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ACQUISITION, PROCESSING, AND INTERPRETATION OF AIRBORNE GAMMA-RAY SPECTROMETRY DATA

by

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CONTENTS

FIGURES

Page

TABLES

SUMMARY

The "Gamma-ray spectrometry project" was initiated in 1974 to study the state of the art in acquisition, processing, and interpretation of airborne radiometric data and related ground and laboratory measurements.

The theoretical and experimental backgrounds to acquisition and processing of radiometric data are presented first in the report, followed by details of computer programs which have been written to process digital airborne radiometric data acquired by BMR. Information is given on different types of data presentation, geological applications, and interpretation of airborne spectrometry.

It is now recognized that height correction coefficients depend on geology as well as on the areal extent of the sources of radioactivity in the ground. It is necessary to determine these coefficients by test flying in each survey area in order to apply the correct values during processing. Stripping ratios are functions of detector volume, detector configuration, ground clearance, and channel limits. Their accurate measurement requires calibration pads and a number of test areas to be established. These facilities would also provide data from which air-to-ground correlations could be routinely made, thereby improving the usefulness of airborne spectrometry; e.g. prediction of ground level radioactivity and surface radioelement concentrations.

Airborne tests made during 1975 have briefly investigated the variation of background radioactivity as a function of ground clearance. It is apparent that background measurements needed for data processing should either be recorded at survey altitude over water, or at about 915 m above the ground. Measurements made at 610 m are likely to include some ground component of radiation and over-estimate the background levels recorded by up to 25 percent.

During the project, investigations were made of ground gamma-ray spectrometry and analytical techniques for determining radioelement content in rock samples. Ground gamma-ray spectrometry can produce approximate quantitative estimates of radioelement concentrations in situ, provided the instrument is properly calibrated and survey procedures are carefully designed. The accuracy is inadequate for in situ geochemical measurement. If higher accuracy is required, a differential scanner should be used with the spectrometer. Laboratory techniques which produce satisfactory results are XRF for uranium and thorium, and atomic absorption analysis for potassium. If higher accuracy or independent checks are required for uranium measurements, delayed neutron analysis, using the AAEC reactor facilities at Lucas Heights, is recommended.

1. INTRODUCTION

The "Gamma-ray spectrometry project" was carried out between May 1974 and February 1976. Its objectives were to review current practices in the acquisition, processing, and interpretation of airborne gamma-ray spectrometry data and related ground and laboratory measurements.

Investigations were conducted under seven inter-related headings: airborne instrumentation, survey techniques, data processing, interpretation, calibration problems, ground radiometric surveys, and the laboratory determination of the radioelement content of rock samples.

2. DATA ACQUISITION

2.1 Factors affecting survey design

Lane width and depth of exploration. In designing an airborne radiometric survey it is useful to know the area and effective thickness of the source from which gamma radiation is received at a detector. If the detector is uncollimated, the volume of material "viewed" by it is infinitely large, but since the gamma radiation is attenuated by the source material and the air between source and detector, the volume of source which produces most of the detected radiation is restricted.

Duval & others (1971) presented computer calculations to estimate the volume of source material "viewed" by an airborne radiometric system. Figures 1 and 2 are reproduced from this reference. In Figure 1 the curves correspond to different percentages of the total radiation received at the detector; e.g. at a ground clearance of 150 m, 90 percent of the radiation detected is received from a strip of ground about 630 m (4.2 h) wide. Figure 1 can be used to estimate the effective coverage obtained from various combinations of ground clearance and flight-line spacing. Using the example above with a flight-line spacing of 1.5 km, 90 percent of the radiation detected is received from about 40 percent of the survey area.

Figure 2 shows how the detected radiation varies with source thickness and source density. It can be seen that most of the radiation detected is produced within the top metre of the source material. This is a result of scattering and absorption in the lower part of the source. The curves have the equation:

$$Y(t) = \left[1.0 - \exp(-\mu\rho t)\right] \times 100$$

where Y(t) is the percentage of total detected radiation from thickness t(cm) of source; μ is the mass attenuation coefficient (value used here is 4×10^{-2} $cm^2.g^{-1}$); ρ is source density in $g.cm^{-3}$.

The curve for any other density can be readily obtained from the curve of $\rho = 1.0$ by appropriate choice of t value.

If the 90 percent emission thickness is defined as the thickness of source which produces 90 percent of the radiation that would be emitted by an infinite thickness of the same source, then

(90 percent emission thickness) x (source density) $\simeq$ 60, where the thickness is expressed in cm and source density in $g.cm^{-3}$.

Gregory & Horwood (1961) presented experimental results obtained with sources of different thicknesses. Their results are very similar to the computed results shown in Figure 2.

Variation of background radioactivity. In an airborne radiometric survey there are four sources of background radioactivity:

(1) Cosmic ray interactions with nuclei present in the air, aircraft, and detector.
(2) Radioactivity from the structure of the aircraft and equipment. This is an unchanging component.
(3) Airborne radioactivity resulting from nuclear bomb tests.
(4) Radioactivity due to atmospheric radon-222 and its daughter products.

Typical variation of radioactivity as a function of altitude is shown in Figure 3. This is reproduced from Hand (1964) and is very similar to results presented by Davis & Reinhardt (1957), except that the minima occur at different ground clearances - about 1200 m and 750 m respectively. At high altitudes the major contributions to the background are the cosmic component and the fallout component. At lower altitudes radon-222 and its daughter products become more important.

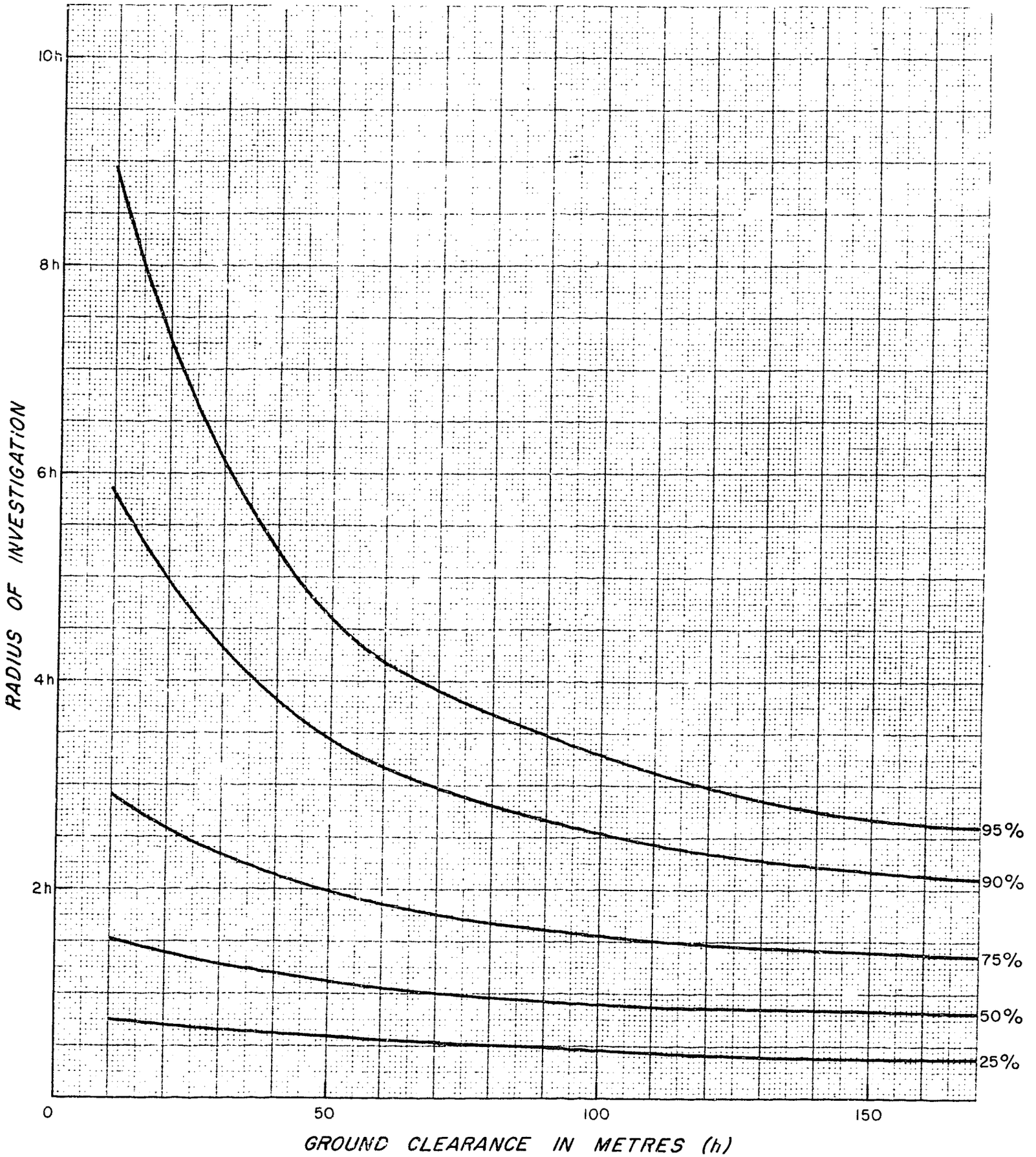

Fig. 1. Radius of investigation as a function of ground clearance. (Reproduced, with permission, from Duval & others, 1971).

