10C.

GAMMA RAY SPECTROMETRIC METHODS IN URANIUM EXPLORATION – APPLICATION AND INTERPRETATION

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Abstract

One of the most significant advances in uranium exploration in recent years has been the development of gamma ray spectrometric techniques. A brief review of the planning and stages of a uranium exploration program using gamma ray spectrometry, and disposition of costs is given as a background to the more technical considerations.

To obtain the fullest advantage of the use of a gamma ray spectrometer for uranium exploration the factors influencing gamma ray measurements must be understood. This paper reviews and discusses such factors as radioactive disequilibrium in the uranium decay series and its ramifications; geometry of the measurements; counting statistics and their effect on accuracy of results and required counting times; background radiation; and calibration of all types of gamma ray spectrometers, including information on calibration facilities.

Reviews and discussions of procedures, including examples of various types of results, presentation formats, and interpretations are given, for gamma ray spectrometric surveys in airborne, surface, underwater and borehole environments.

Résumé

Un des progrès les plus importants dans l'exploration de l'uranium des dernières années a été la mise au point de techniques de spectrométrie à rayons gamma. Une analyse succincte de la planification et des étapes d'un programme d'exploration de l'uranium utilisant la spectrométrie à rayons gamma, et la ventilation des côuts sont données comme point de départ pour une analyse des considérations techniques en cause.

Il faut bien comprendre les facteurs influant sur les mesures faites aux rayons gamma, afin d'obtenir les meilleurs résultats de l'emploi du spectromètre à rayons gamma pour l'exploration de l'uranium. Ce rapport analyse les facteurs comme le déséquilibre dans la famille radioactive de l'uranium et ses ramifications; la géométrie des mesures; les statistiques des calculs et leur effet sur la précision des résultats et sur les temps de calcul; la radiation de fond et l'étalonnage de tous les genres de spectromètres à rayons gamma, y compris l'information sur les installations d'étalonnage.

Le texte procède à l'analyse de marche à suivre, y compris des exemples de divers types de résultats, de modèles de présentation et des interprétations, pour les levés spectrométriques à rayons gamma effectués par voie d'air, en surface, sous l'eau et dans les sondages.

INTRODUCTION

Gamma ray spectrometric surveys of all types form only part of a complex series of interrelated investigations which are referred to as 'uranium exploration'. Before the application and interpretation of gamma ray spectrometry can be discussed, some of the stages of exploration should be considered in order to appreciate where each type of survey may be utilized most profitably.

Exploration Stages

The International Atomic Energy Agency in a report of a panel (IAEA, 1973a) summarized diagrammatically the various exploration methods and programs leading to the discovery of uranium. Stage I includes the selection of the region based on geologic considerations, and the collection of all available data such as regional geological maps, air photos, and topographic maps. Other considerations in the preliminary decision making of stage I are whether the surface exposure is large or small, and whether a multi-element exploration program requiring a geochemical survey is desired. If the surface exposure is large and uranium is the only target, a radiometric survey is warranted as a first step. Stage II, the progressive reduction of search areas, may be based on either a geochemical or radiometric approach. If the ground accessibility is poor or the area large, an airborne survey may be the best approach for this stage. The progressive reduction of search areas based on airborne radiometric surveys is shown in Figure 10C.1 (IAEA, 1973a). This figure indicates the input to the decision making process which results in the selection of an appropriate type of airborne radiometric survey. The method selected may vary from detailed total count (scintillometer) surveys flown over small areas with closely spaced flight lines, to large scale, reconnaissance, high-sensitivity gamma ray spectrometric surveys flown with widely spaced flight lines to provide regional coverage. The desired result of the survey is usually the identification of some form of anomaly or anomalous area which must then be further evaluated. This leads to the surface surveys and ground investigations of stage III. The ground investigations to evaluate these anomalous areas are summarized in Figure 10C.2 (after IAEA, 1973a). Again depending on the size of the area and ease of access, the appropriate type of vehicle-borne gamma ray surveys or foot traverses may be chosen. The final stage of evaluation includes sampling, trenching, drilling, and borehole gamma ray logging.

Other such "stages" in the exploration for minerals of various types have been proposed (e.g. Holmes, 1978), and they all vary in detail. However, the various stages mentioned above relate specifically to uranium exploration. The application and interpretation of the various types of gamma ray surveys (both total count and spectrometric) are interrelated. For example a discussion of the problem of 'geometry' with respect to surface gamma ray spectrometric measurements is also instructive for those interested in

Table 10C.1

Cost comparisons for various radiometric exploration surveys, on both a distance and time basis. Actual costs have increased through inflation but the data are still a good indication of relative costs. (Data from IAEA, 1973b)

	Instrument Cost and Cost Per Unit Distance And Area Covered			Distance or Area Covered Per Unit Time		Total Cost of an Average Minimum Program	Effective Coverage of Area: Comments
		Normal Low	Normal High	Normal Low	Normal High		
Ground surveys by portable GM and scintillation counters	Instrument	GM: $200 Scint: $355	GM: $600 Scint: $1400	—	—	$3000 for instruments plus labour and transportation. Minimum program: 10-20/km^2	100 gm-cm rock and soil. 1-5 m each side of traverse line.
	km	$5/km	$10/km	5 km/d	10 km/d		
	km^2	$50/km^2	$400/km^2	0.25 km^2/d	1 km^2/d		
Gross-count (total-count) carborne surveys	Instrument	$4000	$8000	—	—	$10 000 for instruments. Minimum program: 3000-5000 km or 500-1000 km^2	100 gm-cm rock and soil. 5-10 m each side of traverse line.
	km	$0.50/km	$3.00/km	50 km/d	300 km/d		
	km^2	$5.00/km^2	$30.00/km^2	5 km^2/d	30 km^2/d		
Gross-count (total-count) airborne surveys	Instrument	$12 000	$60 000	—	—	$50 000	150-m-wide belt.
	km	$3.00/km	$6.00/km	600 km/d	1200 km/d		
Portable and carborne gamma-ray spectrometer surveys	Instrument	$3000	$15 000	—	—	$8000 for instruments and one month operation	5-10 m each side of station.
	Point Stations	$3.00/station	$6.00/station	10 min/station	20 min/station		
Airborne gamma-ray spectrometer surveys	Instrument	$30 000	$400 000	—	—	$200 000	150-m-wide belt.
	km	$7.50/km	$25.00/km	600 km/d	1200 km/d		
Radon measurement surveys in soil and sub-soil	Instrument	$1500	$6000	—	—	$3000 for equipment $300-$350/km^2	1 m diameter-often less in clay or wet soil. Upward diffusion of radon in soil probably limited to 5-10 m.
	Samples	$1.00/sample	$15.00/sample	10-20 samples/d	100-300 samples/d		
Exploration drilling (including logging)							Depth and close or wide coverage of areas depending on hole spacing.
(a) Rotary	Metres	$1.50/m	$6.00/m	150 m/d	300 m/d	$50 000	
(b) Diamond drill (8-h shift)	Metres	$15.00/m	$60.00/m	7.5 m/d	25 m/d	$100 000	

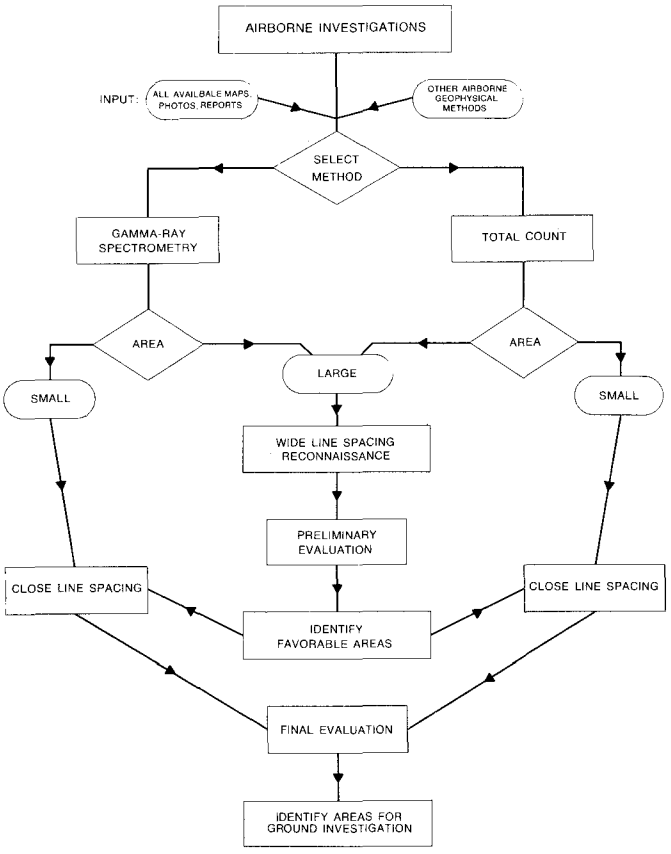


Figure 10C.1. *The selection of an airborne radiometric survey for a uranium exploration program. This leads to identification of anomalous areas to be followed up by detailed investigation (after IAEA, 1973a).*

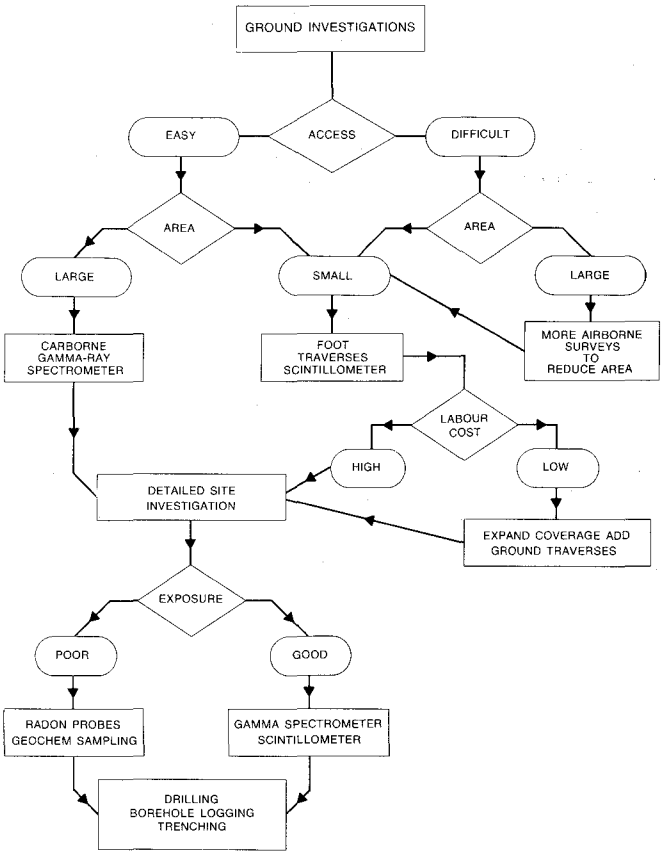


Figure 10C.2. *The selection of a radiometric ground follow-up technique for detailed investigation of anomalous areas (after IAEA, 1973a).*

either airborne or subsurface gamma ray spectrometry. The following is intended to tie together most of the present state-of-the-art information regarding the application and interpretation of gamma ray spectrometric methods in uranium exploration.

Exploration Costs

One additional consideration in the application of any of these methods is cost. The ideal sequence of radiometric exploration techniques may prove to be very costly, and a compromise must be reached in order to balance the size of the area to be searched against the thoroughness of the search. Since costs fluctuate widely from area to area, and with time, it is impossible to associate concrete cost figures with any given method. A useful compromise is the data presented in Table 10C.1, modified after a table given by the IAEA (1973b). The figures refer to average costs in 1972, primarily in North America. However inflation has increased these figures by about 75 per cent. It is the relative costs that are useful here, allowing cost per unit distance (or area) covered, and distance (or area) covered per unit time to be compared, for the various techniques. Low and high values are presented to account for variations in location and other conditions. Costs for radon measurements in soil are included because such surveys are also radiometric. A good breakdown of uranium exploration costs for several different areas has been given by Barnes (1972). His examples of the distribution of uranium exploration expenditures demonstrate some of the modifying factors and also indicate the percentage of the total exploration budget taken up by geophysics and geochemistry. This percentage increases as exploration moves to more remote areas with poor accessibility.

Prologue

The foregoing brief description of costs and stages in a uranium exploration program provides the background necessary to determine the sequence of different types of radiometric surveys for a successful search. The following five sections cover the application and interpretation of gamma ray spectrometric methods.

The common constraints and parameters for each technique are discussed in the next section. These include consideration of radioactive disequilibrium, geometry of the measurements, counting statistics, background, calibration and the parameters affecting calibration, and a description of existing calibration facilities.

The last four sections are specifically directed at reviews of the application and interpretation of: 1) airborne gamma ray spectrometric surveys; 2) surface gamma ray spectrometric surveys including portable (man carried) spectrometric surveys, carborne surveys, and snowmobile surveys; 3) underwater gamma ray spectrometric surveys, and finally 4) borehole gamma ray spectrometric logging. In these last four sections those problems which are unique to the survey mode, vehicle, environment or instrument of each type of gamma ray spectrometric survey are reviewed. This method of organization of the material should present the

reader with a relatively efficient means of obtaining an overview of the state of the art in the application and interpretation of any given gamma ray spectrometric survey method for uranium exploration.

FACTORS INFLUENCING GAMMA RAY SPECTROMETRIC MEASUREMENTS IN URANIUM EXPLORATION

Introduction

It is difficult to make meaningful gamma ray spectrometric measurements, much less interpret them, without a thorough understanding of the factors which affect the measurements. Many of these influencing factors have been investigated in detail whereas others require additional evaluation. The meaning of 'radioactive equilibrium' and its importance as a basic assumption of gamma ray spectrometry will be described first. This is followed by discussion of the subject of geometry of the measurements; the effective sample volume; counting statistics; dead time and sum peaks; and background radiation. Calibration of gamma ray spectrometric equipment is described in detail including a review of the "why, how, when, and where" of calibration. References to the available literature regarding the design and construction of calibration facilities are included.

Radioactive Equilibrium

Radioactive equilibrium or disequilibrium is an important consideration in all gamma ray spectrometric measurements. Gamma ray spectrometry can be used to determine the concentrations of uranium, thorium, and potassium in a rock because gamma rays of specific energies are associated with each radioelement. By looking at peaks in the energy spectrum of gamma rays being emitted by the source, the radioelement content of the source can be inferred. The method involves the counting of gamma ray photons with specified energies, most conveniently those emitted by daughter products, bismuth-214 in the ^{238}U decay series and thallium-208 in the ^{232}Th decay series (see Figure 10C.3). The gamma ray count rate can then be related to the amount of parent, by assuming there is a direct relation between the amount of daughter and parent. This assumption is valid when the radioactive decay series is in a state of secular equilibrium.

A radioactive decay series such as that of ^{238}U is said to be in a state of secular equilibrium when the number of atoms of each daughter being produced in the series is equal to the number of atoms of that daughter being lost by radioactive decay.

The rate of loss by decay is proportional to the amount of radioelement present, for example:

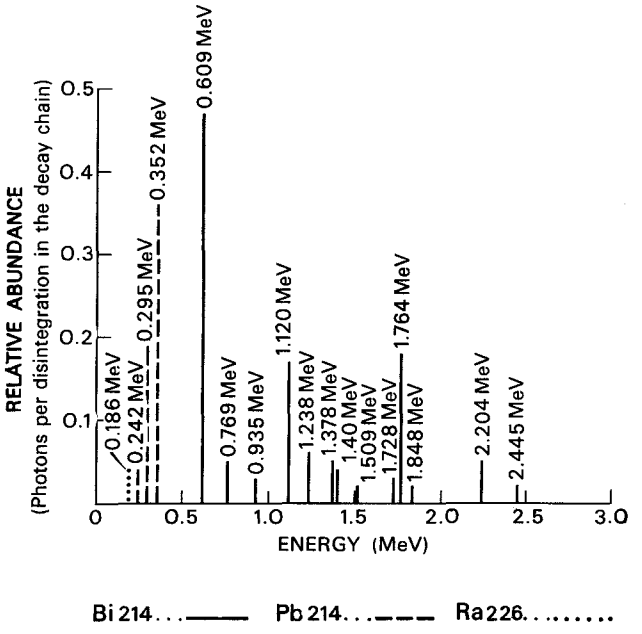
$$\frac{dN_1}{dt} = -\lambda_1 N_1 \qquad (1)$$

where N_1 = the amount of element 1 and λ_1 = the decay constant for the element 1.

In a radioactive decay series, N_1, is decaying into N_2 at the above rate while at the same time N_2 is decaying with the decay constant λ_2 into N_3 and so on. If the parent has a relatively long half life, after a long period of time the amount of any given daughter becomes constant. The rate of production from its parent is equal to its rate of decay. The series is then in a state of secular equilibrium.

For a radioactive decay series, secular equilibrium implies that

$$\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 = \ldots\ldots\ldots\ldots \lambda_n N_n \qquad (2)$$



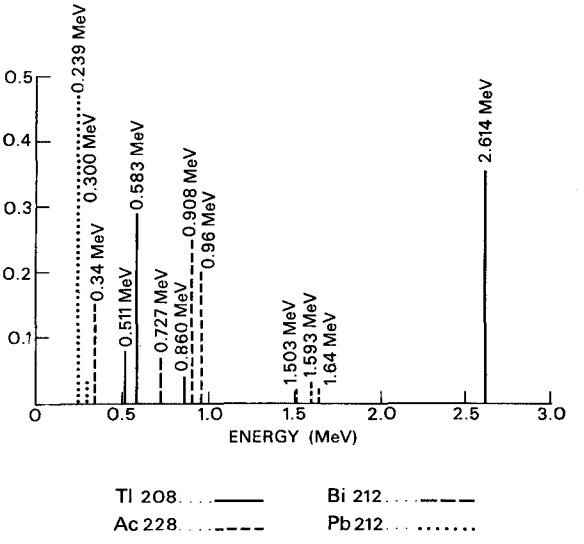


Figure 10C.3. *Theoretical energy spectrum of principal gamma rays emitted by the ^{238}U decay series (top) and by the ^{232}Th decay series (bottom).*

When this condition is obtained it is possible to determine the amount of the parent of the decay series by measuring the radioactivity from any daughter element.

The question then is whether the assumption of secular equilibrium, required for analysis by gamma ray spectrometric techniques, is valid for the geologic material being analyzed for its uranium content.

If one or more of the daughter products is being lost by any process other than radioactive decay, or if the parent was not deposited too long ago, equation (2) is not satisfied. Since each daughter product is an element with its own characteristic physical and chemical properties it may behave differently within a given environment. For example, in

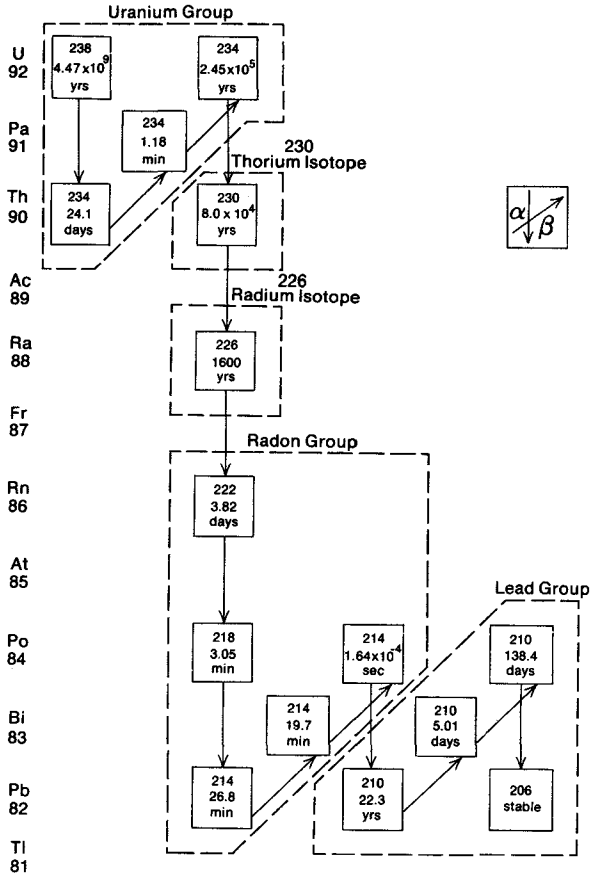


Figure 10C.4. *Classification of natural radioactivity of the ^{238}U decay series into groups of isotopes, with respect to their state of radioactive equilibrium (after Rosholt, 1959).*

the ^{238}U decay system there is a gas, radon-222, with a 3.85 day half life. The solubilities of radium, uranium and thorium differ, and preferential leaching of elements may occur. One of the most complete references on this subject is by Rosholt (1959) who subdivided the uranium decay series into five separate groups, as shown in Figure 10C.4. The elements within each group tend to remain in equilibrium with the parent of the group, although the parent of the group may not itself be in equilibrium with the parent of the decay series, ^{238}U.

How long does it take for secular equilibrium to become established? This is dependent on the half life of the longest-lived daughter in the decay chain below the parent. For example if uranium in solution moves into a chemically reducing environment such as a swamp and accumulates in substantial amounts over a short time, it will be relatively undetectable by gamma ray counting for considerable time. The daughter products must be given time to build up into their equilibrium proportions. If it is assumed (and it reasonably can be) that U isotopes travel in approximately equilibrium proportions then the length of time is controlled by the ^{230}Th with a half life of 80 000 years. The daughters below ^{230}Th have shorter half lives, and will remain in equilibrium with the ^{230}Th as it builds up from decay of the ^{234}U. Fifty per cent of the equilibrium amount of ^{230}Th will be attained in 80 000 years. Another half life will contribute 1/4 of the equilibrium amount, making a total of 75 per cent. A third half life contributes 1/8 for a total of 87.5 per cent and so on. This is illustrated in Figure 10C.5.

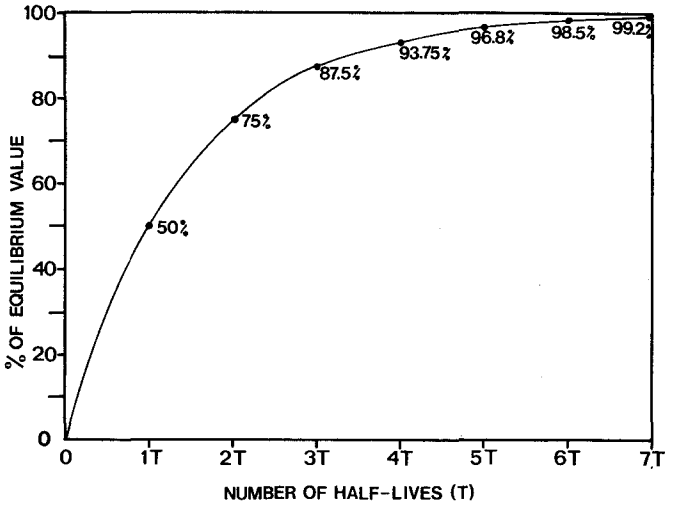


Figure 10C.5. *Length of time (in half-lives; T) taken by a radioactive isotope to reach its radioactive equilibrium value with its parent.*

It can be seen from this figure that after seven half lives (about 560 000 years in this case) the daughter products will reach over 99 per cent of the equilibrium value. For most practical purposes gamma ray spectrometry can be used to determine the amount of parent ^{238}U by counting 1.76 MeV gamma rays from the daughter ^{214}Bi after about 300 000 years (four half lives). ^{238}U itself does not emit gamma rays and so cannot be detected directly. ^{214}Bi is usually chosen because some of its gamma rays are of high energy, and have less interference from gamma rays of similar energies than other daughter isotopes. High resolution solid state detectors make it possible to separate and measure gamma ray peaks which are indistinguishable using sodium iodide or other scintillators. In this way daughter isotopes higher in the decay series can be utilized (see e.g. Tanner et al., 1977a).

Another example of the need to know the length of time to reach equilibrium is the case of rock samples which are crushed for analysis by laboratory gamma ray spectrometry. The crushing operation releases radon and the sample must be placed in a sealed container and allowed to return to equilibrium. In this case it is the radon group as shown in Figure 10C.4 which is out of equilibrium with the rest of the decay series. The ^{210}Pb (half life = 22 years) below the radon group will not be affected by the missing radon if only a short time elapses before the sample is sealed. Again, in about seven half lives of the longest lived member of the radon group (3.85 days; ^{222}Rn) equilibrium will be re-established, i.e. in less than 28 days. In practice it is highly unlikely that all the radon in the sample was lost during crushing. Thus equilibrium could be established in 5 or 6 half lives, or even less. One method to determine this is to analyze the sample, wait a week or so, and re-analyze the sample. If the gamma ray spectrometric analysis is higher the second time, equilibrium was not established at the time of the first analysis. In fact with appropriate calculations, from two such analyses, the final analysis at 100 per cent equilibrium could be computed, without actually waiting for the full 28 days. These calculations were described in detail by Scott and Dodd (1960).

The thorium decay series can generally be assumed to be in radioactive equilibrium. The longest lived daughter in the thorium series is ^{228}Ra with a half life of 6.7 years. Seven half lives, totaling less than 50 years, is a geologic

'instant', and any redistribution of thorium would be followed by a relatively rapid re-establishment of secular equilibrium. Thus in practically all geological samples the amount of parent ^{232}Th can be computed by measuring the 2.62 MeV gamma ray activity of the daughter ^{208}Tl.

In conventional gamma ray spectrometry, the actual elements being measured are ^{214}Bi and ^{208}Tl. If results are expressed in terms of count rates, then it is sometimes the practice to label them as the ^{214}Bi and ^{208}Tl cps. This latter terminology has been used in radiometric results of the U.S. NURE program. However it is preferable that the results are expressed in terms of equivalent uranium and equivalent thorium concentrations, respectively (IAEA, 1976). For this reason determinations of U and Th by gamma ray spectrometry are denoted by a prefixed 'e' (e.g. eU, eTh, and the U/Th ratio becomes the eU/eTh ratio).

Radioactive disequilibrium is accepted as the general case in roll front or sandstone-type uranium deposits. The reason is that uranium is mobile within the sandstone and daughter product formation lags behind. This leads to a distribution of radioelements wherein the daughter products (e.g. ^{214}Bi) are left behind, creating a daughter-excess or parent-deficiency state, with strong gamma ray activity, while at some nearby location there is a (relatively) weakly radioactive uraniferous zone with a daughter-deficiency. For most other rocks, not a great deal is known about the state of radioactive equilibrium in general, although studies of specific areas have been done (e.g. Richardson, 1964). Disequilibrium investigations of the Elliot Lake uranium mining area by Ostrihansky (1976) showed that disequilibrium can occur on a small scale along joints or fractures. Killeen and Carmichael (1976) pointed out that the problem of radioactive disequilibrium is minimized by large sample volumes. Whereas a hand specimen taken from an outcrop might show radioactive disequilibrium, an in situ assay by portable gamma ray spectrometer on the same outcrop comprises such a large sample it may be effectively in equilibrium. i.e. the parents and daughters may have moved apart on the scale of a hand specimen, but not on the scale of a cubic metre of rock. Similarly both parent and daughter nuclides, even if separated on a small scale, could be included in the large surface area "seen" by an airborne gamma ray spectrometer making it more likely that the equilibrium assumption is valid.

Geometry of the Radiometric Measurement

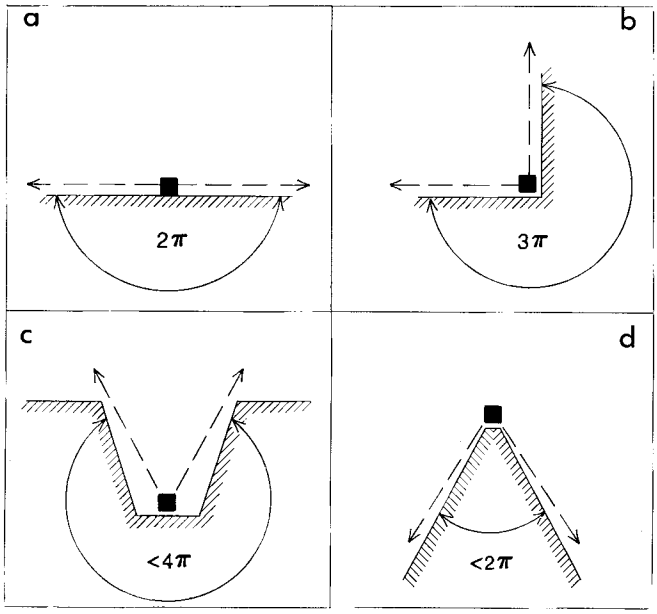
Since the amount of radiation which can be detected is related to the size and shape of the radiometric source as well as its intensity, the so-called "geometry" must be taken into consideration. Generally the angular measurement or solid angle which the source subtends at the detector is used as a reference, where 4π steradians is equivalent to complete enclosure of the detector by the source. For example, in a laboratory the radiation may be collimated by lead bricks or other absorbers such that the source only subtends an angle of a few degrees at the detector. A detector placed above an 'infinite' planar source, would be an example of 2π geometry. Some considerations of geometry of measurements were discussed by Gregory and Horwood (1961, 1963) with respect to laboratory measurements.

The calibration of any gamma ray spectrometer is for a specific geometry. For this reason it is important to know the geometry of the measurements. A hand specimen of 1 per cent U_3O_8 ore will produce a much lower count rate than a rock outcrop averaging 1 per cent U_3O_8, even if the detector is located at the same distance away from the source. Therefore, to make some sense out of recorded count rates, the geometry of the measurement must be noted. A few examples are given below to illustrate situations in which the geometry of a measurement can change to produce a false anomaly, or to mask a real anomaly.

Surface Measurements — 2π Geometry

Generally radiometric measurements made above the surface of the earth by either hand-held portable gamma ray detectors, vehicle-mounted detectors, or airborne detectors are considered to be measurements in a 2π geometry. The instruments should be calibrated on flat calibration sources of effectively infinite diameter, such as the concrete pads discussed in the section on calibration facilities. A measurement made in a trench or near a cliff effectively changes the geometry such that the calibration factors are invalid. A correction factor may be applied if the geometry is measurable, however this is most often not the case.

Consider the portable gamma ray spectrometer field measurements made with the geometry shown in Figure 10C.6a. Assuming the spectrometer was calibrated in 2π geometry, the results will be valid and an in situ assay of the surface can be calculated from the measured count rates. In Figure 10C.6b, the detector is located near a cliff face of the same material. This 3π geometry would produce a count rate 50 per cent higher than the 2π geometry because of the additional radiation "seen" by the detector. Doig (1968) reported measuring the expected 50 per cent increase in count rate in moving the detector from a 2π (flat) to 3π (cliff) geometry. Wormold and Clayton (1976) have carried out an extensive study of the effects of geometry on measurements by a portable gamma ray spectrometer, with a view to applying corrections for measurable geometries differing from the calibration geometry. One such situation occurs when making measurements along the benches of an open-pit mine. Here the geometry is fairly well known. A worse case is shown in Figure 10C.6c where the detector is placed in a trench or gully and the geometry is approaching 4π. The geometry shown in Figure 10C.6b or c can occur during a carborne survey, if the vehicle passes through a road cut. Figure 10C.6d shows a fourth geometrical configuration of less than 2π steradians such as that found in measurements



a) 2π geometry *c) approximately 4π geometry*
b) 3π geometry *d) less than 2π geometry*

Figure 10C.6. *Four different source-detector geometries encountered in surface gamma ray spectrometric measurements in the field.*

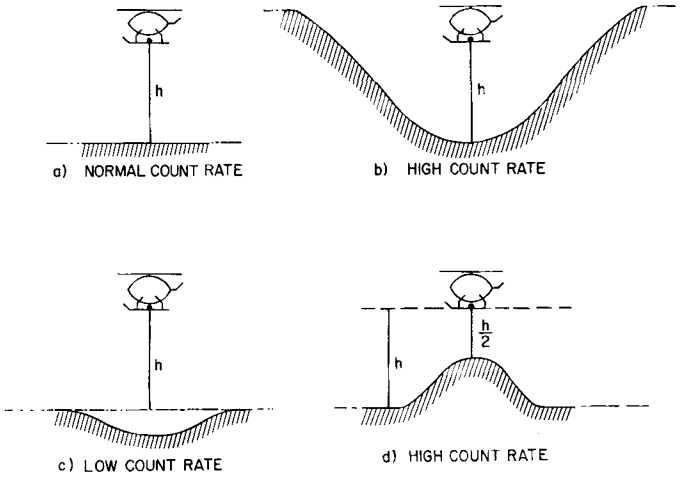


Figure 10C.7. *The effect of source geometry and height upon count-rate for airborne gamma ray spectrometric surveys (after Grasty, 1976a). Note how a topographic depression can cause either a high count rate as in (b) or a low count rate as in (c), depending on whether the source-detector geometry has effectively changed.*

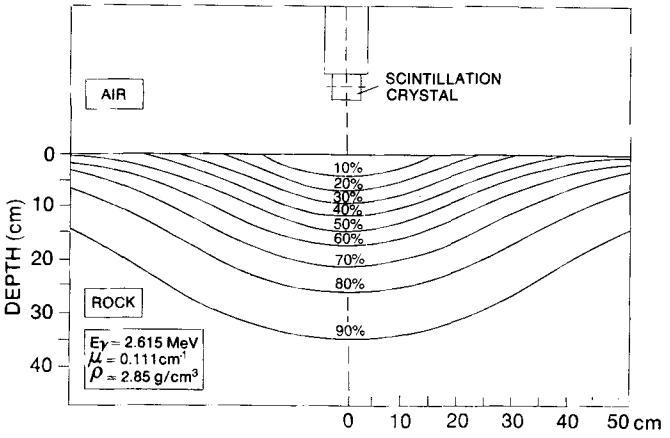


Figure 10C.8. *The sample volume for an in situ assay by portable gamma ray spectrometer as computed by Løvborg et al. (1969). Curved lines represent nearly-hemispherical shells contributing 10 per cent of the detected gamma radiation for the case of the 2.62 MeV gamma rays from the ^{232}Th decay series. (Values computed using attenuation $\mu = 0.111\ cm^{-1}$, $\rho = 2.85\ g/cm^3$; typical of the Illimaussaq intrusion in Greenland.)*

made on a hill or ridge. False anomalies may be recorded if the operator does not make a note of the changes in geometry which cause increased count rates. A good operator can save considerable time and expense in later follow-up investigations if proper field notes are kept.

A solution to problems caused by geometry is the use of a lead shield to control the geometry. Mahdavi (1964) described the use of shielding to measure radioelement concentrations in Texas coast beach sands, and Løvborg et al. (1969) employed a lead-shielded detector for a gamma ray spectrometer used for in situ surface analysis of the rough terrain of the Illimausaq intrusion in Greenland.

Lead shielding to control geometry in a carborne survey is highly impractical, however it may be used beneath the detector to shield it from the road bed if the latter is known to contain non-locally derived material which may be the main source of radioactivity being detected.

Airborne Measurements — 2π Geometry

Generally speaking there is not much variation from 2π geometry for an airborne survey of the reconnaissance type if the terrain is not too rugged. Large fixed-wing aircraft carrying large detector arrays for reconnaissance work however are less manoeuverable than the smaller aircraft or helicopters usually used in detailed follow-up surveys. If the terrain becomes rugged, maintaining a constant elevation is difficult and may become impossible with a fixed wing aircraft. Aircraft elevation corrections may be applied, but geometry corrections may usually be applied only in a qualitative sense or at best semi-quantitatively. Figure 10C.7 (after Grasty, 1976a) illustrates the effect of source geometry and height upon count rate. As shown in this figure the aircraft is able to maintain constant elevation (h) over flat ground (10C.7a) or over broad topographic changes (10C.7b), but over sharp hills (10C.7d) or narrow valleys (10C.7c) the height will be less than h and more than h respectively (Fig. 10C.7). The height correction factors can compensate for this, but not for the changes in geometry. In these last two cases, the geometrical configuration is less than 2π over hills and greater than 2π in valleys, and geometry considerations similar to those for portable gamma ray spectrometer measurements will be applicable.

Borehole Measurements — 4π Geometry

It can easily be seen that the "best" possible geometry is obtained when the source completely surrounds the detector, as in the case of a gamma ray probe inside a borehole. The source effectively surrounds the detector except for a narrow solid angle above and below it.

In an air-filled borehole, the geometry will still be 4π even if a large cave-in or wash-out is encountered, because the rock surrounds the detector. However in a water-filled hole the attenuation of the additional water in the enlarged portion of the hole must be taken into consideration. This is discussed in the section on borehole logging.

The Effective Sample Volume

The size of the sample being analyzed in a field measurement has been discussed by several authors. Dodd and Eschliman (1972) considered the borehole measurement case for total count logging surveys, Løvborg et al. (1971) did considerable work with respect to portable gamma ray spectrometers and Grasty et al. (in press) considered the sample volume of airborne radiometric measurements. Several factors can affect the sample volume, such as the energy of gamma radiation being measured, the density of the source material (rock, overburden etc.), the absorption coefficient of the material and whether the detector is moving or stationary. The definition of sample volume is also important. For example it could be arbitrarily defined as the volume within which 90 per cent of the detected gamma rays originated.

The sample volume for an in situ assay by portable gamma ray spectrometer is shown in Figure 10C.8 (Løvborg et al., 1969). The sample volume for a total count gamma ray log is illustrated in Figure 10C.9, where the distribution of gamma ray sources detected during any given sample interval is shown. This is intended to demonstrate the difficulty of defining the sample 'volume'. In addition the volume includes a cylinder of length L if the detector moves a distance L during the time of measurement. In an airborne gamma ray spectrometric survey, the volume of the sample is the product of the surface area "seen" by the airborne detector, and the thickness of the source material. The sample volume

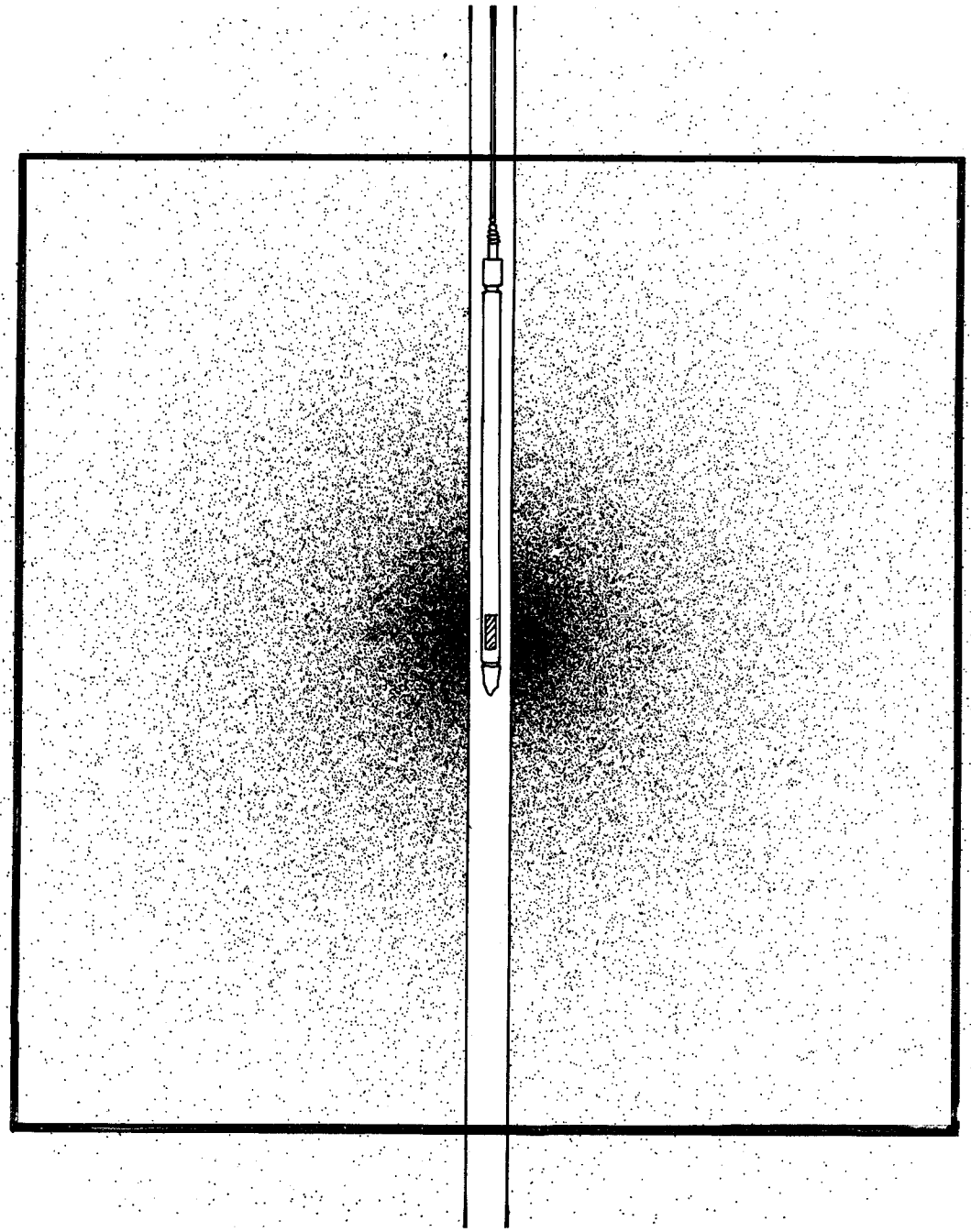


Figure 10C.9. *Sample volume for a total count gamma ray borehole log as shown by the distribution of gamma ray sources detected during any given sample interval Δt by a detector located in a borehole penetrating a homogeneous radioactive zone. The difficulty in defining the boundaries of the 'sample volume' is apparent from this figure (after Conaway and Killeen, 1979).*

for an airborne measurement will depend to a large extent on the height of the aircraft above the ground. This affects the area of the surface which is analyzed. The area of the surface has been called the field of view (F.O.V.), instantaneous field of view (I.F.O.V.), circle of investigation, and area of influence, by various authors. The size of the sample area is a moot point at present, and there is some dispute as to whether the width of the area supplying a given percentage of the radiation detected can be considered the same for measurements made with the aircraft moving or stationary (see Fig. 10C.10, after Grasty et al., in press). Usually the computations are made on the basis of a stationary detector at a fixed height (e.g. see Fig. 10C.11, after Duval et al., 1971). Grasty (1979) has also shown that the diameter of the circular area beneath the aircraft contributing a given percentage of the gamma radiation

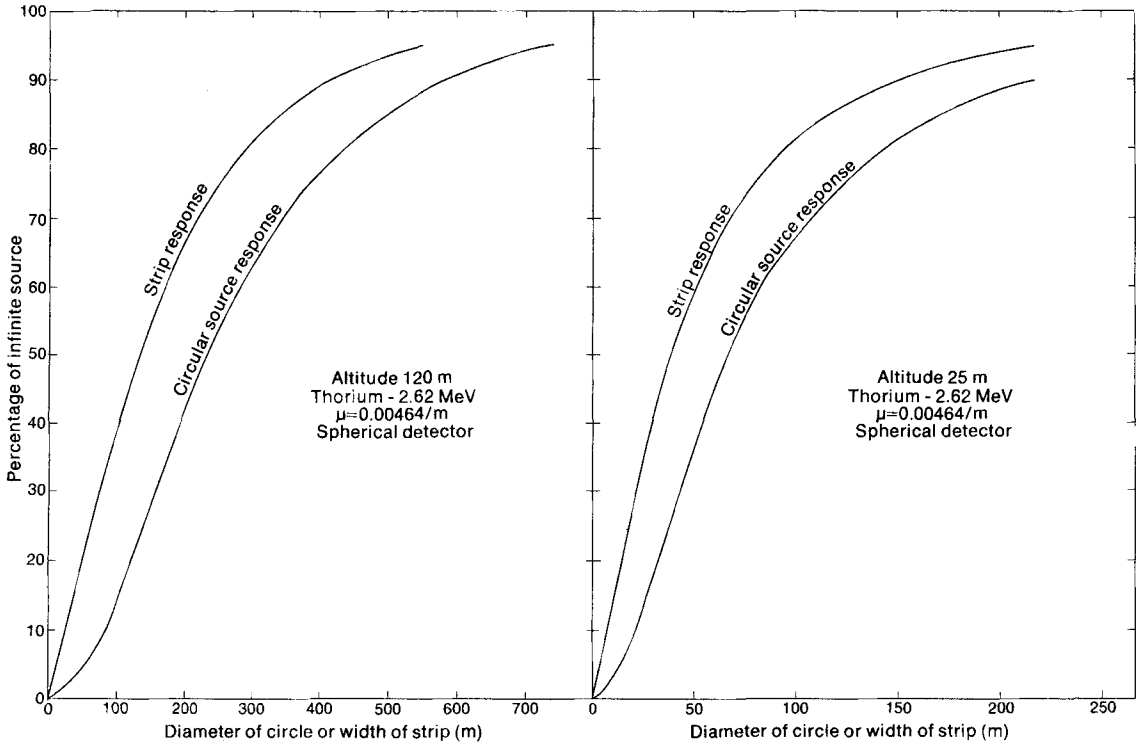


Figure 10C.10. *Area of coverage for an airborne gamma ray spectrometric survey for a stationary detector and a moving detector at altitudes of 120 m and 25 m (after Grasty et al., 1979). For a given percentage of infinite source detected, the width of the strip (moving detector) is less than the diameter of circle (stationary detector). Calculations of amount of surface area covered for a given airborne survey, based on the stationary detector model, will produce over-estimates, since the survey is actually done with a moving detector.*

varied with detector size. This is due to the differing sensitivity of the detectors in different directions, and the data of Figure 10B.7 in Grasty (1979) show the change in diameter can be in the order of 10 per cent variation.

