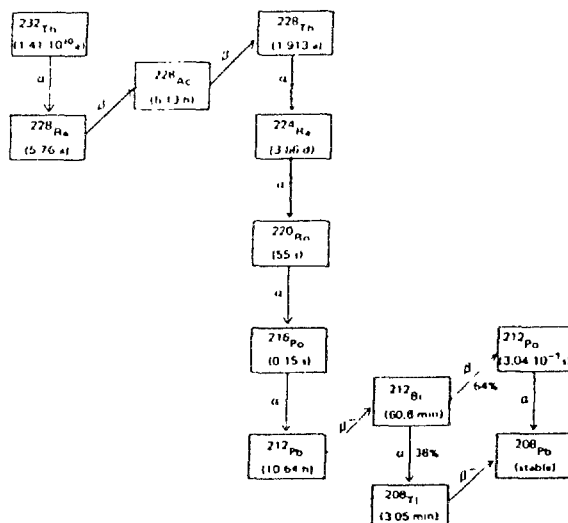


Figure 2.3: The thorium-232 series. Radionuclides produced in quantities of less than 1% are not shown.

The estimate of annual effective dose equivalents from natural radiation sources based on global averages is shown in Table 2.1 [46]. This indicates that radon in indoor air is the largest contributor to the annual effective dose equivalent. Variations in the geological environment will change the relative proportions of these factors. In some countries the inhalation component has been reported to be as high as 80 % of the annual effective dose equivalent [9].

Table 2.1: The global average annual effective dose equivalents from natural radiation sources. Relative contributions in % are indicated in brackets. (After [46]).

Source of Irradiation	External mSv	Internal mSv	Total mSv
Cosmic rays	0.410 (17)		0.410 (17)
Cosmogenic radionuclides		0.015 (1)	0.015 (1)
Primordial radionuclides			
⁴⁰ K	0.150 (6)	0.180 (7)	0.330 (13)
⁸⁷ Rb		0.006	0.006
²³⁸ U - series	0.100 (4)	1.239 (51)	1.339 (55)
²³² Th - series	0.160 (7)	0.176 (7)	0.336 (14)
Total	0.820 (34)	1.616 (66)	2.436 (100)

Indoor gamma ray radiation levels depend on the type of building materials used and on their composition. The ratio of indoor to outdoor gamma radiation has been reported mostly as 1 - 2 [46].

2.2 Radiation Units and Conversion Factors

The SI unit for activity is the becquerel (Bq). Activity of one Bq corresponds to a decay rate of one atom per second. The unit formerly used was the curie (Ci), which corresponds to 3.7×10^{10} Bq. 1 Ci has approximately the activity of 1 gram of ²²⁶Ra.

The definition of exposure to ionizing radiation is based on the amount of ionization in air. The original unit was the roentgen (R). The relationship of R to basic SI units is: $1 \text{ R} = 2.58 \times 10^{-4} \text{ C kg}^{-1}$. The exposure rate is the exposure per unit time. In geological work the unit $\mu\text{R/h}$ is still common.

The absorbed dose in any substance is expressed in terms of energy transfer. The SI unit for absorbed dose is the gray (Gy). 1 Gy is equal to 1 joule (J) kg^{-1} . Previously absorbed

dose was expressed in units of rads. The absorbed dose rate (Gy s^{-1}) is the absorbed dose per unit time. The dose rate of gamma radiation absorbed in air can be related to exposure rate and is used to specify the terrestrial source of gamma radiation.

A quantity that takes into account the characteristics of the particular type of radiation and its potential for causing damage to body cells and tissues is the dose equivalent. The SI unit of dose equivalent is the sievert (Sv). The conversion from Gy to Sv is possible by multiplying the absorbed dose by the relative biological effectiveness (RBE) of the radiation concerned. For natural gamma rays the RBE, also known as the quality factor, has the value of 1.

The term "effective dose equivalent" expresses the effects of man whole body irradiation. The estimated conversion factor to convert dose equivalent due to isotropic gamma radiation to effective dose equivalent is 0.7 [46].

Exposure rate can be converted to absorbed dose rate in air ($1 \mu\text{R h}^{-1} = 2.4139 \text{ pGy s}^{-1}$). Dose is calculated as the product of absorbed dose rate in air and time of exposure. Due to the quality factor for gamma radiation being equal to 1, the dose and dose equivalent are numerically identical. Effective dose equivalent is calculated by multiplying the dose equivalent by the conversion factor 0.7.

Table 2.2: SI units and older units for radiation.

Quantity	SI unit	Older unit	Conversion factor
Activity	becquerel (Bq)	curie (Ci)	$1 \text{ Bq} = 27 \times 10^{-12} \text{ Ci}$ $1 \text{ Ci} = 37 \times 10^9 \text{ Bq}$ $1 \mu\text{Ci} = 37 \text{ kBq}$
Exposure	coulomb/kg (C kg^{-1})	roentgen (R)	$1 \text{ C kg}^{-1} = 3876 \text{ R}$ $1 \text{ R} = 2.58 \times 10^{-4} \text{ C kg}^{-1}$ $1 \text{ R} = 8.69 \times 10^{-3} \text{ Gy}$ (standard air)
Absorbed dose	gray (Gy)	rad	$1 \text{ Gy} = 100 \text{ rad}$ $1 \text{ rad} = 0.01 \text{ Gy}$
Absorbed dose rate	gray/sec. (Gy s^{-1})		$1 \mu\text{R h}^{-1} = 2.4139 \text{ pGy s}^{-1}$
Dose equivalent	sievert (Sv)	rem	$1 \text{ Sv} = 100 \text{ rem}$ $1 \text{ rem} = 0.01 \text{ Sv}$

2.3 Occurrence of Potassium, Uranium, Thorium and other Radiation Sources in the Environment

2.3.1: K, U and Th in rock and soil

The content of potassium in rocks can have a range of 0 to 10 % K but is usually 1 to 5 % K with an average value of about 2 % K. The content of uranium and thorium in rocks

varies from near zero to several hundreds of parts per million (ppm) [10]. The content of K, U and Th depends on rock type and the geological environment. Table 2.3 lists the contents that may be expected in some ordinary rock types. For a specific rock or a specific locality the content of K, U and Th may differ significantly from these average values [7], [10], [11].

Table 2.3: Typical concentration of potassium, uranium and thorium in some common rocks and corresponding absorbed dose rate in air and exposure rate (calculated at 1 m above the ground).

Rock	K %	U ppm	Th ppm	Absorbed dose rate in air $\mu\text{Gy s}^{-1}$	Exposure rate $\mu\text{R h}^{-1}$
Granite	3-4	3-5	10-30	25-50	10-20
Gabbro	< 1	< 1	2-3	4-7	2-3
Limestone	< 1	1-2	1-2	4-7	2-3
Sandstone	1-2	3-5	10-15	15-25	5-10
Average	2.5	2.7	9.6	20.0	8.3

In most areas of the world the bedrock is covered with soil. Therefore the radiation from the soil is the most important contributor to the terrestrial radiation. The content of radioactive minerals in the soil depends upon the content in the original parent rocks. Sometimes the radioactive minerals are concentrated and sometimes spread more homogeneously in the soils. Because many uranium and thorium minerals are small and fragile it is common to find them concentrated in the fine grained fraction, such as clay. In soils the content of K, U and Th is of the same order as in rocks but usually somewhat lower [12]. In most cases the uranium decay series is not in radioactive equilibrium in soils whereas thorium decay series often is. Uranium disequilibrium occurs when some of the radionuclides in the decay series are moved by chemical or physical processes. Table 2.4 lists the average concentrations of ^{40}K , ^{238}U and ^{232}Th in soils with corresponding absorbed dose rate in air and exposure rate [7], [8].

Table 2.4: Average concentration of K, U and Th in soil with corresponding absorbed dose rate and exposure rate (calculated at 1 m above the Ground).

Soil	K %	eU ppm	Th ppm	Absorbed dose rate in air pGy s ⁻¹	Exposure rate μR h ⁻¹
*1)	1.2	2.0	6.3	12	5
*2)	1.4	1.6	6.0	12	5

*1) adapted from UNSCEAR [8]
 *2) adapted from Kogan [7]

A model for the transport of uranium in rock and soil by mechanical and chemical processes in glaciated terrain is shown in Table 2.5 [13]. The uranium content in the example refers to an uranium rich granite.

Table 2.5: A model for the transport of uranium by chemical and mechanical processes [13].

GRANITIC ROCK	15 ppm eU	Transfer of uranium precipitation of U and Ra on the surface of fractures and fissures.
↓ crushing and leaching by water		
↓ ↓ ↓		High uranium and radon content in fracture groundwater
MORaine	8 ppm eU (5-15 ppm eU)	Transfer of uranium
↓ sorting and leaching by water		Precipitation of U and Ra on the surface of fissures, pebbles and grains.
↓ ↓ ↓		
BOULDERS GRAVEL SAND	15 ppm eU 10 ppm eU < 3 ppm eU	Transfer of uranium
↓ sorting by water		Loss of the main part of the fine grained uranium minerals
↓ ↓ ↓		
CLAY	4-8 ppm eU	Deposition, transformation of primary uranium minerals to clay minerals, precipitation and absorption of U and Ra on clay particles

2.3.2: K, U and Th and their daughter products in the atmosphere, hydrosphere and biosphere

The concentrations of K, U, Th and their daughter products in water are much lower than in rocks and soils (see Table 2.6). For obvious reasons the radioactive decay series in water are not in equilibrium.

Table 2.6: K, U and Th in water [7], [14], [15]

<u>Element</u>		<u>Sea water</u>	<u>Fresh water</u>
K	%	0.035	<0.001
	Bq/kg	10	<1
²³⁸ U	ppm	0.003	0.001
	Bq/kg	0.04	0.01
²³² Th	ppm	10 ⁻⁷	10 ⁻⁷
	Bq/kg	-	-

The main contributors to the radioactivity in air and water are the radon isotopes and their decay products. Radon emanates from the ground via soil capillaries into the atmosphere or into the groundwater. Because ²²²Rn has a half-life of 3.825 days whereas ²²⁰Rn has a half-life of only 54.5 seconds, ²²⁰Rn is generally less important to the equivalent dose but may play a minor role indoors. Therefore, in the following discussion the term radon will refer to ²²²Rn.

In open lakes and rivers the radon content is low, usually less than 1 Bq/kg. In small creeks the radon content may rise to higher values due to the influx of radon bearing groundwaters. The concentration of radon in groundwater depends on the radium concentration of the bedrock or soil through which the waters have passed, and may reach levels of several thousand Bq/kg or higher.

The concentration of radon and its daughter products in outdoor air varies with place, time, height above ground and meteorological conditions. Over land, a reasonable estimate of the concentration of radon at ground level is 5 Bq/m³ [46]. In special meteorological conditions, for example under an inversion air layer, the concentration of radon may rise considerably. The concentration of other radioactive elements in the atmosphere is negligibly low.