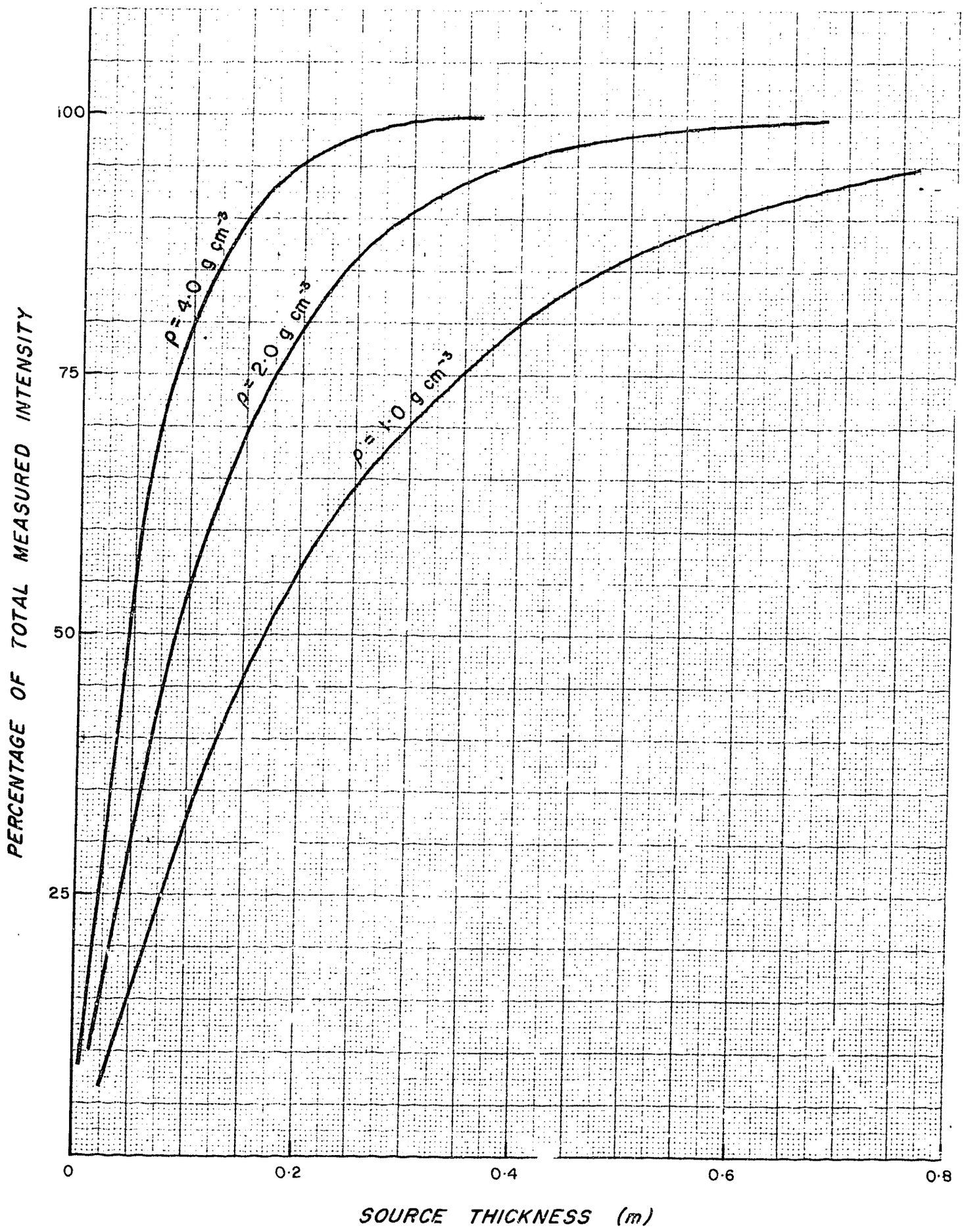

Fig. 2. Effective depth of exploration as a function of source density. (Reproduced, with permission, from Duval & others, 1971).

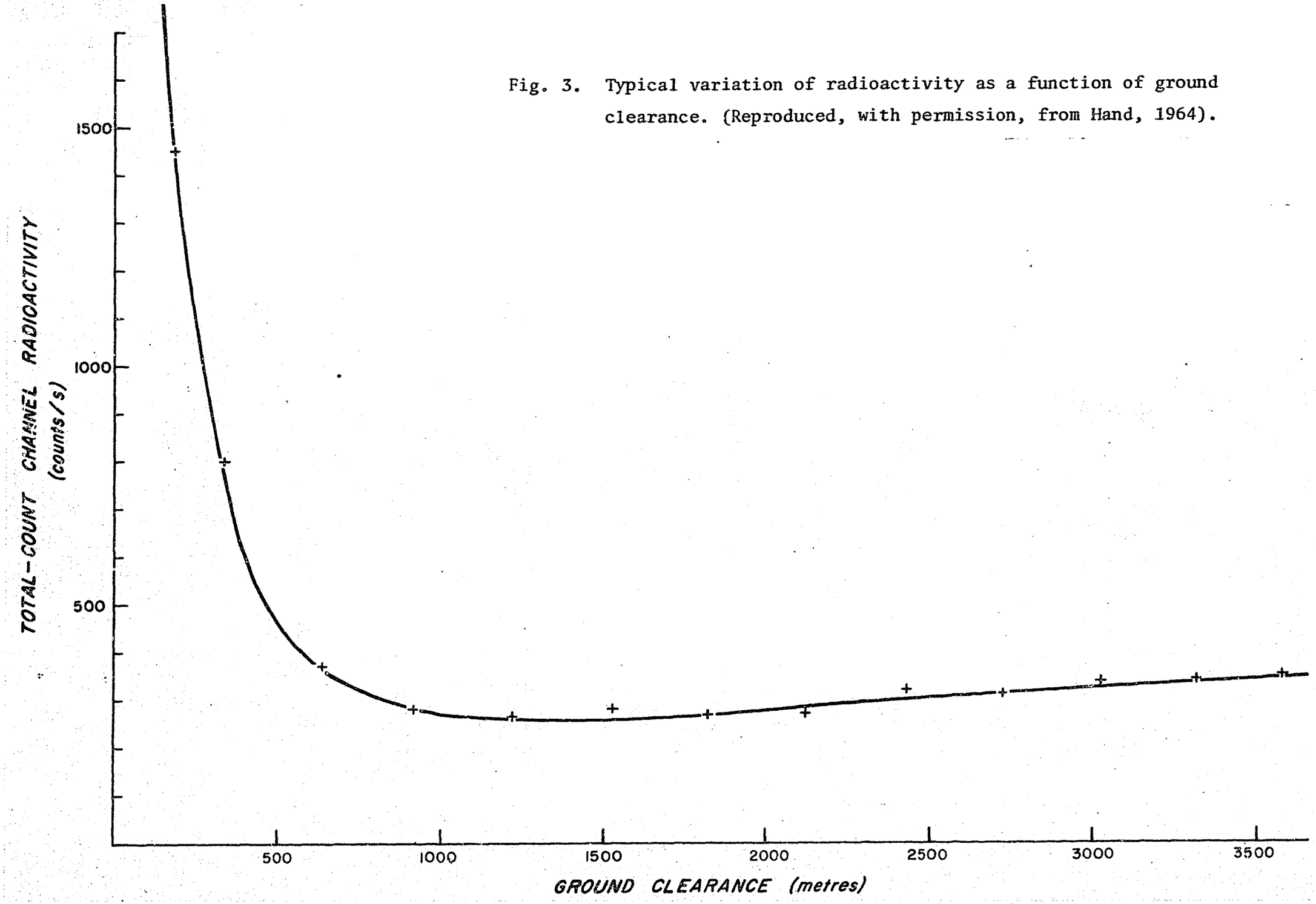

Fig. 3. Typical variation of radioactivity as a function of ground clearance. (Reproduced, with permission, from Hand, 1964).

Radioactivity from nuclear tests lasts for several years, but much of the activity lasts for only a few months. Horwood (1958) investigated the gamma spectrograms of atmospheric dust samples collected in flights over northern Canada. These showed that most of their gamma radioactivity is below 1 MeV. The major emitters and their characteristics are shown in Table 1.

TABLE 1. PRINCIPAL GAMMA EMITTERS FROM NUCLEAR FALLOUT

Nuclide	Photopeak energy (MeV)	Half-life
Caesium-137	0.662	27 years
Zirconium-95	0.723 and 0.756	65 days
Niobium-95	0.236 and 0.765	35 days
Ruthenium-103	0.498	40 days

Doig (1968) reported results of ground gamma-ray spectrometry and showed that fallout peaks below 1.0 MeV were present in his rock spectrograms. With the ending of atmospheric nuclear testing, the contribution from nuclear fallout will become less significant.

The most variable component of background radioactivity is due to radon-222 and its daughter products. Radon-222 is a gas which can diffuse out of the ground. The rate of diffusion depends on air pressure, soil moisture, ground cover, wind, and temperature. Radon-222 has a half-life of 3.82 days and decays to gamma emitters lead-214 and bismuth-214. These become attached to airborne dust, and their resulting distribution is largely determined by wind conditions. The half-lives of lead-214 and bismuth-214 are less than 30 minutes, so the effective distance travelled by these nuclides is determined mainly by the half-life of radon-222. The most significant emission is from bismuth-214 at 1.76 MeV. This is also the peak used for determining uranium concentration in the ground being surveyed;

hence, it is important to be able to distinguish accurately between bismuth-214 emission from atmospheric radon (originating from the ground elsewhere) and that due to bismuth-214 in the uranium decay series from uranium in the ground below the aircraft. Darnley & Grasty (1971) reported that in Canada, on average, 70 percent of the gamma radiation in the uranium channel is due to the atmospheric component. During warm settled weather it is common for atmospheric bismuth-214 (at survey altitude) to be at a maximum in the early morning and decrease by 10-15 percent during the day, as atmospheric mixing occurs. However, more complex variations are often observed and sometimes correlate with meteorological conditions, e.g. Wilkening (1964) and Charbonneau & Darnley (1970a) showed that thunderstorm activity can result in marked changes in concentrations of lead-214 and bismuth-214. Inversion layers often trap radon close to the ground and cause anomalous bismuth-214 levels. Larson & Hoppel (1973) reported on radon-222 measurements related to atmospheric convection. These results showed that the radon levels generally decrease with increasing altitude, but are still measurable at heights up to about 4 km.