The use of the concept of the "field of view" in computing the percentage coverage of an area in a given survey is important in choosing the desired flight line spacing for an airborne survey. Figure 10C.12 shows the thickness of material penetrated for various gamma ray energies computed from the mass absorption data given in Table 10B.3 of Grasty (1979). Figure 10C.12b shows the results using a density $\rho = 2.67$ g/cm^3 (average rock), Figure 10C.12a shows a low density case of $\rho = 2.0$ g/cm^3 and Figure 10C.12c, shows a high density case $\rho = 3.0$ g/cm^3. From these data an appreciation of the sample volume (thickness) can be obtained.

Counting Statistics

One of the factors often quoted as being an important requirement for a survey is "good counting statistics". This is a rather broad term and will be elaborated upon somewhat below, but basically it means that the gamma ray count rate, or total number of gamma rays counted in a given measurement must be large enough to be considered a statistically reliable measurement. This is related to the desired accuracy of a measurement.

Definitions and Effects of Varying Survey Parameters

Radioactive decay is a random process, and one standard deviation (σ) in a counting measurement equals the

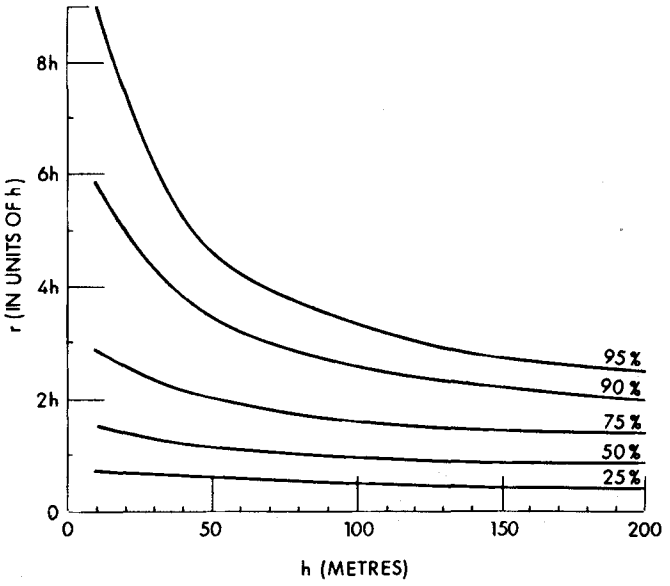


Figure 10C.11. *The radius of the circle of investigation versus altitude for a given percentage of infinite source yield (after Duval et al., 1971).*

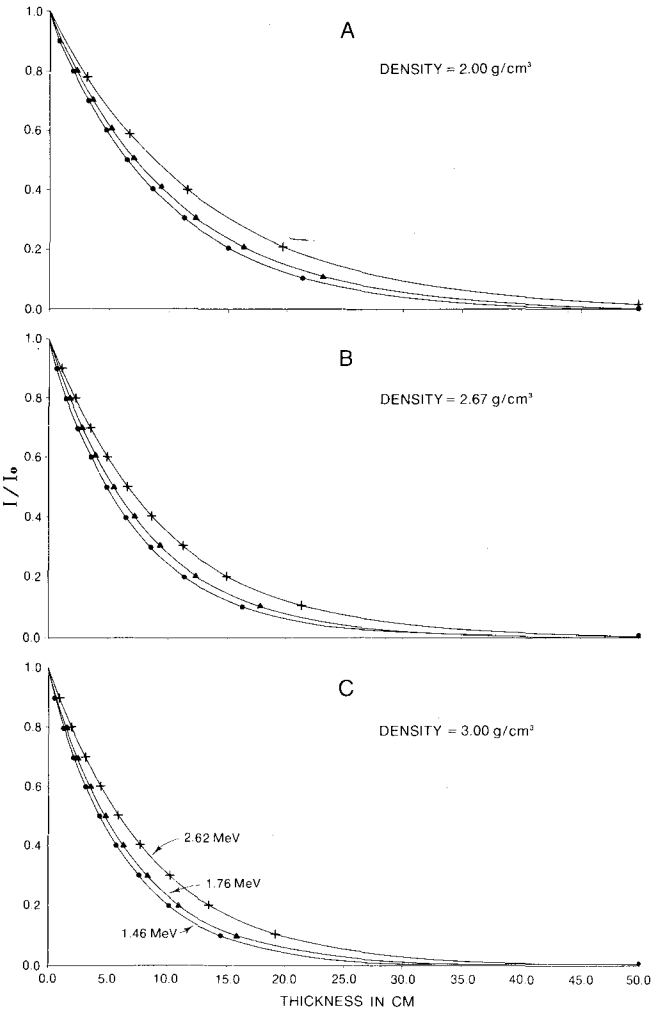


Figure 10C.12. *Attenuation of gamma rays versus thickness for the three gamma ray energies associated with K(1.46 MeV), U(1.76 MeV), and Th(2.62 MeV) for three rock densities (ρ). In a strict sense these curves refer to collimated beams penetrating rock absorbers. However the relative effects on sample volume of both energy and rock density can be appreciated from the figure. (I/I_o = (intensity)/(initial intensity)).*

square root of the count (n) obtained. This can then be expressed as a percentage of the count or percentage error. One standard deviation is:

$$\sigma = \pm \sqrt{n} \tag{3}$$

Thus the standard deviation in a measurement where n = 100 counts is ±10 counts, or a percentage error of ±10%. A count of 1000 would yield ±31.6 counts, about ±3% error.

The standard deviation in the counting rate is

$$\sigma_{RATE} = \sqrt{n}/t = \sqrt{RATE/t} \tag{4}$$

where the counting rate is defined as RATE = n/t.

The error in the final result will be increased when a number of corrections are applied such as background subtraction and spectral stripping, each of which includes a counting measurement with its associated errors.

In subtracting background for example the error in the net count will be

$$\pm \sigma_{NET} = \sqrt{\sigma_R^2 + \sigma_B^2} \tag{5}$$

where σ_R = the standard deviation in the RAW count, and σ_B = the standard deviation in the BACKGROUND count.

Errors are always additive, even though the operation is subtraction of background.

When spectral stripping is included, the error calculations are quite ponderous. The following error analysis is given by Darnley et al. (1969):

"Assuming that all count rates are given in counts per minute, the standard deviation for the corrected count-rates are as follows:

$$\sigma_{Th} = \left[\frac{N_{Th}}{t} + \frac{BGD_{Th}}{T}\right]^{1/2} \tag{6}$$

$$\sigma_U = \left[\frac{N_U}{t} + \frac{BGD_U}{T} + \alpha^2 \sigma^2_{Th}\right]^{1/2} \tag{7}$$

$$\sigma_K = \left[\frac{N_K}{t} + \frac{BGD_K}{T} + \beta^2 \sigma^2_{Th} + \gamma^2 \sigma^2_U\right]^{1/2} \tag{8}$$

where N_{Th}, N_U, N_K are the observed count rates in the Th, U and K channels respectively and BGD_{Th}, BGD_U, and BGD_K are the background count rates in the same channels, t is the measuring time for the interval under consideration, T is the time for which the background was observed. The corresponding relative standard deviations are given by

$$\sigma_{Th}/N_{Th\ corr.}, \quad \sigma_U/N_{U\ corr.} \text{ and } \sigma_K/N_{K\ corr.}$$

where the subscripts refer to the corrected channel count rates.

As an example of the statistical error which arises from the count-rates measured and the application of the various corrections the data obtained from one Elliot Lake test run at 150 m have been used. Mean count-rates obtained by three 12.5 cm x 12.5 cm NaI(Tl) detectors in a 15-sec measuring period were calculated, background was subtracted and Compton scattering corrections were made. The 15-sec counting time at a helicopter speed of 40 km/hr represented a forward travel of about 170 m. The mean counts per minute for 15-sec counting intervals are as follows:

1.35-1.58 MeV, 'K' window 740 ± 11%

1.65-1.88 MeV, 'U' window 190 ± 22%

2.42-2.82 MeV, 'Th' window 230 ± 16%

The quoted uncertainty is based on one standard deviation."

To obtain a lower error the count must be increased; this can be accomplished by: 1) counting for a longer time, 2) increasing the detector size, or 3) moving the detector closer to the source. These three alternatives are relatively easy to accomplish in a laboratory, but in the field, changing these parameters could have far-reaching effects. Increasing the counting time for a portable (man-carried) gamma ray spectrometer reduces the number of readings that can be made each day. In a mobile survey, increasing the counting time means that each measurement is taken over a longer distance, and therefore each is representative of a larger volume of rock. This smoothing effect may not be acceptable, and the vehicle speed may have to be reduced by a direct ratio to the increase in sample time. In the case of an airborne survey, this could reduce the aircraft speed to the point where the selection of a rotary wing aircraft is required, increasing the cost.

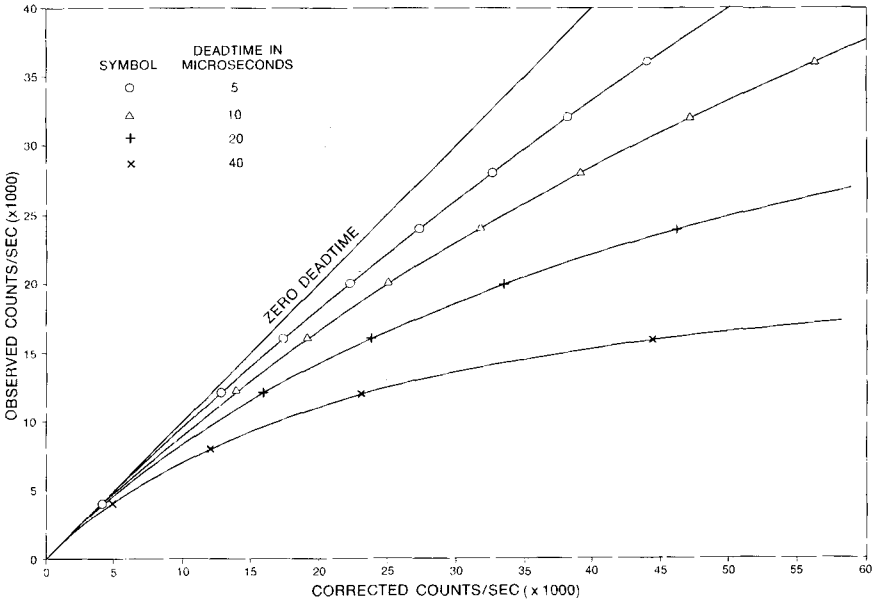


Figure 10C.13. *Deadtime correction curves are based on equation (10): $N = n/(1 - nT)$ (see text). Corrected count rate for any given measured count rate can be determined if the appropriate deadtime curve is known. Because the equation is an approximation, the corrections become increasingly erroneous as the percentage correction increases.*

Alternative (2), increasing the size of an airborne detector package, may require a larger, and consequently more costly type of aircraft. For a portable or a carborne survey, this may be a more economical solution. Alternative (3) moving closer to the source, may be impossible, as in the case of a carborne survey, or it may involve flying at unsafe altitudes for airborne surveys. Under alternative (3) the sample volume will decrease appreciably and it may be necessary to make more closely spaced measurements for the same ground coverage. This of course, also represents an increase in costs.

The relationship between sample time, aircraft speed, and altitude has been considered by Killeen et al. (1975) and Killeen et al. (1971). They suggested that once the exploration target size (or spatial wavelength) is selected, the aircraft altitude is optimized at twice this wavelength. It is then possible to choose from several combinations of speed and sampling time such that:

$$\Delta t = h/4V \qquad (9)$$

where

Δt = sample time in seconds; V = aircraft velocity in metres/sec.; and h = the previously selected altitude in metres.

Once this has been done, and the aircraft selected, the detector size must be chosen to yield good counting statistics.

Dead Time and 'Sum' Peaks

The dead time of a gamma ray spectrometer is effectively the time taken by the equipment to analyze a single gamma ray which has been detected; during this period the equipment is busy and cannot analyze any other gamma rays. This dead time (sometimes called resolving time) is only a few microseconds per recorded count, but it becomes an appreciable percentage of the counting time at high count rates, and must be taken into consideration. The true count N can be computed from the measured count n if the dead time T is known, using the following approximation:

$$N = n/(1 - nT) \qquad (10)$$

Since this correction is an approximation it introduces error when the percentage losses due to dead time are high (Chase and Rabinowitz, 1968). Dead time should be kept at less than 50 per cent in the worst instance and preferably below 10 per cent, by suitably adjusting detector sizes, source-detector spacing, or other variables.

One of the most common methods of measuring dead time is the method of paired sources. Two sources of activities R_1 and R_2 are selected such that, individually counted there are no significant dead time losses, but when counted together (R_{12}) the percentage loss becomes significant. The dead time has been given by Chase and Rabinowitz (1968) as follows:

$$T = \frac{R_1 + R_2 - R_{12}}{2R_1R_2} \qquad (11)$$

where R_1, R_2 and R_{12} are activities that have had the background subtracted. This equation is also an approximation but is more convenient to use than the complex exact equation. Several other approximate relations for computing dead time have been given by Chase and Rabinowitz (1968).

Another method of determining the dead time of a borehole gamma ray logging system has been proposed by Crew and Berkoff (1970). This technique involves measurements in the infinitely thick, homogeneous ore zones in two model holes, which contain uranium ore grades differing by about a factor of 10 or more. They stated that the following approximation will yield dead time values generally within 1 microsecond of the rigorous solution

$$T = \frac{N_{LOW} - G_{RAT}\,N_{HIGH}}{N_{LOW}\,N_{HIGH}\,(1 - G_{RAT})} \qquad (12)$$

where

T = apparent dead time in seconds

N_{LOW} = apparent measured peak count, low model

N_{HIGH} = apparent measured peak count, high model

G_{RAT} = (% eU_3O_8, low model)/(% eU_3O_8, high model) i.e. grade ratio

Having determined the dead time of a system it is important to know approximately the size of the dead time correction at various count rates. Using equation (10), the corrected counts are plotted against the measured counts for several values of dead time in Figure 10C.13. It can be seen from the graph that at a dead time of 20 microseconds, for example, a measured count rate of 25 000 cps would be corrected to 50 000 counts or 100 per cent dead time correction which is unacceptably high. With the same dead time a correction of 50 per cent occurs at 17 500 cps measured, corrected to about 26 250 cps. Thus the upper limit is about 17 500 cps for a system with 20 microsecond dead time and, in fact, it would be preferable to choose equipment which would operate at lower count rates than this in the radioactive zones of interest in the field.

Besides dead time an additional consideration at high count rates is sum peaks or coincidence peaks. These are especially important in the case of gamma ray spectrometry. When two gamma rays strike the detector at the same time, the two scintillations produced are "seen" as one by the photomultiplier tube and only one gamma ray count is registered, at an energy approximately equal to the sum of the energies of the two gamma rays which struck the detector. This is usually only important for a large detector with the source very close to it, as in a laboratory gamma ray spectrometer.

For example the 0.58 MeV and 2.62 MeV gamma rays from the thorium decay series are both of high intensity and the sum peak at 3.20 MeV becomes significant for measurements of samples with high thorium concentrations. Sum peaks can cause gamma rays of low energy to be counted in higher energy windows of a gamma ray spectrometer, introducing the possibility of erroneous results.

Background Radiation

The literature describes two values for background: the "local" background (i.e. the mean count rates), and the "over water" background. Only the latter permits comparison of data from different survey areas.

Background radiation is any radiation detected by the gamma ray spectrometer not originating from the source which is being analyzed; in this case, the lithosphere (IAEA, 1976). In the case of a laboratory it includes radiation coming from or through the walls, ceiling and floor, and the lead counting chamber or shield. In the field it includes the radiation from the vehicle, be it a man carrying the spectrometer, a truck, or an aircraft. In addition there is a cosmic ray component (most important for airborne surveys) and radioactivity in the atmosphere caused by radon and its daughter products, and products from nuclear fallout. To the extent possible the background should be minimized. Flight instrument dials or emergency exit signs etc. in aircraft, which are luminized with radium, should be replaced or removed. Similarly radium dial wrist watches should not be worn by personnel carrying out surface surveys. Calibration sources should be removed completely or at least shielded if they must be carried on the survey. Any remaining background should be measured accurately to enable its subtraction. The greatest problem of background is the variable or unknown component. This is primarily caused by the radioactivity of particles in the air. Grasty (1979) reviewed this in some detail especially with reference to airborne gamma ray surveys. The subject of background radiation in airborne measurements is not included in this section because it has been discussed in Paper 10B (Grasty, 1979).

Background Radiation in Surface Measurements

There are several ways in which the background can be determined for both carborne and portable gamma ray spectrometers. Ideally, a measurement can be made over water in the survey area using a boat or by driving the vehicle onto a bridge (not stone or concrete) over a wide river or onto the ice of a lake (Bowie et al., 1955). This will yield a background value for the equipment itself, the vehicle, cosmic rays and radioactivity in the atmosphere. Bowie et al. (1955) described a method of determining both the cosmic ray component and the vehicle component if it is possible to take readings as follows:

R_o = 2π reading taken on a road crossing a given rock type (include vehicle + cosmic ray component)

R_T = 4π reading in a tunnel through that same rock type (includes vehicle component)

R_l = 2π reading on lake ice (vehicle + cosmic components only)

Then the cosmic ray component (C) is:

$$C = 2R_o - R_T - R_l \quad (13)$$

If the vehicle and equipment are unchanged during the survey and periodic background measurements differ, the difference will be due primarily to fluctuations in the radioactivity of the air. Background can fluctuate significantly both with time and location. Changes with time can be observed by keeping a base-station which is measured every morning and night during the survey. The base station should give the same count rate at all times (within counting measurement errors) except for differences in atmospheric radioactivity or cosmic radiation. Using a base station also provides a check on the condition of the instrument and detector and will permit early detection of electronic problems, a cracked crystal, or other problems.

Another method to determine the background radiation level is to extrapolate to zero concentration the count rates measured on calibration sources such as the ten calibration pads of the Geological Survey of Canada in Ottawa. The pads must be considered to be infinite 2π sources, and this will only hold for detectors placed directly on the pad near the centre.

Background Radiation in Borehole Measurements

Generally the background radiation in a borehole gamma ray log is considered to be zero since the detector is surrounded by the source. Cosmic ray effects are generally negligible, and the radioactivity of the air has no influence in a liquid-filled hole and negligible influence in an air-filled hole due to the small volume of air. Two situations, however, are possible in which the background becomes significant. The first occurs when drilling muds rich in potassium compounds, such as potassium chloride (KCl) and potassium bicarbonate ($KHCO_3$) have been used. Cox and Raymer (1976) discussed the effect of potassium muds on gamma ray logs and concluded that the contribution of mud radioactivity to the gamma ray measurement can be large, that the effect is greater in larger holes than small, and is directly proportional to the concentration of the potassium in the mud. Their correction factors presented in graphical form for various mud weights are instructive, but unnecessary for most hard rock mining applications which utilize small diameter boreholes and water as a drilling fluid.

The second situation in which the background in a borehole becomes significant occurs when the borehole is logged after a considerable time has elapsed since drilling. In this case it is possible that radon will migrate from radioactive zones into the borehole, creating a broader anomaly on the gamma ray log than if the hole had been logged shortly after drilling. This has been reported as a problem in air-filled model boreholes used for calibration but the effect can be reduced to an insignificant amount by keeping water in model holes (IAEA, 1976). The characteristics of radon emanation and corrections for it, have been discussed in detail by Scott and Dodd (1960), Austin (1975) and Barretto (1975).

In the field, it is difficult to know if a radon background problem exists in a borehole. Tanner et al. (1977b) have utilized high resolution solid state germanium detectors (both intrinsic Ge and Ge(Li)) to overcome the problem in areas of known radioactive disequilibrium. It has also been suggested by Lyubavin and Orchinnikov (1961) that disequilibrium (e.g. radon excesses) could be detected by spectral logging methods. Dodd et al. (1969) indicated that although

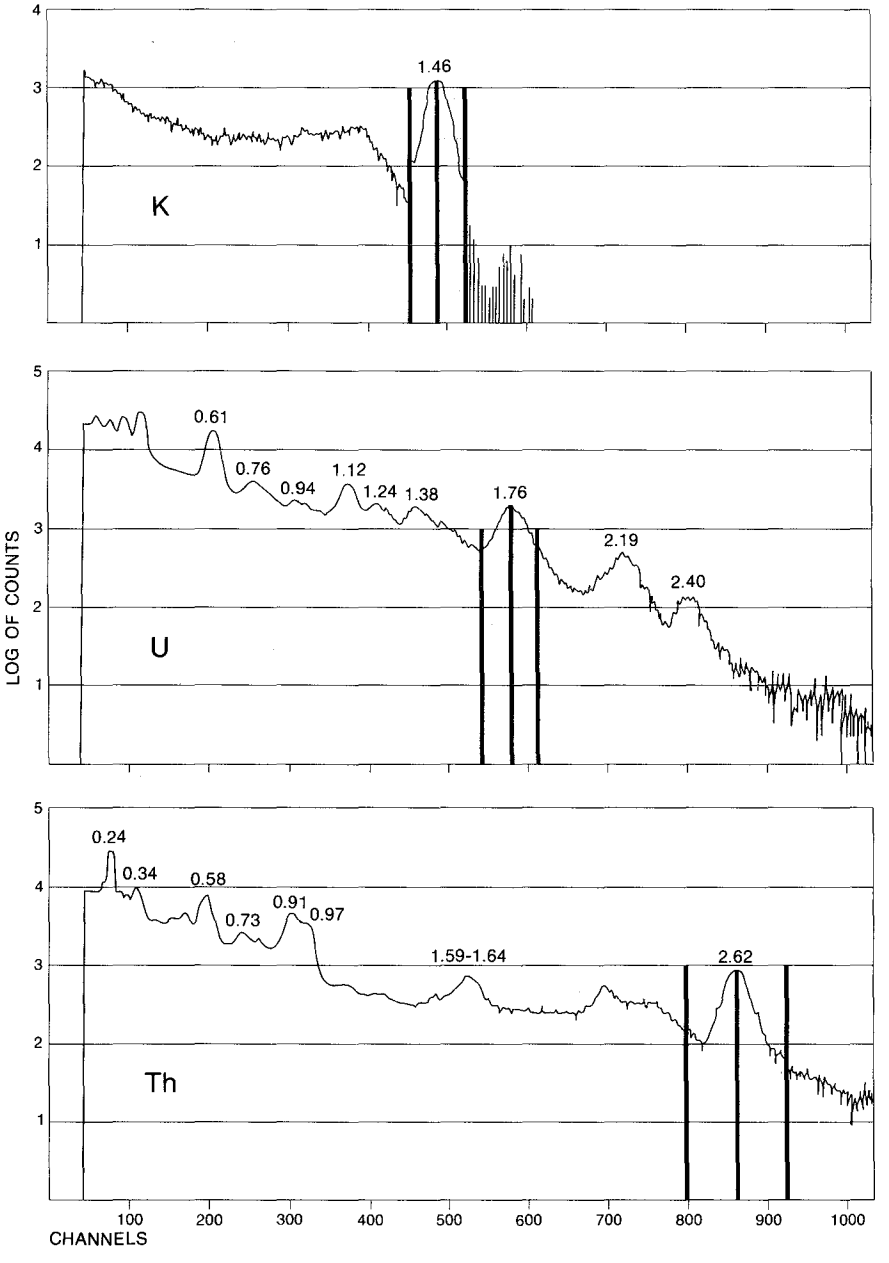


Figure 10C.14. *Measured energy spectrum of gamma rays emitted by ^{40}K (top), the ^{238}U decay series (middle), and the ^{232}Th decay series (bottom). Measurements were made with a 75 x 75 mm NaI(Tl) detector. Energy axis (horizontal) is approximately 3.0 keV/channel. Locations of commonly used windows for gamma ray spectrometry are indicated at 1.46 MeV, 1.76 MeV (^{214}Bi) and 2.62 MeV (^{208}Tl). Window widths are 200 keV, 200 keV, and 400 keV respectively for K, U, and Th (after Killeen and Bristow, 1976).*

preliminary investigations confirmed the feasibility of the idea, the complexity and stability of instrumentation required at that time (1967) exceeded the state of the art for routine application.

Background Radiation in Submarine Measurements

Background measurements with a 75 x 200 mm NaI(Tl) detector for underwater gamma ray spectrometry in lake bottoms in Saskatchewan have been reported by Stolz and Standing (1977) as 100 to 500 cps for total count, 5 to 15 cps for potassium and 0 to 10 cps for uranium and thorium (energies not given). Their detector was towed along the bottom in an 'eel', 7 m long by 17 cm diameter which gouged a trough of semi-circular cross-section in the lake bottom sediments. This background is the non-anomalous or regional radioactive component, rather than the 'true' background in the sense of radiation originating from other than the lake-bottom. "True" background could be obtained by suspending the detector half way between the lake bottom and water surface. Noakes et al. (1974a) used a detector consisting of a sled housing four 75 x 75 mm NaI(Tl) detectors towed along the sea floor sediments seaward of Amelia Island, Florida, at a speed of from three to five knots. They reported background levels on the sea floor for a two channel spectrometer as 50 to 75 counts per second for channel B (less than 1.0 MeV) and 10 to 20 cps for channel A (greater than 1.0 MeV). Gaucher et al. (1974) reported background measurements for sea water which they determined using a 75 x 75 mm detector on a sled. With a 500 second counting time they obtained counts of 144, 19, and 27 for their 'K', 'Th' and 'Ra' windows respectively (energies not given) on a 100 channel spectrometer. Clayton et al. (1976) reported approximately 7 counts per second for background with the probe surrounded by seawater with a detector of 75 x 125 mm. They give typical count-rates for the spectrometer channels (no energies given) of 1500 to 12 000 counts/minute (total count), 90 to 300 counts/minute (K), 10 to 50 counts/minute (U), and 7 to 30 counts/minute (Th) depending on rock type.

Calibration

For any physical measurement to be meaningful, the measuring device must be calibrated with respect to some standard. This is true whether the measurement concerns weight measurements with a spring balance, distance measurements with a ruler, or radioelement measurements with a gamma ray spectrometer. Confusion can result when comparing gamma ray counting measurements made with different instruments, sometimes even when the instruments are of the same manufacture. In addition, different instruments may display the data in different units, such as counts per second, counts per minute, micro roentgens per hour or millivolts. Darnley (1977) pointed out the advantages of standardizing radiometric exploration measurements. The International Atomic Energy Agency (IAEA, 1976) formulated recommendations for standardizing measurements in uranium exploration by calibration, and presenting results in units of concentration (e.g. %K, ppm eU, ppm eTh).

The basic equation relating the detected radioactivity to the radioelement concentration in the source of the radiation is:

$$\text{Radioelement content} = (\text{a constant})(\text{gamma ray intensity})$$
$$= (1/\text{sensitivity})(\text{gamma-ray intensity}) \qquad (14)$$

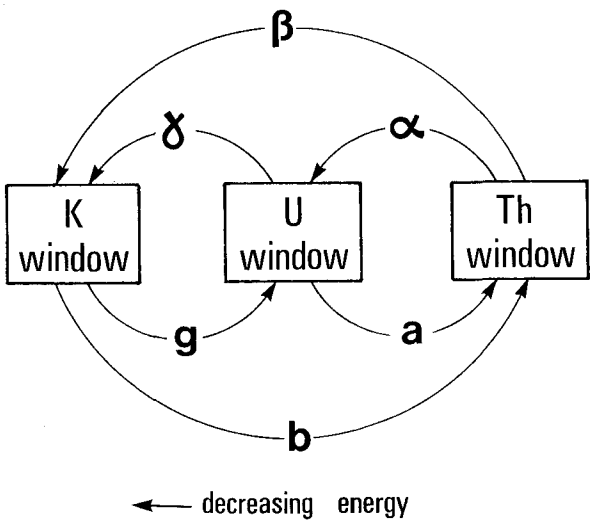


Figure 10C.15. *Schematic representation of the interaction between the K, U, and Th energy windows indicates the stripping factors which are used to remove the interference denoted by the arrows. Commonly used stripping factors are* α, β, *and* γ. *The 'upward' stripping factors a, b, and g are generally small or zero and are often ignored.*

The problem of calibration relates to the determination of this constant which is the "K factor" or the reciprocal of the sensitivity. First, however, the gamma ray intensity must be corrected for background, and for interference from gamma rays related to radioelements other than the one being determined.

The gamma rays emitted by the daughter nuclides of uranium and thorium have been tabulated by Smith and Wollenberg (1972), and a summary of their table of gamma ray energies and intensities is given by Grasty (1979). The principle gamma rays of the uranium and thorium series have also been tabulated in an appendix of Adams and Lowder (1964). Most compilations like these are derived from Lederer and Shirley (1978), Lederer et al. (1968), or Hyde et al. (1964). The principle gamma rays produce the energy spectra shown in Figure 10C.3. The potassium spectrum is a single gamma ray peak at 1.46 MeV. The relative activities or intensities are those obtained under conditions of radioactive equilibrium. Disequilibrium may introduce differences in the relative peak heights depending on whether any given daughter emitter has been removed or deposited in the sample.

Due to the inherently imperfect energy measuring capabilities of scintillation detectors and scattering of gamma rays and degradation of gamma ray energies in the source rock, the measured spectra for uranium and thorium decay series will look more like those shown in Figure 10C.14 (centre) and 10C.14 (bottom) respectively. The measured potassium spectrum will resemble that shown in Figure 10C.14 (top).

Gamma ray spectra for numerous isotopes useful for calibration such as Cs-137, Co-60, Y-88 and the uranium and thorium series have been published (e.g. Heath, 1964; Crouthamel, 1960; Adams and Dams, 1970).

Figure 10C.14 also indicates commonly chosen K, U, and Th energy windows for a differential spectrometer. These are 1.36-1.56 MeV (K window), 1.66-1.86 MeV (U window), and 2.4-2.8 MeV (Th window). Sometimes the upper limit of the K window coincides with the lower limit of the U window, and some workers raise the upper limit of the U window to 2.4 MeV. For a threshold spectrometer, similar lower limits would be used for the three windows, and the upper limit would be at 3.0 MeV or higher. In any case it can be seen that there is interference between the three spectra; some gamma rays originating from the Th decay series will be counted in the U and K windows, some gamma rays originating from the U decay series will be counted in the K window and to a small extent in the Th window, and finally some small portion of the K gamma rays may be counted in the U window. To determine the "K factor" or sensitivity of equation (14) for the individual radioelements K, U and Th, the gamma ray counts due to each individual radioelement must be determined. This is accomplished by the procedure known as spectral stripping.

The Stripping Factors

The determination and various definitions of the stripping factors (often called stripping ratios) have been discussed in numerous papers (Adams and Fryer, 1964; Wollenberg and Smith, 1964; Doig, 1968; Killeen and Carmichael, 1970; Grasty and Darnley, 1971; Grasty, 1976b, 1977a; Killeen and Cameron, 1977; Grasty, 1979). Figure 10C.15 is a schematic representation of the interplay between the three radioelement windows K, U, and Th and identifying the stripping factors, as listed below:

Stripping Factor	Used to Strip Off
α	Th gamma rays in U window
β	Th gamma rays in K window
γ	U gamma rays in K window
a	U gamma rays in Th window (usually small)
b	K gamma rays in Th window (zero)
g	K gamma rays in U window (approx. zero)

For many purposes only the first three stripping factors are used and a, b and g are assumed to be zero. For high uranium concentrations the upward stripping factor 'a' is necessary. It has a value of approximately 0.05 (Grasty, 1975), but the actual value is dependent on factors such as detector size and resolution, window widths and energy settings.

These stripping factors are determined by making measurements on calibration sources, as described below in greater detail. The count rates obtained, and the radioelementanalysis (least squares) computer program which solves for the stripping factors and the sensitivities or K factors.

These sensitivity factors have units of count rate per unit of radioelement concentration. The rigorous solution for the calibration equations is given by Grasty (1979). Since the simplified solution is used in most cases, the method of computing radioelement concentrations from gamma ray counts as set forth by Killeen and Cameron (1977) is reproduced below.

Assume the counts measured in (cpm) in the three spectrometer windows are Kc (potassium), Uc (uranium) and Thc (thorium).

A. To calculate eTh in ppm (parts per million)
   1. Obtain the net thorium count by subtracting thorium background from the measured thorium count:

$$\text{Th net} = \text{Thc} - \text{Thb} \qquad (15)$$

   2. Obtain eTh ppm by dividing the net thorium count by the thorium sensitivity (Ths)

$$\text{eTh ppm} = (\text{Th net})/\text{Ths} \qquad (16)$$

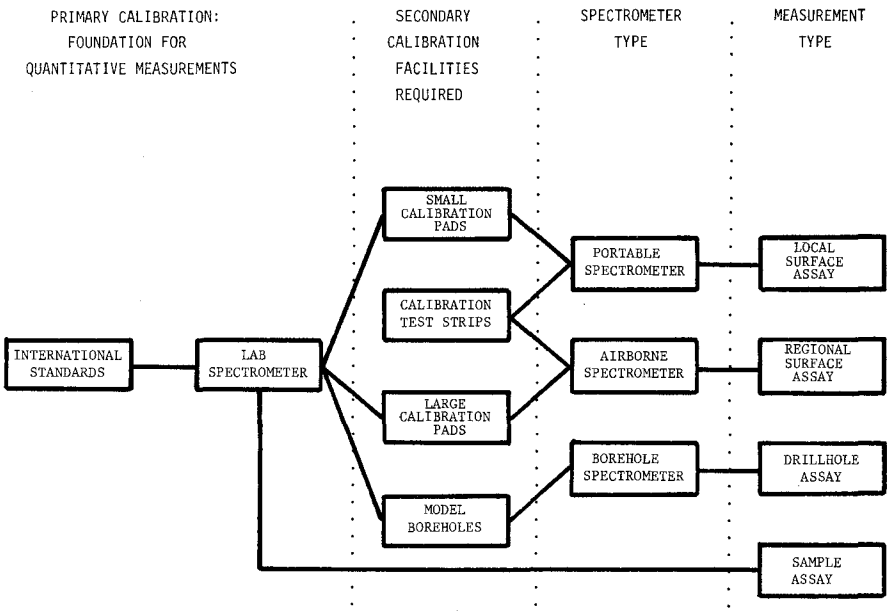


Figure 10C.16. *The relationship between primary and secondary calibration facilities for various types of gamma ray spectrometer. International standard samples are used to calibrate lab spectrometers. These in turn analyze calibration pads and model boreholes which can then be used as secondary calibration facilities for field spectrometers. The calibrated field spectrometers can then carry out assays in situ.*

B. To calculate eU in ppm:
   1. Determine the thorium contribution to the uranium count by multiplying the net thorium count by the factor α:

$$(\alpha)(\text{Th net})$$

   2. Obtain the net uranium count by subtracting the uranium background and the thorium contribution from the measured uranium count:

$$U\ \text{net} = Uc - Ub - (\alpha)\ (\text{Th net}) \qquad (17)$$

   3. Obtain eU ppm by dividing the net uranium count by the uranium sensitivity (Us):

$$eU\ \text{ppm} = (U\ \text{net})/Us \qquad (18)$$

C. To calculate potassium in per cent:
   1. Determine the thorium contribution to the potassium count, by multiplying the net thorium count by the factor β.

$$(\beta)(\text{Th net})$$

   2. Determine the uranium contribution to the potassium count, by multiplying the net uranium count by the factor γ.

$$(\gamma)(U\ \text{net})$$

   3. Obtain the net potassium count by subtracting the potassium background and the thorium and uranium contributions from the measured potassium count:

$$K\ \text{net} = Kc - Kb - (\beta)(\text{Th net}) - (\gamma)(U\ \text{net}) \qquad (19)$$

   4. Obtain the per cent potassium by dividing the net potassium count by the potassium sensitivity (Ks).

$$\%K = (K\ \text{net})/Ks \qquad (20)$$

Killeen and Cameron (1977) also presented a numerical example for the case of a portable 4 channel gamma ray spectrometer with a 75 x 75 mm NaI(Tl) detector.

In 1976, the International Atomic Energy Agency recommended a new unit, the 'ur', or 'unit of radioelement concentration', for total count gamma ray spectrometer or scintillometer results (IAEA, 1976). The unit is described as follows: "A geological source with 1 unit of radioelement concentration produces the same instrument response (e.g. count rate) as an identical source containing only 1 part per million uranium in radioactive equilibrium".

In other words a "geological source", which probably contains some potassium and thorium as well as uranium, produces a certain instrument response (e.g. count rate). This is expressed in units of the amount of equivalent uranium which alone would give the same instrument response. Thus the use of the 'ur' unit replaces the use of the term 'equivalent uranium' which was used in the above sense in many early publications on total count radiometric work. The present-day usage of "equivalent uranium" however refers only to the single element uranium but measured indirectly by counting techniques (see the earlier section on equilibrium).