The most common radioisotope in the biosphere is ⁴⁰K. The average potassium content of plants is about 0.05 % K but in grasses it may be 10 times as high as in woody plants. For a mature forest, potassium gives about 1000 Bq/m² [7]. The concentration of radioisotopes in animals averages about 0.2 % [7]. The average activity of ⁴⁰K in the human body is about 60 Bq/kg.

2.3.3: Cosmic radiation

High energy cosmic radiation from the sun and other sources in outer space irradiates the earth. At the earth's surface most of the radiation dose arises from secondary particles. The cosmic ray intensity shows small fluctuations due to the 11 year solar cycle and the latitude. The cosmic ray intensity increases with altitude, doubling about every 2000 m [12]. The absorbed dose rate in air at sea level is given as 9 pGy s^{-1} [12]. The exposure rate at sea level is given as $3.6 \text{ } \mu\text{R h}^{-1}$ by Lemmelä [16].

2.3.4: Natural nuclei concentrated or relocated by man

There are a number of other sources of exposure to radiation which are a direct consequence of man's technological activities. Examples of these are coal and peat fired power plants, geothermal energy production, mining for uranium and phosphate and the use of phosphate fertilizers on fields. The use of stone and bricks as building materials may lead to elevated outdoor and indoor radiation levels. These activities may increase the gamma ray activity measured on the ground or from the air. The use of fertilizers may increase the gamma ray activity over cultivated areas. The accumulated concentration of ^{226}Ra from fertilizers in West Germany gives a mean absorbed dose rate in air of about 0.2 pGy s^{-1} [17].

2.3.5: Artificial nuclei in nature

In most regions aerial deposition of artificial radionuclides has occurred. Nuclear bomb tests conducted in the atmosphere since 1945 have resulted in the introduction of artificial radionuclides into the environment. Many radionuclides produced in nuclear weapons testing emit gamma rays and so contribute to the external radiation. The most important one from this point of view is ^{137}Cs but other short-lived isotopes were important for a limited time. The relative distribution of the fallout is a function of latitude and is shown in Figure 2.4. The integrated mean deposition today of ^{137}Cs in the north temperate zone (40 - 50 degrees latitude) is estimated to be 2.9 kBq/m^2 [8].

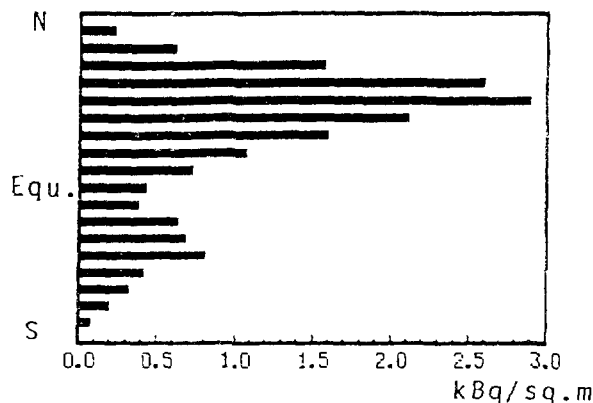


Figure 2.4: The integrated mean deposition of ^{137}Cs in the northern and southern hemispheres.

Other causes of the aerial distribution of man made gamma ray emitters are accidents in the nuclear power industry, loss of medical or industrial applications sources, and the fall of satellites powered by nuclear reactors. Considerable contributions to the terrestrial gamma ray component were caused by the reactor accidents at Windscale, UK (1958) and Chernobyl, USSR (1986), the loss of isotope sources Mexico (1985), Brazil (1987), and by the fall of a nuclear powered satellite in Canada, (1978). Shortlived isotopes will, of course, change the absorbed dose rate in time. For example the absorbed dose rate in air measured in Sweden shortly after the Chernobyl accident in 1986 was, in some places, as high as 2500 pGy s⁻¹ but by 1988 had declined to about 150 pGy s⁻¹ [18].

Fall-out nuclides are radioactive and emit gamma rays that interfere with the detection of the gamma radiation of natural radioactive elements. The most prominent fall-out isotopes, detectable by their gamma radiation on the earth's surface in different stages of contamination are given in Table 2.7. Important fall-out radionuclides with long half-lives are ¹³⁷Cs, ¹³⁴Cs and ¹⁰⁶Ru.

Table 2.7: Significant fall-out radionuclides - sources of gamma rays

Isotope	Half-life	Energy of gamma rays keV
⁹⁵ Nb	35.15 d	766
⁹⁵ Zr	65.5 d	724, 757
¹⁰³ Ru	39.5 d	497, 610
¹⁰⁶ Ru	368.2 d	622
¹³¹ I	8.05 d	284, 364, 637
¹³² I	2.38 h	523, 630, 668, 773, 955
¹³⁴ Cs	750 d	569, 605, 796
¹³⁷ Cs	30.12 y	662
¹⁴⁰ La	40.27 h	487, 816, 925, 1596

2.4 Measuring the Natural Radiation Environment

The disintegration of a natural radioactive element is accompanied by the emission of α and β particles. The daughter nuclei are often in a state of excitation. The excess energy is emitted as gamma rays that have no mass or charge. Because gamma rays are more penetrating than α or β particles they are most often used to characterize the terrestrial component of the natural radiation environment. However, in certain cases, such as the detection of radon, alpha particles are measured.

The measurement of gamma rays for geological purposes started on a large scale in the 1950s when active uranium prospecting began. Later, measurements of natural radiation were made to identify geological boundaries, for the classification of rocks and, indirectly, for prospecting for

minerals other than uranium. Natural radiation may be measured in many different ways but for geological purposes only a few techniques have been used. Recently ground and airborne gamma ray surveys have been used to identify areas with possible radon hazard as well as to calculate the equivalent dose from the natural environment and fall-out [12], [18], [19].

For normal rocks and soils 90 % of the gamma rays measured by a spectrometer survey originate from the uppermost 0.15 m. Thus the gamma ray survey is a surface measurement technique. In most cases the bedrock is covered by soil so that the gamma ray survey shows the activity of the soil and not the bedrock.

Although radioactive elements are not usually present in plants or snow at levels detectable by geological field instruments, plants and snow do have a shielding effect on the measurements. For airborne surveys in Canada the shielding effects of trees was calculated to cause a 15 % underestimation of the exposure rate [12]. Variations in the vegetation cover can also affect ground surveys. For example, the radioactivity of a soil covered by moss and humus will be less than the radioactivity of the bare soil. A mass equivalent to 0.08 m of water will reduce the exposure rate by about 50 % [20]. Because soil moisture has a similar effect and because it varies as a function of time and rainfall, surveys carried out at different times of the year may not give the same estimate of the exposure rate.

2.5 Equivalent Dose to Man from Natural Radiation

Cosmic radiation gives an annual effective dose equivalent of 0.41 mSv [46]. The terrestrial component of radiation varies considerably. World estimates of average outdoor absorbed dose rate in air of 55 nGy h^{-1} (15.28 pGy s^{-1}) give an annual effective dose equivalent of 0.34 mSv. The data of table 2.4 corresponds to 0.27 mSv for a person who stays out-of-doors all year round. The absorbed dose rate in air of 45.3 pGy s^{-1} gives 1 mSv a^{-1} .

Indoor radiation varies with building material. Estimates of average indoor absorbed dose rate in air is 70 nGy h^{-1} (19.44 pGy s^{-1}) [46], giving an annual effective dose equivalent of 0.43 mSv to a person who stays indoors all year round. Estimates of occupancy factors are 0.2 for outdoors and 0.8 for indoors [46], corresponding to an annual effective dose equivalent from terrestrial radiation of 0.41 mSv.

Inhalation of radon in the air is probably the most important contributor to the radiation dose received by man. A radon daughter content of 1 Bq/m^3 gives an annual equivalent dose of 0.081 mSv [22]. The total world population global mean annual dose equivalent has been estimated at 1.2 mSv [46]. The regional variation is large. For example, in Sweden, the estimated average dose equivalent from radon is 3.7 mSv a^{-1} .

3. GAMMA RAY SURVEYS

Gamma ray surveys for geological purposes have been designed in many different ways. To be of use in defining the natural radiation environment it is necessary that the measurements be self consistent and have a direct correspondence to the terrestrial radiation. There are several conditions that must be satisfied. The following sections discuss the instrumentation, measurement techniques, calibration and reporting units.

3.1 Instrumentation

Instruments for measuring gamma rays convert photon energy into an electrical current. The most commonly used radiometric field instruments for geological work are Geiger-Müller (GM) counters and scintillation counters. Most recent gamma ray surveys use NaI(Tl) scintillation detectors. For a scintillation counter the most significant factors are the size of the detector and the energy discrimination threshold.

A NaI(Tl) detector interacts with radiation mainly by Compton scattering and the photoelectric effect. The output electrical signal is proportional to the absorbed gamma ray energy and thus the scintillation detector can be used in a gamma ray spectrometer. Because the number of gamma rays absorbed increases as the volume of the detector increases, larger detectors provide greater sensitivity. The energy discrimination threshold controls the output count rate. Greater details on gamma survey instrumentation is given in IAEA [23] and IAEA [24].

In a total count gamma ray scintillometer instrument all gamma ray signals above an energy discrimination threshold are recorded. Any change in the discrimination threshold will affect the response of the instrument. For small scintillation counters the discrimination threshold is usually set at between 30 and 150 keV, to give high sensitivity. Such instruments usually have no system to stabilize the gain and thus the discrimination threshold which means that the instrument response may change with time. Instruments with stabilization systems eliminate this problem.

In a gamma ray spectrometer a gamma ray energy spectrum is measured which can be used to define the amounts of the different radionuclides. This is done by measuring the count rate in distinct energy windows specific for the gamma ray energy of particular element. Some systems use a multichannel analyzer with as many as 256 channels, while simpler systems use 3 or 4 distinct energy windows. Typical energy windows used for determining K, U and Th are shown in Table 3.1 [25].

The function of a gamma ray spectrometer requires stabilization to avoid the effects of small energy drifts. These cause more severe errors in a spectrometer than in a total count system. Stabilization can be done by controlling the temperature of the detector, by energy stabilization using a reference radioactive source or an LED, or by the use of

Table 3.1: Spectral energy windows commonly used for gamma ray spectrometres.

Element analysed	Isotope used	Gamma ray energy (MeV)	Energy windows (MeV)
K	⁴⁰ K	1.46	1.37 - 1.57
U	²¹⁴ Bi	1.76	1.66 - 1.86
Th	²⁰⁸ Tl	2.62	2.40 - 2.80

measured natural radiation. In the latter case, with a multichannel analyzer, it is possible to correct for energy drifts at the end of the survey.

3.2 Calibration and Reporting Units

Many of the early radiometric surveys carried out around the world were reported in counts per unit time which apply only to the instrument actually used. To provide consistent quantitative radiometric measurements it is necessary to calibrate the instruments.