Choice of flying height, speed and crystal volume. Flying height, flying speed, and crystal volume all affect the measured count recorded per unit distance. Darnley (1973) uses the concept of "Figure of Merit" to compare the effectiveness of different systems. Table 2 is reproduced from that reference. The Geological Survey of Canada's 50 000 cm^3 system is arbitrarily given the figure of 10 for both large area and small area targets. The other systems are then rated against that standard. Flying height and line spacing are inter-related in that a decrease in flying height results in a decreased lane width (effective ground coverage) and a need for closer line spacing to achieve the same degree of coverage. Flying height also determines the resolution of radiometric features on the ground. Whilst increased ground clearance increases lane width, it decreases the resolution obtainable along the flight-line direction.

Crystal volume and counting statistics. Measurements of radioactive decay are subject to statistical limitations on their accuracy. For any measuring time t in which N counts are accumulated, the standard deviation (σ) of the accumulated count is given by the equation $\sigma = N^{\frac{1}{2}}$; the standard deviation in count rate = $N^{\frac{1}{2}}/t$.

TABLE 2. SPECTROMETER SYSTEMS - FIGURES OF MERIT

(Reproduced, with permission, from Darnley, 1973).

System	Detector		Terrain clearance (m)	Speed (km/h)	Merit (normalized count)$^{1/2}$	
	Size (diam. x thickness) (cm)	Volume (cm^3)			Large area	Small area
GSC mapping	12 (22.9 x 10.2)	50 071	122	193	10.0	10.0
GSC reconnaissance	6 (22.9 x 10.2)	25 028	152	225	6.0	5.2
GSC helicopter	3 (12.7 x 12.7)	4 835	76	48	7.1	10.0
Commercial A	4 (15.2 x 10.2)	7 425	91	145	4.9	5.0
B	1 (20.3 x 10.2)	3 294	38	128	4.0	10.0
C	1 (15.2 x 12.7)	2 311	46	97	3.75	6.7
D	3 (15.2 x 10.2)	5 573	46	209	4.0	7.1

Merit calculated from:

$$\text{Large area} \quad \left[\left(\frac{V_x}{50\ 071}\right)\left(\frac{193.1}{S_x}\right)\left(\frac{100}{e^{-\bar{\mu}\,(121.9-H_x)}}\right)\right]^{\frac{1}{2}}$$

$$\text{Small area} \quad \left[\left(\frac{V_x}{50\ 071}\right)\left(\frac{193.1}{S_x}\right)\left(\frac{(121.9)^2}{H_x^2}\right)100\right]^{\frac{1}{2}}$$

V_x = volume of detector crystals (cm^3)

S_x = mean ground speed (km/h)

H_x = mean terrain clearance (m)

$\bar{\mu} = 5.6 \times 10^{-3}$ (m^{-1})

For ratemeter data, σ count rate = $(C/2T)^{\frac{1}{2}}$, where C = count rate (counts/second), and T = time constant (seconds)

For scalar data, the following equations give the standard deviations for the corrected data:

$$\sigma TH_4 = (C_4 + B_4 + B_4/T)^{\frac{1}{2}}$$

$$\sigma U_3 = (C_3 + B_3 + B_3/T + \alpha^2 \sigma^2_{TH_4})^{\frac{1}{2}}$$

$$\sigma K_2 = (C_2 + B_2 + B_2/T + \beta^2 \sigma^2_{TH_4} + \gamma^2 \sigma^2_{U_3})^{\frac{1}{2}}$$

$$\sigma TOT = (C_1 + B_1 + B_1/T)^{\frac{1}{2}}$$

where C_i are the counts/sampling interval above non-geological background B_i in channels i, i = 1 to 4; α, β and γ are the stripping ratios which have to be applied to remove spectral interactions - these are discussed more fully in chapters 3 and 4 of this report; T = number of sampling intervals over which background measurements are made; TOT = total count; K_2, U_3 and TH_4 are the corrected contributions of potassium to channel 2 (the "potassium channel"), uranium to channel 3 (the "uranium channel") and thorium to channel 4 (the "thorium channel").

If the background measurements are made over a sufficiently long period the terms B_i/T become negligible and can be removed from the expression for the standard deviations.

The count-rate levels are directly determined by crystal volume and particularly by the surface area of the "downward-looking" surface. To effectively absorb a sufficient proportion of incident gamma radiation it is necessary for airborne systems to use crystals at least 10 cm thick. Most airborne systems use crystals of this thickness.

It can readily be seen that for two systems, where one is m times as sensitive as the other (i.e. produces m times as many counts in a given energy channel), the increase in signal to statistical noise ratio is $m^{\frac{1}{2}}$. Hence a system which is 4 times as sensitive as another system is able to resolve features on the ground which are only half as radioactive, with the same statistical accuracy.

Table 3 illustrates the order of statistical accuracy which is achieved with a 3700 cm^3 spectrometer system (two 15 x 10 cm detectors). The ground clearance for both these examples was 150 m. The values used for the stripping ratios were: α = 0.70, β = 0.75, γ = 1.10

It can be seen from these examples that the statistical accuracy achieved with small detector systems is very poor particularly for corrected data. This makes the production of ratio data display (U/Th, etc.) extremely suspect, and great care needs to be exercised in using such information. Accuracy is improved by using longer sampling intervals (or preferably by aggregating data during processing), but at the expense of decreased resolution on the ground. If the sampling interval is S seconds the statistical accuracy improves by a factor of $S^{\frac{1}{2}}$ compared to 1-second data.

Selection of energy channel limits. It is sometimes claimed that the use of wider energy channels in a differential spectrometer, or the use of an integral spectrometer, to produce increased count rates compensates for low crystal volume. This is not correct, because the important consideration is statistical accuracy of the stripped data, not the accuracy of the primary data. The determining factors which govern the accuracy of the stripped data are:

(a) The resolution of the equipment,
(b) The conditioning of the set of linear equations which relate the count rates in each channel to the contributions from each radioelement source.

It seems reasonable that there must be energy limits for each channel which maximize the accuracy of the stripped data. McSharry (1973) used the conditioning approach for results from a 7.5 x 7.5 cm detector and showed that the best conditioning was obtained using a "uranium channel" of 1.66-1.86 MeV and a "thorium channel" of 2.4-2.8 MeV. It is not certain whether that particular analysis can be applied to detectors with larger volume. The use of 1.66 MeV as a lower limit for the "uranium channel" would reduce the effect of the 1.60 MeV peak from thorium (see Figure 19 of Appendix 3 of this report). Any shift in the lower limit of a channel set from 1.60-1.90 MeV would produce a significant change in count rate because of the presence of the 1.60 MeV thorium peak. Such shifts could occur through poor stabilization.

TABLE 3. EXAMPLES OF COUNT-RATE STATISTICS ACHIEVED WITH A 3700 CM^3 SPECTROMETER

Channel	(a) Background -corrected count rate	(b) Non-geological background	(c) Corrected count rate after stripping	(d) Standard deviation σ	(e) σ as % of (c)
			Example 1		
1	260	40	260	17	7
2	69	8	45	12	27
3	24	4	11	6	55
4	18	2	16	4.5	25
			Example 2		
1	75	25	75	10	13
2	15	5	6	7	113
3	12	1	6	4	70
4	9	1	9	3	35

N.B. All data are in counts/second

2.2 Equipment

Types of spectrometer. To date three different types of gamma-ray spectrometer have been used to obtain spectral information from airborne and ground surveys. These are:

(1) Multichannel spectrometers, which record the full spectrum in a large number of narrow channels (usually 128 or 256).

(2) Differential spectrometers, which measure count rates in broad channels centred on the photopeaks of potassium-40, bismuth-214, and thallium-208. These instruments usually employ four channels and are the type most frequently used in airborne surveys.

(3) Integral spectrometers, which measure parts of the spectrum in overlapping steps; e.g. a threshold of 1.6 MeV may be used to measure uranium and thorium and a threshold of 2.4 MeV to measure only thorium.

Appendix 1 of this report contains tables of some commercially available ground and airborne spectrometers of the differential and integral type. The International Atomic Energy Agency (I.A.E.A.) has published a report titled "Recommended instrumentation for uranium and thorium exploration" (I.A.E.A. Technical Report 158, 1974). This contains a useful section on airborne gamma-ray spectrometers, which is reproduced as Appendix 2 of this report.