Thus, 1 unit of radioelement concentration is equivalent to 1 part per million uranium in equilibrium, or

$$1\ \text{ur} = 1\ \text{eU} \qquad (21)$$

The use of the ur unit for calibration of total count gamma ray surveys has been discussed by Grasty (1977b). Any natural radioelement calibration source can be used to calibrate in ur units by converting the radioelement concentrations of the source to ur units with the following relations:

$$1\%\ K = 2.6\ \text{ur} \qquad (22)$$

$$1\ \text{ppm}\ U = 1.0\ \text{ur} \qquad (23)$$

$$1\ \text{ppm}\ Th = 0.477\ \text{ur} \qquad (24)$$

These relationships are strictly valid only for measurements of gamma rays above 0.4 MeV. "A total count scintillation detector operated with an energy threshold of 0.4 MeV will enable the determination of radioelement concentration to be made in ur units almost independently of changing proportions of the radioelement" (IAEA, 1976).

Calibration Procedures

In this section the procedures for calibration of gamma ray spectrometer survey equipment are considered. A great deal of this information originates from unpublished experience in gamma ray spectrometer surveys, and from specifications for contracted surveys based on this experience at the Geological Survey of Canada (Bristow et al., 1977).

Calibration or standardization of gamma ray spectrometer equipment depends on some known, primary reference standard. Secondary calibration standards are then derived from the primary reference. This connection between primary and secondary calibration facilities is illustrated in Figure 10C.16. The types of spectrometer and relationships of their measurements to the different secondary calibration facilities are indicated. From the Figure 10C.16 it can be seen that ultimately all measurements depend on calibration

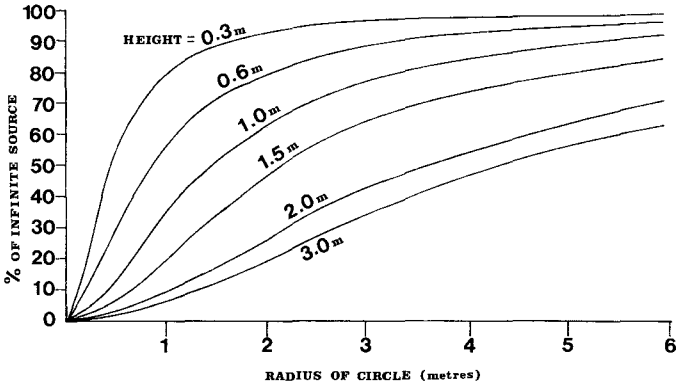


Figure 10C.17. *Radius of the circle of investigation for a 75 x 75 mm NaI(Tl) detector placed at various heights showing the percentage of infinite source area (2.62 MeV gamma rays) for a given radius of circle.*

of a laboratory gamma ray spectrometer using standard samples. The laboratory spectrometer analyzes samples taken during construction of concrete calibration pads, and model holes, and samples taken from test strips. These concrete models become secondary calibration sources for field gamma ray spectrometers. The calibration of an airborne gamma ray spectrometer requires in addition to the concrete calibration pads, a calibration test strip over which test flights may be made. The analysis of this test strip is done partly by in situ assays (or traverses) on a grid with a calibrated portable (or carborne) gamma ray spectrometer, and partly by laboratory assay of samples from the test strip.

The questions of when to calibrate, and how often are also important. Once an instrument is calibrated, it is not calibrated forever, as its characteristics may change with time and it should thus be re-calibrated periodically. It is essential that the user have information about the normal values of the calibration factors for a given instrument. Any large changes upon calibration would probably indicate one or more of the following:

1) a malfunction in the spectrometer,
2) an error in recording the counts,
3) the counting time was too short to provide good counting statistics,
4) an error in entering the data into the computer (compare the computer printout of raw data to your original numbers),
5) calibration just after a rainfall when all the radon daughters in the air are washed out increasing background on the pads,
6) drifting of energy windows due to change in temperature of the detector during calibration,
7) improper setting of the window locations or window widths,
8) low battery power,
9) cracked crystal in the detector package,
10) improper energy calibration.

Thus, calibration, in addition to permitting quantitative measurements also maintains a check on the performance of the system.

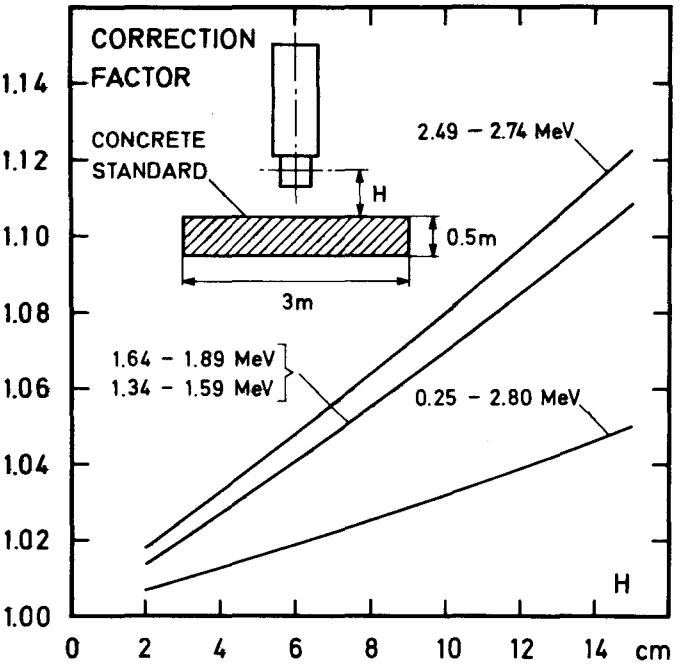


Figure 10C.18. *Correction factors for calibrating portable gamma ray spectrometers on calibration pads of less than infinite diameter (after Løvborg et al., 1972). Factors are for a height H above a pad of 3 m diameter as shown in the inset.*

Temporary calibration facilities can be set up in the field using the calibrated system. This field calibration facility (a base station, test road, test strip of land) can be monitored on a daily basis to ensure the system remains in calibration.

Calibration of Surface Systems

A surface gamma ray spectrometer system may be either carried by a vehicle or placed on the ground surface during the measurement. It is most important to simulate the field geometry during the calibration. The sample time or counting time may be as long as required to provide good counting statistics for the calibration measurement. For a portable gamma ray spectrometer the measurements are usually made by placing the detectors directly on the ground surface. The complete calibration can be carried out by making measurements on a set of calibration pads such as those suggested by the IAEA (1976).

If the detector is to be located at a raised elevation with respect to the ground, such as when mounted on a backpack or a vehicle, the system should first be calibrated with the detector on or near the surface of the calibration pad to ensure that the pad represents an infinite 2π geometry source. The field measurement, with detector mounted will be representative of a larger sample volume.

Figure 10C.17 gives the radius of the circle of investigation for a 75 x 75 mm detector placed at various heights for thorium series 2.62 MeV gamma rays and several different percentages of infinite source area. For example 90 per cent of the radiation from an infinite source area is achieved at a radius of about 5 m for a detector in a backpack carried at 1 m elevation. The 90 per cent radius is 15.8 m for a detector elevation of 3 m, and the 90 per cent

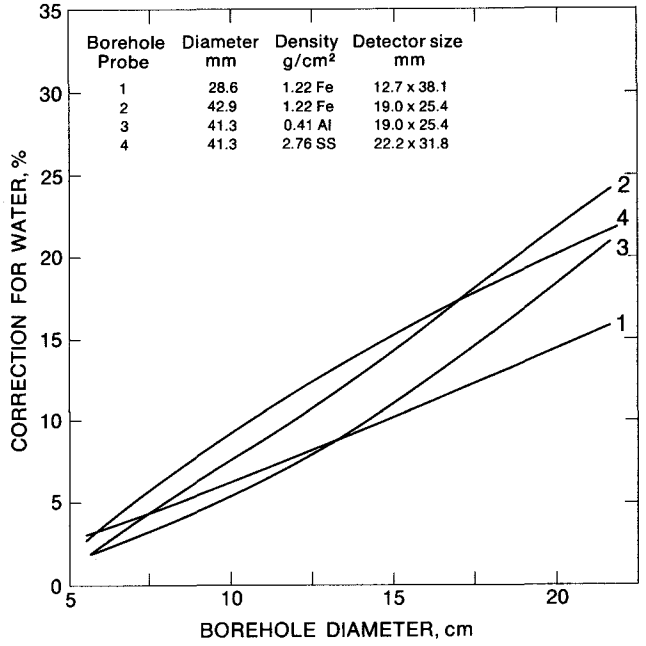


Figure 10C.19. *Water correction factors for gamma ray logging in different diameter boreholes (after Dodd and Eschliman, 1972). Probe housings of iron (Fe), aluminum (Al) and stainless steel (SS) produce different gamma ray attenuations according to the different density of probe shell.*

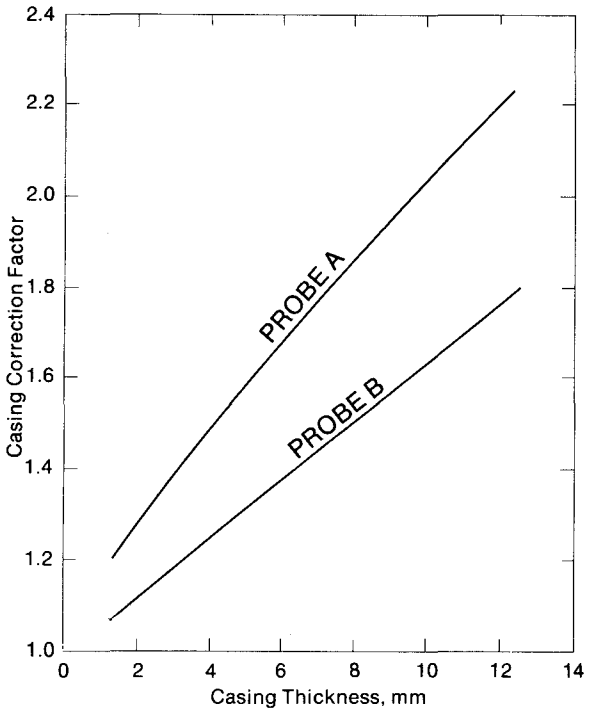


Figure 10C.20. *Casing correction factors for gamma ray logging in different thickness of casing (after Dodd and Eschliman, 1972).*

radius is 29 m for a detector at 6 m elevation (These last two values are not shown in Fig. 10C.17). Similar curves for larger detectors and higher elevations (for airborne surveys) have been given by Grasty (1976b) and by Adams and Clark (1972).

When taking measurements on calibration pads there is always a possibility of some inhomogeneity in the concrete mixture, and in the case of a small detector, several measurements at slightly different locations should be averaged. These measurements (count rates) are then combined with the analyses of the calibration pads in a regression computer program to solve for the calibration factors. It may be possible in the case of a carborne survey, if the detector elevation is not too high, to accomplish the calibration without removing the detector from the system by calibrating on a set of large calibration pads. For example if the detector is about 60 cm above the surface, the pad diameter should be greater than 7 m. It can be judged from Figure 10C.17 whether this is feasible for other detector elevations. Figure 10C.18 (after Løvborg et al., 1972) give correction factors for calibration made at various heights above pads. Matolin (1973) described the problems associated with artificial calibration standards.

Calibration of Airborne Systems

The calibration of an airborne gamma-ray spectrometer system requires both pads and an airborne test strip. The aircraft can be towed or taxied under its own power to a set of concrete calibration pads such as those built by the Geological Survey of Canada at Ottawa, or those built by the U.S. Department of Energy at Grand Junction. The gamma ray spectral measurements made on each pad are combined by a regression analysis program with the analyses of the calibration pads, and a set of stripping factors are derived. The stripping factors, are assumed valid for airborne work, except for the thorium into uranium stripping factor, α, which varies significantly with altitude (Grasty, 1976b). For example Løvborg et al. (1978a) have shown that for a 292 x 102 mm (11.5 x 4 inch) airborne detector, the value of α can increase by over 16 per cent when moving from elevation of 0 to 125 m. Under the same circumstances β (thorium into potassium) and γ (uranium into potassium) increased by 12 per cent and 8 per cent respectively. These increases are not as great for larger detectors.

A test strip is necessary for determination of the height correction parameters. The IAEA (1976) recommends for example that for surveys to be flown at 120 m, that altitude tests be flown between 50 and 250 m spanning the range of normal survey altitudes. Preferably at least five different altitudes should be tested to derive the height attenuation parameters.

The sensitivities for an airborne system are obtained from flights over a radiometric test range or test strip. The stripped count rates (computed using the stripping factors obtained on the calibration pads but corrected to survey altitude using attenuation coefficients derived on the test strip) are combined with the assay data from the test strip to provide the sensitivities.

The desired characteristics for a test strip are sometimes difficult to obtain. The IAEA (1976) made the following recommendations for a test strip:

1) it should be flat (low topographic relief),
2) uniform radioactivity (tested by surface traverses and sampling),
3) minimum dimensions of 1.0 km x 3.0 km,
4) close to a large body of water for background measurements,
5) easy repeatable navigability.

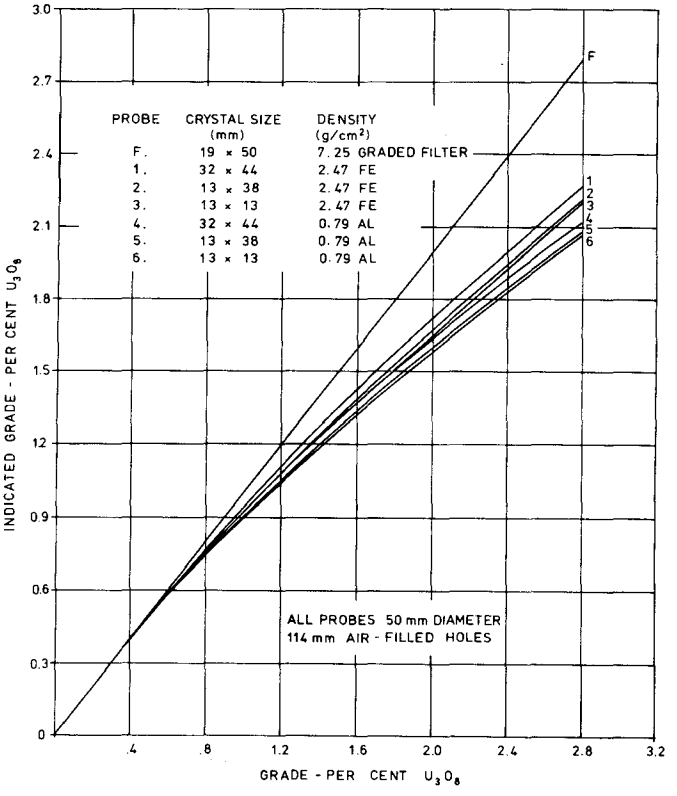


Figure 10C.21. *Non-linear increase of indicated ore grade (computed from count rate) with actual ore grade due to Z effect at high ore grades (after IAEA, 1976). The filtered probe 'F', by attenuating all gamma rays of original energies less than 400 keV produces a linear relation. Note the departure from linearity starts at about 0.5% U_3O_8. At higher grades the count rate (if it includes gamma rays of energies below 400 keV) will always cause an under estimate when computing ore grade.*

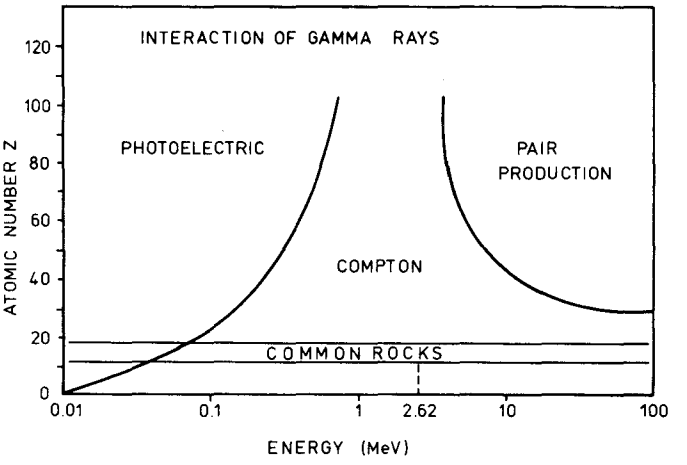


Figure 10C.22. *The most likely type of gamma ray interaction for a range of gamma ray energies and equivalent atomic number (Zeq). The range of Zeq for common rocks is also indicated (after Dodd and Eschliman, 1972). When Zeq of a rock increases due to high uranium content, the photoelectric effect becomes a more dominant reaction at low energies. This causes a non-linear relation between count rate and ore grades unless only energies above 0.4 MeV are considered.*

The Breckenridge test strip used by the Geological Survey of Canada is located on the Ottawa River flood plain which is flat, and uniform in radioactivity (Charbonneau & Darnley, 1970a; Grasty and Charbonneau, 1974), 7 km long, and close to the river which is about 1 km wide. A railroad track along the test strip is a convenient aid to navigation and facilitates reproducible results. Both the over-railway and over-water test strips are flown at altitudes of 60, 90, 120, 150, 180, 210 and 240 m. Typical values for sensitivities, stripping ratios, and height attenuation coefficients are given by Grasty (1979) for various detector sizes.

To ensure the continuing calibration of airborne gamma ray spectrometer during a field survey, the system can be monitored with a series of tests which are carried out daily to see that point sources give unchanging results.

Calibration of Borehole Systems

The calibration of gamma ray spectral logging systems is affected by many parameters, and some of these effects still remain to be determined. However a great deal of information is available on total count gamma ray logging, and calibration for quantitative measurement (Scott et al., 1961; Scott, 1963; Rhodes and Mott, 1966; Conaway and Killeen, 1978a).

The calibration of a total count gamma-ray logging system requires the determination of the K-factor (or sensitivity) which is the constant of proportionality between the grade thickness product (GxT) of a radioactive zone, and the area (A) under the curve of the gamma ray log, i.e.

$$GT = KA \qquad (25)$$

In the case of an 'infinitely' thick homogeneous zone and only in that case is the grade directly proportional to the peak height or intensity (I) of the gamma ray log anomaly, i.e.

$$G = KI \qquad (26)$$

The determination of K is thus simplified by making measurements in model holes with "infinitely" thick ore zones (approximately 1 m thick or greater).

A set of appropriate model holes can also be used to provide water-correction factors, casing correction factors, and dead time measurements (Dodd and Eschliman, 1972). For these measurements, model holes of different diameters and casing or drill pipes of different thicknesses must be available. A graph of water correction factors for different borehole diameters is shown in Figure 10C.19 and typical casing correction factors are shown in Figure 10C.20 for various thicknesses of casing (after Dodd and Eschliman, 1972). These authors also pointed out the nonlinear response of total gamma ray intensity caused by the increasing equivalent atomic number (Zeq) of the rock as the ore grade increases. This effect is shown in Figure 10C.21. Gamma rays of low energies are strongly attenuated when the Zeq increases above that for common rocks.

An important diagram illustrating the relationship between equivalent atomic number (Zeq) and gamma ray energy with respect to the most probable gamma ray interaction is shown in Figure 10C.22. This figure has been used in various forms by Evans (1955), Siegbahn (1968), Adams and Gasparini (1970), and Dodd and Eschliman (1972). It can

be seen that as Zeq increases, the proportion of photoelectric effect interactions increases for low energy gamma rays. However, for gamma rays above about 400 keV there is little change. Thus there should be a linear relation between gamma ray count and ore grade when a suitable filter or shield is used on the detector to eliminate these low-energy gamma rays. Larger detectors can then be used to increase the count rate which was diminished by the filter. In gamma ray spectral logging, a total count channel with a 400 keV low level threshold will provide count rates which vary nearly linearly with ore grade. It has been suggested by Czubek (1968) that this Z effect might be used to advantage by a gamma ray spectral logging system. He suggested the ratio of high energy to low energy gamma ray count rates could be used as a parameter which varies inversely with ore grade (i.e. Zeq). The method has been tested to some extent as mentioned by Dodd and Eschliman (1972), although it has not become commonly used. This may be partly due to the fact that radioactive disequilibrium may produce the same effect as a change in Zeq.

Gamma ray spectral logging systems must be calibrated in model holes containing "ore zones" of thorium, and of potassium, in addition to the usual uranium ore zone found in model holes used to calibrate total count logging systems. The calibration procedure is similar to that described for calibration of surface systems. A statistically adequate count rate must be obtained for each ore zone. These count rates and the radioelement analysis (grade) of the ore zone material are the input data to a regression analysis computer program which solves for the values of the sensitivities and stripping factors as described in earlier sections.

Instead of one K-factor as for the total count gamma ray log, there are three K-factors which relate to the area under the curve of the gamma ray log for each radioelement. Thus:

$$G_K T = K_K A_{K(NET)} \quad (27)$$

$$G_U T = K_U A_{U(NET)} \quad (28)$$

$$G_{Th} T = K_{Th} A_{Th(NET)} \quad (29)$$

where the subscripts denote the particular radioelement. The areas "$A_{(NET)}$" are the areas under the curve of the 'stripped' gamma ray spectral window logs. For example continuing in the simplified fashion of the section describing sensitivities or K-factors for in situ assaying the net counts are:

$$A_{Th(NET)} = A_{Th(RAW)} - B_{Th} \quad (30)$$

$$A_{U(NET)} = A_{U(RAW)} - \alpha X A_{Th(NET)} - B_U \quad (31)$$

$$A_{K(NET)} = A_{K(RAW)} - \beta X A_{Th(NET)} - \gamma X A_{U(NET)} - B_K \quad (32)$$

where the B_{Th}, B_U and B_K are the backgrounds (if any).

For the reduction of data from gamma ray logs recorded in the field, two methods are available. An iterative technique has been described by Scott (1963) and Scott et al. (1961), and a deconvolution or inverse filtering technique has been described by Conaway and Killeen (1978a). Both techniques require that the shape of the anomaly produced by an ore zone in a model hole be accurately determined. This shape defines the response of the gamma ray logging system and is used as the basis for the iteration or the inverse filtering (Conaway and Killeen, 1978b; Czubek, 1971, 1972).

The iterative technique is essentially the fitting of a synthetic anomaly (based on the system response function) to the measured anomaly. The synthetic anomaly is made by summing individual anomalies produced by hypothetical layers. During each iteration the grades of the hypothetical layers are adjusted, the synthetic anomaly is recomputed and its goodness of fit is tested. In the deconvolution technique an inverse filter is developed which can remove the effects of the system response. This inverse filter can be used in nearly real time to produce a deconvolved gamma ray log as suggested by Killeen et al. (1978) wherein the gamma ray logscale has been converted to grade, rather than count rate.

Calibration Facilities

Calibration facilities for total count gamma ray logging were first made available in the USA in the early 1960s, with an additional model hole each for K, U and Th for gamma ray spectral logging being built in 1974 (Knapp and Bush, 1975). The first large calibration pads for calibrating airborne and ground gamma ray spectrometer systems were built in Ottawa in 1968 (Darnley, 1970; Grasty and Darnley, 1971); five pads were built in Grand Junction, Colorado in 1976 (NURE, 1976). Four calibration pads built specifically for portable gamma ray spectrometers were constructed at Risø in Denmark in 1971 (Løvborg et al., 1972; Løvborg and Kirkegaard, 1974; Løvborg et al., 1978a, b). Radiometric test ranges (test strips) were established at Breckenridge near Ottawa in 1970 (Charbonneau and Darnley, 1970a; Grasty and Charbonneau, 1974), and near Lake Mead, Arizona (NURE, 1976). Extensive calibration facilities for borehole gamma ray spectral logging (3 radioelements, 9 models, 27 holes), and for surface portable gamma ray spectrometry (10 pads) were constructed in Ottawa in 1977 (Killeen, 1978; Killeen and Conaway, 1978). In addition seven pads were constructed in Calgary, and 2 model holes in Fredericton. Calibration facilities in South Africa at Pelindaba have been described by Toens et al. (1973). Recently a set of five large calibration pads has been constructed in Iran for airborne gamma ray spectrometry, and a set of large pads is in preparation in Brazil. Additional calibration facilities are being constructed in many countries, as their desirability is being recognized for uranium exploration programs. Some of the existing facilities are described in greater detail below.

Canada

Five concrete pads for calibration of airborne gamma ray spectrometer systems are located at Uplands airport in Ottawa. They are located adjacent to, and level with, a concrete parking area. Aircraft may taxi or be towed onto or off of the slabs. The aircraft must be able to back off each

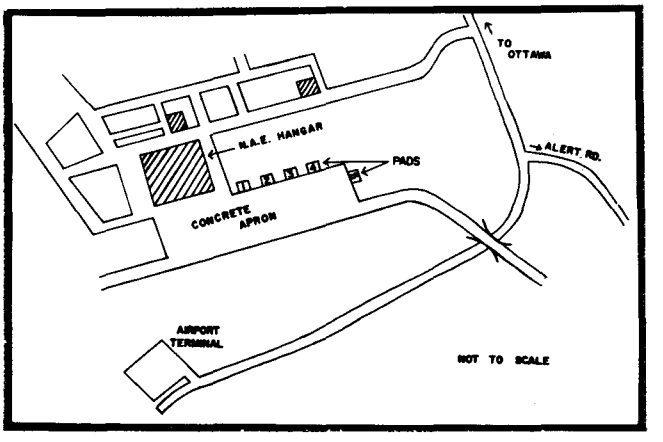


Figure 10C.23. *Geological Survey of Canada calibration pads for airborne gamma ray spectrometric systems at Ottawa, Ontario (after Grasty and Darnley, 1971). Radioelement concentrations are given in Table 10C.2.*

Table 10C.2

Radioelement concentrations of calibration facilities for airborne gamma ray spectrometer systems

Location	Pad Number	K% ± 1σ	eU ppm ± 1σ	eTh ppm ± 1σ
Canada[1]	1	1.70 ± 0.08	2.4 ± 0.2	8.9 ± 0.6
	2	2.27 ± 0.10	7.3 ± 0.2	12.6 ± 0.7
(Uplands Airport,	3	2.21 ± 0.08	3.0 ± 0.3	26.1 ± 0.9
Ottawa)	4	2.21 ± 0.01	2.9 ± 0.3	40.8 ± 1.9
	5	2.33 ± 0.09	11.7 ± 0.3	13.2 ± 0.7
		K% ± 2σ	eU ppm ± 2s	eTh ppm ± 2σ
United States[2]	1	1.45 ± 0.01	2.2 ± 0.1	6.3 ± 0.1
	2	5.14 ± 0.09	5.1 ± 0.3	8.5 ± 0.3
(Walker Field,	3	2.01 ± 0.04	5.1 ± 0.2	45.3 ± 0.7
Grand Junction)	4	2.03 ± 0.05	30.3 ± 1.6	9.2 ± 0.3
	5	4.11 ± 0.06	20.4 ± 1.3	17.5 ± 0.3
Iran[3]	1	2.31	1.80	7.91
	2	2.23	18.64	8.79
(Tehran)	3	2.17	2.80	46.0
	4	2.30	9.71	19.1
	5	2.09	1.93	9.11
Lake Mead Test Range[4] (U.S.A.)	—	2.5	2.6	11.6
Breckenridge Test Range[5] (Canada)	—	2.0	0.9	7.7

[1]from Grasty and Darnley (1971).
[2]from Stromswold (1978).
[3]from D. Blohm, pers. comm. (1978).
[4]from Foote (1978).
[5]from Grasty and Charbonneau (1974).

pad under its own power or be towed onto the concrete apron to reposition the aircraft on the next pad. The pad dimensions are 7.6 m x 7.6 m x 46 cm thick and they are spaced 15.2 m apart. A diagram of their relative locations is shown in Figure 10C.23. The concentrations of the radioelements in the calibration pads are given in Table 10C.2.

The five pads at Uplands Airport, which had also previously been used for calibration of portable instruments, have a limited range of radioelement concentrations because they were designed for calibrating airborne gamma ray spectrometers with large detector volumes. In 1977, a calibration facility consisting of ten calibration pads and 9 test columns with 3 model boreholes in each column was constructed at Bells Corners, approximately 10 km west of Ottawa. The calibration pads are concrete cylinders, 60 cm thick by 3 m in diameter, making effectively infinite sources if the detector of the portable gamma ray spectrometer is located near the centre of, and within a few centimetres of, the upper surface of the pad. Three of the pads contain different potassium concentrations, three contain different uranium concentrations and three contain different thorium concentrations. A tenth pad, referred to as the blank pad, was constructed with no radioelement additives. The radioelement concentrations in these 10 calibration pads are given in Table 10C.3.

For calibration of borehole gamma ray spectrometers under controlled conditions, nine concrete test columns have been constructed along the wall of an abandoned rock quarry at the same location (Fig. 10C.24). Each of these columns is 3.9 m in height with a simulated ore zone 1.5 m thick sandwiched between upper and lower barren zones (Fig. 10C.25). Each test column contains 3 boreholes of nominal diameters 48 mm (size A), 60 mm (size B), and 75 mm (size N) intersecting the ore zones. Three of the test columns contain ore zones of different concentrations for potassium, three for thorium, and three for uranium. The radioelement concentrations in these 9 ore zones are given in Table 10C.4.

Seven additional calibration pads for portable gamma ray spectrometers have been constructed in Calgary with the same physical dimensions as those at Ottawa. The radioelement concentrations are given in Table 10C.3. Two model boreholes constructed in Fredericton have ore zones of uranium, 1.5 m thick and of approximate grades 100 and 1000 ppm. These may be used to calibrate total count gamma ray logging equipment. Additional calibration facilities are planned at other Canadian locations.

The radioelement concentrations measured on the Breckenridge test range for airborne systems (described earlier) are given in Table 10C.2.

The U.S.A.

The U.S. Department of Energy has five concrete calibration pads, each 9.1 m by 12.2 m and 46 cm thick, located at Walker airfield, Grand Junction, Colorado. The pads are arranged in a line as shown in Figure 10C.26, with a turn-around at the end of the line of pads making it possible for an aircraft to taxi in a forward direction from pad to pad and return. The radioelement concentrations are given in Table 10C.2.

Table 10C.3

Radioelement concentrations of calibration facilities for portable gamma ray spectrometer systems

Location	Pad Number	K%	eU ppm	eTh ppm
Canada[1]	PK-1-OT	0.8	—	—
	PK-2-OT	1.5	—	—
	PK-3-OT	3.0	—	—
	PK-4-OT	—	10	—
Ottawa	PU-5-OT	—	45	—
(Bell's Corners)	PU-6-OT	—	450	—
	PT-7-OT	—	—	8
	PT-8-OT	—	—	60
	PT-9-OT	—	—	300
	PB-10-OT	0.2	0.2	1
Canada[2]	PK-1-C	1.4	—	—
	PK-2-C	2.4	—	—
	PU-3-C	—	30	—
Calgary	PU-4-C	—	300	—
	PT-5-C	—	—	45
	PT-6-C	—	—	355
	PB-7-C	0.5	1	2
Denmark[3]	0	1.0	0.8	2.4
	1	7.0	4.2	2.7
Risø	2	0.8	6.3	151.
	3	1.0	198.	8.
South Africa[4]	Uranium - Pad 1	0.29	3731	290
	Uranium - Pad 2	.33	2078	202
	Uranium - Pad 3	.29	1255	114
	Uranium - Pad 4	.37	458	44
	Uranium - Pad 5	.33	12	<0.9
Pelindaba	Thorium - Pad 1	±1.66	280	12570
	Thorium - Pad 2	±1.66	102	3870
	Thorium - Pad 3	±1.66	68	3080
	Potassium Pad	10.1	0.4	0.9
	Mixed Pad	±1.2	763	4395
	Background Pad	0.33	0.5	0.9
South Africa[4] Beaufort West	Uranium Pad	.12	1153	75
United States[5]	Background	2	5	10
	Potassium	7.8	5	10
Grand Junction	Uranium	2	500	10
and Field Sites	Thorium	2	30	700
(Proposed)	Mix	4	350	250

[1]from preliminary data of Killeen and Conaway (1978).

[2]from preliminary data of Richardson and Killeen (1979).

[3]from Løvborg et al. (1978).

[4]from Corner and Toens (1979).

[5]from Evans (1978).

For calibration of portable (total count) scintillometers, four circular concrete pads containing uranium ore of dimensions 43 cm deep by 107 cm diameter are located at Grand Junction. Uranium grades are 80, 260, 1220, and 2830 ppm eU. In addition, two calibration pads are located at each of three field locations

Casper, Wyoming (265 and 1250 ppm eU)

Grants, New Mexico (270 and 1230 ppm eU)

George West, Texas (270 and 1250 ppm eU)

Additional facilities at other field locations are planned.

For calibration of portable gamma ray spectrometers, sets of five calibration pads, 60 cm thick by 1.2 m in diameter, are planned at all sites. The proposed composition of the pads is given in Table 10C.3.

Calibration facilities at Grand Junction for total count gamma ray logging include four uranium models, and a water factor model. These models have the following uranium concentrations: 17 400, 9075, 3765, 2020 and 2710 ppm eU. For gamma ray spectral logging, three model boreholes with ore zones 1.5 m thick are available with radioelement concentrations as given in Table 10C.4. In addition, a spectral or 'KUT' water-factor model was recently completed with proposed radioelement concentrations of 4 per cent K, 350 ppm eU, 250 ppm eTh.

At the three field locations, there are two uranium model boreholes, with additional sets planned at other field locations. The uranium concentrations in the existing models are:

Casper, Wyoming: 16 090 and 2790 ppm eU

Grants, New Mexico: 14 750 and 2630 ppm eU

George West, Texas: 14 400 and 2290 ppm eU.

The U.S. Department of Energy also plans additional spectral logging calibration models at all sites.

Recently, two new models have been constructed in Grand Junction containing thin dipping ore zones (Fig. 10C.27). The beds are 5 cm thick with ore grade of 1780 ppm eU. The models are 1.2 m in diameter, and the four beds or ore zones are at angles of 30, 45, 60 and 90 degrees (i.e. perpendicular) with respect to the borehole.

Besides the above-mentioned man-made calibration facilities, a radiometric test range is available for airborne gamma ray spectrometers. Referred to as the "Lake Mead Dynamic Test Range", it is located about 48 miles due east of Las Vegas, Nevada. Radioelement concentrations are given in Table 10C.2. An additional test range is planned.

Denmark

Four concrete calibration pads were constructed at the Research Establishment, Risø, near Roskilde, with dimensions 3 m diameter by 0.5 m thick. Their radioelement concentrations are given in Table 10C.3. The construction and monitoring of these pads has been described by Løvborg et al. (1978a).

Iran

A set of large calibration pads has been constructed in Iran at an airport in Tehran. These pads are circular with a 30 m diameter, and are spaced approximately 50 m apart in

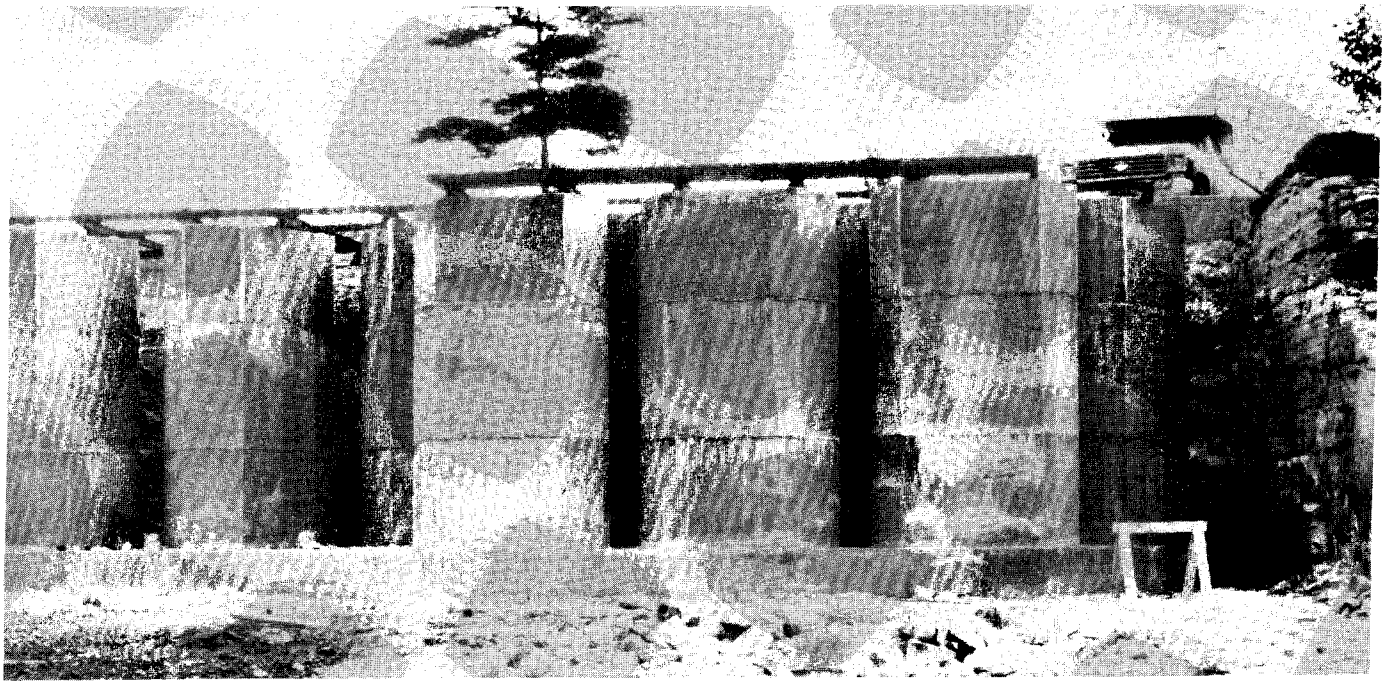


Figure 10C.24. *Geological Survey of Canada concrete test columns containing three model boreholes each, penetrating "ore zones". Bells Corners, Ottawa, Ontario (after Killeen, 1978). Three grades for each radioelement (K, U, and Th) are available as described in the text. Concentrations are given in Table 10C.4. (GSC 203254-O)*

such a fashion as to allow an aircraft to taxi down the row of pads and back onto the tarmac. The radioelement concentrations of the pads are given in Table 10C.2.

South Africa

Calibration facilities were established at the national Nuclear Research Centre in Pelindaba in 1972 (Toens et al., 1973). These facilities now have eleven concrete pads 2 m in diameter by 0.3 m thick (Corner and Toens, in press) including five uranium pads, three thorium pads, one potassium pad, one mixed, and one background pad. The two model boreholes at the facility also contain single uranium and thorium 'ore' zones respectively. The models are 2.2 m long with 'ore' zones 0.95 m thick and a 12 cm diameter borehole. An additional calibration pad and model borehole were constructed in the uranium exploration area of the southern Karoo in Beaufort West. The radioelement concentrations of all of these calibration models are given in Tables 10C.3, 10C.4 (after Corner and Toens, in press). An 8 km long calibration strip for airborne gamma ray spectrometers is also available, located on Ecca Series sediments. Radioelement concentrations in the test strip average 2.44 ppm U, 3.09 ppm Th and 0.43% K_2O (D. Richards, pers. comm., 1978).

The use of the model holes was briefly mentioned by Corner and de Beer (1976).

Other Locations

New calibration pads and model holes are either planned or already under construction in many parts of the world as nations implement the recommendations of the IAEA (1976), (e.g. in Brazil, Spain, Australia). Pads for calibration of airborne gamma ray spectrometers have recently been constructed in Sweden using assemblies of precast concrete blocks fitted together to form large pads. Construction of model boreholes is also planned in Sweden (A. Hesselbom, pers. comm., 1978). A set of four pads, each 8 m square, has been constructed recently at an airport near Helsinki, Finland (Peltoniemi, pers. comm., 1978). Expansion of existing facilities in Canada and the U.S.A. is either planned or underway.

Some Recommendations Regarding Construction of Calibration Facilities

The IAEA has summarized the main points regarding construction of calibration facilities in Technical Report Number 174 (1976). Some data on the details of construction of the calibration pads in Denmark have been presented by Løvborg et al. (1978a, b; 1972). The construction of the large calibration pads for airborne systems was described by Grasty and Darnley (1971) for the pads at Ottawa, and by Ward (1978) for the pads at Grand Junction. A good description of the construction of the three K, U and Th model holes at Grand Junction is given by Knapp and Bush (1975). A description of the detailed construction specifications for the 10 calibration pads and test columns with model holes at Ottawa has been given by Killeen (1977).