Gamma ray spectrometers can be calibrated using a source containing a known amount of the radioelement. These sources must be large enough to be considered of infinite size. Calibration sources are constructed as large concrete pads, usually spiked with one of the three natural radioelements. A fourth, unspiked pad is also constructed [26]. The measurements on the pads show the response of the instrument to the three natural radioelements in each of the spectrometer energy windows. Portable gamma ray spectrometres are calibrated on pads of 3 metres horizontal dimensions. The calibration of an airborne radiometric system is done by making measurements on larger calibration pads and on a test strip. A test strip is a natural area with accurately known ground concentrations of the radioelements. Sensitivities of the spectrometer and altitude dependence of response are determined on the test strip. Calibration facilities and procedures are described by Lovborg [27], Grasty [28], [29] and IAEA [25 & 26].

Total count instruments can be calibrated using calibration pads. Point sources have been used but do not give an adequate calibration for field measurements.

Spectrometric measurements have been reported either in counts per unit time for the three energy windows or as concentrations of potassium, uranium and thorium. In some cases other reporting units have been used such as multiples of 'background' radioactivity. Total count measurements have been reported as counts per unit time, as $\mu R h^{-1}$, ppm equivalent uranium (ppm eU), unit of radioelement concentration (Ur) or as multiples of "background".

3.3 Geological Gamma Ray Surveys

Regional geological gamma ray surveys have most frequently been airborne surveys and sometimes carborne surveys. In exceptional cases ground survey methods have been used. The design of a particular regional survey depends on many factors; the area to be covered, available techniques and equipment, funds and personnel resources. Corrections for the influence of different effects must be applied to gamma ray data. These effects may include cosmic radiation, instrument background, altitude variations, Compton scattering, and source geometry. The effect of radon in the air has been estimated using upward looking detectors in airborne surveys.

Airborne surveys are usually flown on a regular parallel grid using flight line spacings from 0.1 to 10 km. In mountainous terrain contour flying is often used and sometimes irregularly spaced flight lines. Nominal terrain clearances vary from 30 to 150 metres. Navigation and flight path recovery commonly use a combination of visual techniques, electronic positioning and flight path cameras, either video or photographic. Methods for the various corrections noted above are discussed by Darnley [30], IAEA [24] and Grasty et al. [12].

Regional ground surveys include surveys that have covered large areas with carborne or hand held gamma ray measurements. In general these will have been carborne total count or gamma ray spectrometer surveys. Carborne surveys are restricted to existing roads and tracks and are affected by road materials and geometry.

For typical rocks or soils with an air dose rate of 10 - 30 pGy s⁻¹ (4 - 12 μR h⁻¹) total count measurements with hand held instruments will have an accuracy in the order of ± 5 pGy s⁻¹ (± 2 μR h⁻¹). For similar materials a spectrometer with a 3" X 3" NaI(Tl) detector will give standard deviations in the order of ± 0.1 % K, ± 0.3 ppm eU and ± 0.6 ppm eTh using a measuring time of 4 minutes.

The results of gamma ray surveys are presented as maps or profiles. Maps produced include contour maps, maps showing profiles along flight lines, grey scale maps and so on. Maps prepared for early surveys were usually hand drawn which implies interpretation by the cartographer.

3.4 Suitable Data

Many of the regional gamma ray surveys made throughout the world contain much valuable information on the natural radiation environment. Because the techniques and instruments used for these surveys were different, any compilations of these data will require careful analysis of the original specifications of the surveys. If a gamma ray survey is to be used to define the natural radiation environment the data collection and reduction techniques should result in values proportional to the air dose rate. No amount of subsequent analysis or interpretation can compensate for improper data

collection or reduction. Minimum requirements are full documentation and proper field procedures [30], [24], [12]. It is also important to check the accuracy of the geographical positioning of the data. Airborne surveys are particularly suitable for regional compilations because, typically, they cover large areas. Carborne and other regional ground surveys that cover at least several hundred square kilometres are also suitable.

With the exception of detailed surveys of small areas gamma ray surveys cover only a few percent of the area surveyed. In general it could be said that the objective of a gamma ray survey should be to provide data for all of the lithological units within the survey area. In airborne or carborne surveys the data are recorded continuously and thus the density of sampling along the measured line is high. Regional ground surveys consist of point measurements at densities such as 1 per 1 or 2 km².

For airborne gamma ray surveys the flight line spacing should be proportional to the final map scale. In the United States and Sweden a factor of 10⁻⁵ has been used successfully. For example, a map of scale 1:1 000 000 requires a line spacing of 10 km or less. Surveys with irregularly spaced flight lines should have a similar average sampling density.

Because the area measured by a carborne survey is much smaller than that of an airborne survey the sampling of the carborne survey should be more dense. The sampling density of a ground survey should similarly be more dense.

In addition to careful analysis of the technical quality and the parameters of a survey the decision to include the survey in a regional compilation should consider other factors that might affect efforts to back calibrate the survey.

Sometimes the shielding effects of an area may have changed since the survey was carried out. Examples are logging activities and the draining of swamps which may change the soil moisture. Another important factor is radioactive fall-out because the air dose rate due to fall-out will change with time. If the contribution of the fall-out to the total count measurement is less than 2.5 pGy s⁻¹ (approx. 1 μR h⁻¹ or 1 kBq/m² of ¹³⁷Cs) this effect can be neglected (see Figure 2.4).

4. STANDARDIZATION TECHNIQUES

Regional measurements of ground radioactivity for geological purposes were carried out by different methods, instruments, at different times and under different environmental conditions. Early measurements used mostly uncalibrated equipment and reported the data in units that are a relative measure of the radioactivity. The results of more recent gamma ray spectrometry surveys are reported as radioelement concentrations. Standardization procedures can unify disparate data and express them in air dose rate units (Gy s^{-1}). The general procedure to be used includes checking the original radiometric data and their levelling within the survey area and the conversion of the data to air dose rate directly or by means of recalibration (back calibration).

4.1 General Concept of Standardization

Contemporary field gamma ray spectrometry techniques enable us to determine the contents of the natural radioactive elements in surface rock materials. These radioactive elements are sources of ionizing radiation in the environment. Theory and experiments verify that surface radioactivity measurements can be expressed in terms of the air dose rate. If the original data can not be directly converted, procedures using standard geophysical field radiometric equipment can be applied to determine the necessary conversion factors.

4.1.1: General considerations

The materials and information required for these standardization procedures include the radioactivity map of the area, and the conversion constants for air dose rate. If the data cannot be directly converted to the air dose rate, back calibration procedures will be necessary. It is clear that any data to be included in a regional compilation must be of good quality. The radioactivity map should show either the data as concentrations of K, U, Th, corrected count rates in the K, U and Th energy windows, or the total gamma ray activity expressed in specific (e.g. $\mu\text{R h}^{-1}$) or relative units. The data should be in digital form. If not they must be digitized at some point. The map should be accompanied by a description of the techniques used, the methods used to make the corrections that have been applied to the data, and the methods used to make the map.

Regional radiometric surveys are carried out under varying climatic conditions and with a variety of equipment conditions. These varying conditions can cause levelling problems within a single survey as well as between different surveys. Some of the factors that cause these effects are airborne radon, soil moisture, and errors in background correction. Suitable procedures can often be used to eliminate these level differences.

A suitable instrument for the back calibration is a portable gamma ray spectrometer with gain stabilization and a NaI(Tl) scintillation detector that is at least 76 x 76 mm (3' x 3' inches) or 350 cm³ in volume. Calibration methods for portable gamma ray spectrometers have been described [24], [25]. Lovborg [27] gives a detailed discussion of the technical problems associated with instrument calibration based on theory and numerous experimental data gathered in an IAEA sponsored intercalibration project. Darnley [30] describes airborne gamma ray spectrometry, while Grasty [29] illustrates a practical approach to the establishment of a calibration facility. Recommendations for the construction and use of calibration facilities for field gamma ray spectrometers have been prepared by the IAEA [26].

Back calibration is based upon comparisons of the map data to ground measurements obtained with the carefully calibrated portable gamma ray spectrometer.

4.1.2: Conversion of radioelement concentrations to air dose rate

Potassium, uranium and thorium in rocks are sources of gamma radiation. Their effect in the air can be expressed in terms of the exposure rate or the absorbed dose rate in air. Conversion factors from radioelement concentrations in rocks and soils to ground level exposure rate have been estimated from photon transport calculations applied to infinite soil and air media [31], [32]. The numerical solution of this complex mathematical problem evaluates the effects of primary and scattered gamma rays in the ground and in the air which depend on transport equations and K, U, Th energy emission spectra. Lovborg [27] published conversion factors calculated from up-to-date data of the 1981 version of the Evaluated Nuclear Structure Data File [33]. The factors for converting natural radioelement concentration into radiation exposure rate are nearly identical for rocks and soils and are given in Table 4.1.

Table 4.1: Calculated factors for converting radioelement concentrations of an infinite homogeneous plane into absorbed dose rate in air or exposure rate at an altitude of 1 m above the soil plane [27].

Conversion to	1 % K	1 ppm eU	1 ppm eTh
Air dose rate (pGy s ⁻¹)	3.633	1.576	0.693
Exposure rate (μR h ⁻¹)	1.505	0.653	0.287

The values given in Table 4.1 were verified by experimental measurements of the exposure rate with a calibrated ionization chamber over various geological materials with known concentrations of the natural radioelements. Generally good agreement was achieved between

the experimental results and the calculated values [12]. The calculated air dose rate will be incorrect if the radiation source is not infinite because the downward backscattered radiation of an infinite plane contributes up to 13% to the air dose rate. If artificial radionuclides are present they will also contribute to the total gamma ray dose rate. Such contributions may have occurred in existing gamma ray survey data.

4.2 Levelling of Data Within a Survey Area

Raw radiometric data from airborne and ground surveys often reflect the measurement conditions on individual days as well as variations caused by such effects as gain drift and variable background radiation. If not corrected during the data processing, these effects can produce level differences in the radioactivity maps.

4.2.1: Factors causing level differences

Background radiation includes cosmic rays, internal radioactivity of the equipment and airborne radon. The background, determined over water, may differ from values measured at altitudes greater than 800 m because of differences in the amounts of airborne radon and cosmic rays. Also, the amounts of airborne radon over the sea or large lakes is generally less than the amounts over inland terrestrial areas. Contamination of the airplane, car or of the instrument itself can also change the background.

Table 4.2: Background values detected by an airborne gamma ray spectrometer with installed NaI(Tl) detector 29x102 mm, (4168 cm³). Atomic Energy Establishment, Egypt [34].