Stabilization. To minimize drift in the energy limits of the various spectrometer channels, which can be caused by drift in E.H.T. supply and variations in the gain of photomultiplier tubes, caused by temperature changes, some spectrometers use automatic gain or voltage adjustment using an isotope reference source. The most commonly used sources are caesium-137, cobalt-57 and americium-241. Denham (1970) reviewed the use of caesium-137 and americium-241. Caesium-137 generally works satisfactorily, but because its photopeak is at 0.662 MeV, its use requires the total-count channel lower limit to be set at 0.80 MeV or higher. This results in a loss in sensitivity. Figure 4 shows how the sensitivity of a system using two 15 x 10 cm detectors varies as a function of this lower limit. Americium-241 used as an alpha emitter has emission at about 3 MeV. Unfortunately the gamma-energy equivalent of the alpha emission of americium is observed by different detectors at somewhat different energies, and it is therefore unsuitable for use in multi-crystal detector systems. Americium-241 can

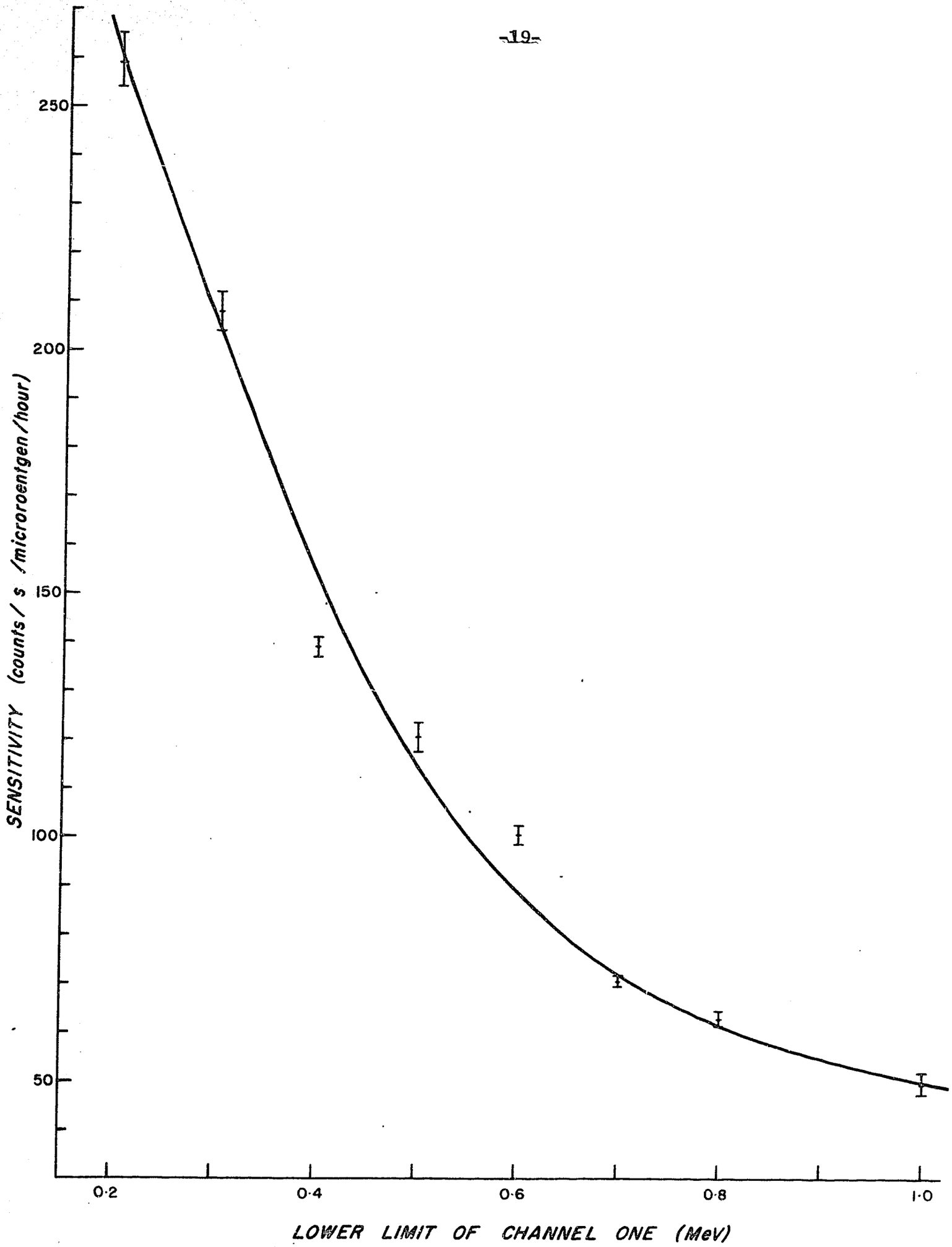

Fig. 4. Variation of channel one sensitivity with different lower limits. For Hamner Harshaw spectrometer, using two 15 x 10 cm NaI detectors, upper limit of channel one = 3.0 MeV

be used as a gamma emitter, using its 59.6 KeV emission. Similarly, cobalt-57 has been used (122 KeV photopeak). Low-energy stabilizing sources are offered with some commercially available systems and are claimed to give satisfactory performance. Another approach is to maintain the whole of the detector system in a temperature-controlled environment. This overcomes the major source of spectral drift - the temperature-sensitive characteristics of photomultipliers.

Large-volume detector systems use up to 50 photomultiplier tubes. The large number of photomultiplier tubes and associated components (e.g. pre-amplifiers) are all likely to exhibit somewhat different temperature and ageing effects and it is thus preferable to be able to vary either the gain or applied voltage individually to each photomultiplier, without assuming similarity in drift characteristics. One stabilizing system which is capable of this is the Geometrics MSS-3002 spectrum stabilizer.

Future developments. The principal limitations in present-day gamma-ray spectrometry are the difficulties in obtaining sufficiently high count rates and adequate spectral resolution. Increased count rates, and therefore increased sensitivity, can be achieved by using larger volumes of sodium iodide detector either as combinations of small detectors (e.g. 15 x 10 cm units) or by using extruded crystals. It is now possible to obtain extruded crystals in single slabs of large volume; e.g. 16 800 cm^3 (1026 in^3) can be obtained in a slab of crystal with dimensions 40.6 x 40.6 x 10.2 cm. A slab of this size requires four photomultipliers as compared with nine required for the equivalent volume made up of 15 x 10 cm detectors. The extruded crystals produce higher count rates per unit volume and have a considerable weight advantage compared with combinations of smaller detectors. Costs appear to be comparable. It seems unlikely that detector volume, using sodium iodide detectors, will increase much beyond 50 000 cm^3 (3000 in^3). It is, however, apparent that many operators are now using detector volumes in the range 13 000 - 33 000 cm^3 (750-2000 in^3).

Two other types of gamma-ray detector which have been considered and tried experimentally (on the ground) are:

(a) Plastic scintillators

(b) Solid-state lithium drifted germanium detectors.

Plastic scintillators are now available which are relatively inexpensive and light. These can be used in large volumes and produce reasonable count rates, but have very poor resolution. Duval & others (1972) presented results of a ground comparison between a solid organic detector and a sodium iodide detector. The volume of organic detector used was 116 810 cm^3, with a weight of 117 kg and a cost of US$9000 (1971 prices). The study showed that the detection limits of this detector were about the same as those for 44 245 cm^3 of sodium iodide detector of weight 150 kg and cost US$60 000. The major disadvantage of the organic detector was its poor spectral resolution, which made it difficult to calibrate and to determine stripping ratios.

Solid-state detectors have high resolution and have been in widespread laboratory use for several years. However they currently have two major limitations for airborne use:

1. They are available only in very small volumes (a few cm^3) and produce very low count rates.
2. They require cryogenic cooling.

The main development likely in the next few years is the increased use of multichannel instruments using sodium iodide detectors. A number of these instruments are already in use in Canada, e.g. the Inax 287B spectrometer, the Sander SPM-12 spectrometer, and the Canadian Geological Survey spectrometer. Each of these uses analog-to-digital conversion (ADC) which assigns a channel number to each pulse entering the system, according to peak height (i.e. energy level). The number of counts in any channel, or groups of channels, can be decoded by standard digital logic circuitry. Parts of the spectrum are selected by front panel switches, program cards, or internal wiring. The main advantages of this approach are:

1. Flexibility and the ability to make use of the complete spectrum; e.g. it has been suggested that measurement of the 0.77 MeV peak from bismuth-214 may be used to monitor background on-line.
2. The problem of relative drift between independent pulse height analysers is overcome. This can be a problem with 4-channel differential equipment.

3. Energy calibration is simplified, because it is possible to identify an individual channel in which the natural potassium-40 photopeak occurs. Similarly, peaks due to artificial sources used for calibration can be identified in particular channels.

Further details of the Inax and Sander spectrometers are available in Hood (1975). Details of the Canadian Geological Survey spectrometer are included in Darnley & others (1969) and Darnley (1970). Recent improvements to this equipment are described in Bristow (1975).

It is of interest to note that the Geological Survey of Canada specifications for contract radiometric surveys specify multichannel equipment as mandatory for all surveys from 1975 onwards. This should stimulate development of such equipment by North American manufacturers and contractors, and presumably contribute to geophysical work in other parts of the world at some later stage.

3. DATA PROCESSING

3.1 Theory

Three corrections are required in processing radiometric data:

(1) Removal of background.
(2) Correction to a constant ground clearance.
(3) Correction for interactions within the source, in the air column between source and detector, and within the detector itself. This is often called the "Compton scattering correction" but this is somewhat misleading, since properly determined correction coefficients also allow for other interactions. McSharry (1973) suggested that "energy stripping" might be a more appropriate name.

Removal of background. This is usually done in one of two ways:

(a) By recording radiation levels over lakes (or the sea) at survey height.

(b) Recording radiation levels at heights of 600-900 m above ground level. At this ground clearance, radiation from the ground is reduced effectively to zero, through absorption in the air. It is assumed that such values recorded are the same as the survey altitude background values.

In Canada the distribution of lakes is such that method (a) is generally used and provides updating of background values during a survey flight. In Australia method (b) is generally used, but different operators fly at different ground clearances to record background levels. In bad weather (e.g. low cloud) background levels are sometimes recorded at considerably greater ground clearances, for safety reasons.

Airborne tests made by BMR during 1975 (Appendix 6 of this report) indicate that background estimates for routine surveys should be obtained in the range 750-1050 m (2500-3500 feet) above ground. Measurements made at 900 m are about 10-15 percent higher than measurements made at 150 m over water. An additional problem is to determine correct background estimates when atmospheric inversion conditions exist.

Five methods (at least) of providing more satisfactory background measurements have been proposed and/or tried:

(1) Collecting dust samples in flight and measuring their beta or gamma activity (Burson, 1973).

(2) The use of "upward-looking" detectors. Foote (1969) used a detector shielded from ground radiation by 10 cm of lead. This method results in a space and weight penalty which would be very serious for some survey aircraft.

(3) More frequent high-level background measurements during a survey flight to provide updating information. Currently, linearity is assumed between measurements made at the start and end of flights. Extra measurements would probably result in better corrections, but would reduce the time available for flying survey lines.