National and International 'Standards'

Recalling Figure 10C.16, it can be seen that all calibration relies on some internationally agreed upon 'standards'. These are usually specially selected samples prepared in bulk, analyzed by several methods by several laboratories, and distributed by some recognized laboratory which maintains a large quantity of the standard for distribution, for a fee. In the United States and Canada, the samples generally used for standards are those available from the Standards and Reference Materials Section, U.S. Department of Energy, New Brunswick Laboratory, Building D350, 9800 South Cass Ave., Argonne, Illinois, 60439. These consist of 100 gram

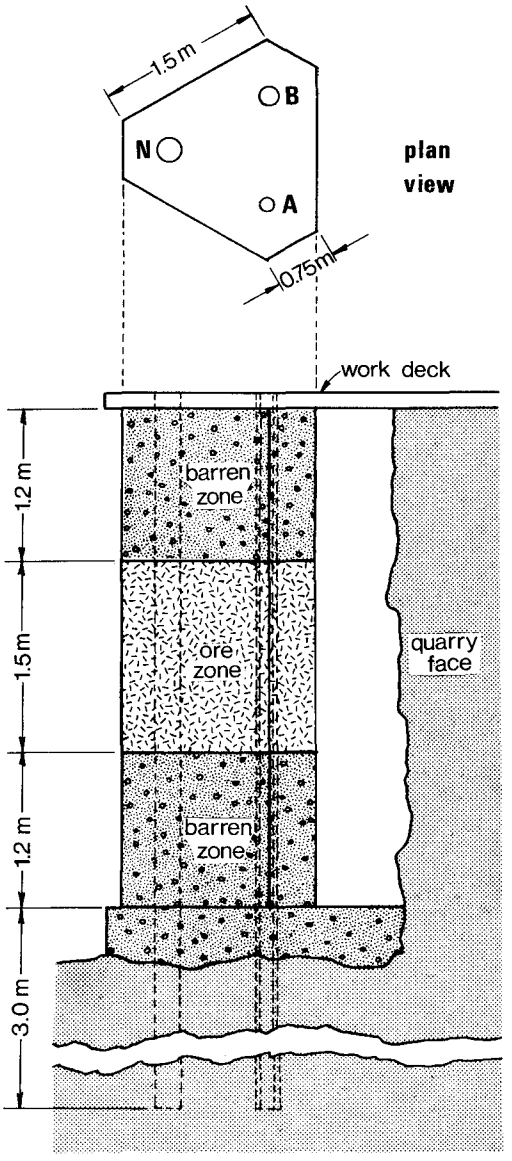


Figure 10C.25. *Construction schematic showing one of the Geological Survey of Canada test columns at Bells Corners, Ottawa, Ontario (after Killeen and Conaway, 1978).*

bottles of crushed uranium ore and are available in concentrations of 10 ppm to 4 per cent U. Thorium samples (monazite sand mixtures) are also available from 10 ppm Th to 1 per cent Th.

It is important that the samples be in radioactive equilibrium or that the state of disequilibrium be known since the samples will be used to calibrate a radiometric method of analysis rather than a chemical method. Another source of standards is the Department of Energy, Mines and Resources, Canadian Certified Reference Materials Project, Mineral Sciences Laboratories, CANMET (Canada Centre for Mining and Energy Technology), 555 Booth St., Ottawa, Ontario, K1A 0G1. Samples available include Beaverlodge, Saskatchewan pitchblende uranium ore in concentrations from 220 ppm U to about 6 per cent U and Elliot Lake uranium ore containing both U and Th up to 1000 ppm.

Table 10C.4

Radioelement concentrations of calibration facilities for borehole gamma ray spectrometer systems

Location	Borehole Model	K%	eU ppm	eTh ppm
CANADA[1]		BK-1-OT	0.7	–
	BK-2-OT	1.1	–	–
	BK-3-OT	3.0	–	–
Ottawa	BU-4-OT	–	15	–
(Bell's Corners)	BU-5-OT	–	100	–
	BU-6-OT	–	950	–
	BT-7-OT	–	–	8
	BT-8-OT	–	–	35
	BT-9-OT	–	–	350
SOUTH AFRICA[2]	Uranium	0.33	1221	114
Pelindaba	Thorium	0.51	19	890
SOUTH AFRICA[2] Beaufort West	Uranium	0.22	127	14
UNITED STATES[3]	K	6.30	2.9	2.5
(Grand Junction)	U	0.95	522	18.7
	T	1.36	26.1	508

[1] from preliminary values of Killeen and Conaway (1978).

[2] from Corner and Toens (1979).

[3] from Mathews et al. (1978).

AIRBORNE GAMMA RAY SPECTROMETRIC SURVEYS

Introduction

The application and interpretation of airborne gamma ray spectrometry rests on the foundation laid by earlier workers in total count scintillometry. Many of the techniques developed for airborne scintillometer surveys with respect to logistics and planning, data reduction and presentation, interpretation and correlation with geology, are applicable to airborne gamma ray spectrometer surveys. It is instructive to read the earlier literature on the subject (see e.g. Stead, 1950; Peirson and Franklin, 1951; Cook, 1952; Cowper, 1954; Agocs, 1955; Gregory, 1955, 1956, 1960; Bowie et al., 1958; Moxham, 1958, 1960; Guillou and Schmidt, 1960; Gregory and Horwood, 1963; Pitkin et al., 1964; Pitkin, 1968).

By 1966 some of the first papers on airborne gamma ray spectrometric surveying were being published (e.g. Pemberton and Seigel, 1966; Hartman, 1967) as well as the first descriptions of the data acquisition systems and processing of airborne gamma ray spectral survey data (see e.g. Bristow and Thompson, 1968; Foote, 1969; Grasty, 1972). The many aspects of data acquisition systems have been reviewed by Bristow (1979) and the theory and operational procedures have been reviewed by Grasty (1979) and Breiner et al. (1976). The application and interpretation of airborne gamma ray spectrometry requires a background knowledge of these two aspects of the subject as well as an integrated knowledge of the geology of uranium and thorium.

Selecting Survey Parameters

Airborne gamma ray spectrometric applications to uranium exploration fall into two main categories: reconnaissance surveys and detailed surveys.

The design of the survey must be aimed at answering the question: "How do the results of such a survey relate to potential uranium deposits?" The literature on reconnaissance airborne surveys and on detailed surveys is

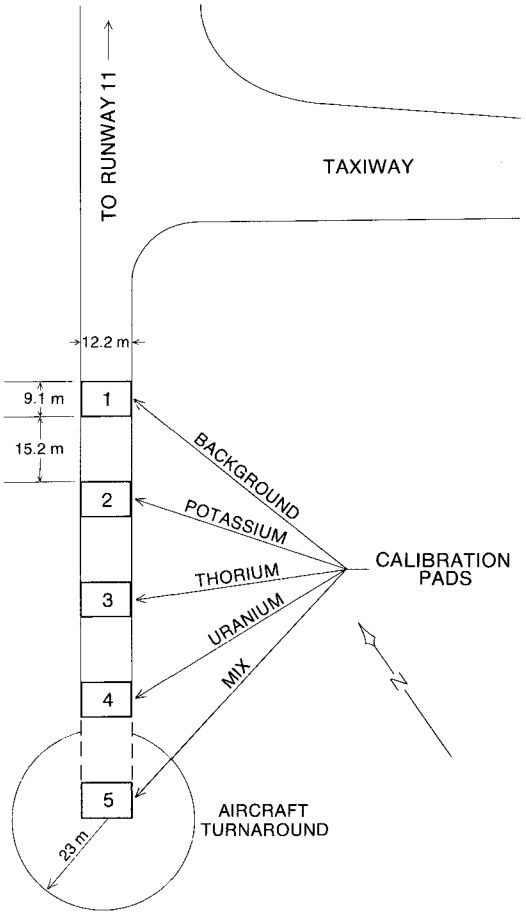


Figure 10C.26. *Arrangement of U.S. Dept. of Energy (U.S. D.O.E.) calibration pads at Walker Field, Grand Junction, Colorado for calibration of airborne gamma ray spectrometers (after Ward, 1976). Radioelement concentrations are given in Table 10C.2.*

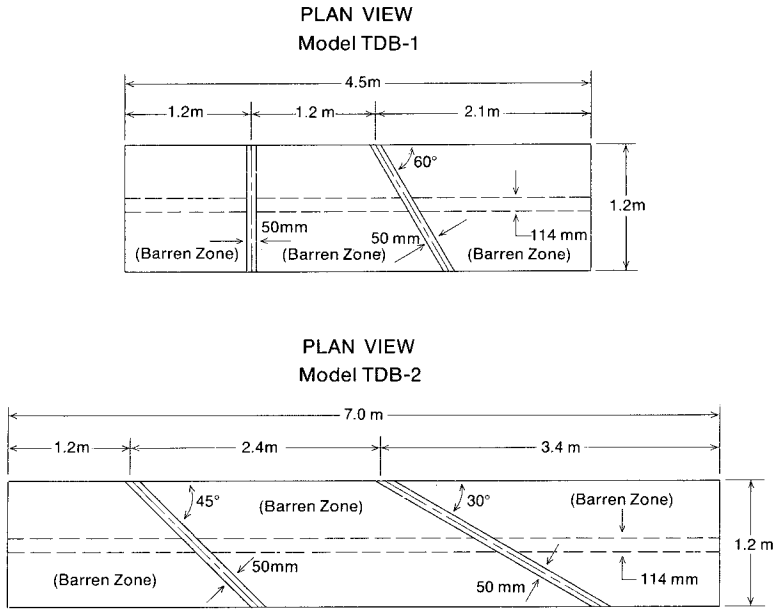


Figure 10C.27. *Thin dipping ore zone models for borehole gamma ray logging at Grand Junction, Colorado (U.S. D.O.E.) (after Evans, 1978).*

often intermingled; the latter is frequently a logical followup to the former. The design of a survey should consider line spacing, terrain clearance, detector volume, aircraft speed and sampling time.

A rather general paper on airborne geophysics by Willox and Tipper (1969) included examples of surveys by gamma ray spectrometry and Tipper (1969) described the airborne gamma ray spectrometer system used and the survey operation. Tipper pointed out that the line spacing (commonly 400 to 800 m) is generally a compromise between cost, the required detail, and the size of the survey area. The size of radioactive targets being sought and the possibility of subsequent more detailed flying must also be taken into account. The ground clearance which is generally between 75 and 150 m should be related to line spacing and aircraft safety. For detailed surveys the aircraft should be flown at a constant terrain clearance which is as low as possible. However, navigation then becomes more difficult, and high quality aerial photography becomes essential for flight path recovery.

A comparison of parameters of both a fixed wing and a helicopter gamma ray spectrometer was given by Darnley (1970) along with some measurements of the correlation between ground and airborne measurements.

A paper by Darnley (1972) includes three appendices on:

1. cost effectiveness of airborne radiometric surveys;
2. sample specifications for high sensitivity gamma ray spectrometer surveys; and
3. common causes of unsatisfactory airborne radiometric surveys.

An early application of Fourier analysis to airborne gamma ray spectrometric data was given by Killeen et al. (1971, 1975). They considered the target to cause an anomaly of a certain spatial 'wavelength', and from the desired target size derived some relations about the effects of altitude and sampling rate. Tipper and Lawrence (1972) presented gamma ray spectrometer profiles across the Nabarlek orebody in Australia flown at four different altitudes (120 to 300 m) as examples in a case history.

Calculations of the volume of material viewed by an airborne gamma ray spectrometer were presented by Duval et al. (1971) and by Grasty (1976a, b, and Grasty et al., in press). Figure 10C.11 shows the computed radius of the circle of investigation plotted as a function of altitude for a given percentage of infinite source yield, after Duval et al. (1971). Further work on the same type of computations was presented by Clark et al. (1972) and by Adams and Clark (1972).

Bowie (1973) discussed airborne radiometric survey requirements as well as other surveys in general. Nininger (1973) in reviewing exploration costs, considered relative costs of reconnaissance and detailed surveys. An IAEA Panel (1973a) summarized the application of airborne gamma ray spectrometer surveys incorporating Bowie's and Nininger's contributions in the following general statement:

"In practice two rather distinct approaches to airborne gamma-ray spectrometry have been developed to meet somewhat different objectives. One method uses a combination of gross-count and a minimal spectral capability to

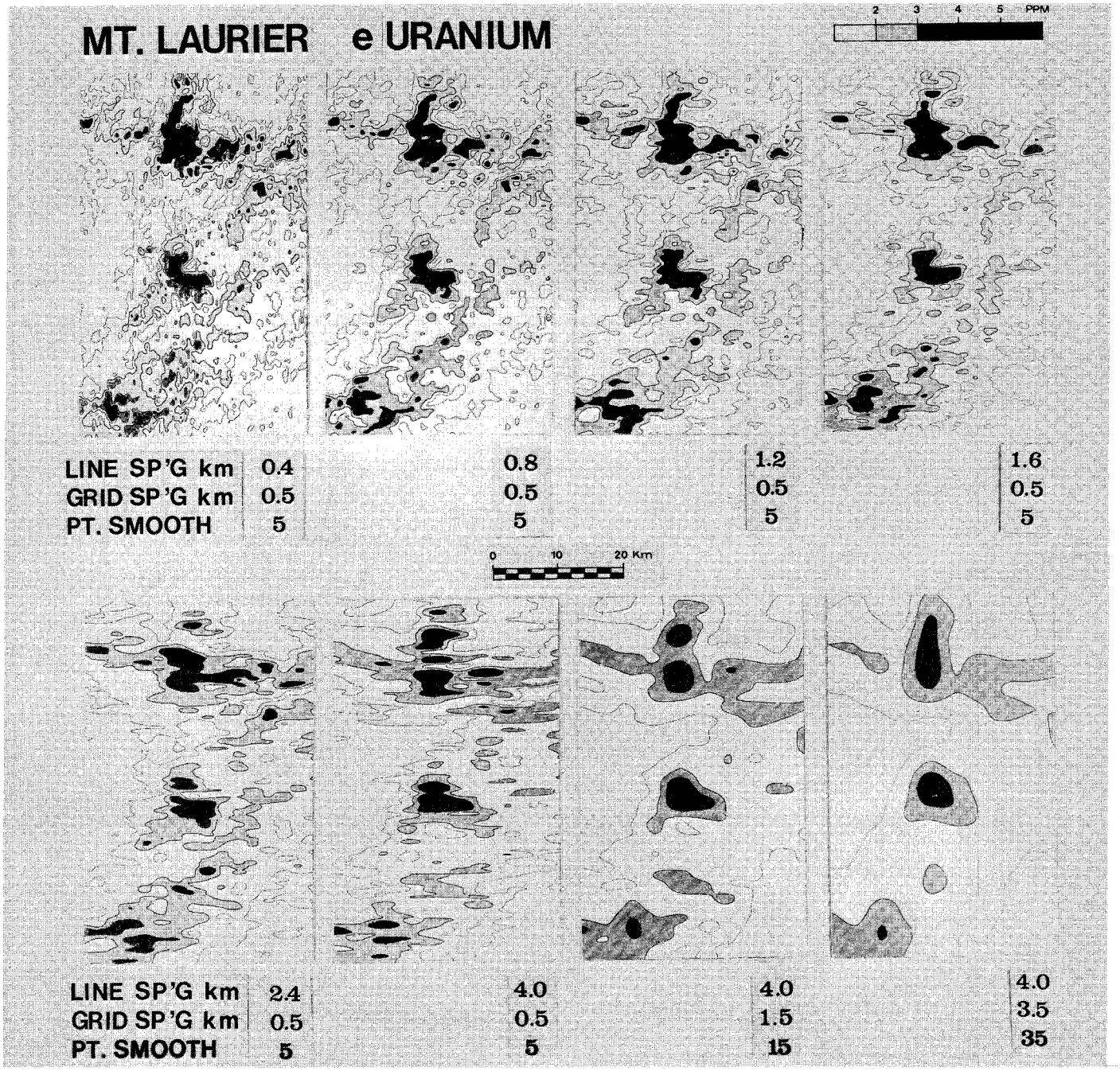


Figure 10C.28. *Comparison of the effect of flight line spacing on contoured eU values from airborne gamma ray spectrometric data (after Cameron et al., 1976). By appropriately deleting flight lines from a detailed (0.4 km spacing) survey, line spacings of 0.8 km, 1.2 km, 1.6 km, 2.4 km and 4.0 km are obtained and contoured with a grid spacing of 0.5 km and a 5 point smooth. A 15 point smooth appears to be optimum to avoid stretching of contours in the 4.0 km spacing case. The regional eU pattern evident from the 0.4 km spacing data is also readily apparent in the map produced from data along flight lines with 4 km spacing.*

achieve limited objectives. The other utilizes a high-sensitivity spectrometric capability to provide a sophisticated multi-parameter geochemical-statistical evaluation. The minimum system depends on gross-count for rapid regional search for anomalies and rudimentary geological mapping; spectral measurement of anomalies may identify the primary isotope, U, Th or K. The high-sensitivity spectral method is used for regional and area geochemical-geological mapping and to detect and map variations in lithology and anomalous radioelement ratios. Continuous ratio mapping is used to discover subtle anomalies often not indicated by gamma intensity alone. Sensitive spectrometry is most efficiently used to evaluate favourability of broad areas and for preliminary geological mapping".

Specifications for airborne gamma ray spectrometric surveys in Finland were arrived at by Ketola et al. (1975) on the basis of the results of a helicopter-borne test survey.

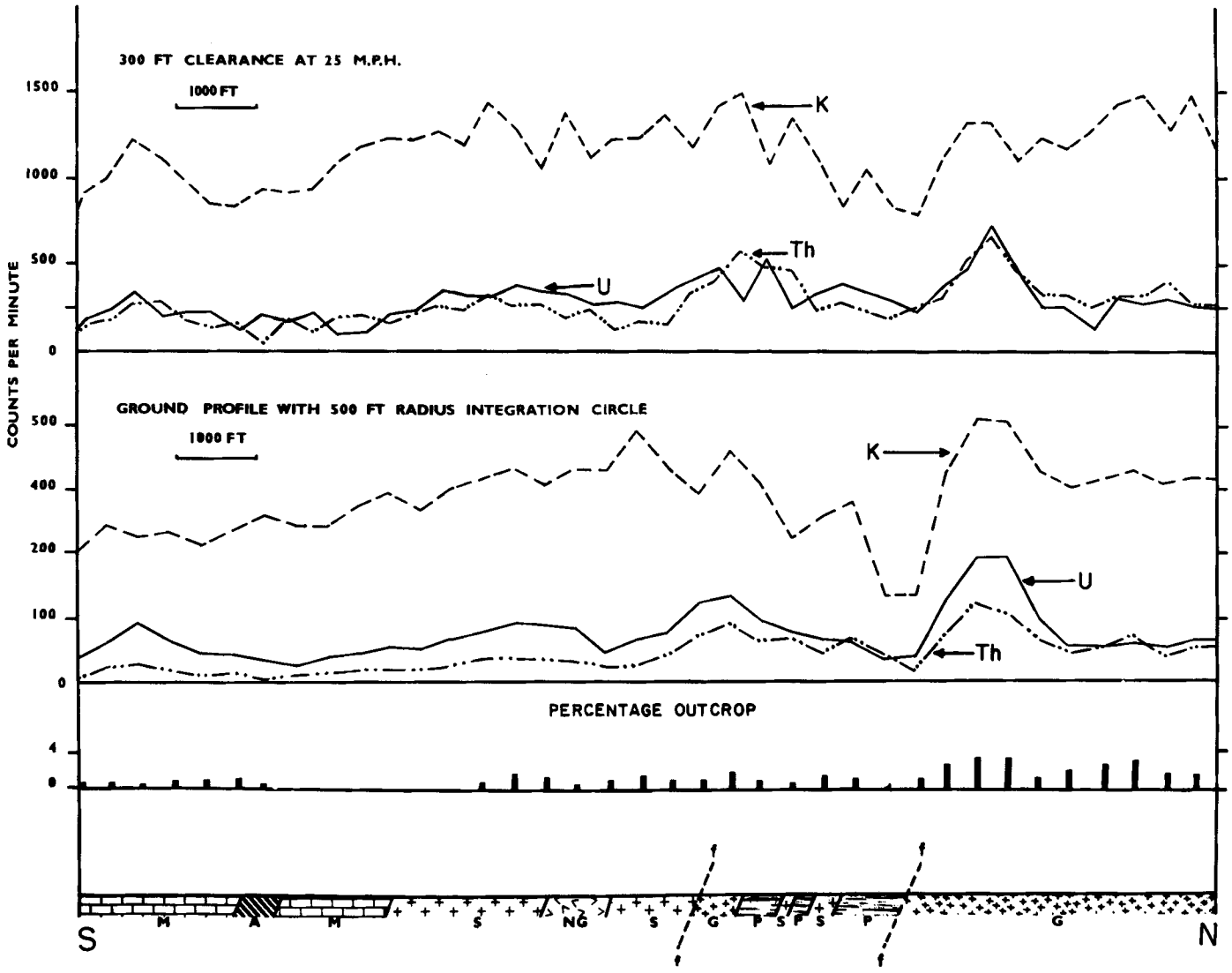


Figure 10C.29. *Count-rate profiles in the Bancroft area measured by an airborne gamma ray spectrometer system at 90 m altitude and by a portable gamma ray spectrometer on the ground (after Darnley and Fleet, 1968).*

They concluded that flight speed, altitude and detector volume were the most essential parameters affecting survey results. They also considered high quality data processing a dominant factor in determining the final result.

The effects of flight line spacing on contoured airborne gamma ray spectrometric data were investigated by Cameron et al. (1976). Using a survey of the Mont Laurier area with 400 m flight line spacing they selectively deleted alternate flight lines to simulate the same area flown with line spacings of 0.4, 0.8, 1.2, 1.6, 2.4, and 4.0 km. The resulting contour maps are shown in Figure 10C.28. They repeated this for the Elliot Lake area obtaining comparisons of flight line spacings of 0.5, 1.0, 1.5, 2.0, 3.0 and 5.0 km. Data from two coincident surveys in the Uranium City area with perpendicular flight line directions were also compared. They were able to demonstrate that surveys with 5 km flight line spacing were adequate to provide data for contoured regional radioelement distribution patterns over the Canadian Precambrian Shield.

Significance of Airborne Spectrometer Measurements

Darnley and Fleet (1968) described ground and airborne gamma ray spectrometry measurements over the Bancroft and Elliot Lake uranium mining areas of the Canadian Shield. A comparison of count-rate profiles measured at 90 m terrain clearance and on the ground is shown in Figure 10C.29 for the Bancroft area. The ground data were obtained from the integration of measurements within a 150 m radius circle moved along the flight line. The ground measurements were made on a grid with 60 m spacing. The airborne measurements were made with three 125 x 125 mm NaI(Tl) detectors in a helicopter flown at about 40 km/h. The similarity between the profiles is clear, indicating that these airborne measurements do indeed reflect the radioelement content of the ground. Darnley and Fleet (1968) presented histograms of count-rates obtained over various rock types, pointing out the potential for airborne gamma ray spectrometry as an aid to geological mapping. This paper drew attention to the importance of the ratio of uranium to thorium and uranium to potassium as indicators of possibly significant uranium mineralization.

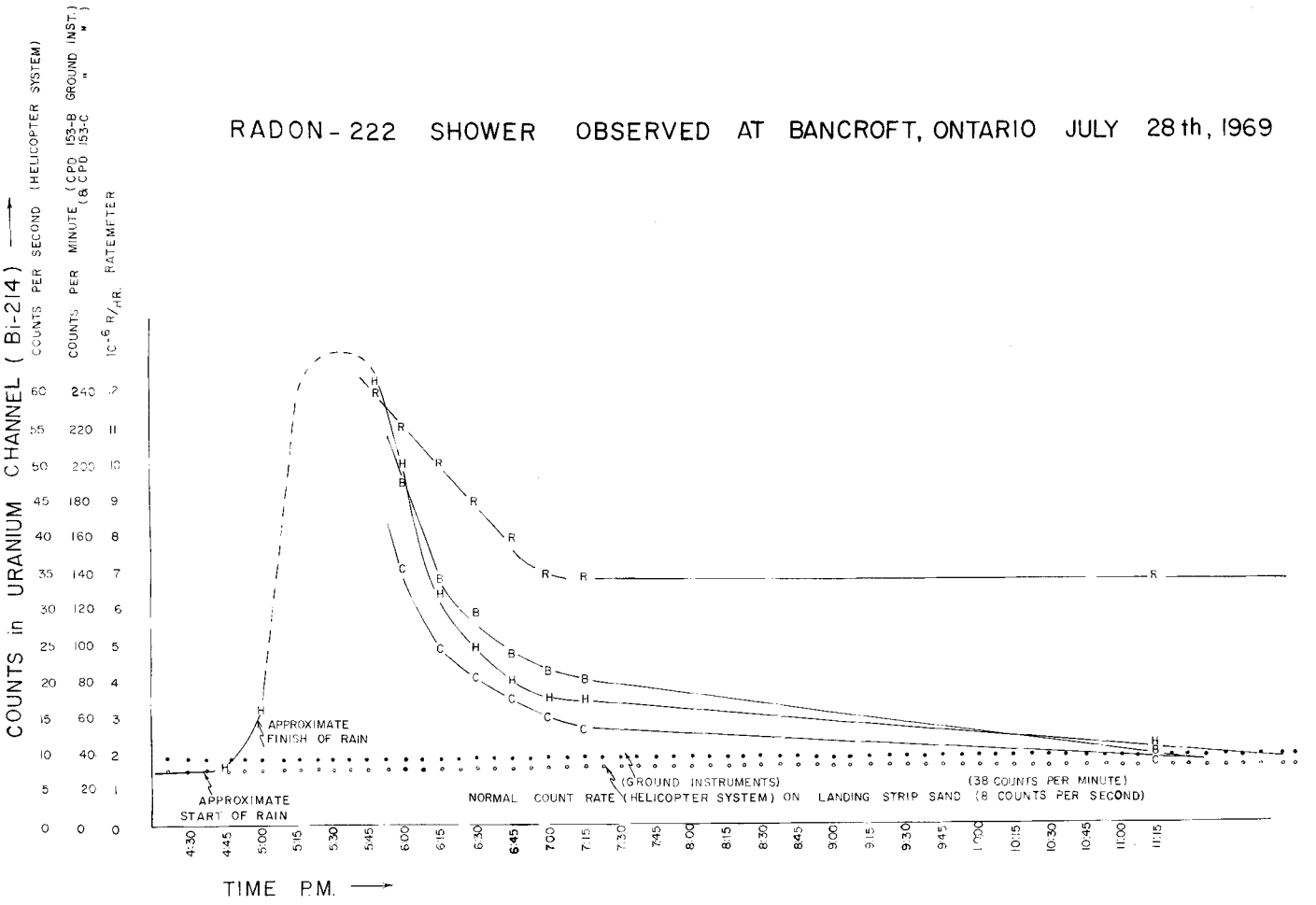


Figure 10C.30. *Count-rates recorded by a helicopter gamma ray system parked on the ground, 2 portable spectrometers, and a ratemeter, from the onset of a rain shower until 7 hours later (after Charbonneau and Darnley, 1970b).*

Experiences with helicopter-borne gamma ray equipment were described by Adams (1969). Profiles were presented for flights across beach sands, and granite jetties in the water off the Texas coast. A 3.5 m wide jetty was easily detected at a speed of 60 km/hr, at 15 m above the water using a 0.5 sec time constant and one 125 x 125 mm NaI(Tl) detector. However, the apparent width of the jetty determined from the anomaly was 58 m. Cook et al. (1971) presented further results using two 125 x 125 mm NaI(Tl) detectors with the same system.

For interpretation of the data other factors must be considered such as vegetation cover, percentage outcrop, and soil thickness and origin. For uncorrected data the variations in terrain clearance when the aircraft passes over valleys or hilltops may produce anomalies. Tipper (1969) indicated that the shape of anomalies on a contour map of total count may help to determine the contribution of the terrain effect. He also recommended that anomalies be interpreted on the basis of the ratios of the amplitudes in the different channels, and an understanding of the interference of the uranium, thorium, and potassium spectra in the energy windows.

Tipper further recommended that a short fixed traverse be reflown at least twice daily at the chosen survey altitude to monitor fluctuations in gamma ray attenuation caused by variations in humidity and soil dampness. These variations

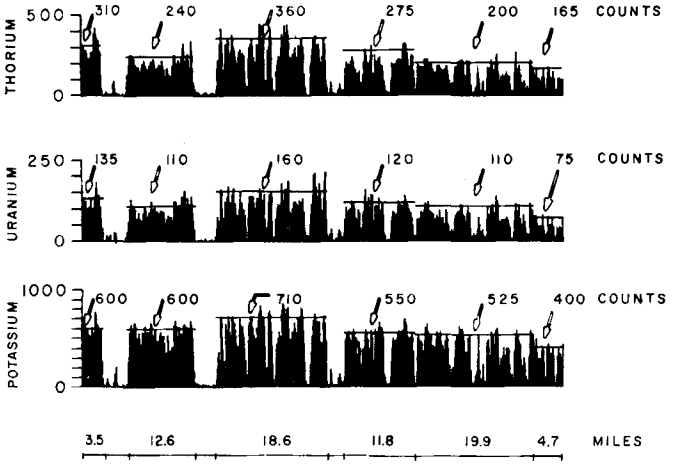


Figure 10C.31. *Illustration of the method of determining the mean count rate levels from gamma ray spectrometric profiles in the Hardisty Lake area (after Richardson et al., 1972) (see text).*

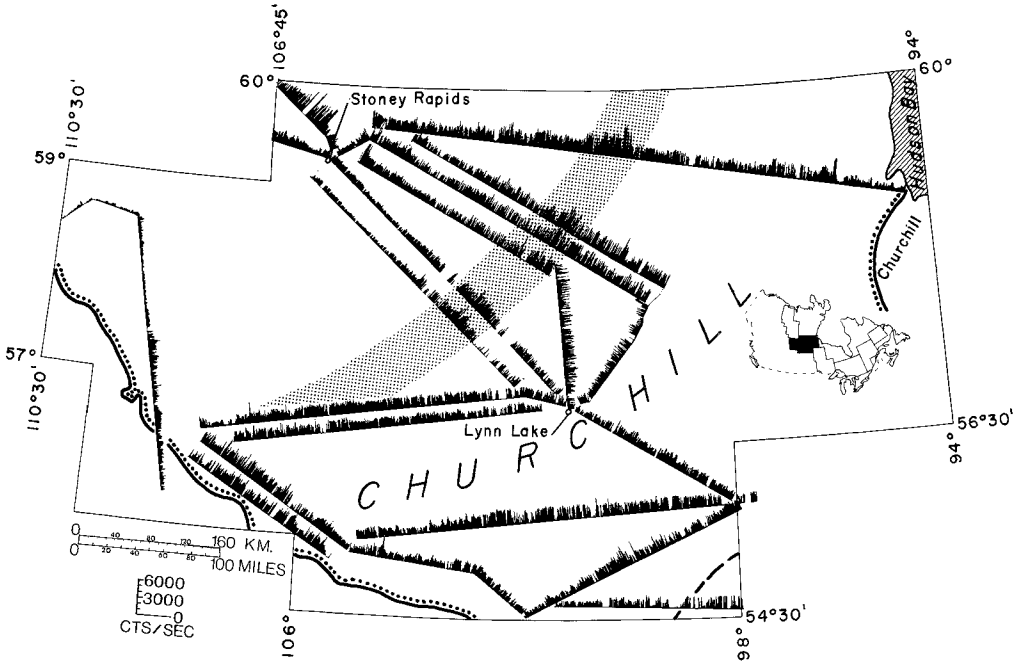


Figure 10C.32. *A set of cross-country profiles illustrating a belt of anomalous radioactivity 70 km wide and 480 km long in the Churchill Province of the Canadian Shield (after Richardson et al., 1972).*

are most significant if the timing of the survey is not carefully related to climate. Unless proper corrections are applied to each profile, spurious linear features parallel to the flight lines may occur on the resultant contour map.

Some measurements of the effect of rain on spectrometer measurements were presented by Charbonneau and Darnley (1970b). They plotted count rate changes with time during and after a heavy July rainfall which lasted for a 20 minute period. Four instruments were used: a helicopter spectrometer (parked on the ground), two portable gamma ray spectrometers, and a scintillometer. Figure 10C.30 shows a plot of the count rates recorded from the time of start of rain at 4:30 p.m. until about 7 hours later. The background radioactivity increased by a factor of 6 to a maximum about one hour after the rain started and thereafter decreased with about 30 minute half-life. Thus it is clear that gamma ray spectrometric surveys should not be carried out during or shortly after heavy rainstorms. Foote (1964) reported similar observations.

Flanigan (1972) described results of an airborne gamma-ray spectrometric survey with two 230 x 75 mm NaI(Tl) detectors in western Saudi Arabia. The area covered was flown with 1 km flight line spacing, and 90 m terrain clearance at 160 km/h. Data were recorded on the tape every 0.5 seconds. The author presented the results in the form of contoured count rates of the three radioelement windows and the total count channel. Count rate ranges were related to rock-type in order to extrapolate lithologies.

An interesting approach to comparison of radioelement concentrations measured on the ground and by airborne gamma ray spectrometry was described by Richardson et al. (1972) for parts of the Canadian Shield. In order to compare results from 14 000 rock specimen assays to the airborne data, they determined average count rates along profiles for each radioelement. The authors described the procedure as follows: They obtained a visual estimate for each of the radioelements from appropriate profile cross sections of different portions of the Shield. They did this by: (1) neglecting narrow zones of high count rate (which constitute a small fraction of the distance along the flight path), (2) ignoring low levels of radioactivity over water and swampy areas, and (3) visually estimating a mean count rate level from the upper surface of the profiles. This procedure is illustrated in Figure 10C.31 which shows thorium, uranium, and potassium profiles along 130 km of cross country reconnaissance flight line over the Hardisty Lake area in the Northwest Territories. Estimated radioelement concentrations were obtained by converting weighted averages of these count rates using the calibration facilities. Using this method of analysis, and compilation of cross country profiles, a number of radioactive belts were defined and their radioelement contents were evaluated. Figure 10C.32 illustrates a set of cross country profiles, and the belt of anomalous radioactivity (70 km wide, 480 km long) defined by Richardson et al. (1972). They gave the mean radioelement content of the belt as 4.8% K, 6.2 ppm eU, and 31.1 ppm eTh. This trend runs along the Wollaston Lake Fold Belt and the parallel gneissic zone to the east. In the same paper, computer contoured K, U, and Th distribution maps of the Fort Smith area, Northwest Territories are presented. Correlation with magnetic data in these areas is also discussed in some detail. The authors suggest that the coincidence of distinct magnetic properties and radiometric properties in certain zones of the crust indicate both have been controlled by the same large scale fundamental processes.

The Canadian Uranium Reconnaissance Program was described by Darnley et al. (1975) who stated that the overall objectives of the program were: "to provide industry with high quality reconnaissance exploration data to indicate those areas of the country where there is the greatest probability of finding new uranium deposits, and to provide government with nationally systematic data to serve as a base for uranium resource appraisal".

The Canadian program involved high sensitivity airborne gamma ray spectrometry over areas of low relief and geochemistry in mountainous terrain and in areas with extensive overburden. The airborne gamma ray spectrometry

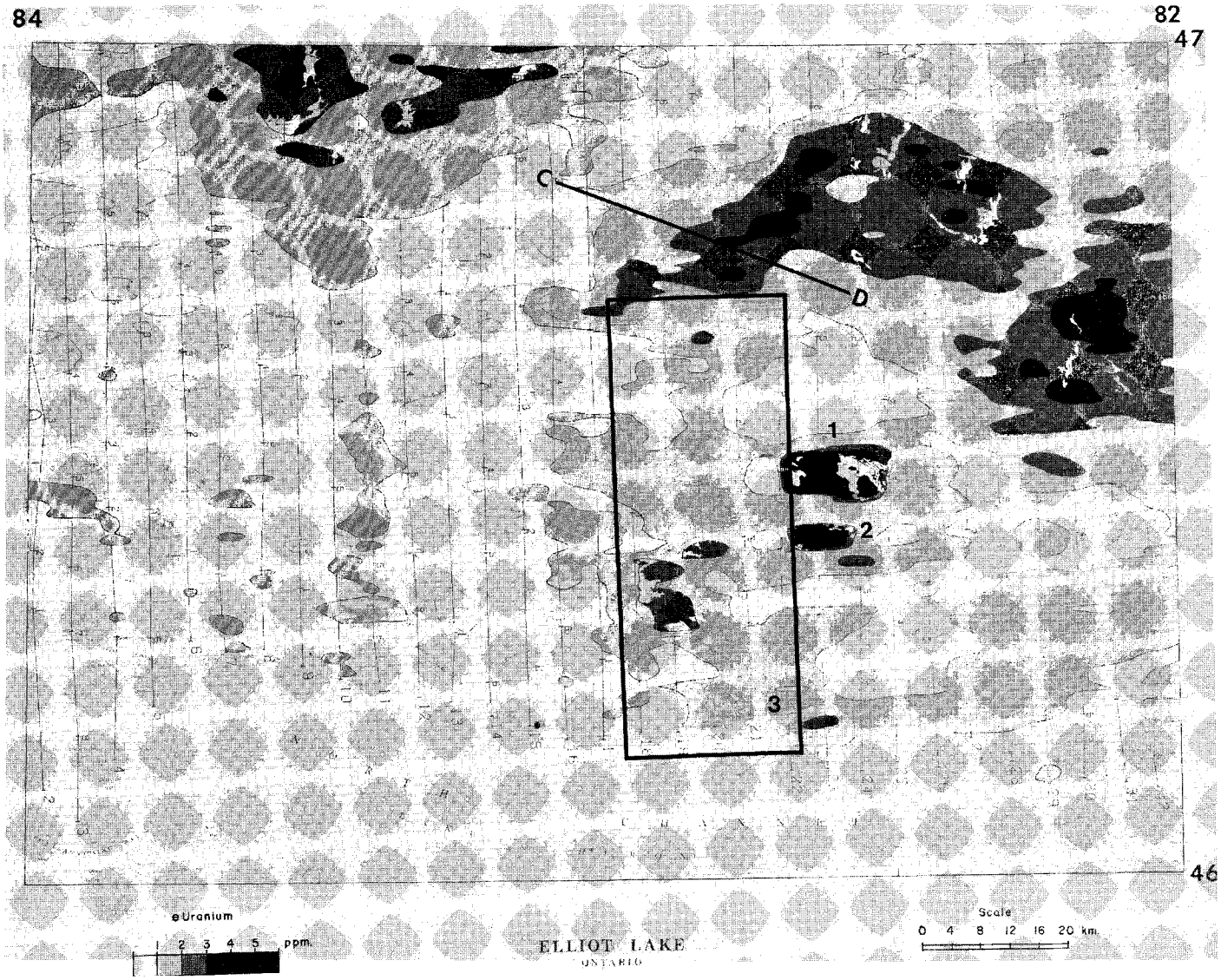


Figure 10C.33. *Contoured eU distribution for the Blind River map sheet, Ontario compiled from the GSC Skyvan data (after Darnley et al., 1977). Note the broad regional high to the north of the Elliot Lake uranium mining area. The principal ore deposits adjoin 1 (Quirke, Denison), 2 (Nordic), and 3 (Pronto). The outlined area, and the profile C-D are discussed in the above-mentioned paper.*

part of the program was carried out with 5 km flight line spacing, 135 m terrain clearance, 200 km/h aircraft speed and 50 000 cm^3 of NaI(Tl) detectors. The basis for the program was given by Darnley et al. (1975) in the following words:

"The program rests upon the concept that most uranium deposits occur within or marginal to regions of the crust containing higher than average amounts of uranium. Uranium may be found to be weakly concentrated in granitic rocks especially those late in an orogenic cycle. It may be found concentrated in high temperature pegmatites or in lower temperature vein deposits. These are all components of a primary source area which through erosion and redistribution can provide the material to form secondary deposits in any suitable adjacent geochemical trap. The reconnaissance program is designed primarily to identify all zones of primary enrichment within the country, and secondly to indicate, if possible, the limits of areas where secondary processes have operated. It is important not to dismiss anomalous areas as simply being low-grade igneous rocks of no economic importance. Such areas may have considerable potential as source areas, and geological knowledge must be brought into play to determine where the eroded material from these source areas has been deposited. It is the first objective of the Uranium Reconnaissance Program to delineate as rapidly as possible the major areas of uranium enrichment in Canada".

The concept above was illustrated with survey data from the Elliot Lake uranium area, the Johan Beetz (Havre St. Pierre) area of Quebec, the Beaverlodge uranium area of northern Saskatchewan, the Bancroft uranium area, and the Mont Laurier area of Quebec (Darnley et al., 1975) and other areas Darnley et al. (1977). Figure 10C.33, reproduced from Darnley et al. (1975), is one of these examples showing the uranium distribution pattern in the Blind River-Elliot Lake area. This map is described by the authors as showing a possible source-area to the northwest of the Huronian sedimentary rocks which contain the uranium deposits of the Elliot Lake area. Further descriptions of this particular

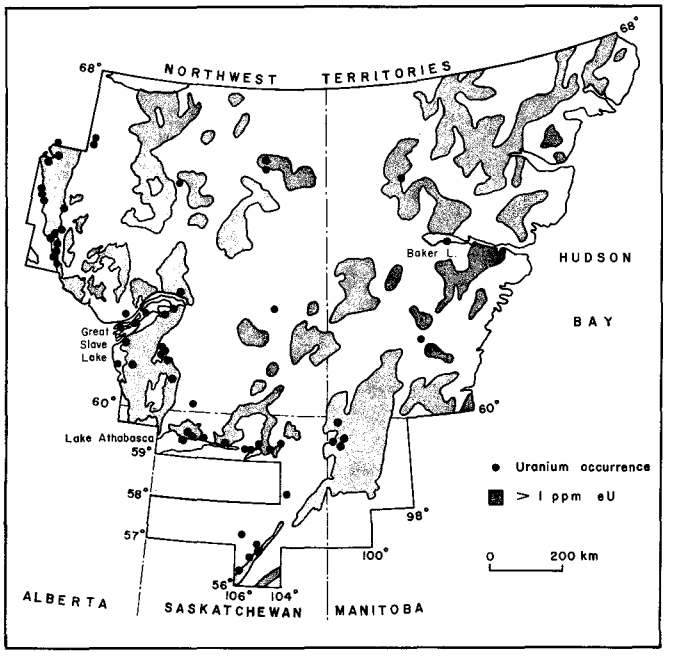


Figure 10C.34. *The relation between uranium occurrences and regional distribution of uranium (after Richardson and Carson, 1976). Based on airborne gamma ray spectrometric data, surface concentrations greater than 1 ppm eU have been contoured and shaded in this compilation from northern Manitoba, northern Saskatchewan and the Northwest Territories. Most occurrences lie within or near areas of regional uranium enrichment.*

survey were given by Richardson et al. (1975). Richardson and Carson (1976) presented a compilation map showing both the location of known uranium occurrences and areas determined to have an average surface eU content >1 ppm as measured by airborne gamma ray spectrometry. Figure 10C.34 shows the striking relationship between occurrences and regional enrichment.