		Energy windows (MeV)			
		TC	K	U	Th
		0.36-2.84	1.34-1.59	1.68-2.32	2.42-2.84
Area	Altitude	Count rate			
	m	c/s	c/s	c/s	c/s
Lake Karon	60	91.7	7.0	6.6	2.2
The Mediterranean	60	66.3	6.3	5.8	1.8
Nile Delta	850	68.3	5.7	6.0	2.4

The accumulation of airborne radon under a temperature inversion layer causes a detectable variation of gamma rays emitted by radon disintegration products as a function of time. Maximum gamma radiation has been observed between four and nine A.M. [35]. Rainfall will cause a temporary increase in the measured radioactivity (Figure 4.1). However, daily and seasonal precipitation and the resulting higher soil

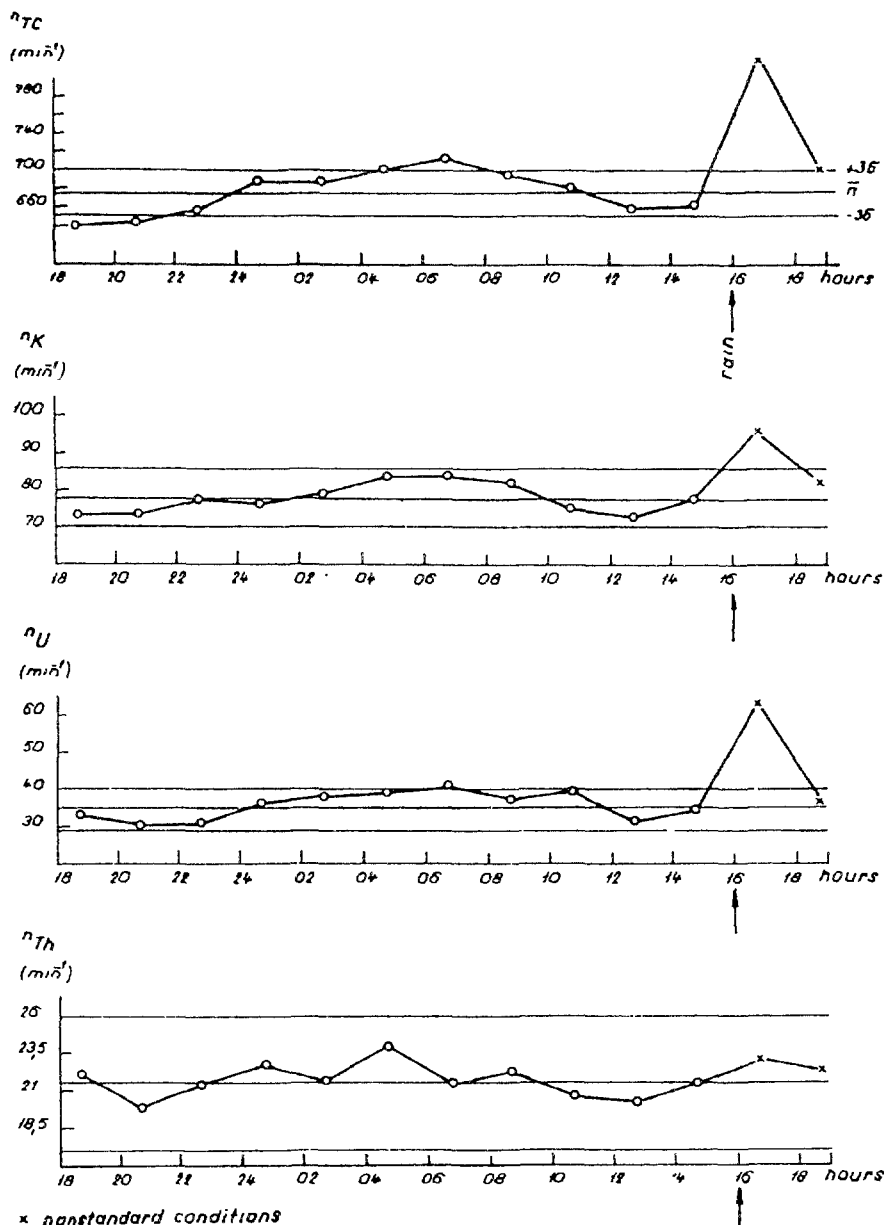


Figure 4.1: Diurnal change of gamma radiation and the effect of radon decay products accumulated by rain, after 16 hours. Measured count rates in the TC, K, U, and Th energy windows by portable gamma ray spectrometer over low activity sand. (After Matolin [35]).

moisture cause an increased attenuation of gamma rays. Snow cover has a similar attenuation effect, but the decreased mobility of radon in frozen or wet soil generates an increase in the surface gamma ray activity.

Instability of radiometric equipment, especially gain changes cause spectral energy shifts, which give rise to variations in the recorded count rates. Illustrative figures were presented by Lovborg [27]. The complex problem of short

and long term gamma emission instability of pads at calibration facilities affects the equipment calibration constants used for survey data processing.

The results of airborne measurements are significantly affected by attenuation of gamma rays in wood biomass (see Chapter 2.4). However, seasonal changes in vegetation influence the surface gamma radiation less than 3% [36], [37], [38], [39]. Summary descriptions and analyses of error factors in gamma ray spectrometry were presented by Filimonov [40] and IAEA [24].

4.2.2: A mathematical approach to levelling

Radiometric maps can be corrected for the effects of variable conditions using a mathematical approach to levelling. The procedures used to correct for inconsistencies in the levels of groups of profiles from different days are different from those used for single profiles. These procedures assume the use of digital data.

The determination of a profile group correction is based on the comparison of data from the survey lines to data from tie-lines. Because the radioactivity field has significant horizontal gradients, the location of the points of comparison must be accurate. Airborne surveys using electronic navigation methods may have positioning error in the order of 5 - 20 m whereas other methods of navigation have typically lower accuracies. Profile group corrections of airborne survey are determined by applying the general condition

$$\sum_{i=1}^N w_i [(n_i - d_{k,i}) e^{\mu(h-h_r)} - (n'_i - d_{k',i}) e^{\mu(h'-h_r)}]^2 = \min \quad (4.1)$$

where: n_i, n'_i are the values of the count rates in one of the spectrometer energy windows for the survey lines, and tie-lines respectively at their i th intersection. These data are assumed to have been corrected for background and stripping,

i is the index of the intersection point of the survey line and tie-line, $i = 1, 2 \dots N$ in the group of profiles,

k, k' are the indices of the group of survey lines and tie lines, respectively,

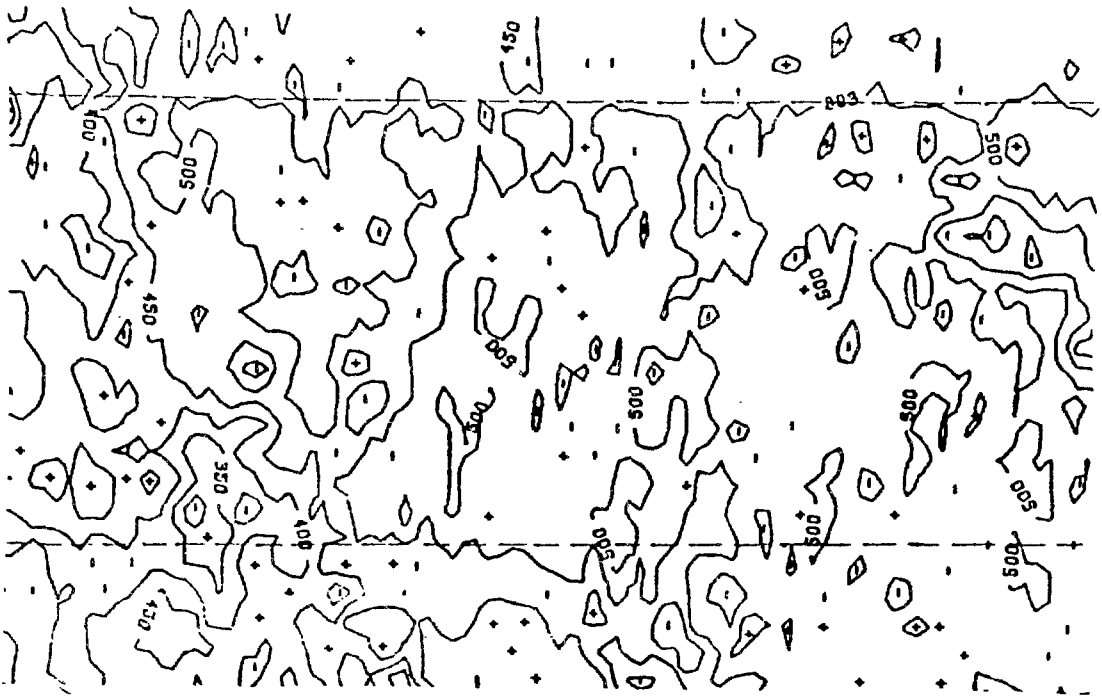
h, h_r are the altitude and reference altitude, respectively.

w_i is a weighting factor for the data at the i th intersection,

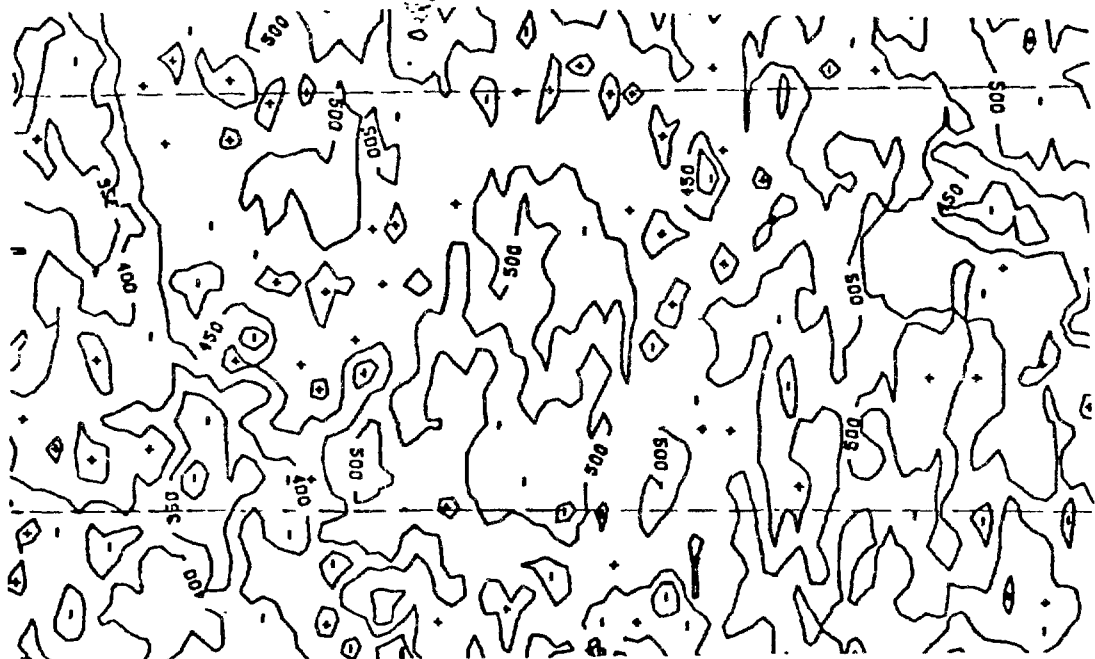
$d_{k,i}, d_{k',i}$ are the correction factors to be calculated.

The weighting factors are proportional to the count rates.

An example of group profile correction is shown in Figure 4.2. Figure 4.2a shows a contour map of an airborne survey prior to correction and Figure 4.2b shows the corrected data.



4.2a



4.2b

Figure 4.2: Contour maps of the TC energy window from an airborne survey. Bounds of daily operation are marked by dashed lines. 4.2a - compiled from original data. 4.2b - identical map levelled by profile group correction. (After Zabadal [47]).