(4) If multichannel recording becomes standard practice, as has been suggested by Darnley (1973), then it may be possible to determine the background on-line by measuring one or more of the low-energy peaks from the uranium-238 series, e.g. the 0.77 MeV peak from bismuth-214.

(5) The use of diurnal monitors on the ground in a similar way to the use of magnetic ground stations. This would require the assumptions that background values are constant across the survey area at any given time and that ground level values apply to survey altitudes. Darnley & Grasty (1971) state that "especially under early morning still-air conditions, there can be measureable differences in atmospheric radioactivity at sites only a few miles apart"; so this approach would appear to be impracticable for large area surveys.

Correction to a constant ground clearance. Radiation from the ground is attenuated in the air column between the ground and the detector. At survey altitudes this attenuation is approximately 10 percent per 15 m difference in ground clearance. This requires data to be corrected to a standard flying height to remove the effect of varying ground clearance. Three algorithms are in current use for height correction:

(1) Godby & others (1952) showed that if the source is considered as a homogeneous half-space the relation between count rate N and flying height H is given by:

$$N = No \int_1^\infty \frac{\exp(-\mu H x)}{x^2} \, dx = No \; E_2(\mu H)$$

The function E_2 is the exponential integral of the second kind and is tabulated (Placzek, 1953); No = ground level count rate; μ = attenuation coefficient.

(2) The most commonly used algorithm is:

$$N = N_s \exp(-\mu \Delta H)$$

where N = count rate at height H; N_s = count rate at standard survey height (H_s); $\Delta H = H - H_s$; μ = attenuation coefficient (determined by experiment).

This algorithm is not as accurate as the exponential integral algorithm, but is usually quite adequate over the ground clearance range 50-250 m. If it is required to directly convert airborne count rates to ground level, it is necessary to use the exponential integral algorithm.

(3) Geometrics International has developed an algorithm which it claims allows for the two-dimensional aspect of the source. The mathematics involves the use of irregular Bessel functions. The result is quite similar to the simple exponential algorithm, but is claimed to be more accurate.

The Canadian Geological Survey has measured the variation in count rate as a function of altitude (Darnley, Bristow & Donhoffer (1969)). This was done by flying a test strip at different altitudes and fitting a simple exponential relation to the data in the four energy ranges (channels) 0.4-2.82 MeV, 1.36-1.56 MeV, 1.66-1.86 MeV, 2.42-2.82 MeV. It should be noted that the values of attenuation coefficients measured over a test strip with abnormally high thorium content will produce lower than normal attenuation coefficients for the uranium and potassium channels, owing to increased scatter into the lower-energy channels. For this reason, test strips should normally be used which have the average relative uranium to thorium ratio of 1:4, or attenuation coefficients should be measured in each a a over representative rock types. Values from the Canadian work mentioned above are presented in Table 4. These are the values currently being used in processing BMR radiometric data.

TABLE 4. EXPERIMENTAL ATTENUATION COEFFICIENTS

Channel (MeV)	$\mu(ft^{-1})$	$\mu(m^{-1})$
0.4 - 2.82	2.0×10^{-3}	6.6×10^{-3}
1.36- 1.56	2.3×10^{-3}	7.5×10^{-3}
1.66- 1.86	1.7×10^{-3}	5.6×10^{-3}
2.42- 2.82	1.7×10^{-3}	5.6×10^{-3}

Similar measurements to determine attenuation coefficients were made very briefly during 1975. using aircraft VH-BMG. The results of this work are included in Appendix 6 of this report.

Attenuation coefficients vary both with radioelement composition of the source and with areal extent of the source. The radiation from sources with small area decreases more rapidly as a function of ground clearance than the radiation from extensive sources. The effective attenuation coefficients are therefore generally higher for the sources with smaller extent. As the extent of sources is seldom known, the usual procedure in assessing airborne data is to use "broad source" coefficients for correcting all the data. This may not fully correct the data, but should rarely result in over-correction. Conversely, the use of small area ("point source") coefficients is very likely to over-correct much of the data. This is illustrated by Figure 5, which is taken from the Broken Hill regional survey 1975. The use of the point source coefficient has over-corrected the data and produced a very strong correlation between the corrected total-count profile and the ground-clearance profile. It should be noted that both corrected profiles have smaller amplitudes than the uncorrected profile. This is because the height correction has been taken to 150 m ground clearance, which is higher than any of the recorded ground-clearance figures.

Figure 6 shows the numerical effect of different attenuation coefficients. This figure can be used in two different ways:

(a) to show how much correction is required for different ground clearances;
(b) to show how different attenuation coefficients affect the correction.

It is of interest to compare experimentally determined attenuation coefficients from airborne measurements with laboratory measurements. Figure 7 shows the variation of total mass absorption coefficients μ_m for monoenergetic gamma-rays in air. The data for this are based on Siegbahn (1966, Vol. 1, appendix 1). Linear absorption coefficients μ are calculated using the relations:

$$\mu = \mu_m \times \rho$$

where ρ is the air density. The air density is a function of pressure and temperature given by:

$$\rho = \frac{1.293}{1 + 0.00367\ T} \times \frac{H}{76}$$

where T is temperature in degrees Celsius; H is pressure in cm of mercury; and ρ is density in $Kg.m^{-3}$.

Combining the two equations, it is possible to calculate linear attenuation coefficients for different temperatures and pressures. The effect of temperature variations on the linear absorption coefficients is more significant than that of pressure differences. Pressure differences produce maximum changes of only 1-2 percent. Temperature changes produce about 3 percent change per $10^{o}C$ temperature difference. Linear attenuation coefficients, for $20^{o}C$ and 76 cm mercury, using the Siegbahn data are also shown in Figure 7. These are very similar to the values shown in Table 4.

Further theoretical work and airborne tests are required to evaluate the effects of different geological sources (with different radio-element ratios) and the effects of different areal extents of the sources of radioactivity in the ground. Further work is also required to study the effects of interactions in the air column between source and detector. Suitable references for the theoretical work are Davis & Reinhardt (1962), Sakakura (1956), Sakakura (1957), Beck & de Planque (1968), and Grasty (1975c).

Spectral interaction correction. The gamma spectrum received at the detector is complex because radiation is received from different members of the uranium and thorium decay series and from potassium-40. It is further complicated by interactions (mainly Compton scattering) in the ground, in the air, and in the detector. The result is that the events recorded in each channel are not independently due to the photopeaks of thallium-208, bismuth-214, and potassium-40. The count rates in each channel can be expressed by the equations:

$$C_2 = K_2 + \gamma U_3 + \beta TH_4 \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$C_3 = U_3 + \alpha TH_4 \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$C_4 = TH_4 + \varepsilon U_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where C_2, C_3, and C_4 are the counts in channels 2, 3, and 4 respectively after background removal and height correction; K_2 is the

contribution to channel 2 from potassium; U_3 is the contribution to channel 3 from uranium; TH_4 is the contribution to channel 4 from thorium; α, β, γ and ε are correction coefficients (often called stripping ratios).

The solutions to the above equations are:

$$K_2 = C_2 - C_3 \frac{(\gamma - \beta\varepsilon)}{(1 - \varepsilon\alpha)} - C_4 \frac{(\beta - \alpha\gamma)}{(1 - \varepsilon\alpha)} \quad \ldots\ldots\ldots\ldots\ldots (4)$$

$$U_3 = \frac{C_3 - \alpha C_4}{(1 - \varepsilon\alpha)} \quad \ldots\ldots\ldots\ldots (5)$$

$$TH_4 = \frac{C_4 - \varepsilon C_3}{(1 - \varepsilon\alpha)} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

With known values for the correction factors α, β, γ, and ε, it is straightforward to calculate K_2, U_3, and TH_4 from equations 4, 5, and 6. The correct determination of the correction factors is quite difficult and will be further discussed in chapter four of this report. The factors depend on channel selection, detector size and configuration, and flying height.

3.2 BMR programs for processing airborne radiometric data.

Both BMR aircraft record four channels of spectrometer data and radar altimeter data each second along the survey line. All data are recorded and stored in integer form. A background line is generally flown at the start and end of each survey flight at a height of approximately 915 m (3000 ft) above ground level.

The conversion of field data tapes to a standard format, editing, file manipulation, and presentation of data are carried out using the software library developed within the Airborne Reductions and Contracts Group by J. Rees. Four programs have been written by B. Wyatt and added to this library, to subtract background, to apply height correction and spectral interaction corrections, to compute ratios between channels, and to filter data. These four programs are described briefly on pages 32 and 33.