Morris (1969) described the use of airborne gamma ray spectrometers in the search for uranium and gave as examples spectrometer records obtained at 150 m above ground with two 150 x 100 mm NaI(Tl) detectors flown over areas in southern England.

Darnley et al. (1969) presented further experimental results of airborne gamma ray spectrometer tests over the Canadian Shield, describing a high sensitivity spectrometer system used by the Geological Survey of Canada. A comparison of mean count rates for arrays of twelve 230 x 100 mm NaI(Tl) detectors and three 125 x 125 mm NaI(Tl) detectors was presented from flights over the Bancroft area.

Darnley et al. (1970) presented example profiles for five different areas of Canada showing variation of total count, K, eU, eTh, and eU/eTh ratio. An example of the interpretation of one of these profiles is given in Figure 10C.35. The authors stated that the figure is a south to north profile from the Bancroft area. The Grey Hawk uranium property is marked by the distinct equivalent uranium peak at 17 miles which is not accompanied by any increase in potassium or equivalent thorium. About two miles to the north the Faraday granite area is marked by another equivalent uranium peak associated with anomalous equivalent thorium and potassium but no eU/eTh ratio anomaly. Further north still there is a localized potassium concentration, without a matching increase in equivalent thorium or uranium. The eU/eTh ratio in addition to clearly distinguishing the Grey Hawk uranium occurrences shows two other weak anomalies which could have been easily overlooked on the equivalent uranium profile alone.

Darnley (1972) has several illustrations of data that demonstrate the use of gamma ray spectrometric data. One of these illustrations, Figure 10C.36, is a profile from the Uranium City area of Saskatchewan demonstrating how a significant equivalent uranium anomaly can be lost in a total count gamma survey because it coincides with low equivalent thorium and potassium values. The existence of the uranium anomaly is clearly indicated by the spectrometric data but not by the integral or total count profile. Figure 10C.37, also adapted from Darnley (1972), is an illustration from the Bancroft area of a small uranium occurrence at 19 km which is readily distinguished by a spectrometric survey, but which would not be found by a total radiation survey. (These last two classic examples have also been used by Grasty (1976c) to illustrate airborne gamma ray spectrometric data.)

Darnley and Grasty (1971) discussed results of surveys in the Bancroft area in detail, presenting seven contour maps showing total count, the three radioelements, and their ratios eU/eTh, eU/K and eTh/K, each superimposed on the geologic map of the area. The authors concluded that use of the ratio maps (e.g. eU/K and eU/eTh) can result in an order of magnitude reduction in the area to be ground searched, as compared with the total count map. Darnley (1973), in reviewing developments in airborne gamma ray survey techniques, stated that districts containing uranium mineralization generally fall within or on the margins of regions containing above-average radioelement abundances. Profiles from the Elliot Lake area, Mont Laurier area, and Fort Smith area in Canada were presented to illustrate this point. Figure 10C.38 is a reproduction of a profile from the Fort Smith, N.W.T. survey, adapted from Darnley (1973). Note the broad regional high in the total count channel, predominantly caused by thorium enrichment as indicated by the equivalent thorium channel. Uranium anomalies are located on the margin of the radioactive high as denoted by the equivalent uranium channel profile and the eU/eTh and eU/K ratios.

A comparison of reconnaissance techniques, made by Allan and Richardson (1974) for the northwestern Canadian Shield, concluded that in that area airborne gamma ray spectrometry and lake-sediment geochemistry can produce similar regional distribution maps for uranium at a similar cost. The comparison involved the high sensitivity airborne system of the Geological Survey of Canada flown at 5 km line spacing, and lake-sediment sampling by helicopter with one sample per 25 km^2. In 1975, Darnley (1975) presented a short review of geophysics in uranium exploration, emphasizing airborne gamma ray spectrometry. The concept of regional uranium enrichment and its relation to source areas was discussed. Several examples illustrating how gamma ray spectrometry can explain the cause of a total count anomaly were given. Some of these included: a classic profile across a thorium anomaly caused by the St. Andrews East carbonatite, a profile across the South March uranium occurrence near Ottawa, and a profile over a potassium anomaly.

Data Presentation Techniques

The form of presentation of results was a major consideration of a paper by Darnley (1972) and several methods of data presentation were compared. The description of the methods and their advantages and disadvantages are reproduced below.

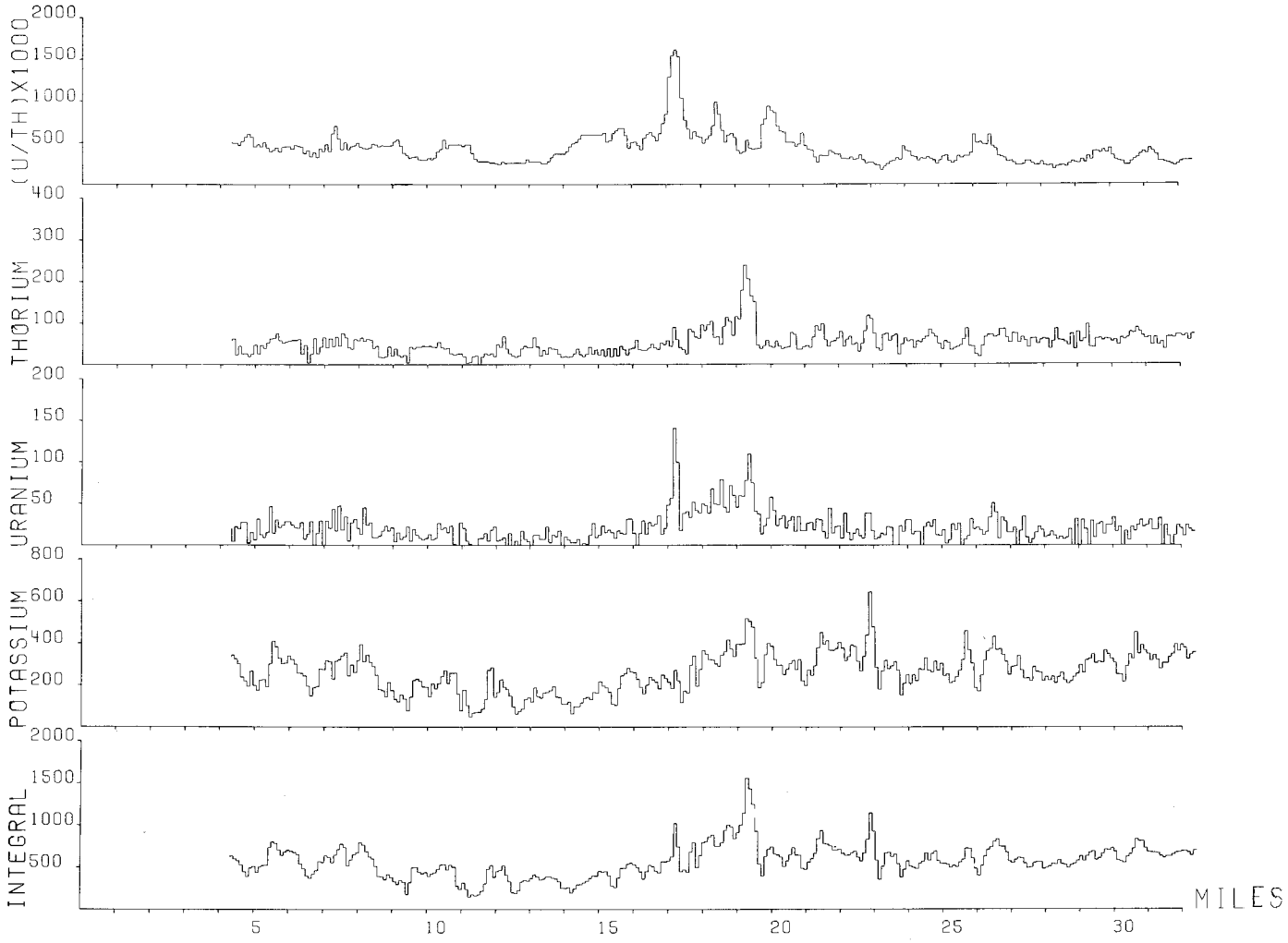


Figure 10C.35. *A radiometric profile from south to north across the Greyhawk uranium property in the Bancroft area; see text (after Darnley et al., 1970).*

The output of the first commercially available gamma ray spectrometers consisted of an analog chart recording with no corrections whatsoever, making only simple data presentations possible. Contouring was either not attempted or was limited to thorium only. A common form of data presentation was the use of a symbol superimposed on a flight line plan to indicate an anomaly exceeding an arbitrary background value by some given factor. Figure 10C.39 is an illustration of this type of uranium 'anomaly map'. This type of presentation although inexpensive is unsatisfactory according to Darnley from several points of view: (1) it is somewhat subjective; (2) since there are no Compton scattering corrections many uranium anomalies could be caused by high thorium values; (3) the background used is the average overland radiation level and therefore the information which the overland radiation base level can provide about the general geochemical environment is ignored; (4) since no terrain clearance correction was applied some anomalies may be caused by topographic highs.

In Figure 10C.40 the uranium and thorium count rates in the anomaly peak are shown along-side the uranium and thorium backgrounds (used in the same sense as the first example). This improves the amount of information available on the map.

A further elaboration is to contour thorium content and add this to the display of anomalies as shown in Figure 10C.41. Since the thorium count is usually more reproducible and statistically more significant than the uranium count it can be used as an aid in interpreting the geology.

Figure 10C.42 shows another type of data presentation, a profile map; also called offset profiles. Here the strip chart data have been plotted on a flight line map alongside the flight lines. In theory this shows the relationship in radiometric pattern from line to line and similar features can be joined. In this particular example, no allowance was made for the lag in plotted positions due to the time constant employed in the survey. Thus anomalies on adjoining lines are laterally displaced relative to one another because adjoining lines were flown in opposite directions.

Darnley (1972) also pointed out that elaborate presentation of data is not warranted if the counting statistics of the measurements are inadequate.

Recently, more effort has been put into displaying the data in forms which make the interpretation easier. The use of statistical treatments to enhance the data, filtering,

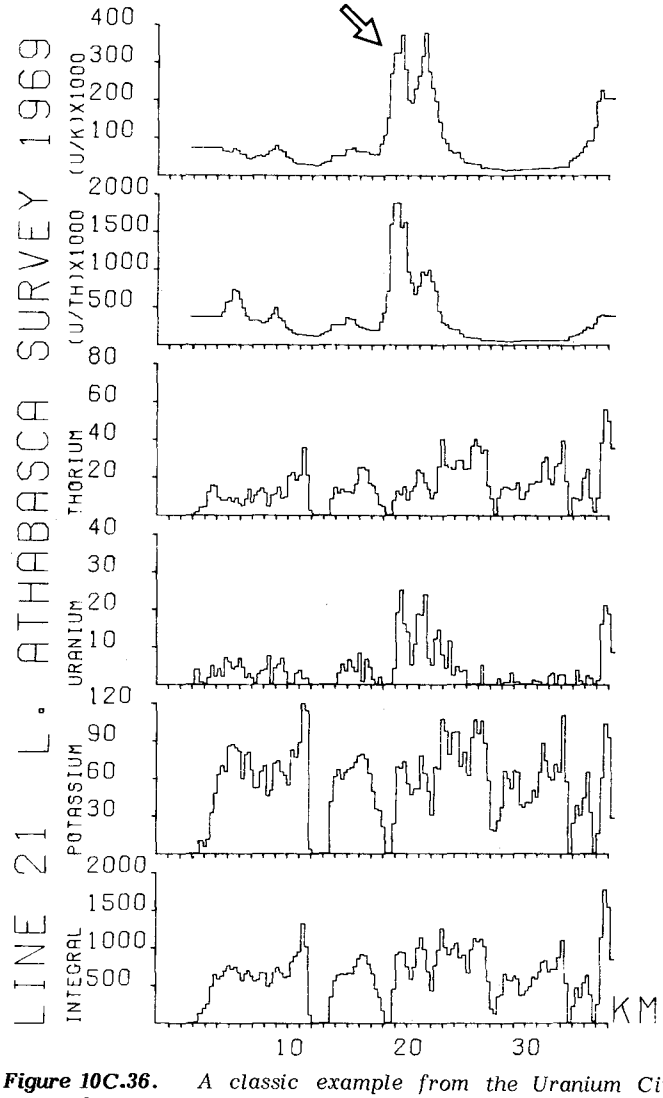


Figure 10C.36. *A classic example from the Uranium City area of Saskatchewan demonstrating how a significant eU anomaly can be lost in a total-count gamma ray survey because it is coincident with decreased eTh and potassium values (after Darnley, 1972).*

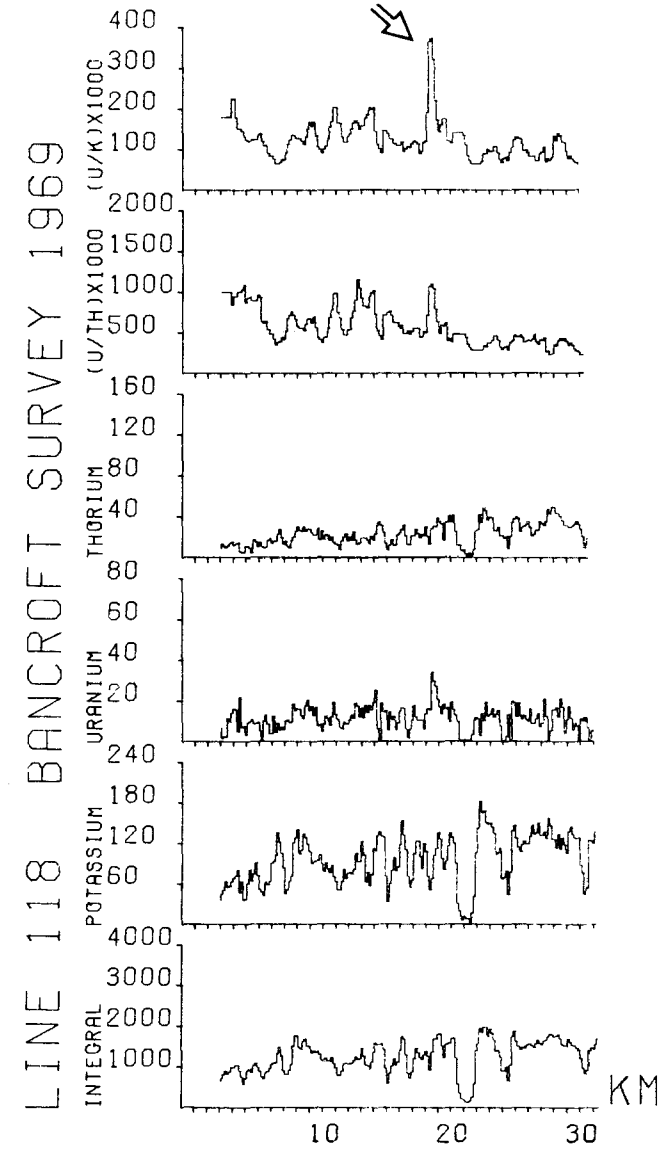


Figure 10C.37. *A small uranium occurrence in the Bancroft area (at 19 km) which does not show on the total count profile, but which is easily seen by a spectrometric survey (after Darnley, 1972).*

factor analysis, and the use of colour to combine information from all three radioelements in one map have been demonstrated and are discussed below.

A standard deviation map has become commonly used (see for example Geodata International, 1975a, b, c) as a form of data presentation by the U.S. Department of Energy in their National Uranium Resource Evaluation (NURE) program. Richardson and Carson (1976) utilized this type of presentation to display data from the Athabasca Formation in northern Saskatchewan which produced a rather uniform level of radioactivity and which was consequently difficult to contour. To produce these standard deviation maps (or anomaly maps) the mean value of equivalent uranium for each flight line was calculated and data points that exceed the mean by 1, 2, 3 or more standard deviations are indicated by 1, 2, 3 or more stars plotted above the flight line. An example from Richardson and Carson (1976) (Fig. 10C.43) shows the geology map for an area and the equivalent uranium anomaly map. "The maps show prominent anomalies on several flight lines near the contact between the quartz monzonitic gneiss (unit 1) and the Virgin River Schist Group (unit 3a). A few young uranium anomalies also occur on the southeastern edge of the quartz monzonitic gneiss, near its contact with biotite-garnet (unit 2) and diorite gneisses and schists (unit 3)" (Richardson and Carson, 1976). The authors suggested that these anomalous zones may be geologically favourable for Key Lake-type uranium deposits.

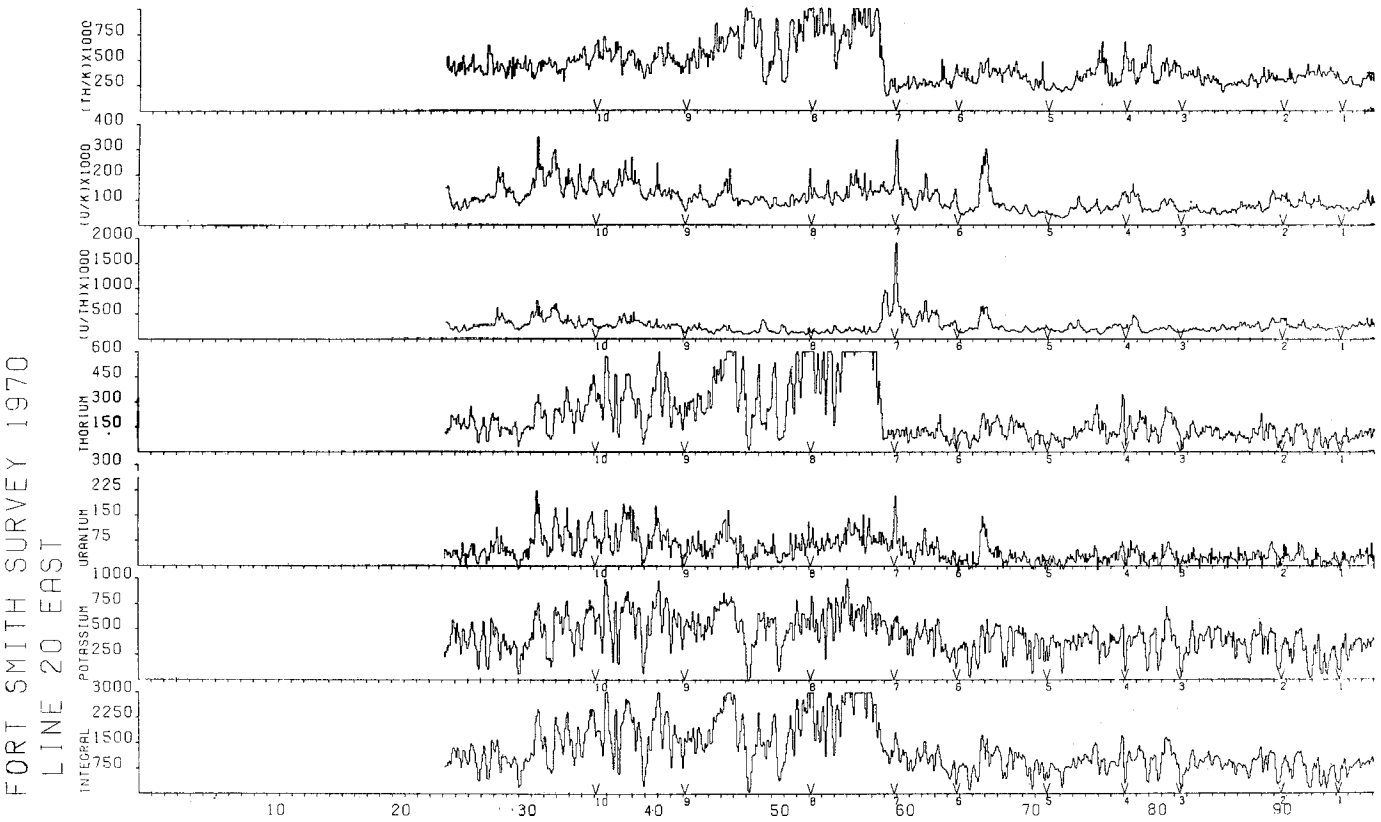


Figure 10C.38. *Airborne gamma ray spectrometric profile from the Fort Smith area, Northwest Territories flown with a high sensitivity system (50 000 cm^3 NaI(Tl), after Darnley, 1972). Particularly interesting is the broad high eTh area of the Fort Smith belt (30 to 60 miles) with a narrow eU anomaly on the flank (at 60 miles), accentuated by the U/Th and U/K ratios.*

In areas of well known geology the mean values for all data measured over each rock unit may be treated as above as has been done for the U.S. NURE program (Foote and Humphrey, 1976; Saunders and Potts, 1976). In this way the standard deviations correspond to a given rock unit rather than to the mean values for a given flight line. Potts (1976) presented a contour map of these standard deviations from the mean for equivalent uranium, calling it a "significance factor map". The significance factors are fractional multiples of the standard deviation above or below the mean, and can be considered the "degree of rarity" of a measurement. Figures 10C.44 and 10C.45 show the uranium count-rate contour map and the significance factor contour map of uranium data for a survey area in South America (after Potts, 1976). The difference between the two maps is surprising, indicating the area with the greatest number of standard deviations from the mean value is nearly 10 km from the area with the highest uranium count rates.

A colour presentation of airborne gamma ray spectrometric data (Linden, 1976) shows the gamma radiation related to K, eU and eTh in the form of coloured columns plotted on the flight lines. The surveys used a 250 x 125 mm NaI(Tl) detector, flown at 200 m flight line spacing, at a height of 30 m. Digital recording of data occurs every 0.4 seconds, representing about 40 m of flight line. Every measurement is taken to represent gamma radiation from an area of 40 m x 200 m, and is depicted on the 1:50 000 map as an area of 0.8 mm x 4.0 mm. Linden (1976) described the process further:

"Within this area are plotted three centre-orientated columns. The lengths of the columns are proportional to the radiation that relates to each element. Potassium is represented by yellow, uranium by red and thorium by blue. Each group of three columns is separated from the next group by a white field equivalent to the width of one column. There is sufficient space to specify 20 different levels of radiation intensity. In areas of abnormally high or low contents of K, eU or eTh it is possible to improve resolution by increasing the contrast between element intensities".

The three component colour map technique has been used with success in Sweden for several years, and has been applied to geological mapping as well as uranium exploration.

Tammenmaa et al. (1976) applied digital time series analysis techniques to airborne gamma ray spectrometric data to derive suitable filters to improve ground resolution and reduce distortion of radiometric anomalies.

Gunn (1978) discussed the deconvolution of airborne gamma ray spectrometric data, and the possibility of utilizing "downward continuation" as it is often applied to gravity and magnetic data. Tammenmaa and Grasty (1977) demonstrated upward and downward continuation of gamma radiation fields. Richards (1977) also applied digital filtering to airborne gamma ray spectrometric data to remove statistical noise.

The technique known as factor analysis was applied to airborne gamma ray spectrometric data by Duval (1976, 1977). Basically the technique can be considered as a method of sorting the K, eU, and eTh data into groupings with similar

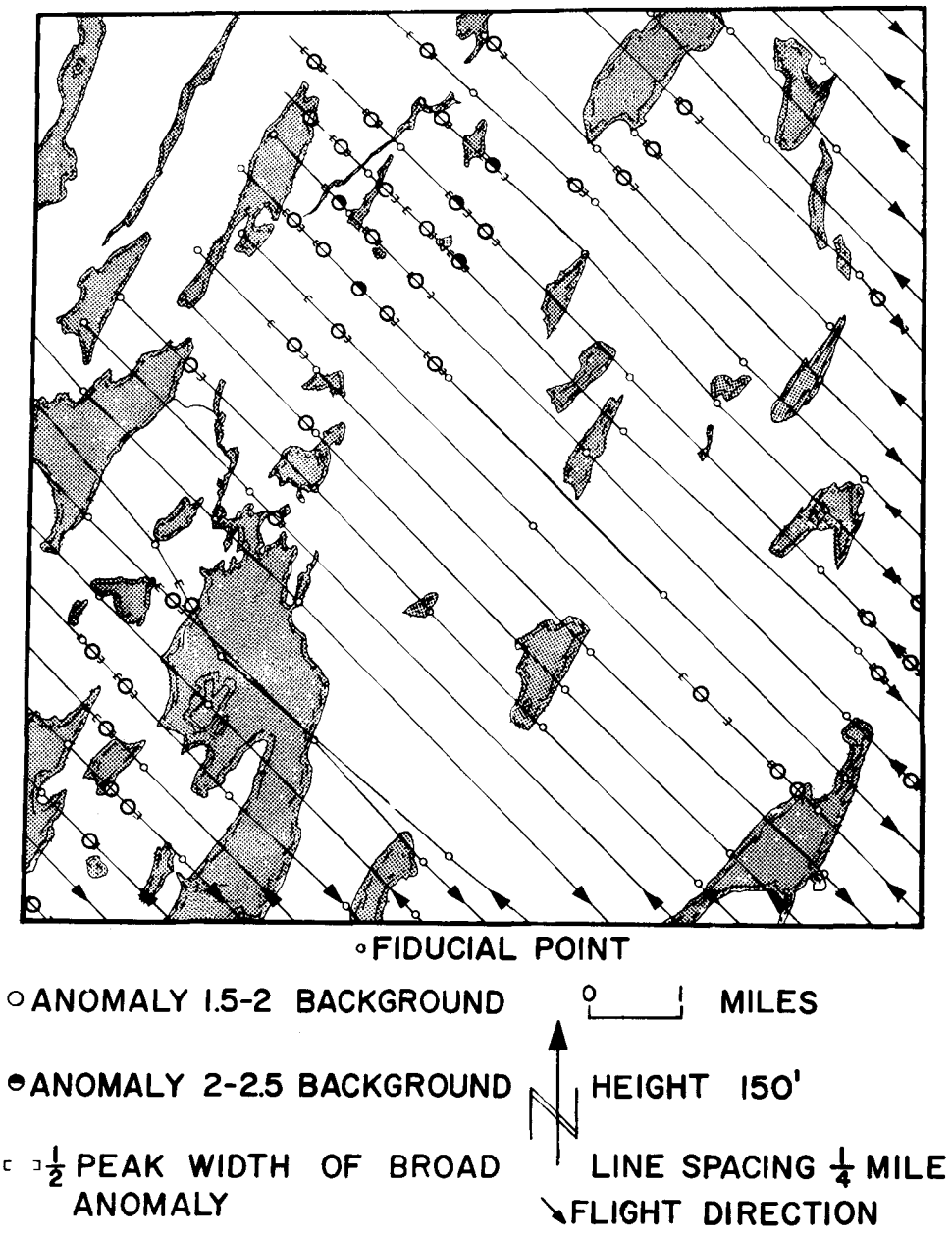


Figure 10C.39. *Data presentation example 1: symbols superimposed on a flight line map indicating anomalies exceeding some arbitrary background value by some given factor (after Darnley, 1972).*

co-ordinates, where the three co-ordinate axes are K, eU, and eTh. A similar approach was described by Killeen (1976a). The areas in which the data fall into groupings with similar co-ordinates are then coloured or shaded on maps. This technique has particular potential as a geological mapping aid. Newton and Slaney (1978) developed a classification system for airborne gamma ray spectrometric data in a survey area based on test flight lines which were studied in detail by photogeology to assign radiometric signatures to each rock type. Once rock classes were identified they were used to classify the entire survey area. The authors stated that zones of anomalously high radioactivity often cross lithological boundaries and may be considered useful indicators for uranium exploration. Further results of these investigations have been presented by Slaney (1978).

Ziegler (1976) discussed some trial applications of geostatistics to airborne gamma ray spectrometric data. Some of the techniques tried included locating maximum variance segments of the data, "robust" techniques, cluster analysis, discrimination analysis, and data display by histograms and three-dimensional maps of frequency distribution by flight line for each given geological formation.

Foote (1976) reviewed the data presentation techniques currently in use by the U.S. NURE program including the following data presentation formats:

"1. Flight line profiles of intensity of radiation from uranium, potassium, thorium, and their ratios.

2. Histograms showing data distribution.

3. Radiation data by surface geologic unit.

4. Radiation data by flight line showing statistical variation from a mean value.

5. Data by flight line superimposed on surface geologic map."

Several other commercially used data presentation techniques are described below. The "zoning technique" first used in 1968 is described as follows by Hogg (pers. comm., 1977).

First, the equivalent thorium, equivalent uranium and potassium channels as presented in an analog airborne record or a computer-compiled multichannel profile are analyzed. The boundaries of recognizable changes in signal amplitude, ratio or character are marked on the profile. These subunits are described semi-quantitatively by an alpha-numeric code. K, U and T refer to the potassium, equivalent uranium and equivalent thorium channels, respectively, and the signal strength indicated by symbols ((+) strong, ( ) average and (-) weak) which relate to preselected levels (Fig. 10C.46). A computer/plotter may then be used to produce a profile map of fully corrected total count profiles with the zone boundaries and related coding annotated (Fig. 10C.47). These maps may then be coloured using different intensities for count rate amplitude and a different colour for each radioelement K, eU, and eTh. The advantage of this technique is that all of the information is presented on one map. The main disadvantage, however, is the amount of time involved in the initial steps of the processing.

Another data presentation method (Hogg, pers. comm., 1977) consists of a computer line-printer listing of anomalies meeting specified criteria. Thus for each anomaly, a set of

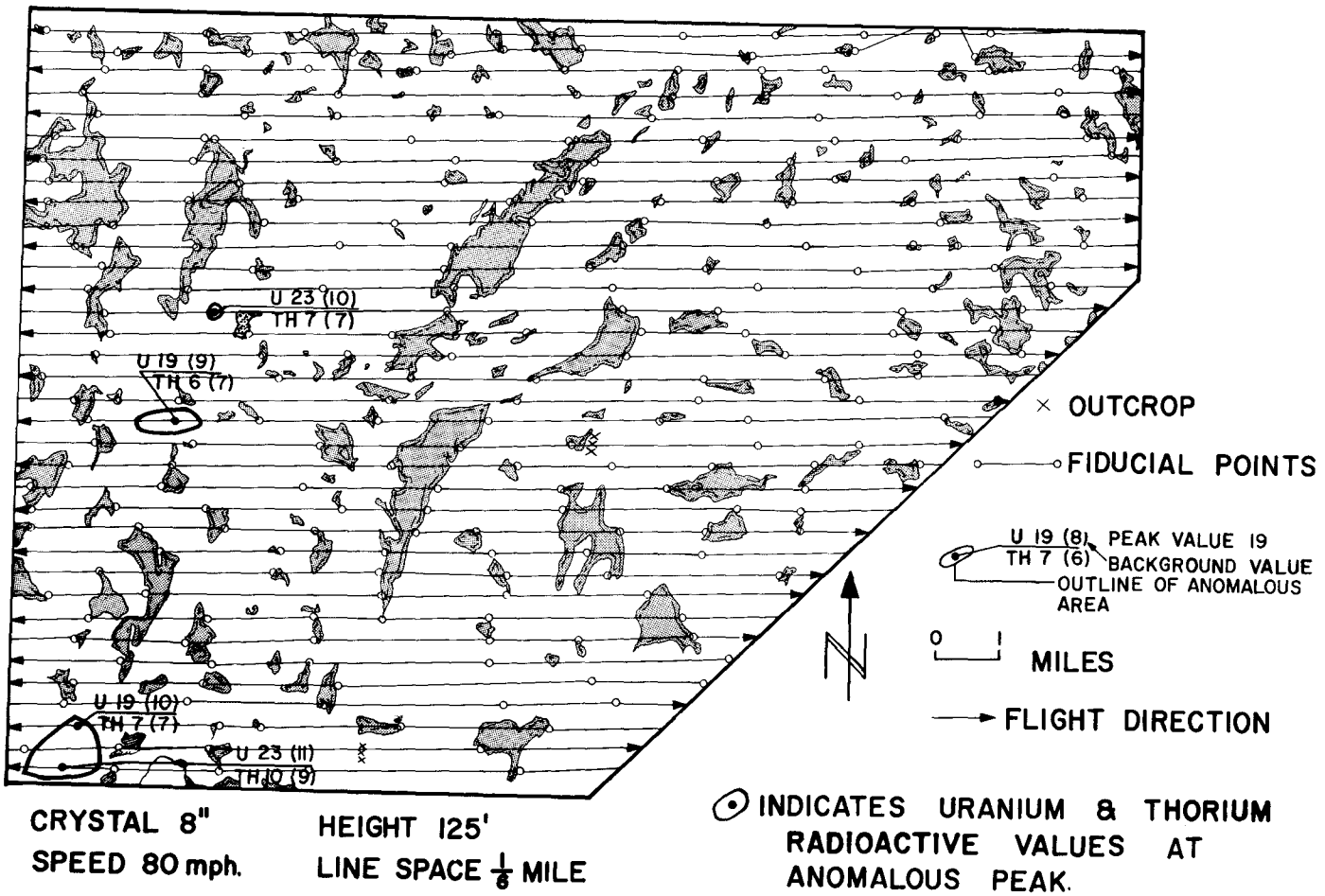


Figure 10C.40. *Data presentation example 2: uranium count-rate in the anomaly peak is given beside the uranium background, and the thorium count-rate in the anomaly is given beside the thorium background (after Darnley, 1972).*

statistics is printed including flight line number, fiducial numbers nearest the anomaly, anomaly amplitude, half width (left), area (left side), half width (right), area (right side), total half width, total area as shown in Figure 10C.48. Postscripts 1 and 2 refer to parameters calculated from stripped, smoothed, altitude-corrected equivalent uranium profile with subtraction of either: (1) atmospheric background or (2) local background plus atmospheric background. A line printer plot may also be produced to illustrate roughly the shape of the anomaly. Below the printer plot are given the count rates and ratios calculated at the uranium anomaly peak.

A useful anomaly classification technique has been described by D.B. Morris (pers. comm., 1977). The count rates in the three radioelement channels are expressed as a percentage of the count rates in the total count channel by a normalization process. Then the position of the anomaly is located on a ternary diagram as shown in Figure 10C.49. The diagram has 100% K, 100% eU, and 100% eTh as the three points of the triangle. It can be seen that any anomaly can be located on the diagram by the relative percentage contributions to the total count from channel 2 (K), channel 3 (U) and channel 4 (Th). The ternary diagram is divided into 9 fields.

An example of the application of this anomaly classification system is given in the anomaly analyses presented in Table 10C.5. Three example anomalies have been analyzed by this process and they fall into fields S, K, and L respectively.

Locating Favourable Areas for Uranium Exploration

In the past, most interpretation efforts were directed toward explaining, classifying, and setting priorities on gamma ray spectrometric anomalies to aid exploration. However, locating a favourable area in the first place is another problem. Reconnaissance surveys will outline large regions with above average radioelement content (geochemical provinces) which may be considered favourable areas, or in the vicinity of favourable areas (Darnley et al., 1977). Dodd (1976) described two suggested techniques to outline favourable areas. One approach consists of first producing the uranium anomaly map as described earlier, in terms of positive and negative standard deviations above or below the mean for each geologic unit. Anomalies were defined as data points exceeding one standard deviation either positive or negative. Areas of major and minor clusters of positive anomalous eU records were marked on the map, followed by the contouring of the ratios of the number of positive to the number of negative anomalies within each

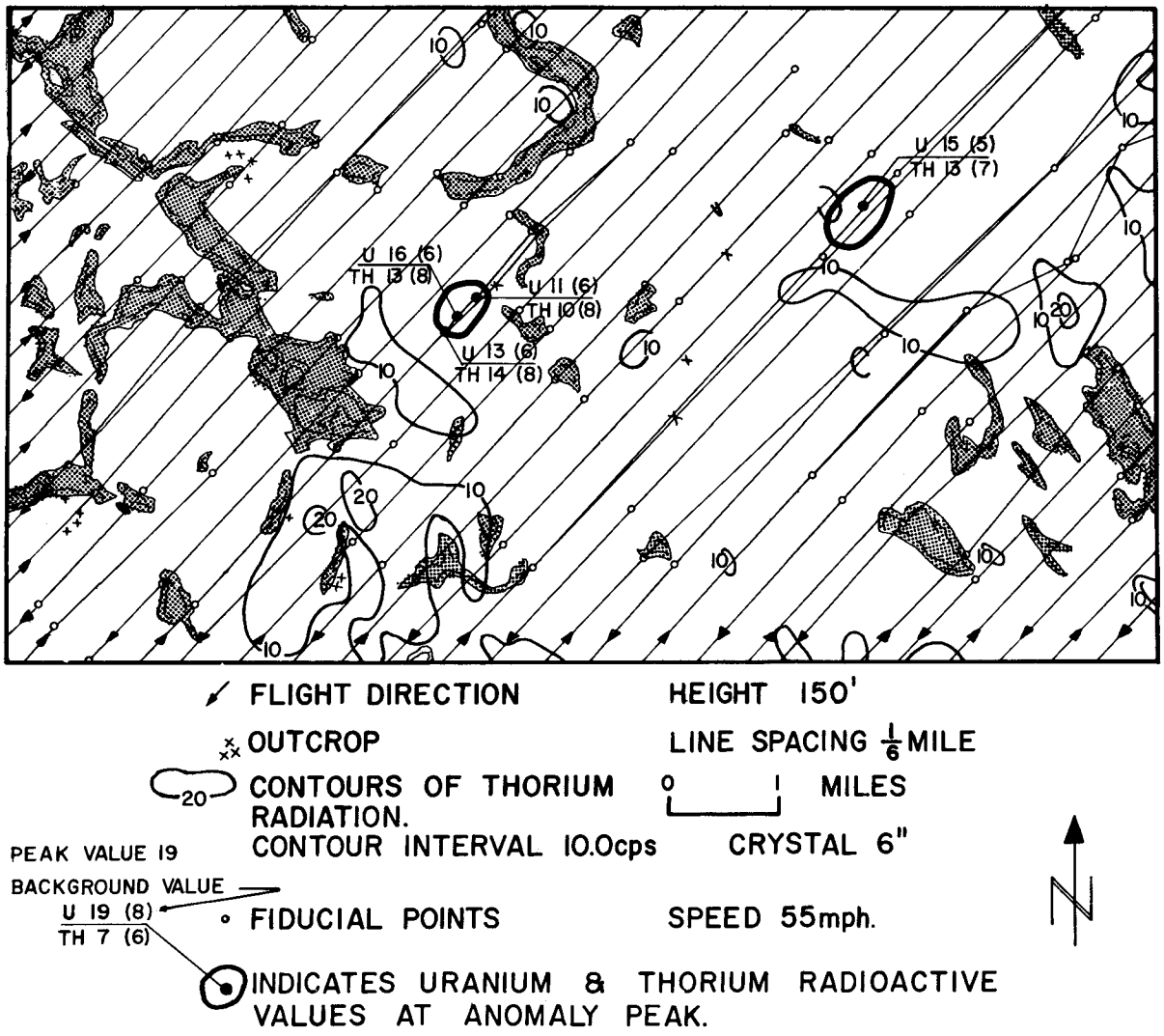


Figure 10C.41. *Data presentation example 3: similar to Figure 10C.40 but with eTh content contoured in the vicinity of the anomalies (after Darnley, 1972).*

fifteen minute quadrangle. This procedure was applied to an area of 37 300 km^2 in Wyoming. The resultant favourable areas (Fig. 10C.50) show good correlation with the Gas Hills, Crooks Gap-Green Mountain, Shirley Basin and Copper Mountain mining districts.

The second method described by Dodd (1976) is illustrated in Figure 10C.51. Here average values of the radioelement concentrations and their ratios are computed for each flight line in a survey with 8 km line spacing. These values are plotted as a profile spanning 410 km along the strike of the Goliad Formation on the Texas Gulf Coast. There is a regional change of K and eU and all known uranium occurrences are restricted to the area covered by lines 1 to 31. This area is the region of the Goliad formation containing the higher mean values on the profile.

Saunders and Potts (1978), attempted to determine a general "uranium favourability index" by plotting histograms of various possible indices such as the eU/eTh ratio for about 30 different areas where existing mines and occurrences were known to be favourable. They concluded that the median values of aerial gamma ray spectrometer parameters for geologic map units could be used as a guide to identify uraniferous provinces, reasoning that where the crustal abundance of uranium is high it is available to be chemically concentrated in economic deposits. They further reasoned that geochemical processes must have concentrated a part of the uranium in deposits. Removal of uranium from "average" rocks, separating it from thorium and potassium, results in low eU/Th and eU/K median values. They found the following parameters decrease with increasing uranium potential (where M denotes mean value): M (eU/eTh), M (eU/K), MeU/MeTh, and MeU/MK.