Level shifts of individual survey lines can be corrected by applying the concept of general continuity of the radioactivity field. This concept is applicable for closely spaced flight lines. The distance between flight lines depends upon the geology. In terrain with highly variable geology the spacing might have to be as small as 200 m but could be as much as 1000 m or more in areas of homogenous geology. The average differences of observed values at neighbouring points of adjacent survey lines should be close to zero.

$$\sum_{i=1}^M w_{i,j} (n_{i,j+1} - n_{i,j} - f_j)^2 = \min \quad (4.2)$$

where: i is the point of observation on the profile,
 j is the profile number,
 n is the fully corrected count rate,
 $w_{i,j}$ is a weighting factor,
 f_j is the correction to be calculated.

An example of single profile correction is shown in Figure 4.3. Both of the above procedures are presented only to introduce the concepts. A detailed description is given in [47].

4.2.3: Levelling of data using image techniques

Image levelling techniques that utilize image processing equipment and procedures can make the task of back calibration easier. These techniques present the data in an image format on a display screen. The image format enables rapid recognition of levelling errors and estimation of correction factors. In some cases the use of this approach can eliminate the need to make ground spectrometer measurements. In particular, spectrometric data can frequently be standardized conveniently by this method because level differences are often a result of scaling differences caused by calibration errors, soil moisture, and/or snow cover. However, if the levelling differences require the addition of a constant followed by a scaling factor, the imaging method is not appropriate and the mathematical methods described in section 4.2.1 should be used. In the case of total count surveys, the latter type of correction is likely to be required.

Figure 4.4 shows grey-tone images of the spectral data from an aerial gamma ray survey. As indicated on the figure the images on the left show the data as delivered by the survey contractor. It is obvious that the data are not internally consistent. The images on the right side of Figure 4.4 show the data after levelling corrections have been applied. Each of the images shown in the figure was produced by first gridding the data with an appropriate grid interval



4.3a



4.3b

Figure 4.3: Map of an airborne gamma ray survey. 4.3a - map compiled from original data showing inconsistent values on one line. 4.3b - the same map after individual profile correction. (After Zabadal [47]).

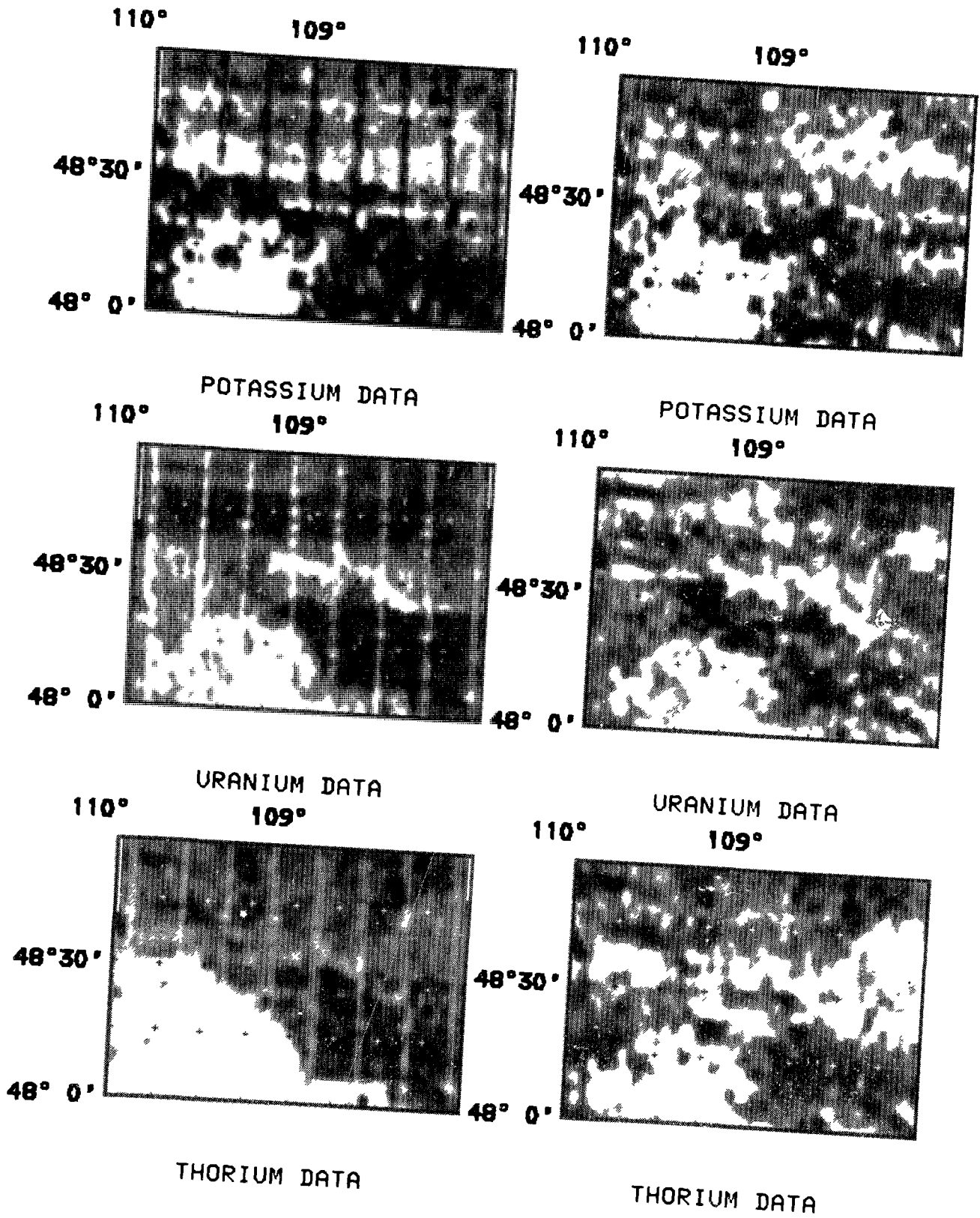


Figure 4.4: Spectral gamma ray data prior to any levelling corrections (left), and after levelling corrections (right).

and then converting the data from the original data units to integer values in the range from 1 to 254 as shown in Figure 4.5. The images have also been contrast-enhanced to emphasize the flight lines with levelling problems. Because the data for this data set have been corrected by the contractor for background radiation, altitude variations, and airborne ^{214}Bi , the assumption was made that the levelling problems are the result of calibration errors or soil moisture content. The corrections were, therefore, made by multiplying the data for individual flight lines by a constant. Each of the radioelements (K, eU, eTh) were corrected separately and independently. The criterion used to judge that the levelling problems were corrected was that the individual flight lines can no longer be seen in the images. Experience with this correction technique has shown that differences as small as 5 percent can be seen in the images. Because the precision of the original measurements is, in certain cases, probably no better than about 20 - 30 percent, these corrections might be viewed as cosmetic, although the image format actually increases the statistical validity of the data. The correction procedures frequently do not remove all linear trends parallel to the flight lines and, in addition, the gridding procedures sometimes produce linear trends perpendicular to the flight lines. Strike or trend filtering techniques may be appropriate to reduce those trends parallel and perpendicular to the flight lines. Such filters were applied to the corrected images for potassium and uranium.

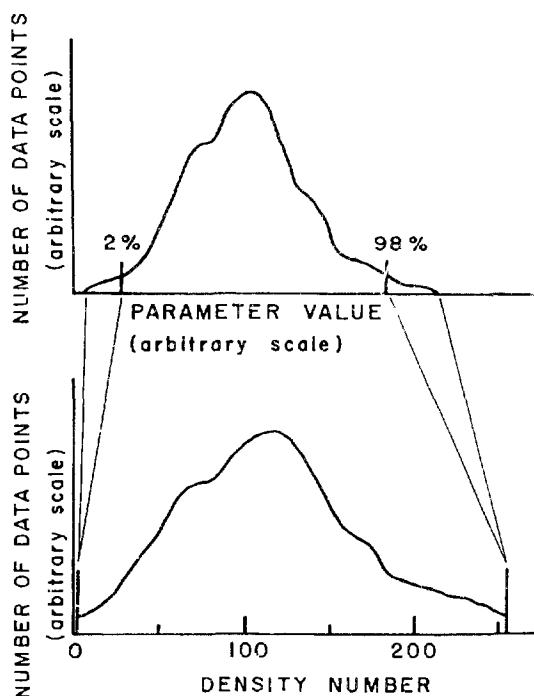


Figure 4.5: Conversion of original data units to integer values in the range 1 to 254.

4.3 Levelling of Data Between Survey Areas

The results of regional gamma ray surveys in adjoining or widely separated areas can differ in their levels. Compilation of large scale radiometric maps from the results of individual surveys stages of national programmes will require levelling of the data from the different areas. Levelling is based on regional airborne gamma ray tie-lines, and on comparisons of the statistical radiometric characteristics of ground and laboratory group assays with field data, or on systems similar to back calibration.

4.4 Procedure for Standardization of Spectrometer Surveys

The radioactivity of the ground has been measured by various types of equipment, both calibrated and uncalibrated. Procedures for standardization will differ for the individual cases.

4.4.1: Gamma ray spectrometer surveys with calibrated equipment

Airborne, carborne and portable gamma ray spectrometers should be calibrated using calibration pads at a calibration facility. The results of gamma ray spectrometer surveys with calibrated equipment are reported in concentrations of K, eU and eTh. If the radiation source corresponds to an infinite plane source, the constants given in Table 4.1 can be used to convert the data to air dose rate. The individual effects of contributions are then summed and used for the compilation of the radioactivity map. Assuming average errors in determining the radioelement concentrations, the air dose rate map can be contoured with a contour interval 4 - 5 pGy s⁻¹.

4.4.2: Gamma ray spectrometer surveys with uncalibrated equipment

The results of gamma ray spectrometer surveys with uncalibrated equipment can be reported as fully corrected count rates (c/s) for each energy window. The corrections applied for airborne gamma spectrometer data include background corrections, stripping corrections and altitude corrections. The corrections applied for portable gamma ray spectrometer include background corrections and stripping corrections. Conversion of these corrected count rates to air dose rate requires back calibration. Depending on the geological setting of the area of interest, back calibration can be carried out in two ways.

Large, radioactively homogeneous geological bodies of differing radioactivity in the area of realized regional radiometric survey can serve for back calibration. It is recommended that a minimum of five extensive radioactively different level areas be measured. Twenty or more stations are measured in each with a calibrated portable gamma ray spectrometer, with the detector positioned 1 m above the ground surface to accumulate a statistical group of data.

Using a NaI(Tl) detector volume of 350 cm³, a minimum measurement time of 4 minutes at each station is recommended. The concentrations of K, U, Th are determined and the mean value for each element, K, U, Th, is calculated for the individual areas. This will result in separate conversion equations for each of the radioelements. The conversion factors can then be calculated using a linear regression fit to the mean radioelement values for the individual areas versus average values of the fully corrected count rates in respective energy windows. The resulting regression equation can be considered acceptable if the errors between the calculated and measured concentration values are all less than 20%.