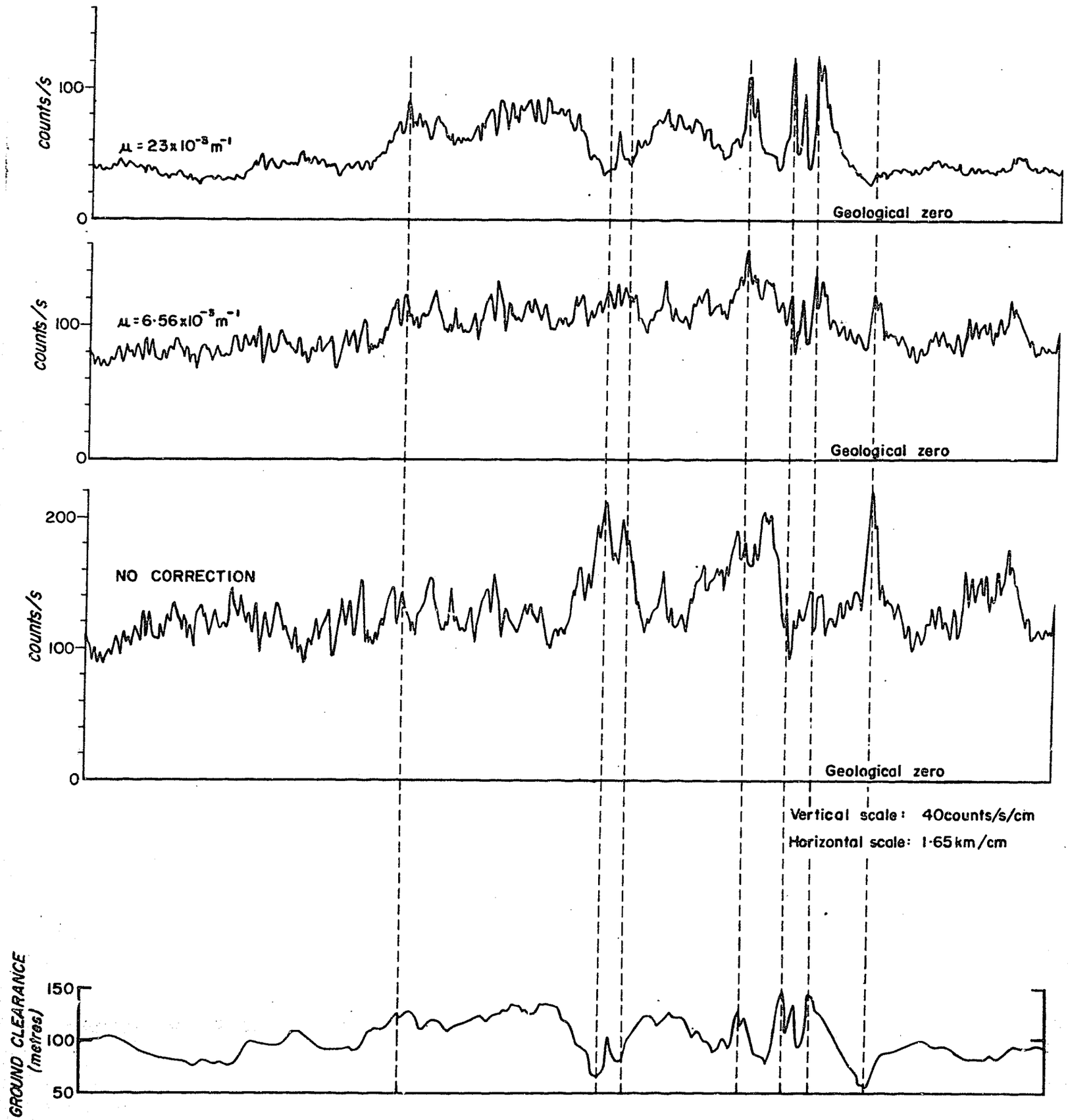

Fig.5. Example of processing total-count data with different height correction coefficients.

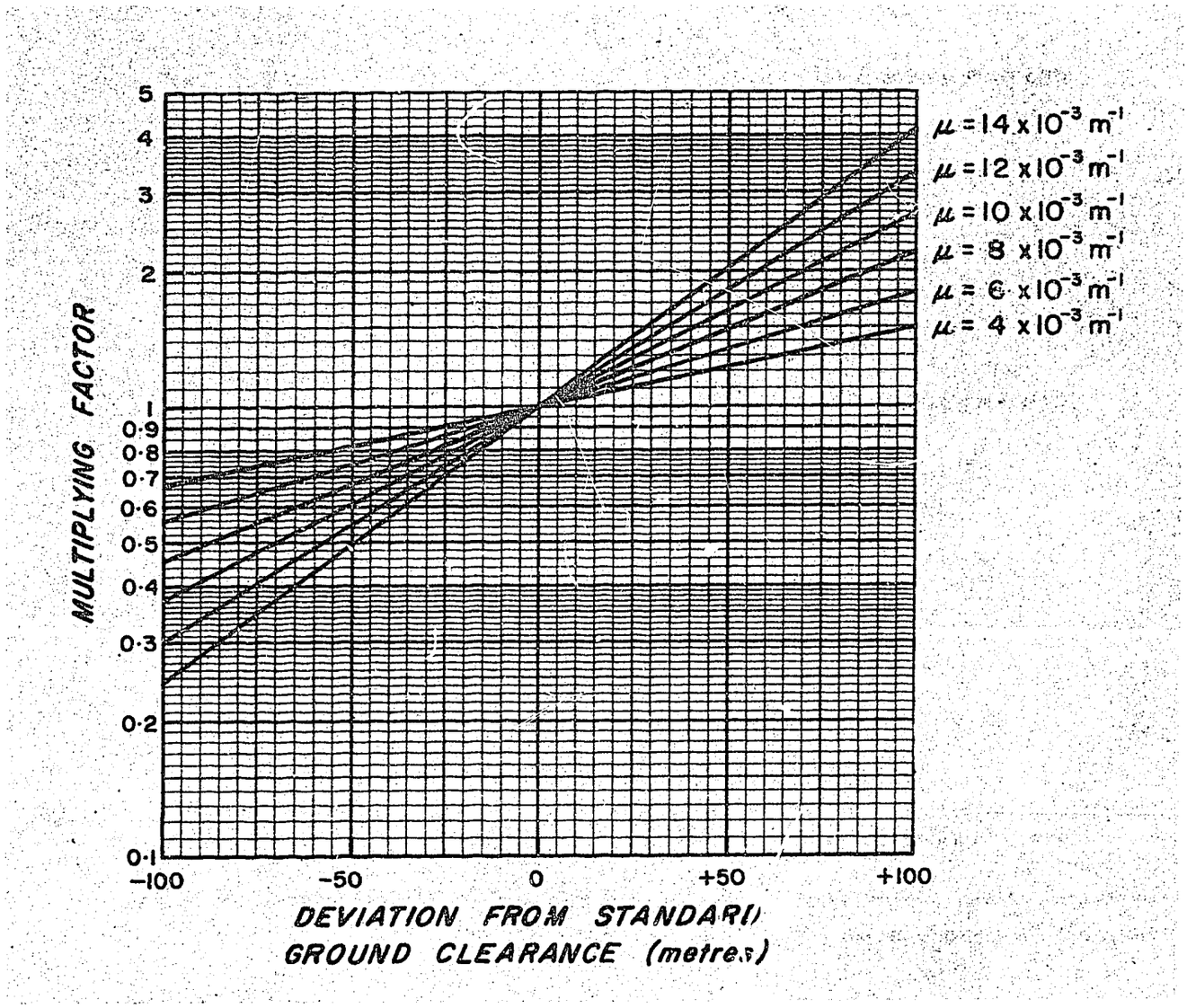

Fig. 6. The numerical effect of different values of attenuation coefficients.

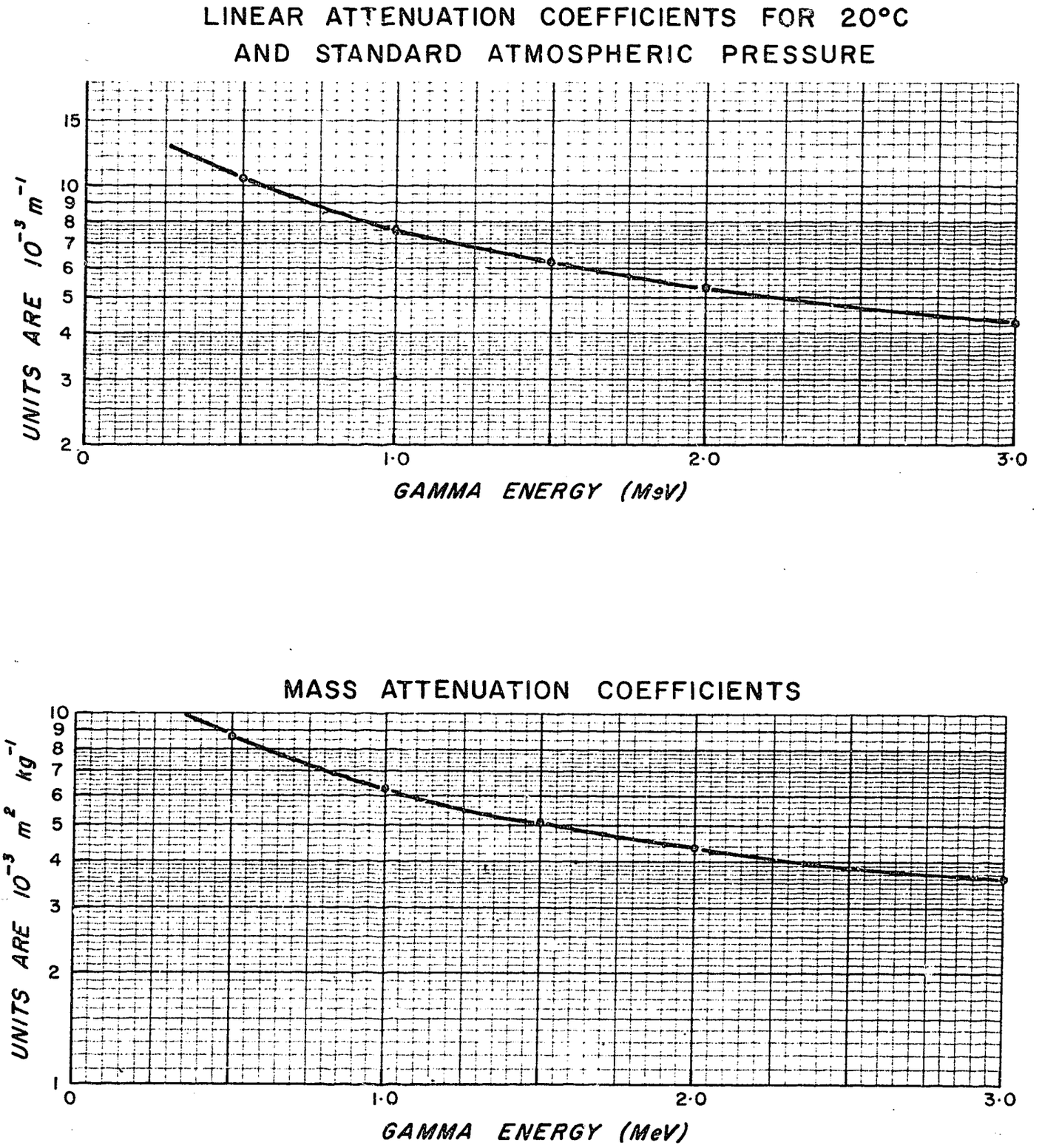

Fig. 7. Attenuation coefficients for mono-energetic gamma-rays in air. (Siegbahn data for mass attenuation coefficients).