Parameters which generally increase with increasing uranium potential are: MeU, MeTh, MK, RSD eU, RSD (eU/eTh), and RSD (eU/K)

where RSD = relative standard deviation. i.e. (standard deviation/mean). Saunders and Potts (1978) thus arrived at a uranium favourability index, U_1, given by the equation:

$$U_1 = \frac{(MeU+MeTh+MK) \cdot RSD\ eU \cdot RSD(eU/eTH) \cdot RSD(eU/K)}{M(eU/eTh) \cdot M(eU/K)} \qquad (33)$$

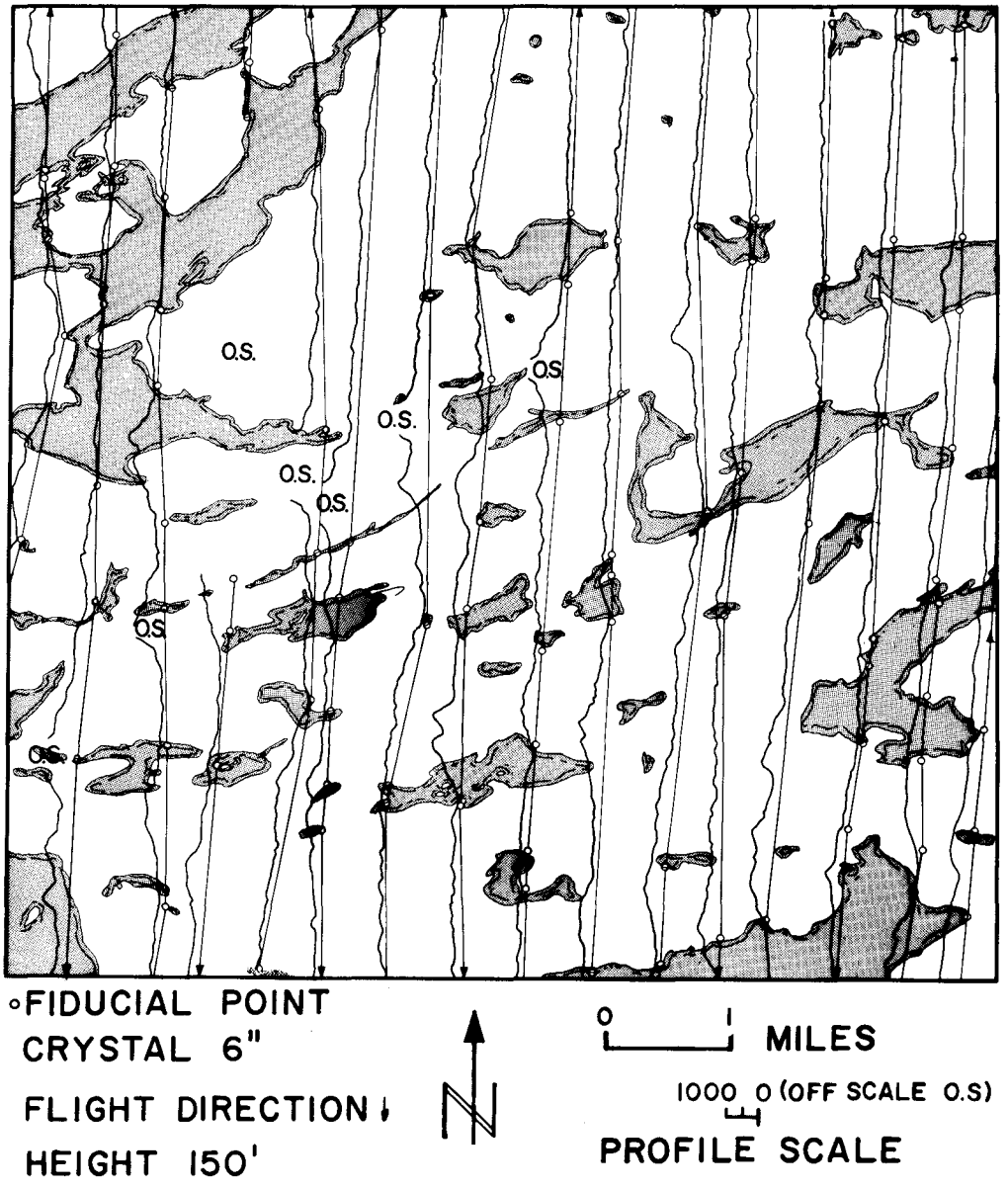


Figure 10C.42. *Data presentation example 4: A profile map, or 'offset profiles'. The radiometric record is plotted beside the flight lines (after Darnley, 1972).*

A simpler uranium index which avoids the use of RSD values was also suggested by Saunders and Potts (1978). Based on the observation that high mean uranium content indicates there is sufficient uranium for possible geochemical concentrating processes to work, and that low mean eU/eTh and eU/K values indicate these processes took place, they derived the index U_2:

$$U_2 = \frac{MeU}{\frac{MeU}{MeTh} \cdot \frac{MeU}{MK}} = \frac{MeTh \cdot MK}{MeU} \qquad (34)$$

The histogram in Figure 10C.52 illustrates how the uranium index indicates the high uranium potential of the Casper and Delta areas, and ranks the favourability of 27 other quadrangles below them. The Casper area contains three major mining districts, and the Delta area contains one mine and numerous uranium occurrences.

Deriving a uranium favourability index for a region is a complex problem. The parameters reflecting high favourability for a sandstone-type deposit such as those discussed above may not be applicable to other types of deposits.

SURFACE GAMMA RAY SPECTROMETRIC SURVEYS

Introduction

Portable gamma ray spectrometers are versatile instruments and have been used in carborne surveys, underwater surveys, airborne surveys and borehole logging. This section will deal principally with hand-carried spectrometers, i.e. foot-traverse surveys and detailed ground investigations of anomalies detected by other radiometric surveys, such as airborne or carborne. A number of instruments are available from different manufacturers ranging from simple single-channel instruments to four-channel instruments, with analog and/or digital outputs, audible alarms and stabilization. Some instruments can be programmed to present results corrected for spectral scattering and reduced to counts per second. Count rate displays are by LED, LCD or rate-meter needle, and a variety of detector sizes are available. The choice of instrument depends on many factors such as the skill or training of the operator, the objective of the survey, the locality (desert area, tropical jungle, cold northern areas), the cost, and possible future usage of the instrument. For example the immediate requirement may be for a simple model, but if a foreseeable survey requirement includes analog chart recording then the instrument chosen should have an analog output. Size and weight of the instrument or use in aircraft or lab also play an important role. Many aspects of surface gamma ray spectrometry such as energy windows, calibration, in situ assay, sample volume, counting statistics, geometry, deadtime and background are considered in other sections of this paper.

Portable Gamma Ray Spectrometers

The earlier reports on the use of portable instruments in the field were primarily concerned with scintillometers (e.g. Russell and Scherbatskoy (1951), Gross (1952), Russell (1955)) or interpretation of laboratory gamma ray spectrometer measurements of rocks (e.g. Hurley, 1956; Horwood, 1960;

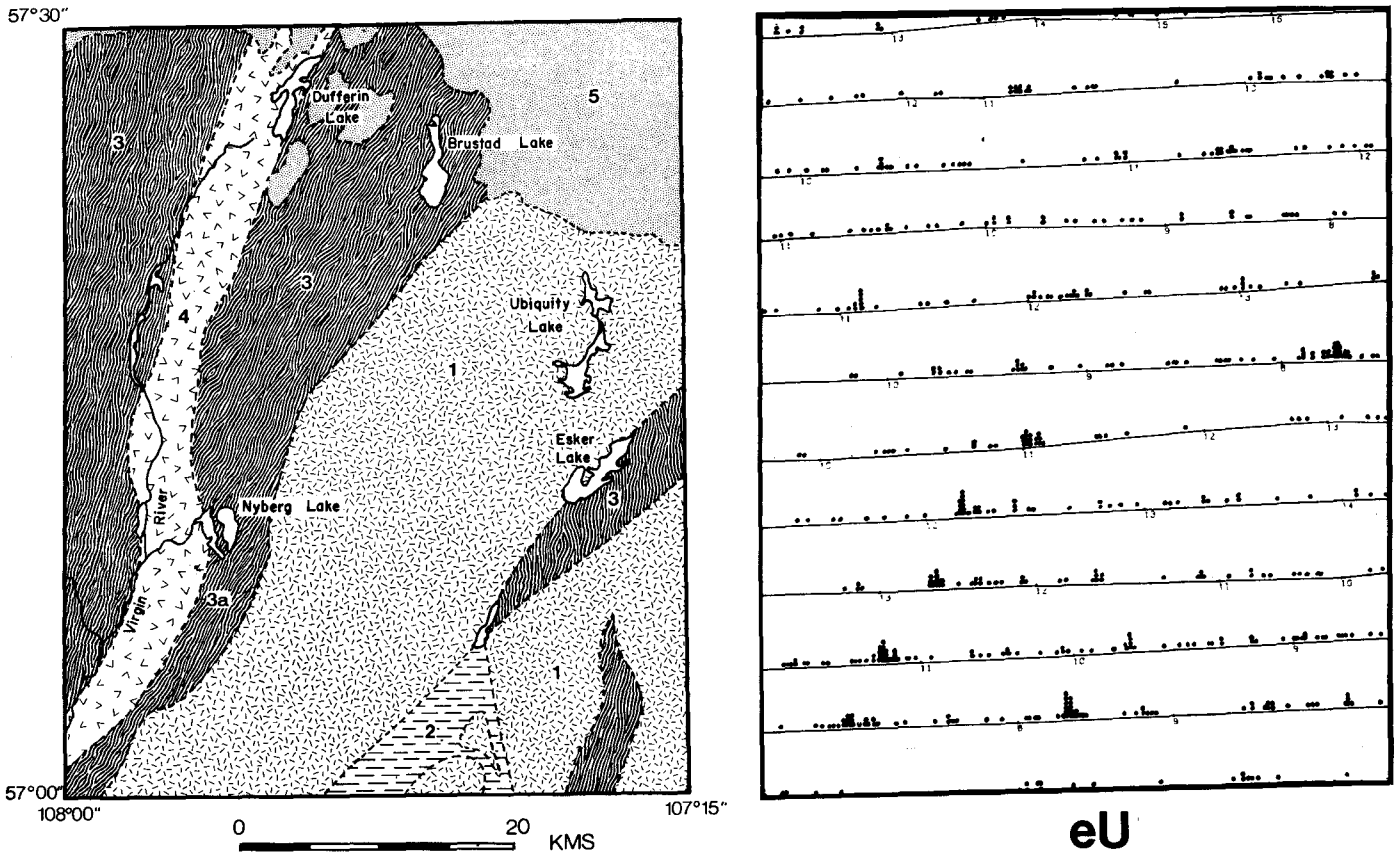


Figure 10C.43. *Comparison of geology map and eU anomaly map for the Nyberg Lakes – Brustad River area (after Richardson and Carson, 1976). The statistical treatment of the data (described in the text) produces a map which relates to the geology of the area, whereas the simple eU contour map did not.*

Mero, 1960; Bunker and Bush, 1966). Gregory and Horwood (1961) carried out some fundamental research on the shape of gamma ray spectra with variation of source thickness. They demonstrated the feasibility of field gamma ray spectrometry. Adams and Fryer (1964) described the first portable gamma ray spectrometer in use in the United States, and Mahdavi (1964) described its application to the study of K, U, and Th concentrations in beach sands of the Gulf of Mexico coast. This spectrometer utilized a lead shield for collimation of the gamma rays. In Canada the first portable gamma ray spectrometer was constructed (Doig, 1964, 1968) under the auspices of the Geological Survey of Canada. Killeen (1966) and Killeen and Carmichael (1972) described the application of that spectrometer to uranium exploration in the Elliot Lake area. Darnley and Fleet (1968) produced gamma ray spectrometer maps of test areas at Bancroft and Elliot Lake. The first commercially available portable gamma ray spectrometers in Canada were described by Pemberton (1968). About the same time in the United States, airborne gamma ray spectrometers, which had been developed potentially for tracking the effluent of nuclear submarines, were becoming de-classified by the military. Foote (1969) reported on both surface and airborne applications of spectrometry to mineral exploration. Almost simultaneously with the development of portable gamma ray spectrometers in Canada and the U.S.A., Løvborg et al. (1969) developed a field portable unit in Denmark. They applied it to exploration for uranium and thorium deposits of South Greenland. Due to the rugged terrain a detector with lead collimator was used to control the geometry. They also described the calibration procedure, which consisted of comparison of field count rates to laboratory analyses of samples. Killeen and Carmichael (1970) described a similar method of calibration for an uncollimated portable gamma ray spectrometer. Adams and Gasparini (1970) reviewed all aspects of gamma ray spectrometry in a text book on the subject. Kogan et al. (1969) also provided extensive mathematical background on the subject. Miller and Loosemore (1972) described a portable gamma ray spectrometer with automatic gain stabilization, and more recently Clayton et al. (1976) described the updated version. Puibaraud (1972) summarized the generally desirable characteristics for a variety of portable radiometric equipment, including gamma ray spectrometers.

Løvborg et al. (1971) presented a detailed description of their use of the portable gamma ray spectrometer to evaluate the Ilimaussaq Alkaline intrusion in South Greenland. Making measurements on grids of 1 m spacing with a collimated detector, and taking as many as 100 measurements per day, it was possible to contour the resulting data. The same paper reported on calibration with a new set of concrete calibration pads. The computation of the "effective" sample volume was described. This is different from the 90% source volume commonly used to define the sample (i.e. the volume from which 90% of the detected radiation originates). The "effective" sample volume is defined as the "rock body in which the variance of a particular radioelement is equal to the estimation variance of a gamma ray spectrometric

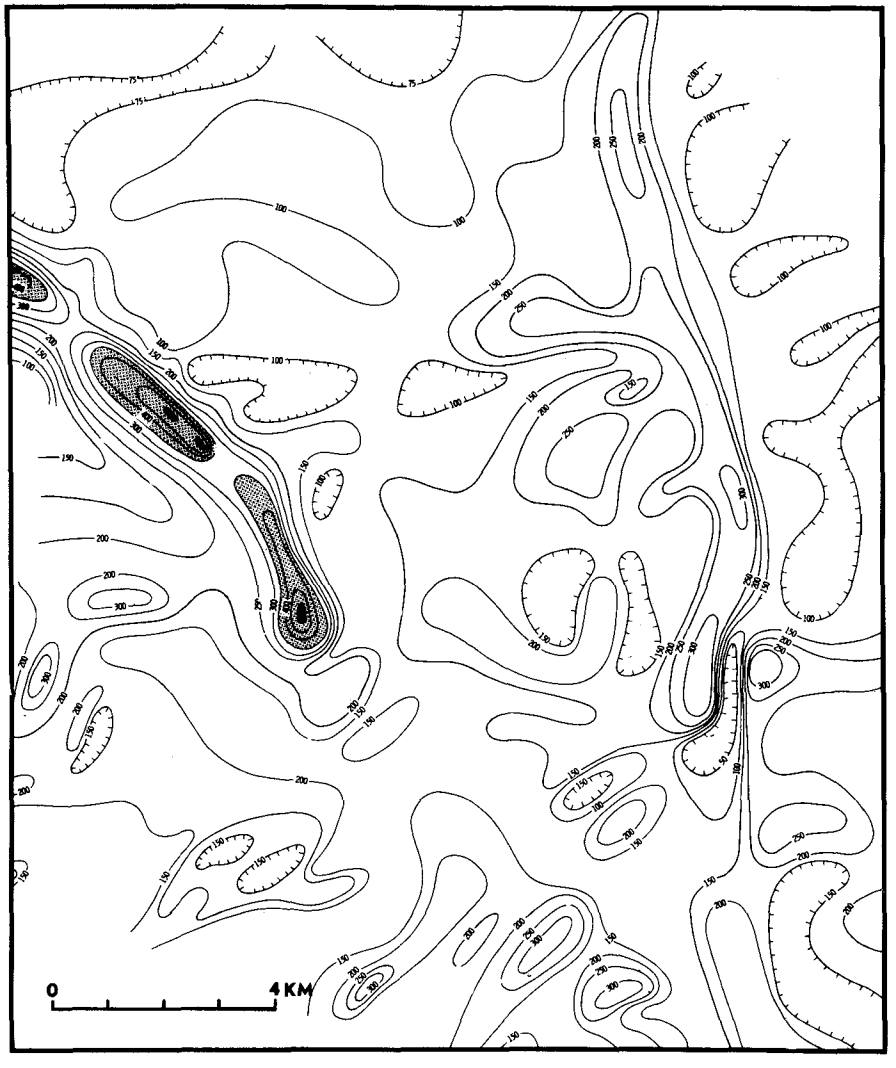


Figure 10C.44. *Uranium count-rate contour map (counts per 2 seconds) for the area in South America shown in Figure 10C.45 (after Potts, 1976) based on airborne gamma ray spectrometry.*

Figure 10C.45. *Significance factor contour map (described in the text) for the area in South America shown in Figure 10C.44 (after Potts, 1976).*

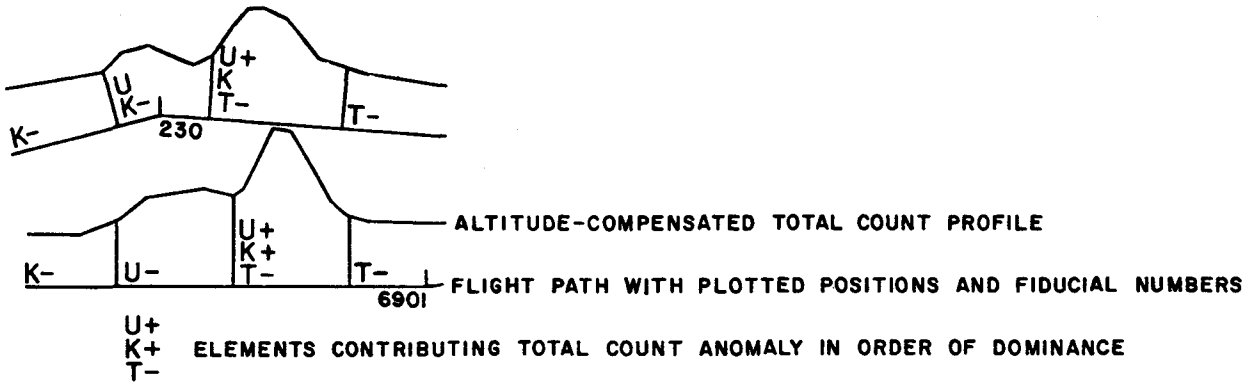


Figure 10C.46. *The "zoning" technique applied to a section of radiometric total count profile as described in the text (after Hogg, pers. comm., 1977).*

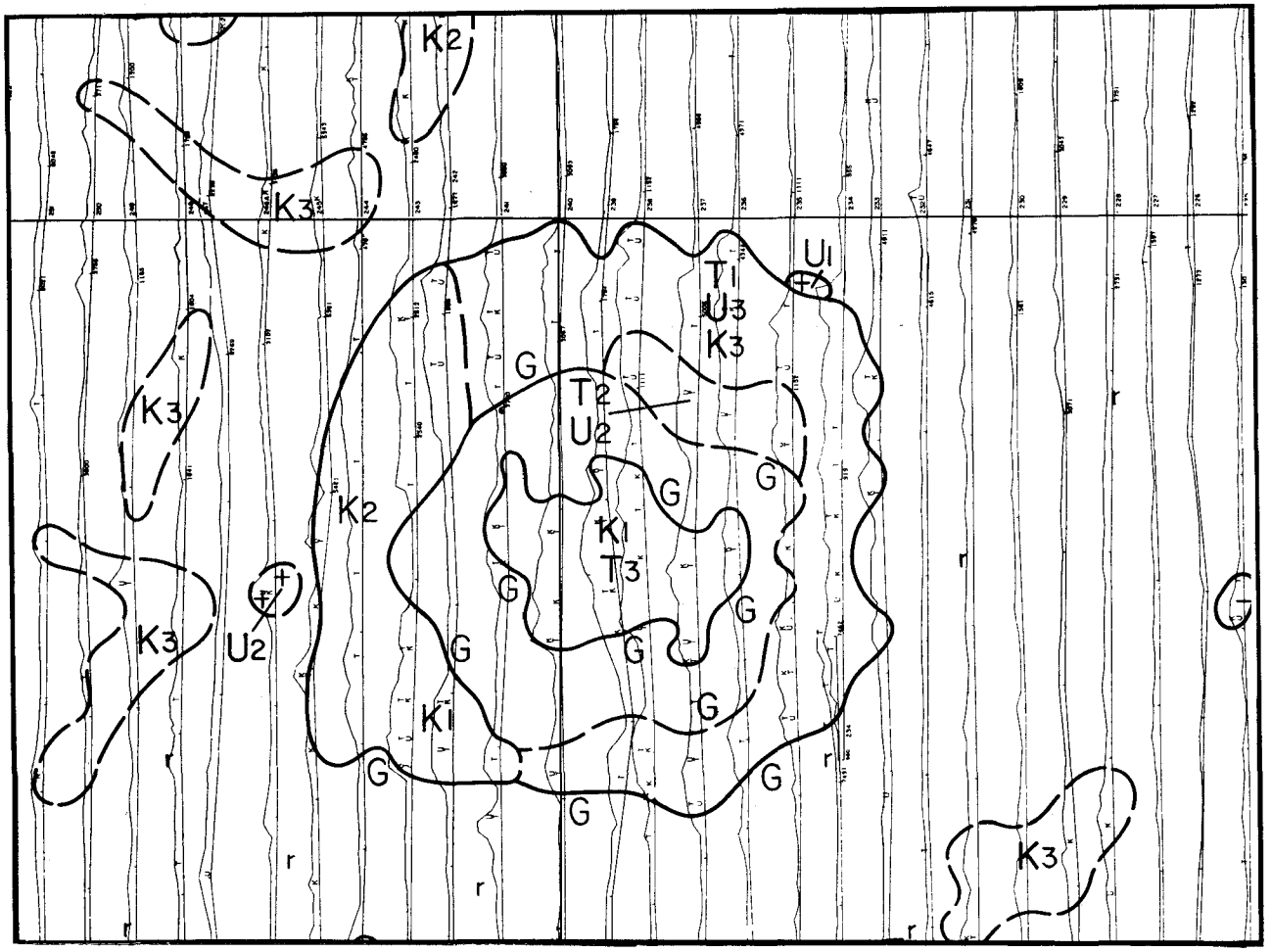


Figure 10C.47. *The "zoned" map based on total count profiles processed as in Figure 10C.46, with the zone boundaries joined (after Hogg, pers. comm., 1977).*

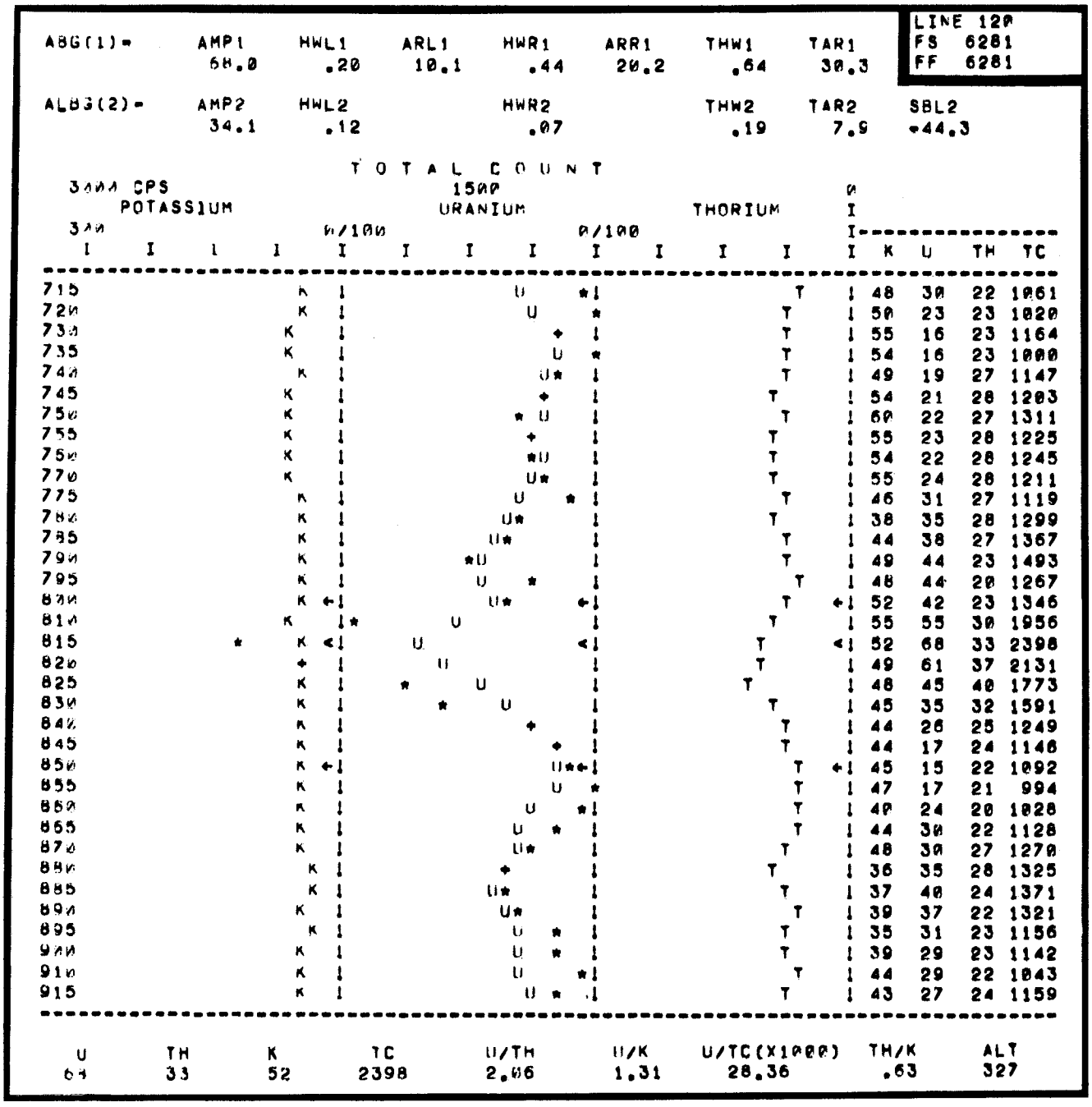


Figure 10C.48. *A 'printer-plot' anomaly description (see text) used as an aid in classifying anomalies for symbol presentation on maps (after Hogg, pers. comm., 1977).*

determination of this radioelement" (Løvborg et al., 1971). The "effective" sample contributes only about 60 per cent of the detected gamma rays. They stated that "for an isotropic detector the volume of the 60% effective sample is about one-tenth the volume of its 90% counterpart". A good discussion on accuracy and precision of field gamma ray spectrometric measurements is given. Løvborg (1972) reviewed the applications of gamma ray spectrometry and the portable spectrometer developed in Denmark was also described.

Løvborg et al. (1972) described a mathematical approach to the computation of theoretical gamma ray energy spectra. From this they were able to derive correction factors to compensate for the finite dimensions of concrete calibration pads which are assumed to be of infinite extent (2π geometry) when calibrating a portable spectrometer. For example, using their graph of correction factors (see Fig. 10C.18) count rate corrections of +8% in the 2.62 MeV channel, +7% in the 1.76 and 1.46 MeV channels and +3% in the total count channel would be applied when the detector is 10 cm above the pads. These studies were

expanded (Løvborg et al., 1976) to include airborne spectrometers and the effects of sodium iodide's inherent characteristics in geophysical work.

A comprehensive table of gamma ray energies for the ^{238}U, ^{232}Th, and ^{235}U radioactive decay series, compiled by Smith and Wollenberg (1972), is a valuable aid to the interpretation of gamma ray spectra. Løvborg (1973) considered the future of gamma ray spectrometry, reviewing the available equipment, the precision of measurement, counting statistics and calibration standards. A modeling study of the response of 75 x 75 mm NaI(Tl) detectors was done by Løvborg and Kirkegaard (1974) to improve their computation of theoretical gamma ray spectra and aid in interpretation of field recorded spectra.

Sibbald (1975) described in considerable detail the ground follow-up program to investigate anomalies located by airborne gamma ray spectrometric surveys in northern Saskatchewan. Airborne radiometric anomalies were first marked on airphotos and then outlined on the ground by pace and compass traversing, with a scintillometer. Readings were taken continuously at hip level, and in contact with the surface at interesting locations. Samples were collected, and the geology was recorded. Of 21 anomalies, five were selected for more detailed investigation, and an integrated geological-geophysical-geochemical program was carried out. On the basis of geology, anomalies were divided into type 1 (relating to granites) and type 2 (relating to granite pegmatites). Pegmatitic anomalies were investigated in more detail than granitic anomalies. All outcrops were located and mapped, and checked with scintillometers in the detailed investigations. A grid was established at either 7.5 or 15 m spacings and portable four-channel gamma ray spectrometer readings were taken at waist height using 10 second counting intervals. The nature of the terrain was recorded at each station. The geology was mapped from these grid results alone in the less detailed investigations. Sibbald (1975) indicated that type 1 anomalies are commonly well exposed and occupy high land areas. The anomalies are typically recorded as spectacular and often broad highs in radiometric profiles. Type 2 anomalies occur in deeply eroded valleys and are less well exposed.

Another ground follow-up investigation in northern Saskatchewan between Wollaston Lake and Reindeer Lake was described by Munday (1975). The anomalies had been located by the GSC Skyvan survey flown in 1974 on flight lines at 1600 m spacing at an altitude of 120 m, and speed of

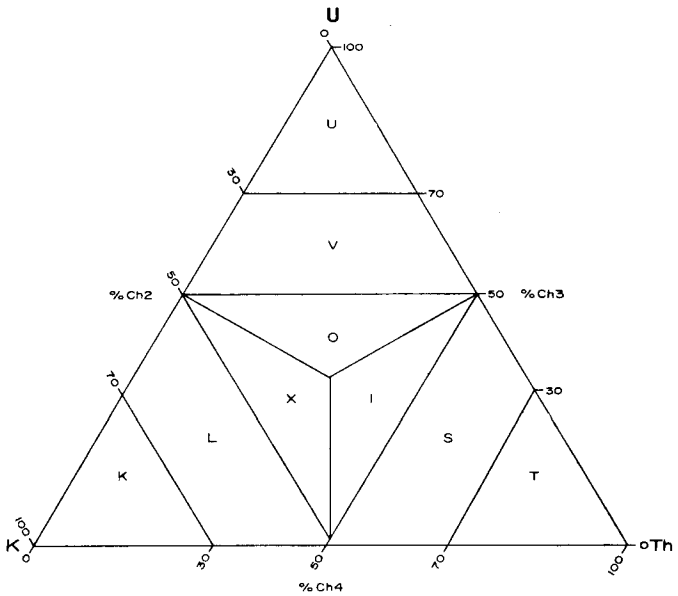


Figure 10C.49. *Ternary diagram illustrating a process for classifying airborne gamma ray spectrometric anomalies into nine different fields (after Morris, pers. comm., 1977).*

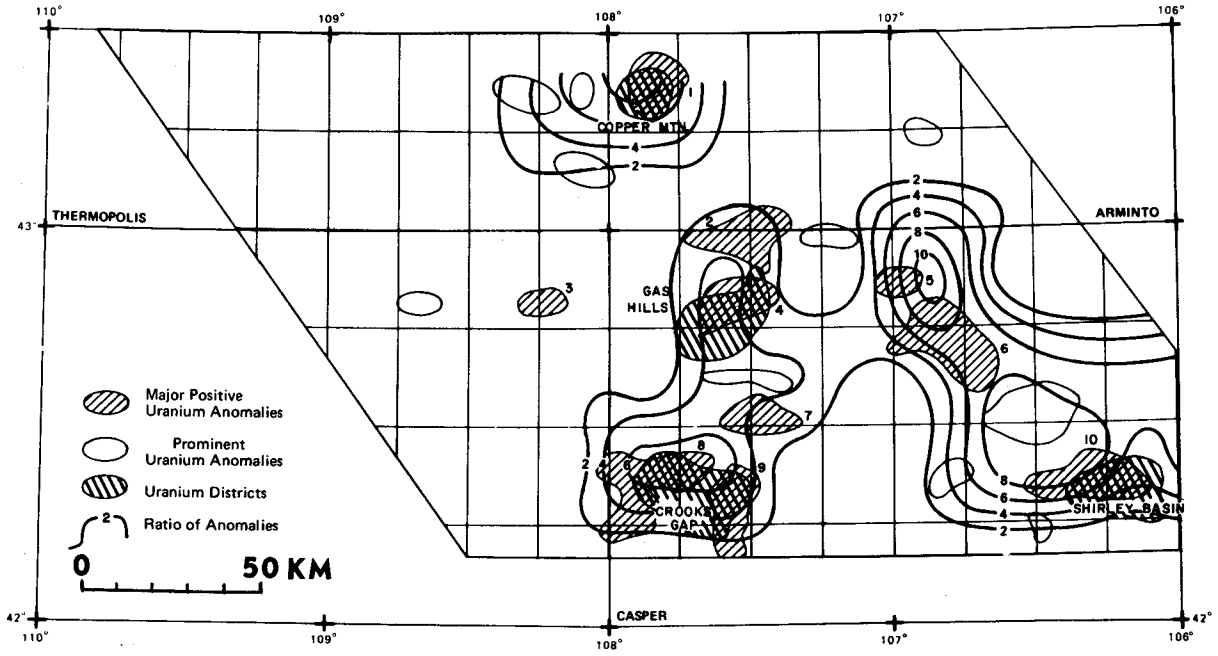


Figure 10C.50. *Favourable areas for uranium exploration in Wyoming delineated by clusters of positive anomalies and high values of the contoured ratios of the number of positive to the number of negative anomalies (after Dodd, 1976).*

Table 10C.5

Example of three anomalies classified as type S, K, and L using the fields shown in Figure 10C.49 (after Morris, pers. comm., 1977).

Line 5881										
Anomaly No. 6	Channel 1				Peak	Corrected Counts B/ground	Anomaly	%		
	Peak time	6478	Secs						U/Th ratio	0.0
	1/2 width time 1	6476	Secs	Channel 1	200.	124.	76.		Th/K ratio	1.9
	1/2 width time 2	6482	Secs	Channel 2	31.	21.	10.	35	Anomaly type	S
	Peak Altitude	426	Feet	Channel 3	11.	10.	2.	0		
	Peak raw counts	707.	CPS	Channel 4	19.	8.	11.	65	Source	Th+U/K
	Ch 3 peak time	6475	Secs							
Anomaly No. 7	Channel 1				Peak	Corrected Counts B/ground	Anomaly	%		
	Peak time	6578	Secs						U/Th ratio	.3
	1/2 width time 1	6575	Secs	Channel 1	131.	59.	72.		Th/K ratio	.9
	1/2 width time 2	6605	Secs	Channel 2	29.	13.	17.	45	Anomaly type	X
	Peak Altitude	471	Feet	Channel 3	15.	9.	6.	14		
	Peak raw counts	514.	CPS	Channel 4	16.	6.	9.	41	Source	Mixed(K)
	Ch 3 peak time	6580	Secs							
Anomaly No. 8	Channel 1				Peak	Corrected Counts B/ground	Anomaly	%		
	Peak width time 1	6600	Secs						U/Th ratio	.1
	1/2 width time 1	6575	Secs	Channel 1	116.	50.	67.		Th/K ratio	.6
	1/2 width time 2	6605	Secs	Channel 2	31.	10.	21.	61	Anomaly type	L
	Peak Altitude	468	Feet	Channel 3	13.	9.	4.	4		
	Peak raw counts	599.	CPS	Channel 4	15.	6.	9.	35	Source	K+U/Th
	Ch 3 peak time	6597	Secs							

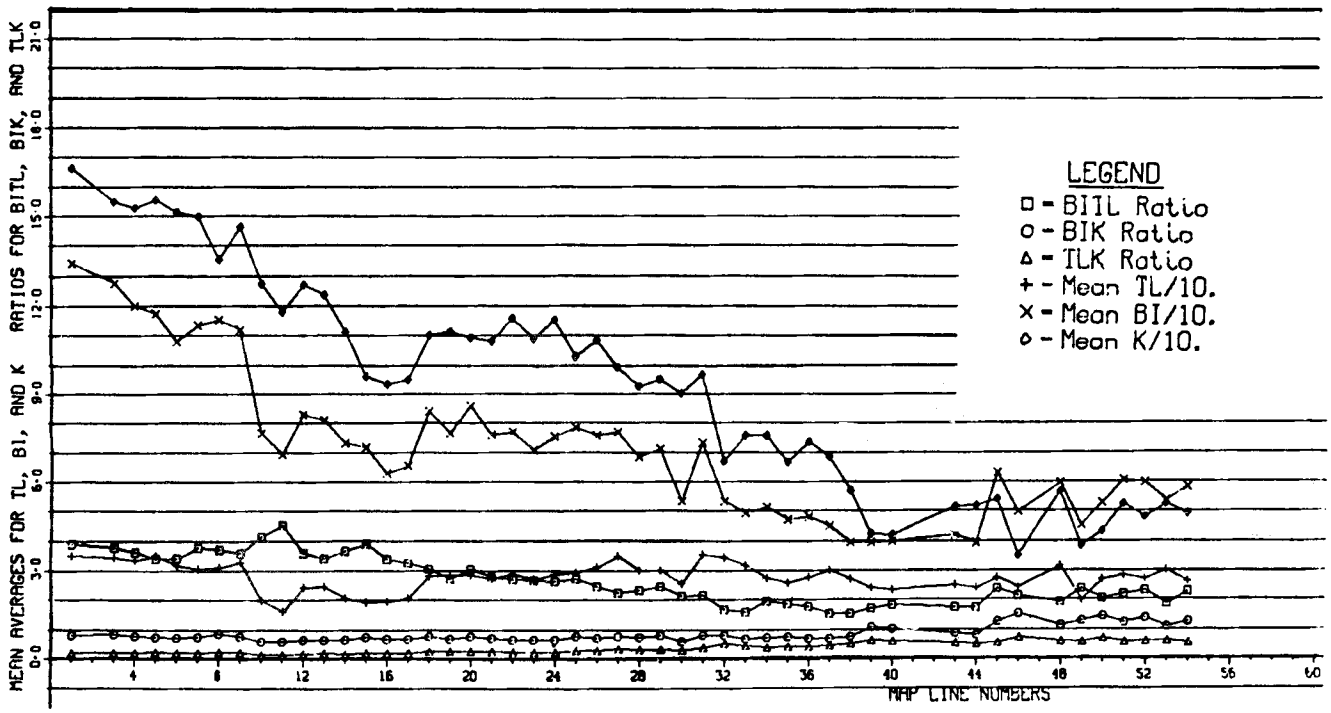


Figure 10C.51. *Favourable areas (see text) indicated by high average eU and K values for flight lines 1 to 31 over the Goliad formation of Texas (after Dodd, 1976).*

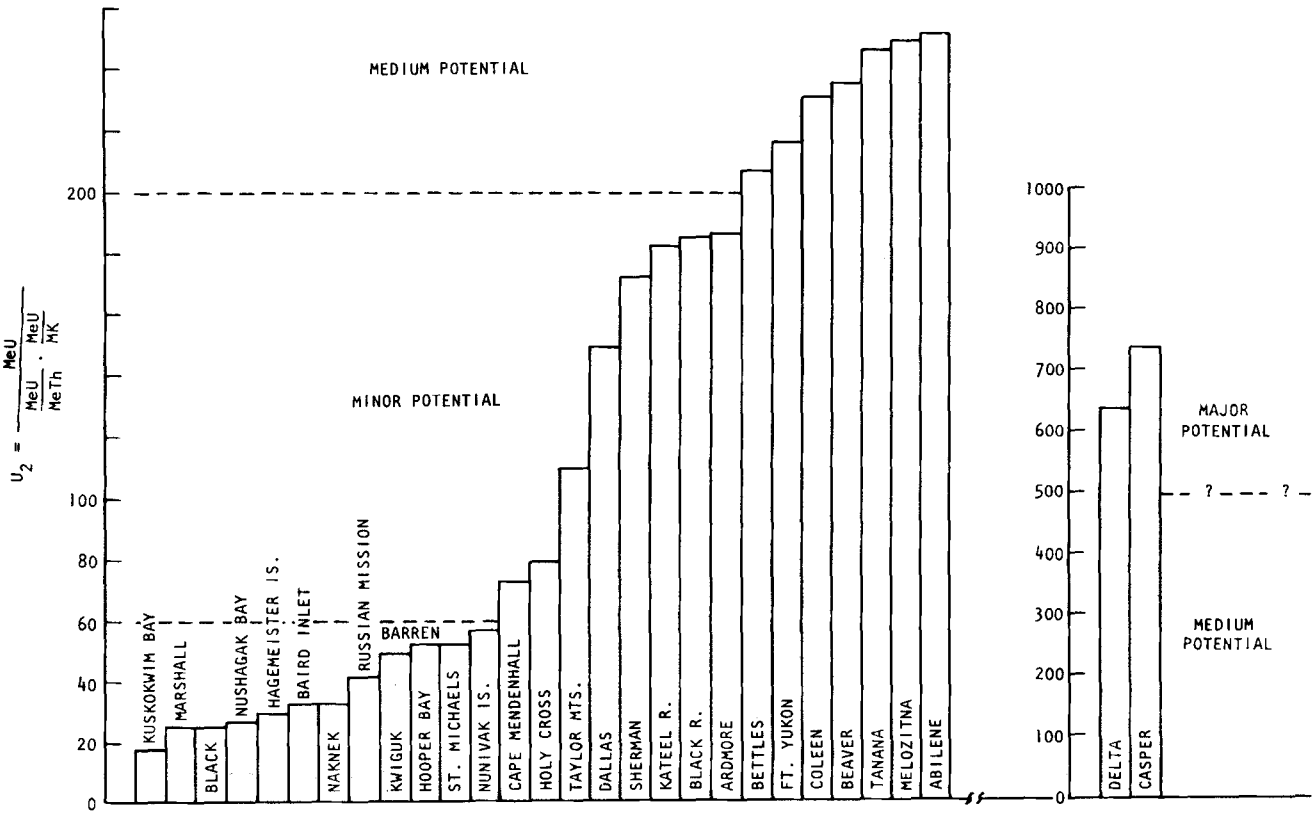


Figure 10C.52. *Histogram of "uranium favourability indexes" as described in the text (U_2 values) for whole quadrangles. A high value indicates high potential for uranium (after Saunders and Potts, 1978).*

190 km/hr with 50 000 cm^3 of NaI(Tl) detector. The following priorities were adopted for investigating the anomalies:

Priority 1 Anomaly:
high total count with high eU/eTh ratio

Priority 2 Anomaly:
low total count with high eU/eTh ratio.