The regression equation should ideally intersect the origin of the axes of the variables. Any shift of the regression line in a vertical or horizontal direction indicates an incorrect background subtraction in the original survey or back calibration data. The regression is, none-the-less, valid.

Once acceptable regression equations have been calculated enabling conversion of fully corrected count rates to radioelement concentrations, the survey data can be converted to air dose rate.

The second method employs similar procedures using data along selected line segments. Five or more segments with minimum lengths of 1000 m should be selected. These segments should have relatively constant radioactivity and the average radioactivity of the different segments should be as different as possible. The ground data measured by a calibrated portable gamma ray spectrometer should be obtained at intervals of 25 m along the line segment with the detector 1 m above the ground. Using a NaI(Tl) detector volume of 350 cm³, a minimum measurement time of 4 minutes at each station is recommended. The average values of K, U, Th are then determined for each line segment. The calculation of the conversion factors uses a regression analysis as described above. The locations of the line segments must be accurate. In order to consider the line segments or areas as radioactively distinct, they should fulfil the following criterion:

$$n_1 - n_2 > 1.3 (s_1 + s_2) \quad (4.3)$$

where: n_1, n_2 are the mean values of the fully corrected count rates for two of the segments or areas,

s_1, s_2 are the standard deviations of the count rates for two of the segments or areas.

If the results of gamma ray spectrometer surveys with uncalibrated equipment are reported as raw window count rates, the back calibration requires more complex data processing. The raw window count rate n_i in the i^{th} window

is the sum of the background count rate b_i and three products of sensitivities s_{ij} of the instrument and concentrations C_j [24, 26].

$$n_i = b_i + \sum_j s_{ij}C_j \quad (4.4)$$

A minimum of four areas with different levels of radioactivity must be measured with a calibrated gamma ray spectrometer in the region of the regional survey and the mean concentrations C_K , C_U , C_{Th} determined for each area. Using the original raw count rates n_i and the calculated concentrations C_j from the four investigated areas, the background rate b_i and sensitivities s_{ij} for the original instrument can be determined from equation (4.4). Knowing b_i and s_{ij} , the original raw window count rates can be converted to radioelement concentrations which can also be used to evaluate the air dose rate (Table 4.1).

4.5 Procedures for Standardizing Total Count Surveys

The single measured values of total count surveys, which are dependent on instrument construction, make the task of defining the environmental radioactivity more difficult.

4.5.1: General problems related to the use of total count surveys

The response of total count instruments to the radiation of K, U and Th in the ground is generally not proportional to the contributions of these elements to the air dose rate. The response of a total count instrument depends on type of detector, its dimensions and on the energy discrimination threshold used. For this reason it is important to understand the limitations of using total count surveys to estimate the air dose rate.

The detection efficiency of detectors is dependent on their properties and the energy of the detected gamma rays. The detection efficiency of a scintillation counter decreases significantly with increasing gamma ray energy [25]. Total count instruments measure gamma rays of energies greater than the energy discrimination threshold, and the responses of total count instruments to K, U, Th radiation differ [24]. The relationship between the corrected count rate and concentrations C of K, U, Th in the ground is:

$$n_{TC} = a_K C_K + a_U C_U + a_{Th} C_{Th} \quad (4.5)$$

where: n_{TC} is the total count rate,

a_K , a_U , a_{Th} are the sensitivities of the instrument to K, U and Th radiation,

C_K , C_U , C_{Th} are the radioelements concentrations.

The sensitivities are expressed in terms of the count rate per unit concentration in an infinite plane source, and their values depend on the properties of the detector and the energy discrimination threshold. Total count instruments typically have energy discrimination thresholds in the range 30 - 150 keV. The total count energy threshold of gamma ray spectrometers is usually set in the range 400 - 800 keV.

Equation (4.5) can be written in the form:

$$n_{TC} = a_U \left[\frac{a_K}{a_U} C_K + C_U + \frac{a_{Th}}{a_U} C_{Th} \right] \quad (4.6)$$

where a_K/a_U is the uranium equivalent of potassium and a_{Th}/a_U is the uranium equivalent of thorium. The term uranium equivalent refers to the concentration of uranium that gives an identical count rate in a total count measurement as 1% K or 1 ppm Th. The ratio a_K/a_U changes significantly with detector volume and energy discrimination threshold, but a_{Th}/a_U is nearly constant.

Table 4.3: Typical uranium equivalents of potassium and thorium for field total count instruments. Data based on NaI(Tl) detector; infinite plane source; concentrations expressed as K %, U ppm, Th ppm [41].

NaI(Tl) volume cm ³	Energy discr. threshold keV	a_K/a_U	a_{Th}/a_U
29	30	1.57	0.37
82	50	1.56	0.38
348	400	2.37	0.41
348	500	2.67	0.41

Table 4.1 shows the air dose rate caused by unit concentration of K, U and Th. It is evident that the air dose rate from 2.30 ppm U and 0.44 ppm Th are equivalent to 1% K and 1 ppm Th. Table 4.3 shows the equivalent concentration with respect to instrument response. It follows from Tables 4.1 and 4.3 that the response in the total count energy window is nearly proportional to air dose rate for an instrument with an NaI(Tl) detector 76 x 76 mm (348 cm³) and an energy discrimination threshold in the range of 400 KeV [42]. For instruments with different technical parameters the measured count rates do not correspond linearly to air dose rate.

If total count instruments are calibrated over extensive U containing plane sources or over infinite rock plane source in which radioelements are expressed in uranium equivalent, the sensitivity a_U can be then expressed in c/s per ppm eU. Equivalent uranium concentrations can be determined by dividing the corrected count rates by the constant a_U . Equivalent uranium concentrations multiplied by the conversion constant 1.576 (Table 4.1) give air dose rate values, that are only correct for an instrument of technical parameters specified above. Response of other instruments to radiation of K, U and Th is not linearly proportional to air dose rates of K, U and Th and the results are determined with error increasing with K/U and Th/U ratios.

Figures 4.6 and 4.7 illustrate the magnitude of the relative error in the air dose rate determined by an arbitrary total count instrument calibrated over a uranium pad. The relative error is calculated as the ratio of the difference between the experimentally determined air dose rate and the true air dose rate to true air dose rate $(D_e - D_t)/D_t$.

An examination of the data in the figures shows the importance of size of detector and discrimination threshold. Instruments having values of $a_K/a_U = 2.30$ and $a_{Th}/a_U = 0.44$ determine the air dose rate correctly regardless of the K:U:Th ratios in the ground. For an instrument of less than ideal parameters, with increasing C_K/C_U ratio relative to similar increases in the C_{Th}/C_U ratio, error increases more rapidly for K than for Th .

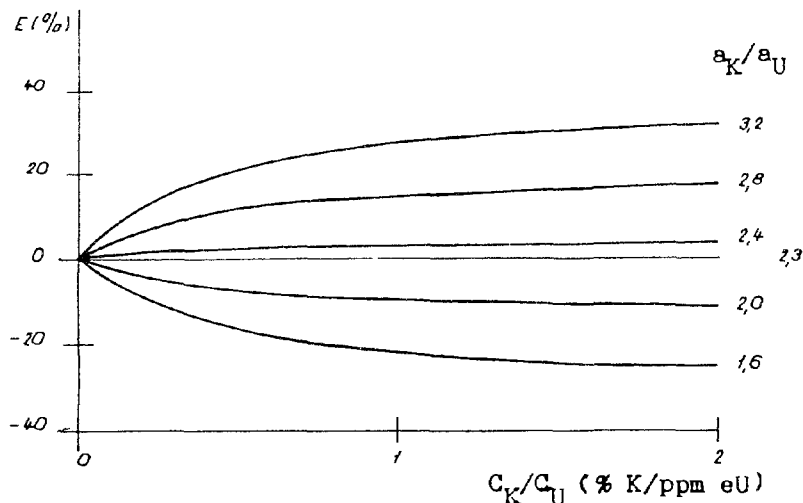


Figure 4.6: Dependence of the relative error $E(\%)$ of the determined air dose rate on the K/U ratio in rocks for a total count instrument calibrated over a U pad, and having uranium equivalent of potassium a_K/a_U .

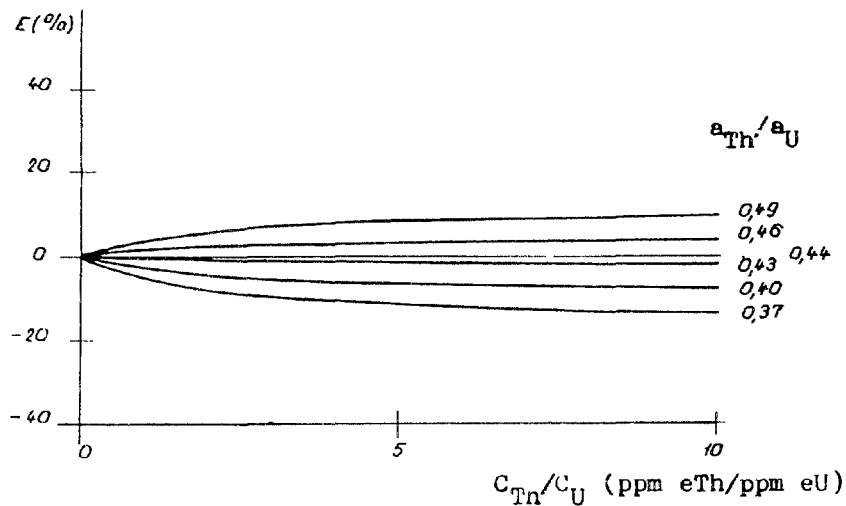


Figure 4.7: Dependence of the relative error $E(\%)$ of the determined air dose rate on the Th/U ratio in rocks for a total count instrument calibrated over a U pad and having uranium equivalent of thorium a_{Th}/a_U .

Total count instruments with a low discrimination threshold (30 - 50 keV, $a_K/a_U = 1.6$; $a_{Th}/a_U = 0.37$) underestimate the true air dose rate for $C_K/C_U = 2$ by about 25% and for $C_{Th}/C_U = 10$ by about 13% relatively. An instrument with a discrimination threshold of 400 keV estimates the air dose rate with an error less than 3% even for extreme K:U:Th ratios. An instrument with a discrimination threshold greater than 400 keV ($a_K/a_U > 2.3$; $a_{Th}/a_U > 0.44$) will overestimate the air dose rate by up to 25%. The curves of Figures 4.6 and 4.7 can be used to estimate the likely errors in the air dose rate if the energy discrimination is known.

Calibration procedures by means of a ^{226}Ra point source will result in an overestimation of air dose rates. An instrument with an energy discrimination threshold of 30 keV gives nearly twice the correct air dose rate [43]. For this reason, such calibration procedures are not recommended. If proper calibration facilities are not available a natural site that has been characterized by laboratory or field gamma ray spectrometer measurement can be used for calibration.