Program GRAADJ extrapolates and/or interpolates input base values to give an estimate of the background radiation levels throughout the flight or line, and subtracts these from each data channel. The base values are generally computed from statistical analyses of the background lines at the start and end of each flight, but they can also be upgraded using values obtained over large expanses of water. The program also has the facility to multiply the data by a constant.

Program GAMADJ corrects for deviations from mean terrain clearance, in all channels and/or for Compton scattering contributions to the observed potassium-40 (channel 2) and bismuth-214 (channel 3) counts. The program also has facilities to subtract constants from the data and/or multiply all data by a constant.

The program assumes exponential attenuation of intensity with ground clearance up to a maximum of 250 m. The equations used for height correction are:

$$C_1 = C_1\ (h)\ \exp(\mu_1 \Delta h)$$

$$C_2 = C_2\ (h)\ \exp(\mu_2 \Delta h)$$

$$C_3 = C_3\ (h)\ \exp(\mu_3 \Delta h)$$

$$C_4 = C_4\ (h)\ \exp(\mu_4 \Delta h)$$

C_1, C_2, C_3, and C_4 are the height-corrected counts and C_1 (h), C_2 (h), C_3 (h), and C_4 (h) are the measured counts in channels 1 to 4 respectively at a height h above the ground, after background subtraction; μ_1, μ_2, μ_3, and μ_4 are the attenuation coefficients for each channel; $\Delta h = h - hs$ where hs is the standard ground clearance.

The spectral interaction corrections are made using the equations:

$$K_2 = C_2 - \gamma U_3 - \beta TH_4$$

$$U_3 = C_3 - \alpha TH_4$$

$$TH_4 = C_4$$

These are the same as presented earlier except that has been ignored. is very small (about 0.04) and, except in areas of high uranium/thorium ratios, its omission is justified. Values of attenuation coefficients and correction factors are put into the programs by the user. If the ground clearance is greater than 250 m or if data are missing for any one spectrometer channel, then all of the corresponding spectrometer data are deleted.

Program FILTR1 applies either time constant, weighted bandpass (including high- and low-pass), or user-input filter coefficients to any specified data channel. The usual filter is a weighted low-pass filter with 5 to 11 coefficients, which reduces statistical noise in the data.

Program GAMRAT computes the ratios U_3/Th_4, U_3/K_2, Th_4/K_2, and also U_3^2/Th_4, and (U_3/Th_4) x TC if required; TC is total count. Data gaps are generated when the denominator falls below 1 count/second because of the high probability of creating false anomalies when using such low numbers.

Programs are also available to plot any data channel as a function of another, or to plot any three channels on a triangular composition diagram.

A consequence of low count rates is the accumulation of rounding errors if values are stored as integers. For this reason it has been found necessary to multiply the data by 1000 and to process and store them in units of milli-counts/second. Inaccurate values for background levels, attenuation coefficients, and stripping ratios can produce processing errors. These are generally amplified by later stages of processing.

3.3 Presentation of radiometric data

The range of possible presentations for analog radiometric data is very limited because of the difficulties inherent in handling and processing analog data. The only correction that is easy to do is background subtraction. Because of the handling difficulties, many presentations have shown only a small part of the acquired data and have also often been somewhat subjective. Some examples of analog presentations and comments on them are included in Darnley (1971).

With digital acquisition of radiometric data it is now possible to present data in a variety of different ways. Accordingly, it is necessary to establish which are the most effective for particular applications. A

minimum processing requirement is that background subtraction and height correction should be done. It is most important to ensure that survey procedures generate sufficient and accurate data on background variation and height attenuation coefficients. Contour maps, in particular, are very susceptible to errors in background levels and poor height correction. If comprehensive processing is required, to produce profiles and/or contour maps of stripped data, accurate stripping ratios for the particular equipment used are essential. In general, errors at any stage in processing become magnified in subsequent processing stages and degrade the final presentation. The statistical accuracy of processed data is relatively poor for data from a detector of low volume, and should always be considered in the assessment of such data. Filtering improves the interpretability of the data, but at the expense of reduced spatial resolution. The statistical accuracy of ratio calculations is poorer than that of the individual processed channels of data and is very seriously affected by errors in background levels, height correction, and stripping ratios.

The three main types of presentation are: (a) profile displays, (b) contour maps, (c) 3-dimensional displays. Comments follow on each of these three types.

Profiles. These are good for comprehensive display of all radiometric and altimeter data, either in raw form or after various stages of processing. A major advantage of profiles is that a large part of the data acquired during field operations can be displayed and is available for interpretation. To produce accurate and meaningful profiles of corrected data, it is necessary that good knowledge of background levels, attenuation coefficients and stripping ratios be available for the particular equipment used and geology of the survey area. Profiles can be produced on either a distance or a time base. Distance-based profiles are generally preferred for final presentation because of their constant horizontal distance scale.

Contour maps. These are good for presenting an overall plan view of the variation of radioactivity within an area. In this respect they are superior to profiles. Contour maps show only a small part of the total acquired data, and their use tends to over-emphasize areas of high radioactivity. The intensity of radioactivity is very much influenced by the amount of outcrop, and type and thickness of overburden, so that intensity is not

necessarily a good guide to the importance of anomalies, e.g. in uranium search. Contour maps assume continuity between adjacent flight-lines. With a wide spacing between lines this assumption may be invalid; e.g. a survey with 1.5 km spaced lines flown at 150 m above the ground detects radiation from only about 40 percent of the surveyed area (i.e. strips 600 m wide centered under each flight-line). Follow-up work, during 1975, of airborne survey results published for the Mount Liebig, N.T., 1:250 000 Sheet area demonstrated that some of the continuity shown by the airborne results did not reflect the radioactivity measured on the ground. In that airborne survey, lines were flown at 3.2 km spacing and 250 m ground clearance. Lane width is clearly an important consideration in determining whether contour presentation will accurately represent the variation of radioactivity on the ground.

Three-dimensional perspective displays. These have not been tried, to date, by BMR, but it would be worth producing some examples for evaluation.

It is recommended that profiles of fully processed data (i.e. background subtracted, height corrected, and energy stripped) should be the normal primary products, provided that all the parameters are accurately known. From a study of the profiles, decisions can be made on what contouring and/or 3-dimensional displays would be useful. Final presentations should show the values of any constants used during processing, i.e. height correction factors, stripping ratios, filter coefficients, and possibly the range of background values subtracted.

During the course of the gamma-ray project the newly developed processing programs have been used for routine surveys and a number of examples are now available, e.g. Broken Hill regional and detailed survey (1975). Examples have also been obtained from overseas, e.g. Canadian Geological Survey, Prakla, and Geometrics. All of these are available for inspection in the Airborne Subsection of BMR. An interesting approach to presentation is being investigated by the South African Geological Survey (Richards & Walraven, 1975). This is the use of computer controlled colour-contour mapping, in which three channels of spectrometer information are each produced in different single colours and combined to form a full colour map. The different colours of this map represent different combinations of response from each of the three channels. Further details of this technique have been published by Lowenstein & Howarth (1973).

4. CALIBRATION OF AIRBORNE AND GROUND SPECTROMETERS

4.1 Determination of stripping ratios

The correct determination of stripping ratios requires consideration of interactions in all three of the following:

(1) Within the source material.
(2) In the air column between source and detector.
(3) In the detector.

For ground spectrometers the effect of (2) is not as important as it is for airborne spectrometers, because the volume of air between source and detector is very much smaller.

Gregory & Horwood (1961) investigated changes in spectral shape using different thicknesses of source material. Their experiments were conducted with the equipment configuration shown in Figure 8. The source materials used were thorite-silica sand and pitchblende-silica sand. Their results showed that the spectral shape changed with source thickness. Figure 9 illustrates this change for two source thicknesses, 13 mm and 457 mm. It is apparent that there is greater build-up in the Compton continuum with increased source thickness. The stripping ratio α (the ratio of counts in the uranium channel to those in the thorium channel for a thorium source) increases with increasing source thickness. Similar changes occur with the other stripping ratios. It is thus necessary in determining stripping ratios to use sources of similar thickness to the effective thickness of real geological sources. The work of Duval & others (1971), referred to in chapter 2 of this report, showed that for a density of 2 $g.cm^{-3}$, 90 percent of the gamma emission originates in the top 30 cm of source material. It is also necessary to use sources of sufficiently large area to correctly simulate the geometry which applies when survey measurements are being made. Measurements made with small hand-held sources do not satisfy either the thickness or the areal criteria, and should not be used to determine stripping ratios for either ground or airborne spectrometers.