Munday (1975) indicated that areas of abnormal radioactivity were outlined by traversing in a direction roughly perpendicular to the glacial strike. Traverses were made at 1000 m spacing with scintillometer readings every 15 m at ground and waist level. Readings at 7 m and 3.5 m intervals were tested but the increased detail did not warrant the extra time. Also they found that waist height readings gave a better indication of general radioactivity, especially after a 3 point running average filter was applied to the data. Munday (1975) described the boulder count technique to determine the shape of the boulder fan and thus locate the source as follows:

"When anomalies had been delimited, boulder counts were taken every 150 m along traverse lines. Only boulders of 25 cm or more, diameter were measured and the scintillometer crystal was centered on the boulder. At least 100 radioactivity readings were established for each station and plotted as a histogram. Background glacial till yields a log-normal distribution, but as anomalous populations invade the system, bimodal distributions appear. Finally, when an anomalous population dominates the background, a second log-normal distribution can be plotted with higher mode value. The anomalous population is readily attributable to a

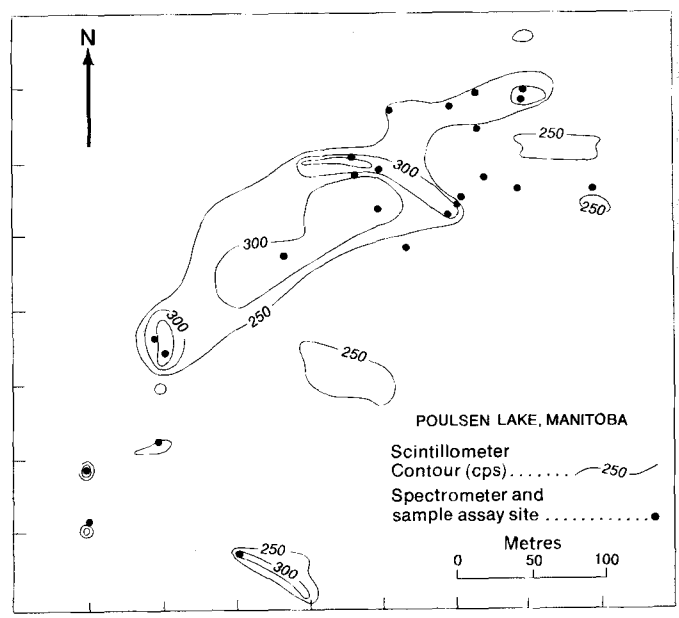


Figure 10C.53. *Contoured scintillometer data, Poulsen Lake uranium occurrence, Manitoba (after Whitworth et al., 1977). The anomaly size and shape are typical of a boulder train, and as such is useful in estimating target size for an airborne survey.*

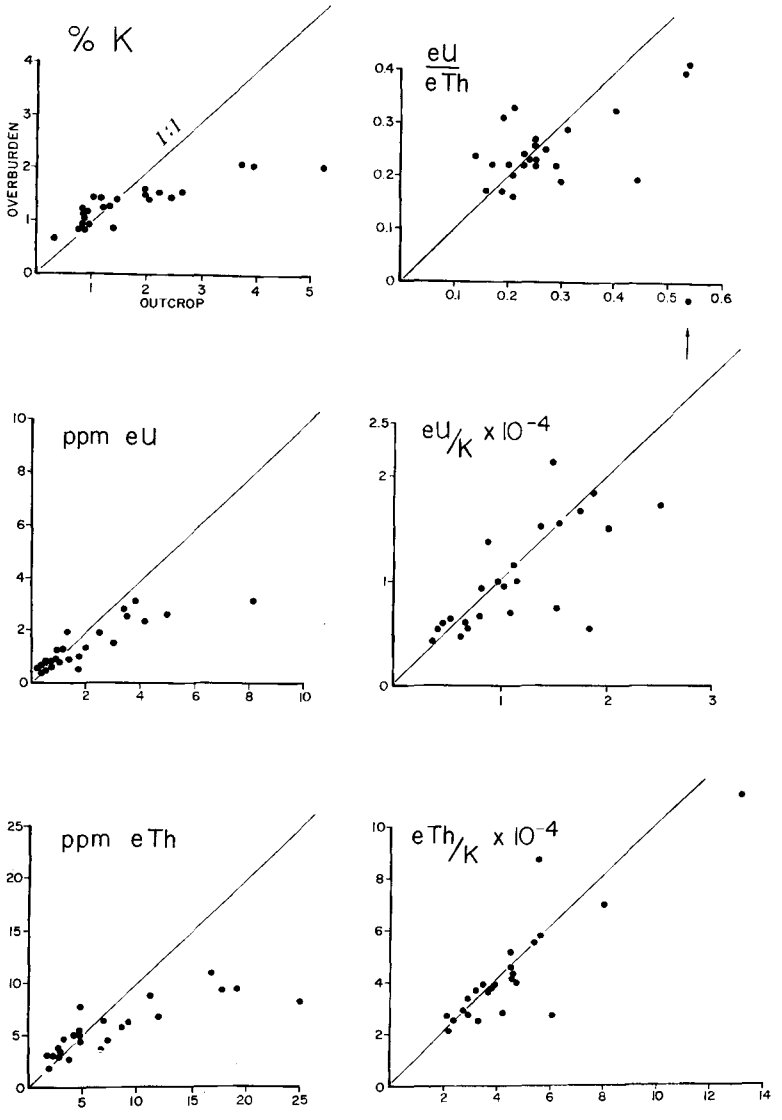


Figure 10C.54. *Mean radioelement values in outcrop versus radioelement values in the associated overburden for 24 different rock types in Canada (after Charbonneau et al., 1976). Radioelement ratios in outcrop and overburden cluster about the 1:1 line, whereas the radioelement concentrations in overburden do not increase in 1:1 with increasing concentration in outcrop.*

source in the field, and in this area was invariably related to a pink leucogranite. By systematically mapping the areal distribution of the anomaly, a fan was established and source area determined".

Several ground follow-up investigations in northern Manitoba were described by Soonawala (1977), Garber and Soonawala (1977), Whitworth et al. (1977), and Smith et al. (1977). These were investigations of anomalies located by airborne gamma ray spectrometric surveys of the Canadian Uranium Reconnaissance Program. The systematic exploration sequence began with a helicopter-borne scintillometer survey at 250 m flight line spacing, 40 m terrain clearance, and speed of 110 km/hr. The detector was a 150 x 100 mm NaI(Tl) (1850 cm^3). This was followed by ground scintillometer surveys (with NaI(Tl) detectors having a volume of 43 cm^3) in many cases on grid lines at 50 m spacing with stations 5 m apart. Anomalies located by this survey were evaluated by a combination of in situ assay by portable gamma ray spectrometer, and laboratory sample analyses. The scintillometer survey results were contoured, and the in situ and laboratory assays were marked on the contour map. The contoured scintillometer data obtained at the Poulsen Lake occurrence (Whitworth et al., 1977), reproduced in Figure 10C.53, delineates the shape of a boulder train. In situ spectrometric assays at several locations along the boulder train indicated equivalent uranium concentrations in boulders of up to 870 ppm, with several discrete groupings of boulders in the 250 to 500 ppm range.

Other descriptions of ground follow-up investigations with portable gamma ray spectrometers and scintillometers have been given by Charbonneau and Ford (1977, 1978) and Charbonneau et al. (1975). Charbonneau et al. (1976) compiled portable gamma ray spectrometer data consisting of over 2500 in situ assays from 24 sites across Canada. These results established two relationships:

1. The sympathetic relationship between radioelement contents of glacial overburden and the underlying bedrock.
2. The relationship between "average surface" radioelement concentrations measured by airborne gamma ray spectrometry, and concentrations measured on the ground.

Figure 10C.54 is a plot of the mean radioelement values in outcrop versus the radioelement values in the associated overburden, for 24 different rock types (after Charbonneau et al., 1976). Note that the radioelement ratios (eU/eTh, eU/K, eTh/K) show relatively little difference between the overburden and bedrock. Figure 10C.55 compares ground and airborne measurements of eU and eTh in the Elliot Lake and Mont Laurier areas. The values along the horizontal axis are the contour levels from the airborne spectrometric maps; values along the vertical axis are averages of ground-measured concentrations for each of the airborne contour levels. Radioelement concentrations in glacial drift measured on the ground are slightly higher than indicated by contoured radioelement values measured by the airborne survey in the same area. This is believed to be the result of the presence of surface waters within the area of investigation by the airborne system, which will reduce the measured airborne values. Radioelement concentrations in bedrock measured in situ are considerably higher than corresponding airborne measurements indicate, and this difference between bedrock and airborne survey values increases at higher radioelement concentrations. Similarly, outcrop radioelement contents become increasingly greater than the associated overburden radioelement contents, as the radioelement concentration increases.

In the areas discussed by Charbonneau et al. (1976) the airborne survey radioelement contour maps are primarily a measure of overburden radioelement content, but the airborne results do give an indication of the bedrock radioelement content. For example, an airborne measurement of 3 to 4 ppm eU in a drift covered area probably relates to an overburden content of 4 to 5 ppm eU, and a concentration of about 8 to 10 ppm eU in the underlying bedrock. Airborne contour maps of the radioelement ratios give values that are similar to the ratios determined by ground measurements on overburden and outcrop.

It has been suggested that portable gamma ray spectrometer surveys be carried out with solid state detectors rather than sodium iodide. The main advantage of the solid state detectors (e.g. lithium drifted germanium (Ge(Li)), or

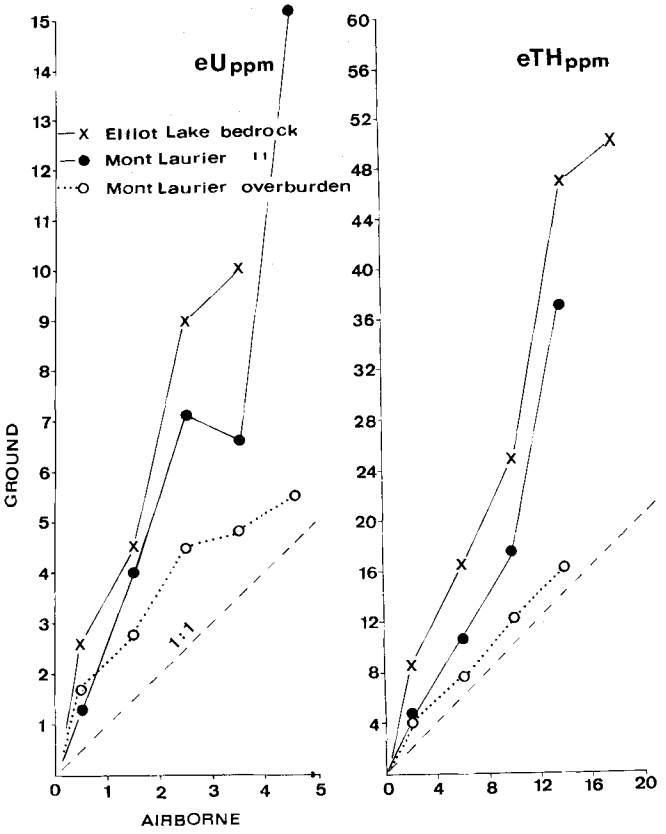


Figure 10C.55. *Comparison of ground measurements and airborne measurements by gamma ray spectrometer in the Elliot Lake and Mont Laurier areas of Canada (after Charbonneau et al., 1976). Ground measurements are average values for all ground stations within the contour intervals indicated on a map from the airborne measurements. The ground measurements are higher than the corresponding airborne measurement since the latter is an 'average surface measurement' and includes water, swamp, outcrop and overburden.*

hyperpure germanium) is energy resolution which permits distinction between peaks in the gamma ray energy spectrum which are indistinguishable with sodium iodide detectors. The main disadvantages of solid state detectors are the requirement to operate at liquid nitrogen temperature and the increased counting time necessitated by the relatively small detector size. To take advantage of the high resolution, a multi-channel spectrometer (preferably 4096 channels) is required. Field spectrometer systems using solid state detectors have been described by Arispaugh et al. (1972), Ragaini et al. (1974), Dickson et al. (1976), and Finck et al. (1976). The high resolution of solid state detectors presents the possibility of relatively direct determination of uranium concentration by spectrometry as well as indirectly by detection of the daughter ^{214}Bi. This has been investigated by Moxham and Tanner (1977) and their results indicated that at least a semi-quantitative measure of the state of equilibrium can be obtained in the field.

Carborne Gamma Ray Spectrometric Surveys

Most of the literature presently available pertaining to carborne surveys concern total-count rather than spectrometric surveys. Many of the principles involved and the field procedures will be illustrated with examples based on total-count surveys, but which apply to spectrometric surveys.

Calibration of Carborne Systems

Calibration of a carborne gamma ray spectrometer system has been mentioned earlier in the discussion of calibration of surface systems. It is difficult to do quantitative work with a carborne system since the geometry generally varies along the road traverses. However, accurate determination of the stripping factors on a set of calibration pads makes it possible to produce stripped counts and therefore radioelement ratios can be utilized. This is advantageous because the ratios of the radioelements are not seriously affected by geometry changes or changes in vegetation or moisture content (Charbonneau et al., 1976).

Detector Type and Volume

Some consideration has been given to the volume of the detector and its location in the vehicle by Berbezier et al. (1958). They also compared different types of detectors including Geiger-Muller (GM) tubes, sodium iodide crystals, and plastic scintillators. They found that a volume of 232 cm^3 of NaI(Tl) gave about the same results as 3750 cm^3 of plastic scintillator (tetraphenylbutadiene), but they considered the higher cost and fragility of NaI(Tl) was a disadvantage. However they pointed out that NaI(Tl) crystals make it possible to do gamma ray spectrometry and therefore determine which radioelements were present in the source. The GM counters were much less sensitive, produced lower count rates and consequently required a longer time constant than the NaI(Tl), making it difficult to detect narrow anomalous sources. Bowie et al. (1955) also compared GM counters with a sodium iodide scintillation counter and Kamiyama et al. (1973) reported on usage of two 75 x 125 mm detectors by carborne survey teams in Japan.

Nelson (1953) presented a thorough discussion of carborne radiometric surveying with a GM counter. With today's more modern electronics and the present availability of sodium iodide crystals, the other types of detectors mentioned above may be considered outmoded. For gamma ray spectrometry, scintillation crystals are mandatory. Irrespective of the type of detector, the determination of the required detector volume will depend on the desired reproducibility of measurement. Nelson (1953) considered an acceptable standard deviation to be ±10%. Recalling the earlier section on counting statistics, this requires N to be at least 100 counts in a given counting period. The next consideration is the minimum target or anomaly width which it is desired to detect. The anomaly could be considered to be of a certain 'wavelength' (Killeen et al., 1975). By sampling theory the minimum wavelength detectable is given by

$$\lambda_m = 2V\Delta t \qquad (35)$$

where

V is the velocity of the vehicle in m/sec.

Δt is the sampling time in seconds.

Thus, for example, at a speed of 15 km/h (i.e. 4 m/sec) and a sampling time of 1 second, then λ_m = 8 m. Note that this anomaly of wavelength 8 m would only be sampled twice when crossing it at a velocity 4 m/sec. To define it more accurately a larger number of samples, at least four, is desirable. The important point is that once the target size is chosen, the speed and sampling time are essentially also determined. For example, if the target size is 4 m, it is desirable to make a measurement every metre; with a velocity of 15 km/hr, then the value of Δt is 0.25 seconds. This means for a desired 10% standard deviation per measurement, the count must be 100 counts in 0.25 seconds or at least 400 counts per second in areas of background

Figure 10C.56. *Carborne gamma ray spectrometric survey installation in Mexico (Instituto Nacional de Energia Nuclear) with roof mounted detector. (GSC 203254-I)*

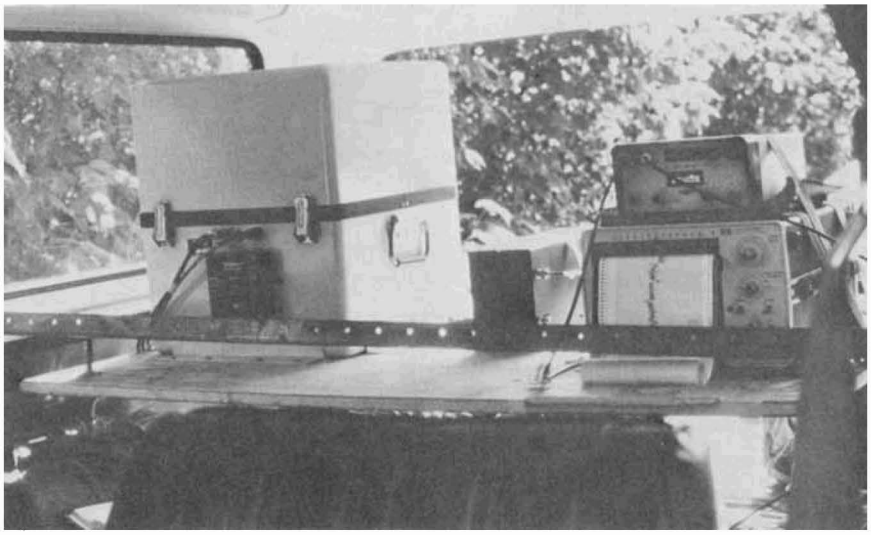


Figure 10C.57. *Carborne gamma ray spectrometric survey installation in Canada (after Killeen et al., 1976); detector mounted inside the vehicle (left), portable gamma ray spectrometer and single pen strip chart recorder (right). (GSC 202941-E)*

radioactivity. From this information the detector volume can be determined if the count rate per cubic centimetre of detector is known approximately for that background radioactivity from some preliminary measurement.

The detector volume required for a gamma ray spectrometric survey would be considerably larger than for a total-count survey. The IAEA (1973a) stated that "This type of survey should not be attempted unless a large volume of crystal can be provided". No specific volume was suggested.

Detector Location and the Sample Volume

The detector should be located as high as possible in the vehicle. This increases the diameter of the circle of investigation, and the percentage of radiation contributed by the material at the roadside and beyond, and decreases the percentage contribution from the road itself. Some discussion of the effective sample volume can be found earlier in this paper. Figure 10C.17 illustrates the effect of increasing the height of the detector in increasing the sample volume and minimizing road effects. Generally, however, the detector height is limited by bridges, tunnels and overhead wires. Goso et al. (1976) reported a carborne radiometric survey in Uraguay in which a 1230 cm^3 NaI(Tl) detector was mounted in a tower on the vehicle at an elevation of 3.50 m. The installation of a 1850 cm^3 detector on the roof of a 4 wheel drive jeep used by the Instituto Nacional de Energia Nuclear (INEN) of Mexico for gamma ray spectrometric work is shown in Figure 10C.56. The installation of 4200 cm^3 detector inside a four wheel drive vehicle used for a carborne gamma ray spectrometric survey on Prince Edward Island, Canada (Killeen et al., 1976) is shown in Figure 10C.57. Moxham et al. (1965) utilized a 6800 cm^3 NaI(Tl) detector on a tripod at 2.5 m height to make stationary measurements of gamma ray spectra with a 400 channel analyzer in a panel truck.

The orientation of the detector is not usually considered, but can be of some significance, especially if the thickness and diameter of the detector are very different. Nelson (1953) considered this problem with respect to the orientation of GM tubes. He arranged the detectors so as to present the largest detector surface area to gamma rays emitted from roadside rocks. The smallest area was then oriented to minimize gamma rays detected from road material below and cosmic rays above. If a prismatic (100 x 100 x 400 mm) sodium iodide detector were to be used for a carborne survey, it should be oriented with its long axis vertical.

Shielding by the Vehicle

In addition to the above considerations, the shielding effect of the vehicle may be used to advantage, especially if it is known that the road material is not locally derived. In some cases the radioactivity of the road material presents considerable interference, especially if the road material changes frequently, introducing man-made anomalies. A lead shield beneath the detector may be necessary in addition to the shielding by the vehicle (Bowie et al., 1955). In areas of unimproved dirt roads the vehicle shielding may be a hindrance, and the detector may be suspended behind the vehicle or over a hole in the floor. Shideler and Hinze (1971) in a carborne radiometric survey relating to petroleum exploration of glaciated regions encased the detectors in "lead containers" (not described) to minimize the effects of cosmic rays.

Pre-Survey Performance Checks

It is important to run some pre-survey tests under known conditions in order to be able to recognize anomalies when traversing new territory. In addition it is instructive to evaluate the effect of various parameters on the performance of the carborne system.

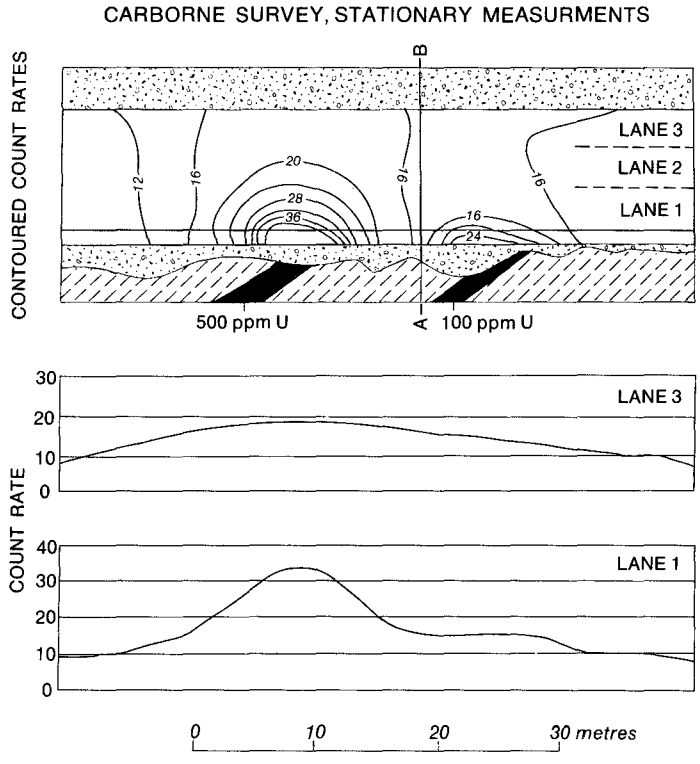


Figure 10C.58. *Radioactive zones of 500 and 100 ppm uranium as a test area for carborne gamma ray survey (after Nelson, 1953). Traverses in the "near" and "far lane" made with stationary measurements are shown. A cross-section A-B of the highway is shown in Figure 10C.59.*

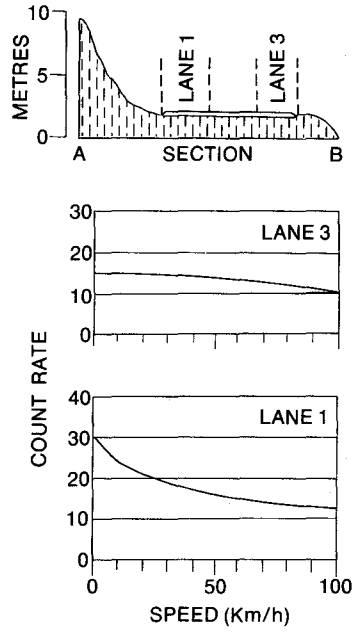


Figure 10C.59. *Effect of vehicle speed on the maximum amplitude of the anomaly detected both in the "near" and "far" lane (after Nelson, 1953). The cross-section A-B (top) shows the source-detector geometry in Figure 10C.58.*

A good example of this type of pre-survey performance study was given by Nelson (1953). For his test area Nelson chose a road cut which intersected two radioactive zones containing approximately 500 ppm and 100 ppm uranium respectively as shown in Figure 10C.58. A series of stationary total-count measurements were made past the radioactive zones with the carborne system and these are plotted for two highway lanes. It can be seen from the bottom of Figure 10C.58 that both the maximum amplitude of the anomaly and its sharpness are decreased considerably for measurements made in the "far lane". Figure 10C.59 (also from Nelson, 1953) illustrates the effect of vehicle speed on the maximum amplitude of the anomaly for both the "near lane" and "far lane". For these tests, an analog ratemeter with a time constant of 2 seconds was used. Similar graphs were constructed by Bowie et al. (1955) from data recorded with a carborne system traversing across an artificial vein 5.6 m long, 0.3 wide, and 0.3 m deep, filled with a homogeneous mixture containing 0.5 per cent U_3O_8. A profile of stationary measurements made across the vein showed an interesting unexpected asymmetry in the anomaly, caused by the detector having more absorbing material near one end than the other.

Field Procedure

Some of the first considerations in designing a carborne system are the installation of the survey equipment in the field vehicle, the source of power for the equipment, and the desired form of data presentation and hence the recording method to be used. For long-term surveys it is generally recommended that the source of power be furnished from the vehicle power supply (generator or alternator, and battery). This may require replacing the generator and regulator with equipment which can furnish additional power at low speeds (Berbezier et al., 1958; Bowie et al., 1955). For shorter term use, power may be supplied from a spare set of car batteries which can be recharged daily or as required (Killeen et al., 1976; Chandra and Leveille, 1977).

The addition of an adjustable threshold audible alarm has been found useful in many carborne surveys (Nelson, 1953; Bowie et al., 1955; Berbezier et al., 1958), especially if the chosen survey procedure is to investigate anomalies as soon as they are detected, rather than to return later after inspecting the recordings made during the road traverses. For this purpose it is useful to have an additional portable detector available in the vehicle. If the carborne survey is purely a total-count survey, a portable gamma ray spectrometer would enable the operator to determine whether the cause of a given anomaly was uranium, thorium or potassium by stopping to inspect it.

Killeen et al. (1976) utilized a four-channel portable gamma ray spectrometer with a single-pen strip chart recorder. Traversing was carried out while recording the output of the total-count channel. Anomalies were checked later by re-traversing while recording the output of the differential windows on the strip chart. The portable spectrometer could also be removed from the vehicle and attached to a 75 x 75 mm NaI(Tl) detector for in situ assaying. Chandra and Leveille (1977) recorded all four channels of a portable gamma ray spectrometer with a four-pen recorder in a carborne survey, returning to the interesting anomalies to inspect them on foot with the same spectrometer connected to a small detector. They also re-traversed anomalous sections of road while recording stripped count rates on the chart.

The methods of recording carborne radiometric data range from simply indicating anomalies on the road map with an X as they are spotted, to recording on strip charts anywhere from one to four channels of information plus

fiducials or event markers. In any case, all of the roads to be traversed in the area of the survey are first marked on the field map. The beginning and end of each traverse are pre-marked with numbers such that each traverse has its own characteristic identifying numbers. Some workers prefer to pre-mark, with numbers on the map, any special land mark which can be used for navigation and location recovery such as road crossing or bridges (Killeen et al., 1976). Because anomalies may be smeared by effects of analog time constants the direction of the traverse should also be indicated on the map. Long traverses may be broken into segments, also with identifying codes (Chandra and Leveille, 1977). When a strip chart recording is made, event or fiducial marks are valuable. Thus, when a landmark is passed a manually operated event marker can be activated or the operator must make these marks by hand. Some carborne surveys have been equipped with automatic fiducials which are activated by an interconnection to the speedometer of the vehicle (e.g. Berbezier et al., 1958).

As with other gamma ray spectrometers, carborne systems require proper calibration. Pre-survey calibration should be carried out with the use of calibration pads as described above with respect to portable gamma ray spectrometers. Usually a calibration source such as ^{137}Cs or Th is used for the initial survey calibration. This calibration ensures that the energy windows chosen to represent K, U, and Th are in their proper positions. Because of instrument drift with temperature changes some spectrometric systems require periodic checking, while others have automatic stabilization or warning indicators for out-of-calibration conditions. The calibration source, if carried in the vehicle, must always be stored in the same location (producing a constant contribution to the background) and should be shielded (to reduce the contribution to background). It may be possible to use the battery of the vehicle as a shield. All systems should be shock mounted and have thermally insulated detectors to minimize drift. The thermostatically controlled, heated, insulated detector packages often used in airborne spectrometer systems are usually unnecessary for carborne surveys since frequent calibration checks are easier to make.

Most gamma ray spectrometer systems in use today have available a digital readout after a preset counting time, of the counts accumulated in the four windows (TC, K, U, Th). This feature is used to calibrate the scales on the strip chart recorder. The strip chart is allowed to run while the vehicle is stationary at the beginning of a road traverse, and counts are accumulated for a preset time. Then the results are marked on the chart, and used to determine and check the chart scale factor. This type of check should be carried out at the beginning and end of each traverse, and also at a base station occupied at the beginning and end of each day. This latter check ensures the reproducibility of results, is a check on background, and indicates instrumental problems. In addition, background measurements should be made periodically over water, if possible, during the survey (see the earlier section regarding background in surface measurements).

Carborne radiometric surveys have been used to advantage in France (Berbezier et al., 1958), in West Africa, South Africa and Norway (Bowie et al., 1955), in the United States (Nelson, 1953; Shideler and Hinze, 1971), in Canada (Killeen et al., 1976; Chandra and Levielle, 1977), and in Japan (Kamiyama et al., 1973). The success of the survey depends primarily on the nature and extent of the road network available.

The method of data presentation does not differ greatly from that used in airborne surveys. Data from each road traverse may be plotted in the same way as data from a flight line, as profiles. If road traverses are closely spaced the data may be contoured. It is therefore instructive when planning a carborne spectrometric survey to read the more abundant and generally more up to date literature on airborne radiometric surveying.

Snowmobile Surveys

Radiometric surveys over snow can be successful, even though the snow attenuates gamma radiation emitted by the underlying rock or overburden. This application is based on the assumption that the snow cover absorbs most of the radioactivity emitted from the ground and only very highly radioactive occurrences would be detected. About 7 cm of water will attenuate the gamma radiation by 50 per cent. This could represent from 14 to 70 cm of snow, depending on its density. Minor changes in radioactivity would be undetectable beneath the snow-blanket and the method could be considered as "prospecting for hot spots". In many areas the only time of year when there is good accessibility is during winter when there is snow cover. The target of uranium rich boulders in glacial terrain seems well suited to this technique (Ketola and Sarikkola, 1973).

Field Procedure

The snowmobile survey technique has been used with some degree of success in Scandinavia. The detector assembly, which is fragile and must not be subjected to rapid temperature changes, was pre-chilled slowly in a thermostatically controlled refrigerator before the survey. Once it had reached outdoor field survey temperature, the detector assembly was always left outdoors where the temperature was relatively constant.

The survey procedure was relatively simple, consisting of traversing the area with closely spaced parallel lines. The traverse lines had to be kept close together since attenuation by snow off to the sides of the traverse line was greater than directly below the snowmobile. Anomalies were investigated as they were detected, by stopping and digging a hole in the snow (R. Sinding-Larsen, pers. comm., 1976). A pole with a

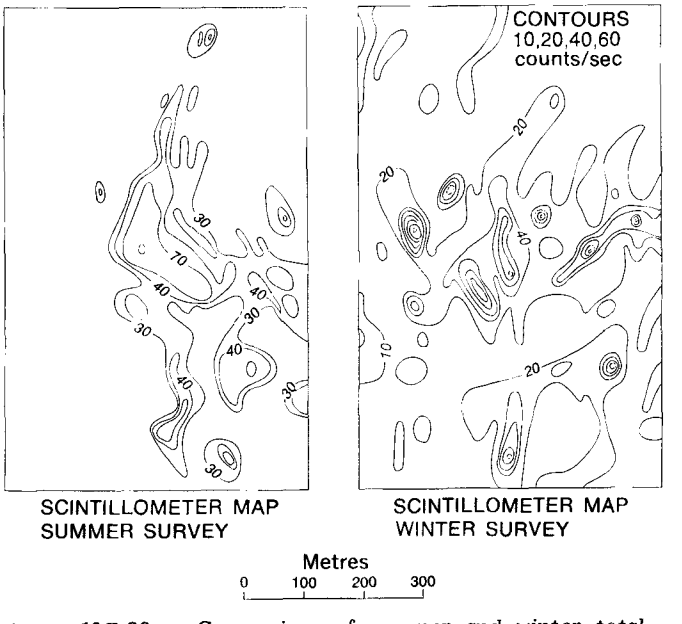


Figure 10C.60. Comparison of summer and winter total count ground gamma ray survey over a boulder train in Finland (after Ketola and Sarikkola, 1973, see text).

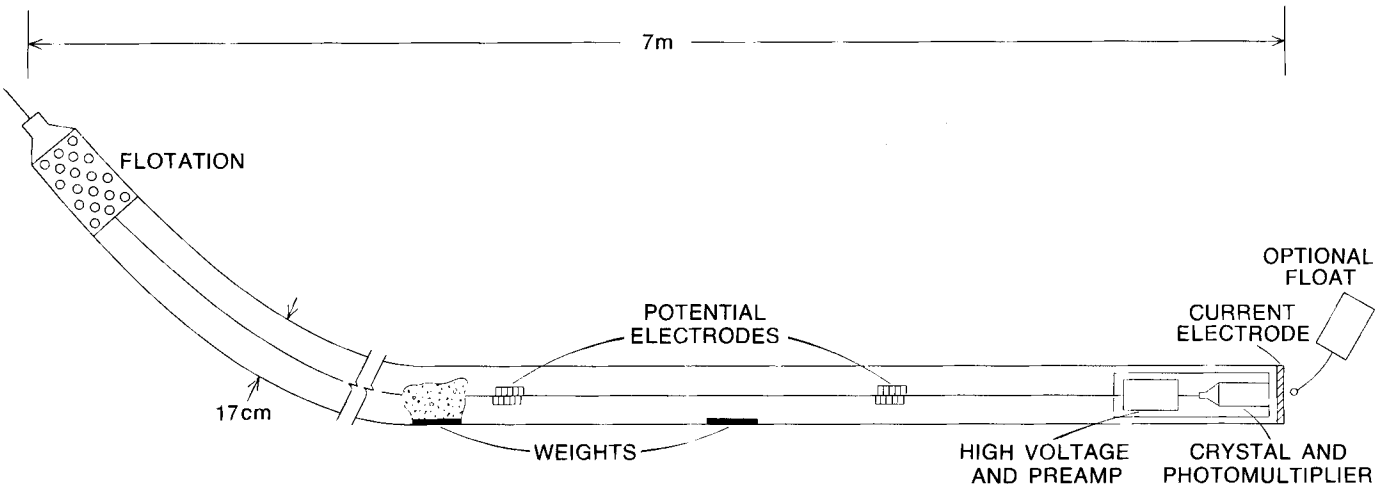


Figure 10C.61. *Diagram of 'eel' assembly used for underwater gamma ray spectrometry in northern Saskatchewan (after Stolz and Standing, 1977). Detector dimensions are 75 x 200 mm NaI(Tl) (see text).*

flag was erected at the location, and the approximate location was marked on a field map so that it could be found again in the spring after the snow melted.

In another type of winter radiometric survey, stationary measurements are made by pushing the detector into the snow. An example comparison of summer and winter total count gamma ray surveys over a boulder train in Finland carried out by Ketola and Sarikkola (1973) is shown in Figure 10C.60 to illustrate the validity of winter surveys. The survey employed a 50 m separation between traverses and a 10 m spacing between stations. Discrepancies are explained by two factors:

1. In winter the detector of the scintillometer is pushed into the snow to the bottom layers while in summer measurements are made at about 0.5 m above the surface (a geometry problem).
2. Radon gas may be trapped and concentrated below the impermeable frozen layers of snow producing more anomalies (a background problem).

UNDERWATER GAMMA RAY SPECTROMETRIC SURVEYS

Introduction

The earliest underwater gamma ray surveys, using total count scintillometers, were for applications other than uranium exploration. For example Summerhayes et al. (1970) used a conventional NaI(Tl) detector in a sealed container for stationary sea floor measurements to locate phosphorite by detecting radiation from its high uranium content. The application of radiometric techniques to locating offshore mineral deposits has increased, and much of the experience gained is useful for uranium exploration (see for example Noakes and Harding, 1971; Noakes et al., 1974a, b, 1975).

Offshore Sea-Bottom

One of the first reports of the use of a gamma ray spectrometer for sea-bottom surveying was given by Bowie and Clayton (1972). They described a prototype system consisting of a 75 x 75 mm NaI(Tl) detector mounted in a stainless steel cylinder 125 mm in diameter, fixed at the end of a reinforced rubber hose of the same diameter to avoid the possibility of the probe being caught on the bottom. This "eel", 25 m in length, was towed on a double armoured coaxial cable at a speed of 3 to 4 knots in up to 200 m water depth. The system employed a weak link and marker buoy to facilitate recovery in case of a snag on the bottom. The spectrometer was a 4 channel portable model. Miller and Symons (1973) presented total count, eU and eTh profiles, from a survey with this system off the Yorkshire Coast of England, showing the correlation with the geology of the seabed material. Some of the problems they encountered which could explain some discrepancies in the correlation were:

a) limited accuracy in position fixing.

b) lack of detailed knowledge of the seabed geological succession, and

c) the inconstent geometry of the detector with respect to the sea floor i.e. the variable depth of furrow cut by the 'eel' which could, in fact, be zero sometimes if the 'eel' left the sea floor.

The latest version of this system with a stabilized spectrometer was described by Clayton et al. (1976). The stainless steel probe contains a 75 x 125 mm NaI(Tl) detector. The 'eel' is reinforced P.V.C. of diameter 17.5 cm and length 30 m. Towing speed is normally 4 to 5 knots, with a maximum limit of 7 knots. The system is designed primarily for geological mapping of the seabed, and gives a spatial resolution of approximately 25 m at 4 knots with the total count channel, and 1 km at 4 knots with the K, U, and Th channels. The data are recorded on paper tape, and subsequently computer processed to produce contour maps. The system could be modified for use on smaller vessels for uranium exploration on lake-beds. Miller et al. (1977) reported on the use of this equipment for surveys of the continental shelf.

Gaucher et al. (1974) described a sea-floor system mounted in a sled. Experiments with two NaI(Tl) detectors (75 x 75 mm and 150 x 100 mm) towed at 1 knot produced reasonable results with 500 second counting times for the smaller detector and 300 seconds for the larger detector. Results of a survey off the Mediterranean Coast near Banyuls, at the eastern extension of the Pyrenees mountains were presented as contour maps of the potassium and thorium channel count rates which related to the sea-bottom unconsolidated materials.

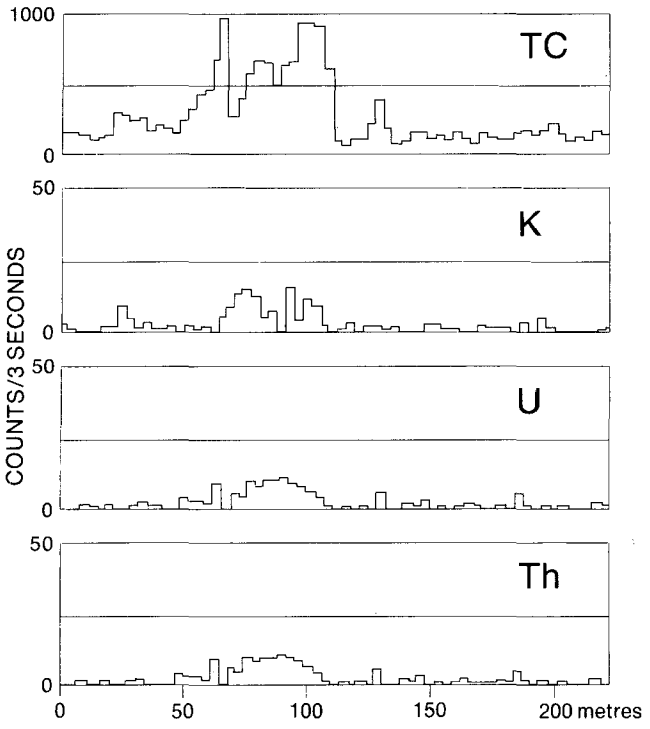


Figure 10C.62. *Anomaly caused by sand, gravel and boulders from granite and pegmatite measured in lake bed gamma ray spectrometry survey in northern Saskatchewan (after Stolz and Standing, 1977).*

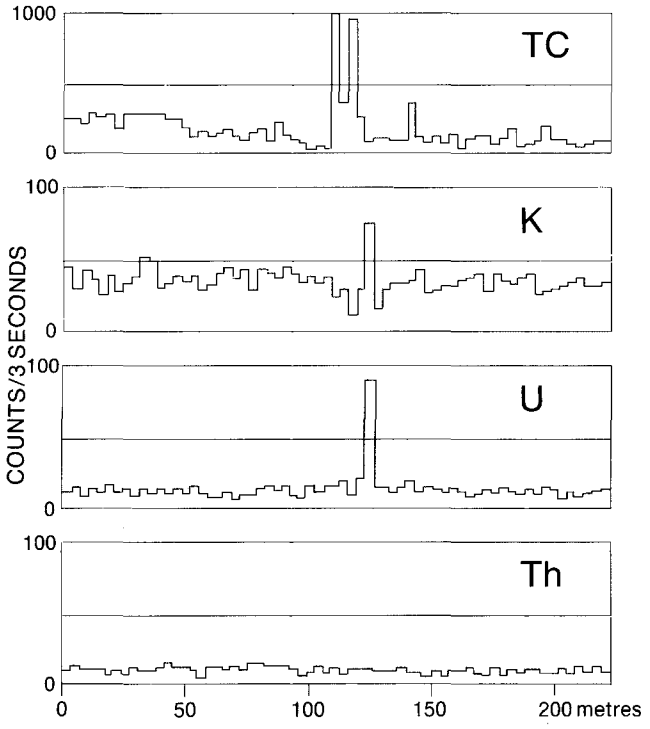


Figure 10C.63. *Anomaly caused by radioactive boulders in lake bed gamma ray spectrometry survey in northern Saskatchewan (after Stolz and Standing, 1977).*

Lake-Bottom Surveys

In regions where a significant percentage of the land is covered by lakes, and if the lakes cover geologically favourable areas for uranium exploration, a lake-bottom gamma ray spectrometer survey may be warranted. Such is the case in northern Saskatchewan where about 40 per cent of the land surface is covered by lakes and rivers. The lakes and rivers are often expressions of fractures, faults and other lineaments which have potential for uranium mineralization.