4.5.2: Total count surveys with calibrated equipment

The sensitivity of an instrument calibrated over extensive uranium enriched plane source or over infinite rock plane source is expressed in c/s per ppm eU and, consequently, the results of survey are reported as equivalent concentrations of U (ppm eU). The conversion of these data to air dose rate can be performed by means of the constant given in Table 4.1. If the air dose rate or exposure rate over the U calibration source is known, the results of the survey can be converted directly to air dose rate or exposure rate.

4.5.3: Total count surveys with uncalibrated equipment

Instruments that have not been calibrated over an infinite plane source are considered to be uncalibrated for the purposes of this manual. The results of surveys with uncalibrated total count instruments, reported in count rate (c/s), provide only a relative measure of the environmental gamma radiation. Conversion to air dose rate units requires back calibration. The back calibration procedures to be used are similar to those described in section 4.4.2. In the case of the total count back calibration procedure the portable spectrometer data are first converted to the air dose rate contributions from the three radioelements. These contributions are then summed to obtain the total estimated air dose rate. The total air dose rate versus the total count survey data are used to obtain a regression equation, which is used to convert the survey data to air dose rate. As before (see section 4.4.2) the resulting regression equation can be considered acceptable if the difference between the calculated and measured air dose rate values are all less than 20%. If the differences do exceed 20% then the back calibration data are inadequate. This means that either the survey data are unacceptable for inclusion in a regional compilation or additional back calibration data are required. Comparison of available relative results with air dose rates acquired by measurement with portable calibrated gamma ray spectrometer in the survey area determines conversion constants.

5. DATA PRESENTATION

The presentation of the data from gamma ray surveys is a subject of some importance. The process of preparing the data for presentation requires considerable effort and will depend on the use to which the presentation material will be put. Maps are a common form of data presentation for gamma ray surveys but the type and complexity of the map presentation will depend on the audience. Generally, technical workers using the maps will require a less polished but more complete depiction of the data, whereas maps prepared for public distribution will require a less detailed but more graphically forceful presentation.

5.1 Graphical Form

The data should be presented as contour maps using the units of pico grays per second (pGy s^{-1}) with a contour interval of 5 pGy s^{-1} (see section 4.5.1). If the maps are intended to be useful for geological applications, the contour interval might have to be smaller. In general, the data should be in digital form for greater ease of data handling.

Standard gridding and contouring practices should be followed. In particular, care should be taken to eliminate areas of invalid contours (e.g. over large lakes). A rule of thumb to determine when to delete the contours would be to do so only for areas of 1 square centimetre or larger at the final map scale.

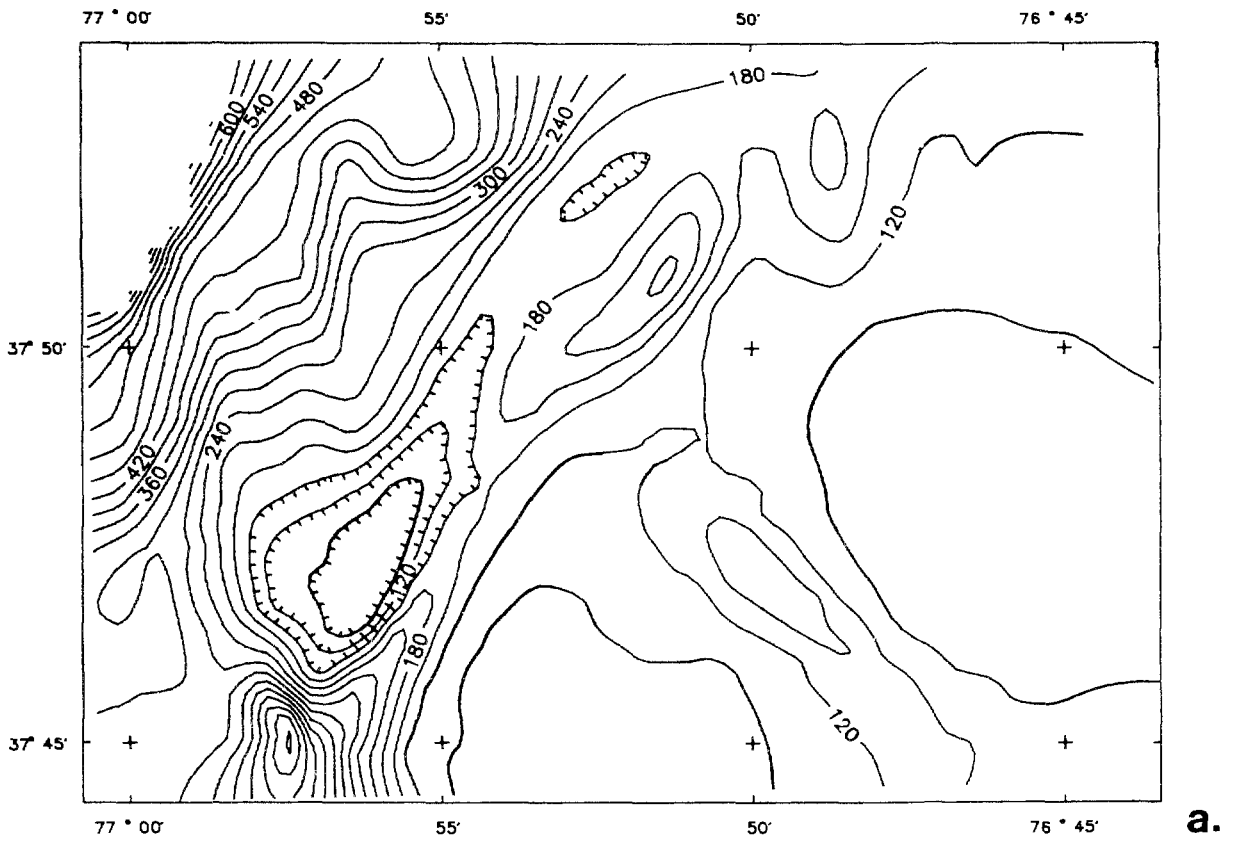
5.2 Map Compilation

The process of compiling a variety of surveys that have been standardized as described in Chapter 4, above, can be either manual (analog) or automatic (digital). In general, digital compilation is to be preferred over manual methods because the digital process will result in a data base that can be manipulated and augmented as new data become available. If, however, a large fraction of the available data are not already in digital form, the effort required to digitize the data may be considered excessive and preference given to manual compilation. The availability of suitable hardware and software for data processing and digitizing will also be factors in determining the preferred compilation method.

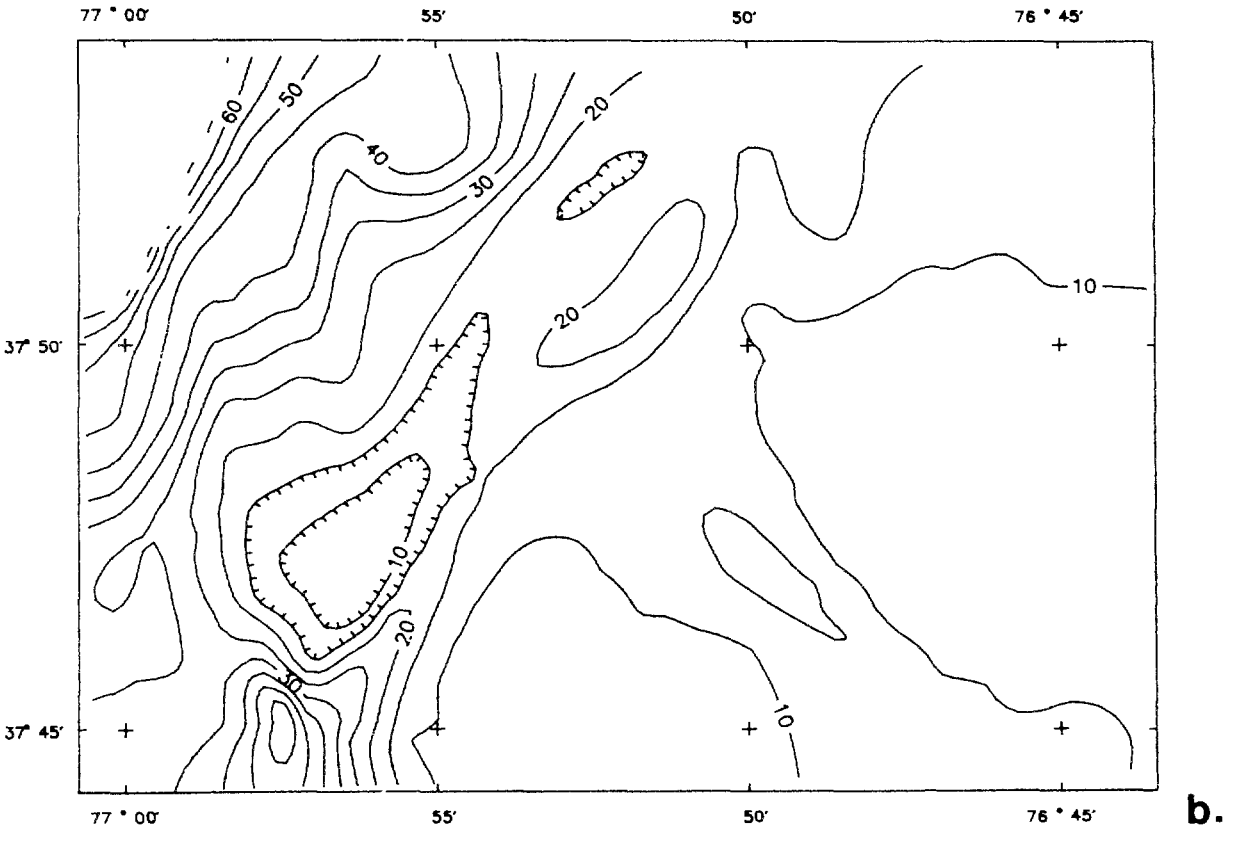
5.2.1: Manual compilation

The first step in a manual compilation procedure is to redraft an existing contour map using the conversion equation defined by the recalibration procedures described in Chapter 4. For example, if 50 c/s are equivalent to 5 pGy s⁻¹, the 50 c/s contour level would be redrafted and labelled as 5 pGy s⁻¹. In most cases, however, the existing contours on the contour maps will not coincide exactly with the contours needed for a 5 pGy s⁻¹ contour interval. In this case, the correct position of the contour line will have to be determined using linear interpolation between existing contours. Figures 5.1a and 5.1b show an example of a maps of exposure rate determined by linear interpolation.

After the map has been completely redrafted, it must be changed to the final map scale. The scale change can be done photographically or using any of a variety of projectors commonly used to change map scales (e.g. a Salzman projector). After the map is at the correct scale, it is physically placed in the correct location on the regional map. Ideally the recalibration process will eliminate all levelling differences between different surveys. In practice, level differences will still be present. However, if such differences exceed 20 percent, the back calibration should be considered suspect and should be examined for possible errors. Even if the level differences are small, the contour lines are unlikely to match either in areas of overlap or at join lines. In areas of overlap, a decision must be made regarding which survey is considered the more reliable and the contours from the other survey should be eliminated. At the join lines the contour lines will need to be redrafted to produce smooth contours. Figure 5.2 illustrates this procedure.



a.



b.