Hoeve (1975) and Beck et al. (1977) reported on the 'St. Louis Fault Project', the evaluation of a lake bed gamma ray survey in the Beaverlodge area. The survey was carried out in Alces Lake, 40 km northeast of Uranium City. The lake is situated on the postulated extension of the St. Louis Fault on which two uranium mines are located. The lake is elongate, about 8 km long by 0.8 km wide. The field procedure consisted of collecting lake-bottom samples and making lake-bottom scintillometer readings at locations about 20 m apart along grid lines at 200 m spacing. About 80 stations were sampled per day. The survey was carried out from an inflatable rubber boat with two canoes lashed alongside catamaran-style, on which a large wooden deck surface was constructed. For sample locations, distances were measured along a nylon rope tied to markers on either shore. The scintillometer used in this work (Goldak, 1975) comprised a waterproof detector package which was lowered to the lake-bottom while the readout electronics remained in the boat. At each station an echo sounder was used to provide depth information.

In 1976 the same field method was used in Seahorse lake, a part of which overlies the Key Lake uranium deposit, and Prince Lake on the postulated extension of the St. Louis Fault (Parslow and Stolz, 1976). Grid lines were located closer together (50 m) than in the Alces lake survey.

In addition to the above-mentioned stationary lake-bottom measurements, a gamma ray spectral logger, or continuous measurement system has also been evaluated (Stolz, 1976). The system included the measurement of apparent electrical resistivity of the lake-bottom, and a "scrape" microphone to assure the operator that the probe was scraping along the bottom. A diagram of the 'eel' assembly is shown in Figure 10C.61 (after Stolz and Standing, 1977).

It is expected that the system can detect differences of about 10 ppm uranium. Typical background count rates for the system have been given in the earlier section on backgrounds for submarine systems.

Because of attenuation of gamma radiation by the water, the width of the swath contributing gamma rays to the detector is quite narrow (e.g. 7 cm of water attenuates 50% of the gamma radiation). Thus, if the objective is to map uraniferous boulder trains as in exploration in glaciated regions, close line spacings are necessary. The gouging of the trench by the 'eel' increases the count rate by improving the geometry, but further narrows the width of the effective coverage thus hindering the detection of boulders. The angle between the cable and horizontal is kept small (less than 30°; Stolz, 1976) to prevent the eel from lifting off the bottom. This means the eel is a long way out and its precise location is not known. This makes follow-up investigation of the anomalies quite difficult.

For follow-up of anomalies found with the above system, hand held underwater single channel spectrometers containing 75 x 75 mm NaI(Tl) detectors were developed (Stolz, 1976; Stolz and Drevor, 1977). Counts are displayed on a four digit LED display and when the count rate exceeds a preset level, a flashing light turns on.

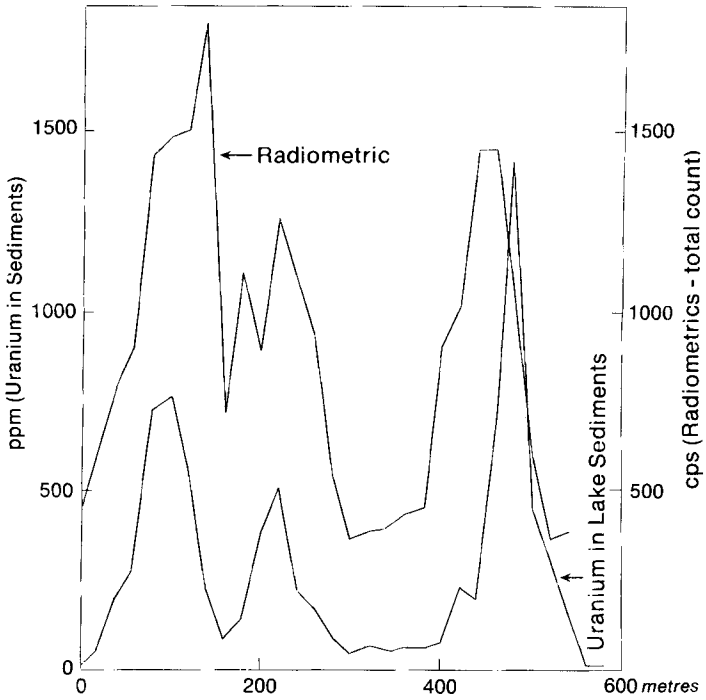


Figure 10C.64. *Profile across Seahorse Lake, Saskatchewan comparing lake sediment sample assays at 20 m intervals with gamma ray profile (after Stolz and Standing, 1977).*

The follow-up procedure consisted of prospecting the bottom in the vicinity of the anomaly with the underwater spectrometer in total count mode (thresholds at 0.30 MeV to 4.00 MeV). Background readings were typically 100 cps, with the anomaly in Seahorse Lake, Saskatchewan reading 1100 cps. Stolz (1976) reported that although underwater visibility was good, when the divers disturbed the bottom sediment, visibility became poor. The divers could read the LED display on the instrument but couldn't orient themselves. To avoid the problem and to locate anomalies more exactly, the anomalies were re-traversed until the count-rate reached a maximum over the anomaly and the boat was stopped. The divers then followed the cable down to the detector which was very close to the source.

Stolz and Drevor (1977) reported on additions and modifications to the above equipment and procedures. The major changes included recording all parameters separately on a six channel recorder, and the addition of an acoustic navigation system. Stolz and Drevor (1977) reported on the use of the system in Black Lake and near Brochet Island in Lake Athabasca. They concluded that the geophysical portion of the system worked well and several significant radioactive anomalies were discovered, but no detectable halos were found around uraniferous boulders. They recommended very close line spacing (<20 m) to map boulders on lake bottoms. The acoustic navigation system did not perform well in shallow, confined inland water. Stolz and Standing (1977) indicated the effective range of the navigation system is generally less than 1 km. They also report additions to the system such as a sub-bottom profiler (seismic) for added bottom sediment information. Thickness of up to 10 m of soft sediment on bedrock can be measured.

Figure 10C.62 shows an example from Stolz and Standing (1977) of the broad low amplitude anomaly characteristic of sands, gravels, and boulders from mechanical weathering of granite and pegmatite. Radioactive boulders produce short-wavelength, high-amplitude anomalies as shown in Figure 10C.63 (after Stolz and Standing, 1977). The lake bottom logger results were in good agreement with bottom sediment uranium contents. The agreement between the geochemical and radiometric data is clearly shown in Figure 10C.64, a profile across Seahorse Lake where lake sediments were collected at 20 m intervals. The authors concluded that underwater radiometric surveying is both effective and economical for detecting and mapping radioactive occurrences and boulders. They further indicated that since the underwater survey requires very close line spacing it is more suited to detailed surveying of areas with high potential rather than reconnaissance.

BOREHOLE GAMMA RAY SPECTRAL LOGGING

Introduction

A number of specific borehole logging parameters common to other types of gamma ray spectrometric surveys such as the question of geometry, dead time, background, calibration, the effects of borehole diameter and casing, and of the equivalent atomic number of the rock have been covered in earlier sections. Many of the parameters are energy-dependent, and experimental data are sparse or unavailable with respect to variation with energy. However, as in the case of the previously discussed modes of gamma ray spectral surveying, a great deal can be learned from the experience gained in total count gamma ray work.

Previous Reviews

An early review by Russell (1955) included a good description of gamma ray logging, and discussion of the effects of some of the logging parameters. An idea of the potential usefulness of gamma ray logging as a lithological tool can be obtained by observing the mean radioelement concentrations of a number of different rock types given in Table 10C.6. With gamma ray spectrometry there is the additional possibility of determining ranges of radioelement ratios as identifiers of rock-types. Gamma ray logging specifically for uranium was reviewed by Stead (1956). Technical details of the logging equipment in use at that time were also described.

Beckerley (1960) presented a good review of all nuclear methods for subsurface prospecting, including the state of the art on gamma ray spectral logging. The calibration facilities established by the American Petroleum Institute at the University of Houston in 1959 were described. The use of these model holes was intended to improve the inter-comparison of gamma logs. This would mean that differences between measurements by different service companies would be real and not just calibration differences. Gamma ray spectral logging was described as having great potential. It is interesting that Beckerley (1960) predicted that the problems involved with gamma energy detection techniques made it likely that spectral logging would remain scarce unless there was a real break-through.

A very well organized review of the application of nuclear techniques in oil and mineral boreholes was given by Clayton (1967). Natural gamma and gamma ray spectral logging were represented by about 35 of the 187 references given, and therefore the text is heavily weighted towards neutron and related logging. Dodd et al. (1969) reviewed borehole logging methods for uranium exploration covering the principles of calibration and analysis, the effects of many borehole parameters on the gamma ray log, and presented the state of the art in gamma ray spectral logging. They stated that "the advantages of downhole spectral measurements largely remain to be developed and demonstrated". The use of the energy region above 1 MeV for spectral logging was

Table 10C.6

Radioelement concentrations in different classes of rocks[1]

Rock Class	U (ppm)		Th (ppm)		K (%)	
	Mean	Range	Mean	Range	Mean	Range
Acid Extrusives	4.1	0.8 - 16.4	11.9	1.1 - 41.0	3.1	1.0 -6.2
Acid Intrusives	4.5	0.1 - 30.0	25.7	0.1 -253.1	3.4	0.1 -7.6
Intermediate Extrusives	1.1	0.2 - 2.6	2.4	0.4 - 6.4	1.1	0.01-2.5
Intermediate Intrusives	3.2	0.1 - 23.4	12.2	0.4 -106.0	2.1	0.1 -6.2
Basic Extrusives	0.8	0.03- 3.3	2.2	0.05- 8.8	0.7	0.06-2.4
Basic Intrusives	0.8	0.01- 5.7	2.3	0.03- 15.0	0.8	0.01-2.6
Ultrabasic	0.3	0 - 1.6	1.4	0 - 7.5	0.3	0 -0.8
Alkali Feldspathoidal Intermediate Extrusives	29.7	1.9 - 62.0	133.9	9.5 -265.0	6.5	2.0 -9.0
Alkali Feldspathoidal Intermediate Intrusives	55.8	0.3 -720.0	132.6	0.4 -880.0	4.2	1.0 -9.9
Alkali Feldspathoidal Basic Extrusives	2.4	0.5 - 12.0	8.2	2.1 - 60.0	1.9	0.2 -6.9
Alkali Feldspathoidal Basic Intrusives	2.3	0.4 - 5.4	8.4	2.8 - 19.6	1.8	0.3 -4.8
Chemical Sedimentary Rocks*	3.6	0.03- 26.7	14.9	0.03-132.0	0.6	0.02-8.4
Carbonates	2.0	0.03- 18.0	1.3	0.03- 10.8	0.3	0.01-3.5
Detrital Sedimentary Rocks	4.8	0.1 - 80.0	12.4	0.2 -362.0	1.5	0.01-9.7
Metamorphosed Igneous Rocks	4.0	0.1 -148.5	14.8	0.1 -104.2	2.5	0.1 -6.1
Metamorphosed Sedimentary Rocks	3.0	0.1 - 53.4	12.0	0.1 - 91.4	2.1	0.01-5.3

*Includes carbonates

[1]compiled from English language literature by Wollenberg, pers. comm. (1978).

advocated since photopeaks in the lower energy region are obscured by scattering. The possibility of detecting radioactive disequilibrium was mentioned, but the required instrumental stability was cited as a real problem. Dodd and Eschliman (1972) expanded on the previous review indicating that many of the problems of spectral logging had been solved by the latest generation of instrumentation, but most of the review was concerned with total count gamma ray logging. Czubek et al. (1972) in a review of nuclear techniques in geophysics in Poland discussed natural gamma ray logging briefly, especially considering the effect of the equivalent atomic number of the rock. Scott and Tibbetts (1974) reviewed borehole logging techniques for mineral deposit evaluation, in which 67 references in English and 109 references in other languages were cited. The review is organized according to the different metals (e.g. uranium) and all the available techniques which can be used to evaluate the associated mineral deposits for each metal are given. References to gamma ray logging figure prominently in the section on uranium evaluation methods.

In a technical report entitled 'Recommended Instrumentation for Uranium and Thorium Exploration' the IAEA (1974) set forth a list of the advantages of gamma ray logging methods, along with some of the limitations. Often many of these are overlooked or disregarded, and proper importance is not given to gamma ray total count or gamma ray spectral logging in an exploration program. For this reason these lists are reproduced here from the IAEA (1974). The advantages of total count gamma ray logging include:

"1) High-cost coring can be largely replaced with less expensive non-core drilling.

2) Logs provide information lost by poor core recovery.

3) Data can be obtained from holes drilled previously for other purposes.

4) The volume 'sampled' is generally larger, virtually undisturbed and hence more representative than most cores or cutting samples.

5) Delays and costs of sampling and laboratory analysis are reduced.

6) The continuous log permits 'resampling' for additional statistical and economic studies.

7) Logs are objective and unbiased by personal observation and experience.

8) Logs require minimal space to store the information."

The IAEA (1974) report goes on to list the limitations of total count gamma logging in general:

"1) Inability to identify or separately measure the specific radio-isotopes which are the source(s) of the gamma radiation. This precludes independent analyses for K, U, and Th at normal to slightly anomalous concentrations in the rock.

2) The components of mixed ores of U and Th cannot be readily evaluated.

3) Disequilibrium within the uranium (and thorium) decay series may introduce locally significant errors in the quantitative analysis for U (or Th).

4) Variation from standard conditions of calibration, e.g. borehole fluid and diameter, formation moisture and composition (Z equivalent), casing etc., will influence the response; additional logs may be required to obtain reliable correction values".

The first three of these limitations may be overcome through the use of gamma ray spectral logging, although the third may require the use of solid state detectors. Gamma ray spectral logging includes all of the advantages of total count gamma logging and eliminates many of its limitations.

Killeen (1975) reviewed nuclear techniques for borehole logging in mineral exploration, briefly discussing the 'passive' systems of gamma ray logging and gamma ray spectral logging in addition to the 'active' systems which employ radiation sources for their measurements. Dodd (1976) discussed gamma ray spectral logging in some detail in a review of uranium exploration technology. An example was presented to illustrate the advantage of gamma ray spectral logging over total count gamma logging in an environment with significant concentrations of the three radioelements K, U, and Th. Dodd (1976) stated that experience at the U.S. Department of Energy (formerly ERDA) indicates that for reliable counting statistics, detector size and logging speed must be matched for the concentration levels being measured. Dodd estimated that about 100 to 200 cm^3 of NaI(Tl) could adequately measure typical rock concentrations (Clarke values) in one minute in a borehole. He suggested that assaying a sample length (thickness) of 1.5 m was possible at a logging speed of 1.5 m/min. Smaller detectors may be used for higher radioelement concentrations (e.g. 500 ppm eU or 1000 ppm eTh). A dual detector probe was being developed and tested by the U.S. Department of Energy to cover both high and low radioelement ranges (Dodd, 1976). In addition to the above mentioned reviews, useful information on gamma ray logging applications can be found in Faul and Tittle (1951) and Fons (1969); the advantages of digital logging were discussed by Burgen and Evans (1975) and by Moseley (1976); slim tool systems were described by Reeves (1976); some of the advantages of correlating gamma ray log information with data obtained by other logging techniques especially in uranium roll front exploration were discussed by Daniels et al. (1977).

Total Count Gamma Ray Logging

Sometimes referred to as 'gross count' gamma logging, total count gamma ray logging became firmly established as a quantitative method of measuring uranium concentrations with the publication of papers by Scott et al. (1961) on quantitative interpretation of gamma ray logs. Scott and Dodd (1960) discussed corrections for disequilibrium based on a knowledge of the ratio of chemical assays to radiometric assays in the area in question. Scott (1962) described the computer program 'GAMLOG' developed to carry out the quantitative interpretation of the gamma ray logs. Pirson (1963) described the gamma ray log, calibration in API units, and presented example logs. Scott (1963) gave further information on the use of the 'GAMLOG' program, describing in detail the iterative process of analyzing the logs. Carlier (1964) described work in France on quantitative measurements by gamma ray logging, pointing out some of the problems encountered when other than "text book ore zones" were evaluated. Dodd (1966) updated the earlier reports, presenting information for quantifying some of the necessary correction factors to the gamma ray log. Edwards et al. (1967) considered the application of gamma ray logging to quantitative evaluation of potash deposits, in a similar fashion to the work on evaluation of uranium deposits.

Hawkins and Gearhart (1968, 1969) discussed uranium prospecting with gamma ray logging, including information on many practical details, often omitted by other authors, such as logging practices and cable types. Spectral logging was mentioned briefly, and a gamma ray spectrum from a sample of monazite thorium sand was shown, as obtained by a detector with 470 m of standard 4 conductor 5 mm logging cable. Some practical 'rule-of-thumb' types of information were given by Hallenburg (1973) in a discussion of the interpretation of gamma ray logs. Sprecher and Rybach (1974) described a total count logging probe (25 mm outside diameter) designed for slim hole exploration in Switzerland. A good discussion of the determination of uranium grade in boreholes in South Africa by gamma ray logging was presented by Corner and de Beer (1976). Example logs from numerous boreholes were given, and disequilibrium problems were discussed. They found that uranium grades could be calculated to an accuracy of better than 10 per cent since the equipment was calibrated in the model holes located at Pelindaba, provided the ore was in equilibrium and thorium-free.

Corner and de Beer (1976) found disequilibrium was prevalent in the Karoo, primarily consisting of uranium depletion relative to its daughter products in the holes which they logged. This disequilibrium was mostly confined to the zone above the water table (i.e. in the air filled holes). They concluded that the high radiometric background levels observed over extended distances in some boreholes in Karoo-type occurrences were indicative of radon-gas buildup. Corner and de Beer (1976) indicated that radiometric borehole logging, to a great extent, could replace chemical assays for determining uranium grade for ore-reserve calculations. However they suggested that chemical checks for disequilibrium be made.

Pochet (1976) described the present practice in France for quantitative gamma ray logging. Restricted to very slim holes, a number of logging tools (probes) with very narrow diameters have been developed. The standard gamma ray probe is only 22 mm outside diameter, and contains a GM (geiger mueller) tube section (two GM tubes 1.5 x 4 cm each) for high grade ore evaluation, and a scintillation section (either a 1.2 cm x 2.5 or 1.2 x 5.0 cm NaI(Tl) detector). This solves the problem of a wide range of radioelement concentrations, but ambiguity is still present when mixed U and Th ores are encountered.

Gamma Ray Spectral Logging

The earliest pulse height analyzers utilized in gamma ray spectral logging tests were of the photographic type, and were not easily adaptable to quantitative measurements (Brannon and Osoba, 1956). Caldwell et al. (1963) reported gamma ray spectral measurements made through 1500 m of logging cable with a 64 x 64 mm NaI(Tl) detector and a pulse height analyzer of the type in use today. Most of the paper, however, was devoted to the study of gamma ray spectra resulting from bombardment of the rock by a neutron source. Rhodes and Mott (1966) presented a series of curves computed from theory which were designed to provide correction factors for gamma ray spectral logs. Correction factor curves for a range of gamma ray energies (up to 8 MeV) are given for the effects of casing, mud density, eccentricity of the detector, bed thickness and borehole diameter. Much of the data is for oil-well situations (e.g. large diameter holes, heavy drilling mud etc.) but some would be applicable to uranium exploration boreholes. Corroboration of the theoretical curves by empirical measurements is also necessary. Czubek (1969) considered the effect of borehole parameters (size, fluid, casing, etc.) on the spectral log using a different theory of absorption of gamma rays: the

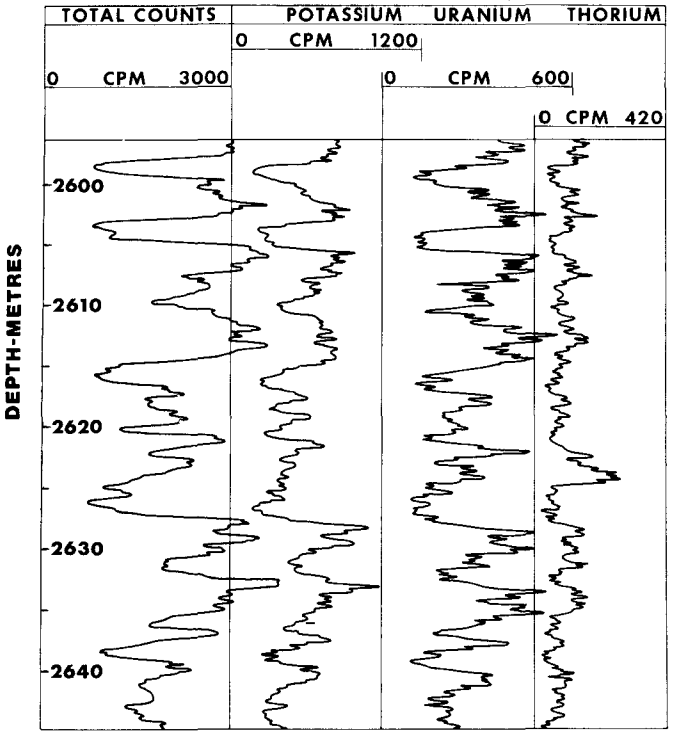


Figure 10C.65. *A gamma ray spectral log showing a thorium marker anomaly just below 2620 m not shown on the total count log (after Lock and Hoyer, 1971).*

so-called transmission factor (T). Czubek (1969) claimed this gave improved results and closer agreement between theory and experiment than other treatments of the problem. Czubek and Lenda (1969) considered the problem of the choice of units in which gamma ray logging measurements should be expressed by studying gamma ray energy distributions. They concluded that in any case measurements can only be standardized if the low level discriminator is set at 200 KeV, or for rocks with a high Zeq (equivalent atomic number) set at 400 KeV. This agrees with the more recent discussions concerning the so-called 'ur' unit used for total count scintillometry. Lock and Hoyer (1971) described a gamma ray spectral logging system and gave an example spectrum recorded through 6700 m of cable. They stated that "experience has shown that the potassium peak is always strong enough to provide a dependable reference for monitoring gain during the logging operation". They indicated that the gamma ray spectral log proved very useful in recognizing a distinctive thorium-rich bed that was used as a marker bed, but which did not appear in the total count log. Figure 10C.65 (after Lock and Hoyer, 1971) illustrates a gamma ray spectral log, and the thorium marker anomaly just below 2620 m on the log. (No spectral stripping has been performed on the logs shown in Figure 10C.65.)

Løvborg et al. (1972) compared data from a laboratory drill-core-scanning gamma ray spectrometer and total count gamma ray borehole logs. They found consistency between U and Th contents determined by scanning the drill core, and the total count gamma ray borehole log, with the exception of an apparent downward displacement of the gamma-log peaks by about 1.5 per cent which was attributed to cable stretching. Gamma ray spectral logging incorporating stripping was described by Wichmann et al. (1975). The output of a 512 channel analyzer was fed in groups of channels to three single channel analyzers with associated ratemeters. Window energies were 1.37 to 1.55 MeV for K(^{40}K), 1.58 to 1.95 MeV for U(^{214}Bi), and 2.40 to 2.85 MeV for Th(^{208}Tl). One of the main features was the use of a set of four "calibrators" each consisting of a cylindrical source constructed of plaster of paris. These contained K, U, Th, and a mixture of the three. These sources were placed on the detector by sliding the probe inside a hole along the axis of the source. They were then used to derive the stripping factors. The API gamma ray test hole in Houston (4%K, 13 ppm U, 24 ppm Th) was analyzed with this logging system and very close agreement was reported. The detector size was unspecified, but the probe dimensions were 92 mm in diameter by 2.1 m long. Wichmann et al. (1975) recommended logging speeds of less than about 4 m per minute. Hassan et al. (1976) referred to the gamma ray spectral log as the differential gamma ray log. They mention the problem of low count rates at high gamma ray energies and suggest several improvements such as increasing detector size, reducing logging speed, or increasing the number of energy windows. They suggested adding the ^{228}Ac peak at 0.91 MeV and the ^{214}Bi peak at 1.12 MeV to improve the Th and U window count rates respectively. Marett et al. (1976) attempted to incorporate all the counts from all the windows (channels of a multi-channel spectrometer) to improve counting statistics. The standard logging speed was quoted as 4.6 m/min. and the detector was a 5.1 cm diameter by 30.5 cm long NaI(Tl) crystal. A gamma-reference source was used for stabilization of the gain of the photomultiplier. Data was transmitted in digital form, multiplexed on a single conductor. The technique was used in the North Sea to identify micaceous sandstones, utilizing crossplots of the radioelements to help in the identification. Some examples of the use of this system in crystalline Precambrian basement rocks in northern New Mexico were presented by West and Laughlin (1976). The authors were able to recognize biotite-rich granitic or granodioritic gneiss and felsic dykes. Fracture zones with increased uranium concentration were interpreted as either sealed or open depending on whether or not Th and K peaks in the log were associated with the U peaks.

The use of portable borehole gamma ray spectral loggers for uranium exploration was reported briefly by Killeen (1976b), and in more detail by Killeen and Bristow (1976). They evaluated two commercially available types of spectral loggers in boreholes in uranium mining areas. Results using three different detector sizes were compared. Probes were slim (outside diameters 32 mm and 38 mm). Detectors were NaI(Tl) of dimensions 19 x 51 mm, 19 x 76 mm and 25 x 76 mm. Gamma ray spectra obtained with the three detectors were presented, both for K, U, and Th sources, and for in-hole measurements. Some example gamma ray spectral logs recorded in the same hole (Total Count, K, U and Th) were given for comparison. Recording was by single pen analog strip chart. Suggestions for improvement of portable borehole gamma ray spectral logging systems were given. Killeen et al. (1978) reported on an improved portable gamma ray spectral logging system which incorporated digital recording on cassette tape. This facilitated data processing by computer. The system was designed for Canadian uranium exploration conditions where access to boreholes by vehicles is often extremely difficult. The entire battery operated system weighed 73 kg including spectrometer, chart recorder, tape recorder, winch, cable, probe, and other accessories. The offline processing of data recorded on cassette tape by this system was accomplished by a mini-computer as described by Bristow (1977). This 'mini' was part of a larger truck mounted digital gamma ray spectral logging system referred to as the Geological Survey of Canada 'DIGI-PROBE' logger (Killeen et al., 1978). In situ assaying in the boreholes was also discussed, and a list of recommendations were given for a new generation of portable

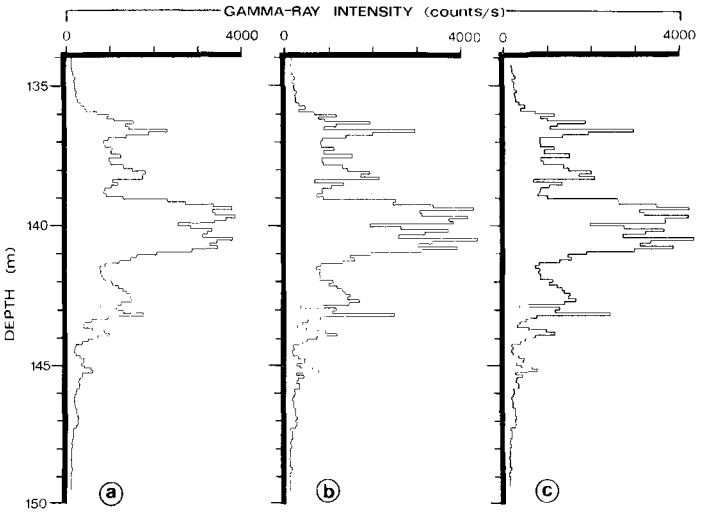


Figure 10C.66. A comparison of (a) a raw gamma ray log and the same log processed by: (b) iteration, and by (c) inverse filtering (after Conaway and Killeen, 1978b).

gamma ray spectral logger. The suggested system could produce a Radiometric Assay log (RA-log) directly in real time by deconvolving the raw gamma ray logs using a microprocessor. A detailed description of the deconvolution technique (also called inverse filtering) was presented by Conaway and Killeen (1978a). This inverse filtering technique is based on the determination of the response function of a gamma ray detector using data obtained in model boreholes such as those available in Ottawa, Canada or in Grand Junction, U.S.A. From the measured response an inverse operator is derived, to be used as a filter on the raw gamma ray log, removing the deleterious effects of the logging system response function. The method is illustrated with numerous theoretical examples of the effects of the processing technique on thin beds, thick beds, widely separated and closely spaced beds and a bed with linearly increasing radioelement contents across its width. An example of data recorded in a model borehole at the GSC calibration facilities is also given, processed to produce the RA-log. Conaway and Killeen (1978b) compared the inverse filter technique with the iterative technique that forms the basis of the GAMLOG computer program (Scott, 1963) which is commonly used to process gamma ray logs. They determined that the iterative technique and the inverse filter technique approach theoretical equivalence as the number of iterations increases. Two advantages of the inverse filter technique are the reduction in computing time (by a factor of over 20), and the possibility of processing data in real time by minicomputer or microprocessor with very little core storage required. Figure 10C.66 illustrates a comparison of a raw gamma ray log (digitally recorded at Δz = 10 cm intervals) and two processed logs, one by iteration and one by inverse filtering (after Conaway and Killeen, 1978b). The similarity is evident. With shorter sampling interval improved resolution is possible. An example comparison similar to the above, but for Δz = 3.3 cm is also shown by Conaway and Killeen (1978b). For the shorter sampling interval a smoothing operator is required by both techniques; GAMLOG at present has no facility for smoothing.

A detailed description of a truck-mounted borehole gamma ray spectral logging system developed by the U.S. Department of Energy was presented by George et al. (1978). The system includes a dual detector probe (small NaI(Tl) = 115 cm^3, large NaI(Tl) = 500 cm^3) to cover a wide range of radioelement concentrations. Three single channel analyzers and a lower level discriminator provide the K, U, Th, and Total Count outputs. The count rates from each window are recorded digitally on magnetic tape cartridges, and also displayed on an analog strip chart. Data are collected on a depth basis rather than on the more commonly used time basis. The large detector (5.1 x 25.4 cm) is used except when count rates exceed 20 000 cps. The smaller detector (4.4 x 7.5 cm) is switch selected by the operator in that case. A stabilization source of Mn-54 is used for each detector, providing a peak at 835 keV. Typical logging speed is 1.5 m/min. Counts are accumulated for 10 seconds during each measurement, representing about a 25 cm interval. A discussion of the calibration of the system, and some example applications are included in the report. Bristow and Killeen (1978) also presented a detailed report on the construction and operation of the G.S.C. DIGI-PROBE logging system, which records up to 1024 channels of gamma ray spectral logging data on 9-track tape as often as every 0.25 seconds, displaying the reduced K, U, and Th and/or any radioelement ratio data on a 6 pen strip chart recorder via digital to analog converters. The whole system is built around a 16-bit minicomputer operated interactively via a keyboard and a CRT display with alphanumeric and graphic capabilities. Commonly the DIGI-PROBE system utilizes slim hole probes with 25 x 76 mm CsI(Na) or NaI(Tl) detectors (or smaller) inside 38 mm outside diameter probes (or smaller), at logging speeds of 0.6 m/min. to 6.0 m/min., recording 256 channels of data with sample times of 1.0 second to 0.2 seconds respectively, representing sample intervals of 1 or 2 cm.

Gamma Ray Spectral Logging with Solid State Detectors

The main advantage of the solid state detector is its high energy resolution compared to sodium iodide detectors. This makes it possible to detect daughter products other than ^{214}Bi for uranium estimation, thus avoiding the problem caused by radioactive disequilibrium. The main problem in the application of solid state detectors such as lithium drifted germanium (or Ge(Li)) is their low operating temperature of below minus 150°C. The detector must be cooled by liquid nitrogen or some other equivalent coolant at all times, or it is rendered useless, losing its detection properties. Also large detectors are difficult to manufacture and are therefore very costly. Lauber and Landstrom (1972) reported on the use of a Ge(Li) borehole probe for gamma ray spectral logging in a uranium mine in Sweden. Their cryostat kept the probe cool for ten hours under working conditions, after which time the liquid nitrogen had to be replenished. The natural gamma ray spectrum recorded in the Ranstad uranium mine was illustrated to show the possibilities of the method. This is reproduced in Figure 10C.67. The counting times however were fairly long due to the small size of the detector (22 cm^3) and the need for a larger number of channels to utilize the high resolution of the detector. The authors suggested a 4 to 6 channel analyzer with its channels centred on peaks of interest should be a viable arrangement. Gorbatyuk et al. (1973) suggested the use of a borehole Ge(Li) detector to determine the uranium content of ore from the size of the 186 keV gamma ray peak which is a combination of the 185.7 and 186.2 keV gamma rays from ^{235}U and ^{226}Ra respectively. They also tried the 1.001 MeV peak of ^{234}Pa. This is a low-count peak, but is high energy and relatively free of interference and is as high as possible in the decay series. Boynton (1975) described a simplification of the detector cooling problem. It consists of using canisters or cartridges of solid propane 3.7 cm diameter by 57 cm long instead of liquid nitrogen. The solid propane converted to a liquid during the cooling, without much volume change, unlike the liquid nitrogen which converts to a gas, increasing in volume drastically requiring venting to be incorporated in the probe design. Landstrom (1976) described the interesting

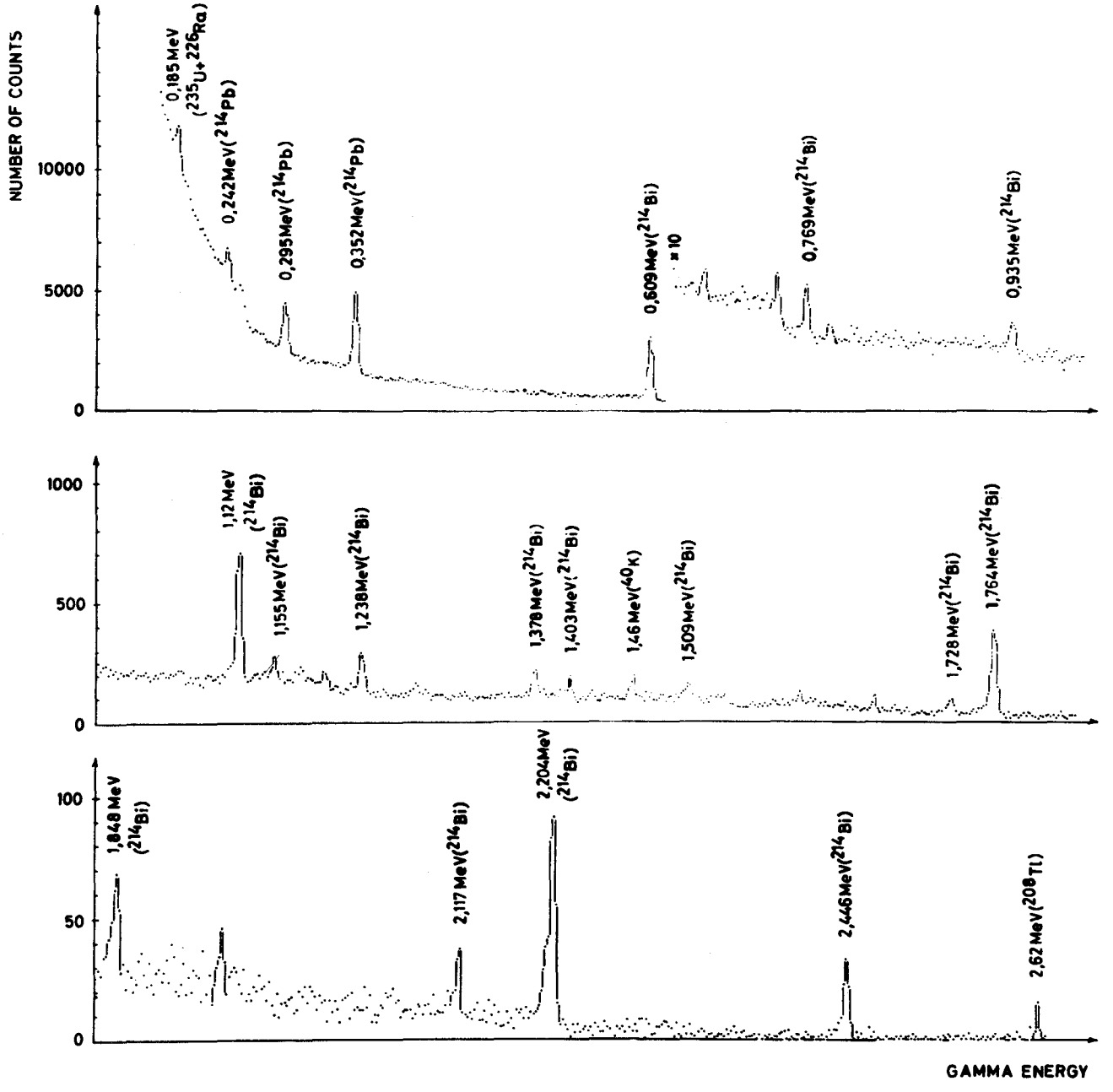


Figure 10C.67. *Ge(Li) spectrum recorded in a borehole in the Ranstad Uranium mine, Sweden. Drill core assay; 400 ppm U, 10 ppm Th, 4% K; counting time: 10 min. (after Lauber and Landstrom, 1972).*

possibilities of identifying elements in boreholes by X-ray fluorescence using natural gamma radiation as the source of excitation. Evaluation of the source itself must be carried out by gamma ray spectral logging. Christell et al. (1976) reviewed nuclear geophysics in Sweden, describing borehole gamma ray spectral logging measurements with both NaI(Tl) and Ge(Li) detectors. Senftle et al. (1976) described the use of intrinsic germanium (also called hyperpure Ge) in borehole probes used for uranium exploration. The intrinsic Ge has the advantage of only requiring cooling to operate, but not during storage or transportation as is the case with Ge(Li) detectors. They discussed several gamma ray peaks which may be utilized for analysis of uranium such as the 63.3 keV peak of ^{234}Th, first daughter of ^{238}U. Tanner et al. (1977a) described the measurement of disequilibrium by using a solid state detector in a borehole probe. They utilized two probes, one with a Ge(Li) detector, the other with an intrinsic Ge detector. The latter is suitable for low energy gamma ray measurement, whereas the former, being of larger volume (45 cm^3) is used for high energy gamma ray measurements. Their procedure is to first delineate zones for detailed investigation by logging continuously at about 1.0 m/min.

The interesting zones are then analyzed with 10 minute counting times to determine their state of radioactive equilibrium or disequilibrium. In situ assaying is based on the 63.3 keV gamma ray of ^{234}Th and also the 1001.4 keV gamma ray of ^{234}Pa. These are in equilibrium with the parent ^{238}U. In total six isotopes or groups of isotopes are evaluated in a single measurement of disequilibrium. Tanner et al. (1977a) showed comparisons of scintillation detector logs and solid state detector logs. A series of holes drilled through a roll front uranium deposit were logged, and the state of equilibrium was displayed as an equilibrium ratio. Sensitivity of the method is about 80 ppm U_3O_8, for the 10 minute counting time.

It is apparent that the use of the solid state detector has a number of advantages over scintillation detectors but which can be obtained at present only with some difficulty. The recent rapid improvements in the application of solid state borehole probes in only a few years indicates that it won't be long before it is a commercially viable technique and will be offered by logging service companies.

CONCLUSIONS

It is evident that gamma ray spectrometry has made considerable advances in the last 10 years. Its applications have expanded into many different environments as the equipment has become more refined and the effects of these environments on gamma radiation have become better understood. It is likely that the next 10 years will see further improvements which will permit the extraction of more information from the gamma ray spectral measurements than is presently possible in routine surveys.

In the future, microprocessor technology will permit the presentation of the data, completely corrected and processed in the field for increased on-site decision-making in exploration as well as recording the data for later enhancement.

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