Figure 5.1: Maps showing the conversion by interpolation of the contours in counts per second (5.1a above) to contours in pGy s^{-1} (5.1b below).

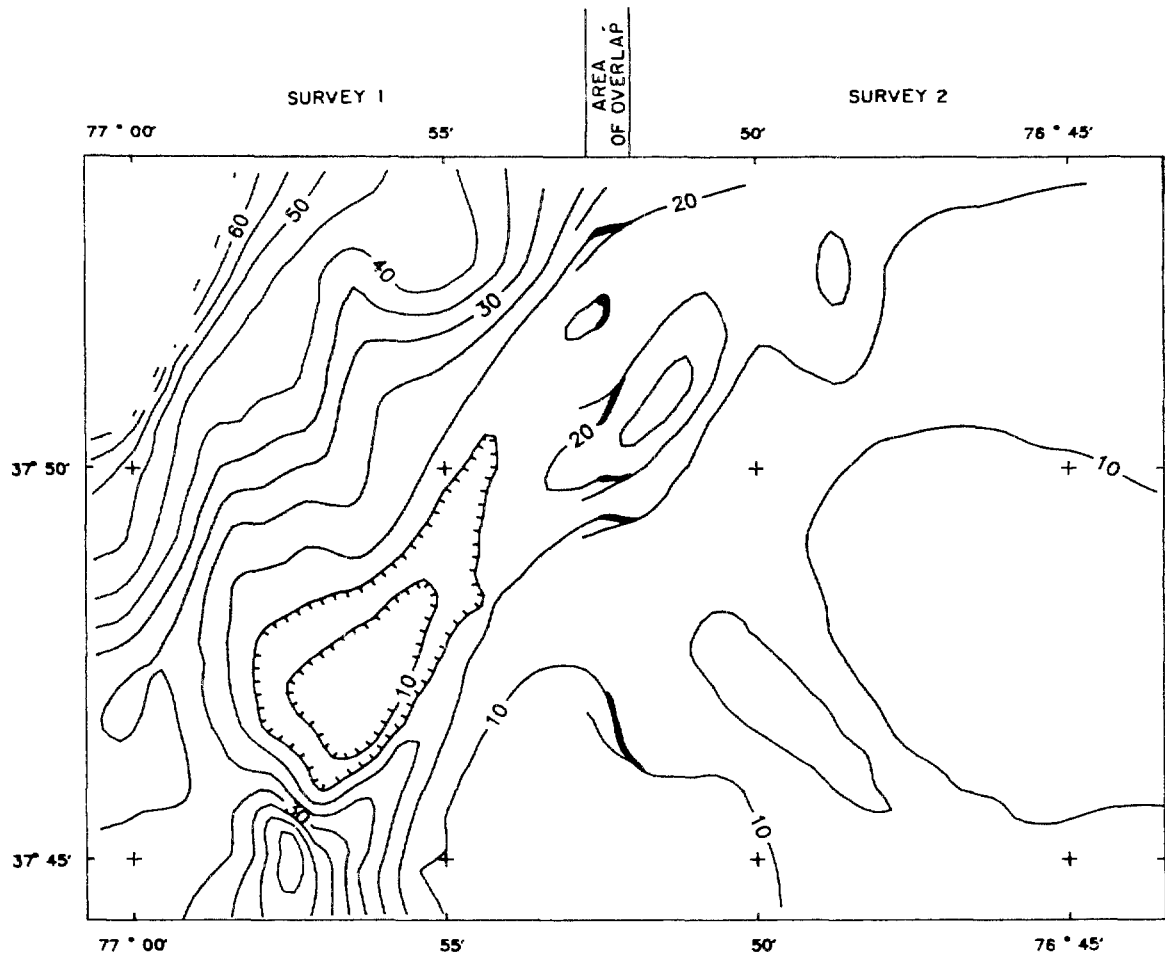


Figure 5.2: Adjustment of contours in the area of overlap between two different surveys.

5.2.2: Digital compilation

If the data are already in digital form, the regridding and compilation procedures are straight forward. Figure 5.3 illustrates the general procedure where the data would be gridded in overlapping blocks and the resulting grids inserted into the final grid. If the data are not in digital form, they will have to be digitized. If the original flight line locations are known, the data should be digitized only along the flight lines. Otherwise, a regular grid could be used or the actual contour lines could be digitized. If it is necessary to digitize maps, care must be taken to ensure that the digitized data accurately represent the original map. One way to verify the accuracy of the digitizing is to make a new map at the same scale and with the same contour intervals as the original map and compare them. Prior to digitizing, the maps should first be back calibrated and redrafted. In the case where spectral data are available, the element data should also be compiled into separate maps because they will be useful for geological applications. In all cases

any digital data should be carefully preserved in a digital data base.

6. INTERPRETATION AND USE OF THE MAPS

Geochemists have long recognized the significance of geochemical surveys to environmental studies. In many countries this awareness is now spreading to scientific policy makers. More importantly, scientific concern about the rate of global-change is beginning to attract media attention and is creating some popular pressure for government action. Recognising that most existing geochemical surveys were conducted for geological/mineral exploration purposes, there is now a need to maximise the environmental usefulness of existing data in order to provide baseline geochemical information of use in global change environmental, agricultural and health studies as well as geological research. The radioelement exploration data are one part of this material that can be of great value, put to proper use.

A statistical relationship between strong irradiation and health effects has been proved. The relation between low level radiation and its effects on the human organism is a subject of controversy. Organizations such as the ICRP, WHO, UNSCEAR, BEIR accept the assumption that the number of health effects, caused by radiation is proportional to the absorbed radiation dose [44]. Figure 6.1 shows (A) proved, and (B) assumed proportions of the probability of health effects to the absorbed dose equivalent in the human body. Natural environmental radiation also contributes to the overall irradiation of the human body.

Maps of the air dose rate can be used as a basis for calculation of the annual effective dose equivalent. Since conversion of air dose rate data to whole body absorbed dose rate is calculated by means of the conversion factor 0.7 [46] and the quality factor of gamma radiation is equal to 1, the annual effective dose equivalent caused by terrestrial gamma radiation is given by the relationship:

$$1 \text{ pGy s}^{-1} = 2.21 \cdot 10^{-2} \text{ mSv a}^{-1} \quad (6.1)$$

The ICRP has recommended 1 mSv a^{-1} as the limit on the annual effective dose equivalent from sources other than natural radiation. A recent ICRP report recommended the limitation of that component of the dose absorbed from the natural radiation environment when it can be reduced [22].

Standardized radioactivity maps denoted in units of air dose rate can be used for the assessment of environmental radioactivity and for the delineation of areas of greater radiation risk in a country. For most rocks and soils the contribution of natural terrestrial radioactivity to annual effective dose equivalent is less than 0.5 mSv a^{-1} but

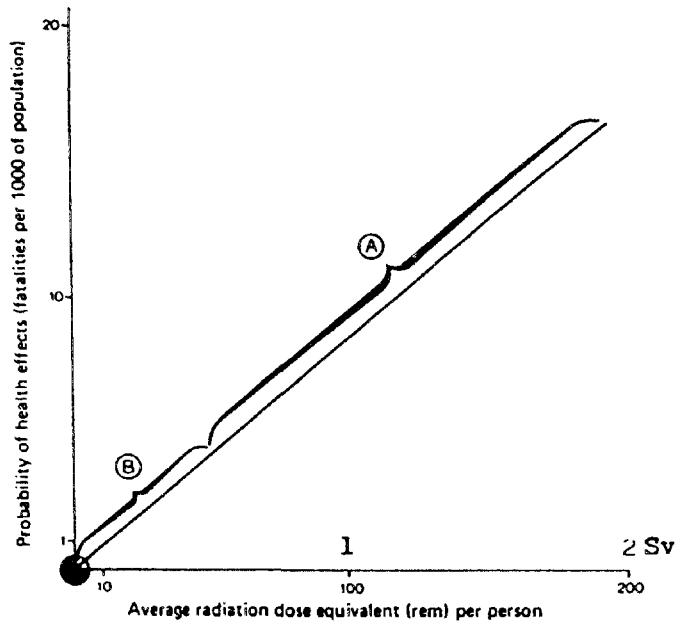


Figure 6.1(A): Simplified graph showing the health effects resulting from radiation. (After IAEA [44]).

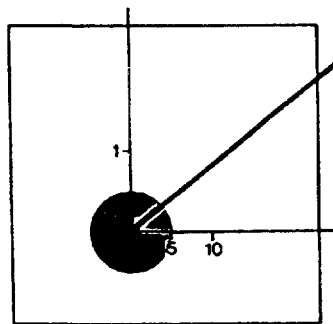


Figure 6.1(B): Portion of Figure 6.1(A), enlarged.

levels up to 2 mSv a^{-1} are frequent. In exceptional cases terrestrial radioactivity causes effective dose equivalents of 5 to 10 mSv a^{-1} . Examples of the evaluation of environmental radioactivity have been published in Canada and Sweden [12], [45]. Distinct regional radioactivity was determined in the Variscan and Alpine Systems in Czechoslovakia [48] with values of air dose rate of 19.4 and 13.9 pGy s^{-1} respectively with an average value of 17.0 pGy s^{-1} . Similar data on air dose rate have been published for 24 countries [46]. Examination of air dose rate maps along with regional and local gamma ray spectrometry maps showing uranium concentration, enables the recognition of areas of increased radiation and radon risks.

Maps of the natural radiation environment also serve as a basis for comparison in the event of a nuclear accident. Repeated measurements give information on the decrease of radiation to original levels with time following such an accident.

If the data are of a quality sufficient to permit the production of concentration maps of the individual radioelements, either directly, or after back calibration following the procedures outlined in this manual, their use in the fields of the earth sciences are much increased. With this in view the International Geological Correlation Programme (IGCP)/UNESCO Project 259, "International Geochemical Mapping" has recently been launched. The purpose of the project is to encourage and facilitate the compilation of an international series of systematic surficial geochemical maps by national/international organizations based on the most appropriate types of sample material. It is expected that the project will provide evidence of the extent to which different portions of the earth's crust are characterised by distinctive geochemical assemblages and patterns. In conjunction with other geological/geophysical evidence the data will assist in correlating areas separated through past plate tectonic displacements.

The maps will show abundance levels, delineate regional trends and geochemical provinces, and permit the recognition of large scale anomalous features. They will compliment existing international geological and geophysical map series, and will be published at scales suitable for direct comparison. The International Atomic Energy Agency has assumed special responsibility for the Radioelement Geochemical Mapping subprogramme.

Radioelement maps contain a wealth of information of use in mineral exploration for a number of commodities, including molybdenum, tungsten and gold. The potassium alteration that frequently accompanies certain types of copper mineralization is often clearly demarcate on potassium distribution maps obtained through airborne gamma ray spectrometer surveys. Geologists carrying out geological mapping have learned the value of combining the information contained on radioelement maps with the magnetic maps they have long used. As with other geochemical element distribution maps the radioelement maps when prepared on a regional, continental or global scale, frequently depict major earth scale structural and tectonic features not seen in any other way.

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