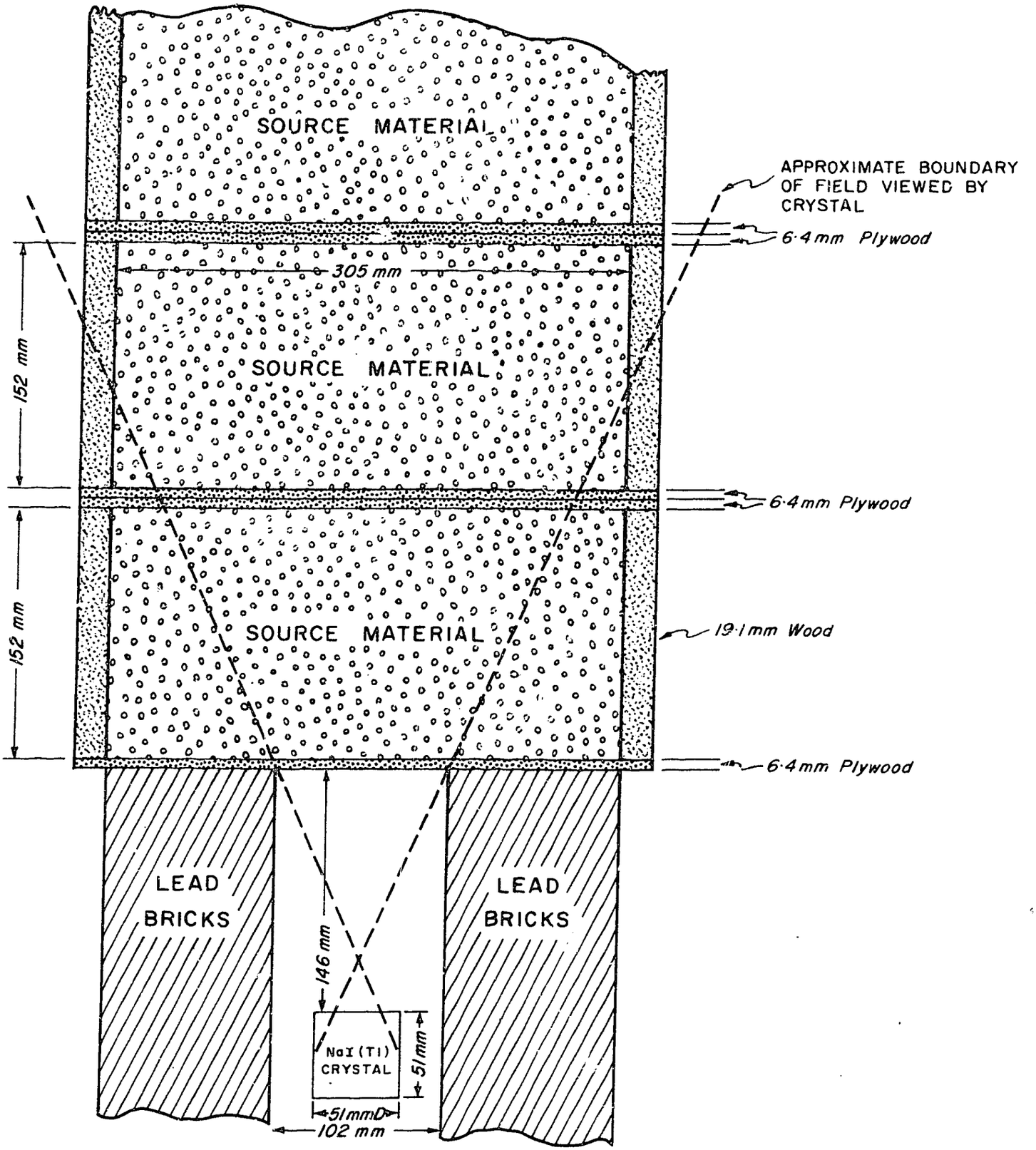

Fig. 8. Sketch of source-crystal geometry - vertical section.
(Reproduced, with permission, from Gregory & Horwood, 1961).

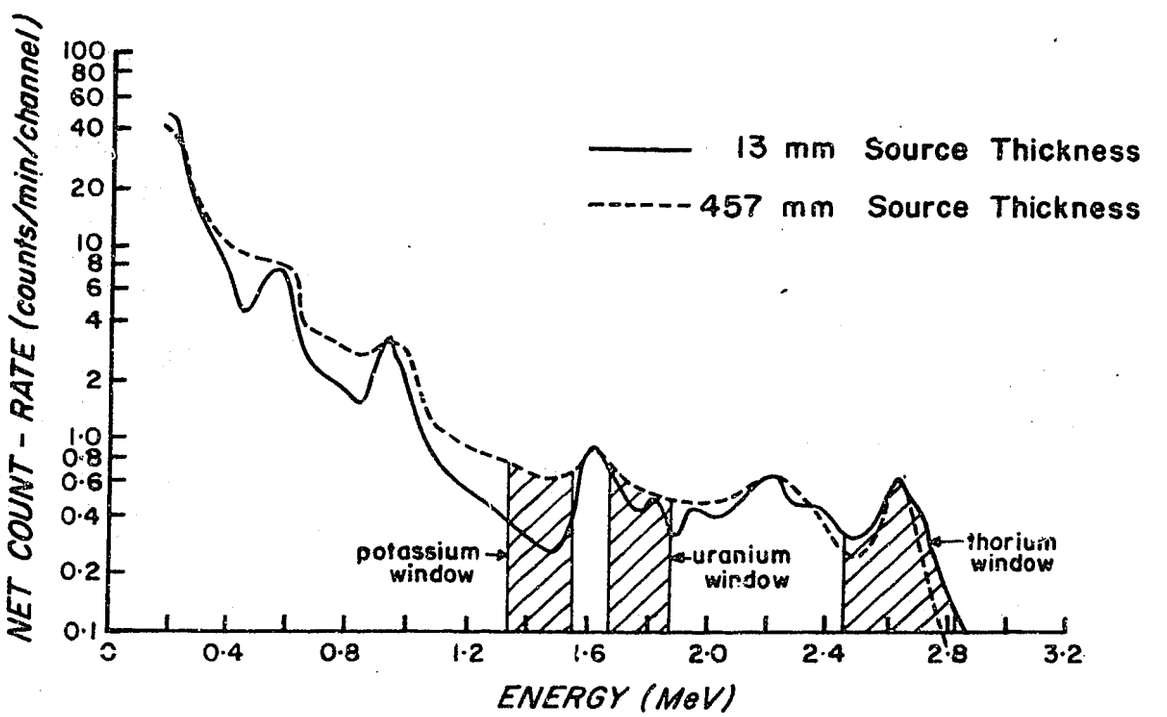

Fig. 9. Variation of gamma-ray spectrum with thorium source thickness. (Reproduced, with permission, from Grasty & Darnley, 1971).

The need for more realistic artificial sources has led to the construction of artificial test pads. Grasty & Darnley (1971) described the construction and use of concrete calibration pads built at Uplands airport, Ottawa, for the Canadian Geological Survey (G.S.C.). More recently calibration pads have been constructed in Denmark (Løvborg, 1973). The Canadian pads are 7.6 m x 7.6 m x 0.46 m and the five of them form part of the aircraft parking area at Uplands airport. The Danish pads at Risø are circular with a diameter of 3 m and thickness of 0.5 m. They are designed to calibrate ground spectrometers only, whereas the Canadian pads were designed to be extensive enough for both airborne and ground spectrometer calibration. Concentrations of potassium, uranium, and thorium in the Canadian and Danish pads are given in Table 5.

TABLE 5. RADIOELEMENT CONCENTRATIONS IN TEST PADS

Pad	% K	ppm U	ppm Th
G.S.C. 1	1.70	2.4	8.9
" 2	2.27	7.3	12.6
" 3	2.21	3.0	26.1
" 4	2.21	2.9	40.8
" 5	2.33	11.7	13.2
Risø Z	1.02	0.76	2.4
" K	6.98	4.2	2.7
" T	0.81	6.3	151
" U	1.01	198	8

Measurements over these pads provide data from which values of stripping ratios and sensitivity contents can be determined. Typical values of stripping ratios obtained are given in Table 6, which is reproduced from Grasty & Darnley (1971).

TABLE 6. STRIPPING RATIOS FOR THREE SPECTROMETERS

NaI(Tl) Detector	α	β	γ
One 3 x 3 inch	0.710	0.878	1.03
Three 5 x 5 inch	0.426	0.622	0.908
Twelve 9 x 4 inch	0.348	0.331	0.560

It can be seen that the stripping ratios decrease with increasing detector volume. This is to be expected, because the larger detectors more completely absorb the total energy of gamma-rays entering the detector.

Until recently, it was generally assumed that the gamma-spectrum shape is unchanged by the effect of the air column between a source and an airborne detector. However, it is now evident that because of scattering which occurs in the air, there tends to be a build-up in the lower-energy part of the spectrum with increasing distance from source to detector. This results in an increase in the stripping ratio values which have to be applied to airborne data. Experiments in Canada (Grasty, 1973) have simulated the effect of the air column by using the Canadian test pads covered by different depths of water; 15 cm of water corresponds to approximately 120 m of air. Results of this work have not yet been published. However, some similar work (Grasty, 1975a), using a thorium oxide source immersed in water, showed a relative increase in the uranium channel count with increasing water depth, owing to the scatter of high-energy photons from thallium-208. This has been combined with a theoretical approach to produce height-dependent correction factors for an infinite homogeneous radioactive half-space. Figure 10 is reproduced from Grasty (1975a) and shows the differences between the values of stripping ratio α for a point source close to a detector, and for measurements made at various heights above an infinite source.

Grasty (1975b) has published some airborne results which confirm the difference in stripping ratio α values between measurements on the calibration pads and the theoretical height-dependent values. The technique used was to analyse airborne data from an area with high content, and determine the minimum channel 3: channel 4 ratio.

From earlier in this report:

$$C_3 = U_3 + \alpha TH_4$$

$$C_4 = TH_4 + \varepsilon U_3.$$

Neglecting ε ,

$$\frac{C_3}{C_4} = \frac{U_3}{TH_4} + \alpha .$$

Hence the minimum value of C_3/C_4 tends towards α and in the limit, when $U_3 = 0$,

$$\frac{C_3}{C_4} = \alpha .$$

Using the G.S.C. 50 000 cm^3 system, α values were as follows:

(a) on the calibration pads $\alpha = 0.348$

(b) in the air at 120 m ground clearance $\alpha = 0.42$.

The difference of 0.07 is in good agreement with the difference shown in Figure 10.

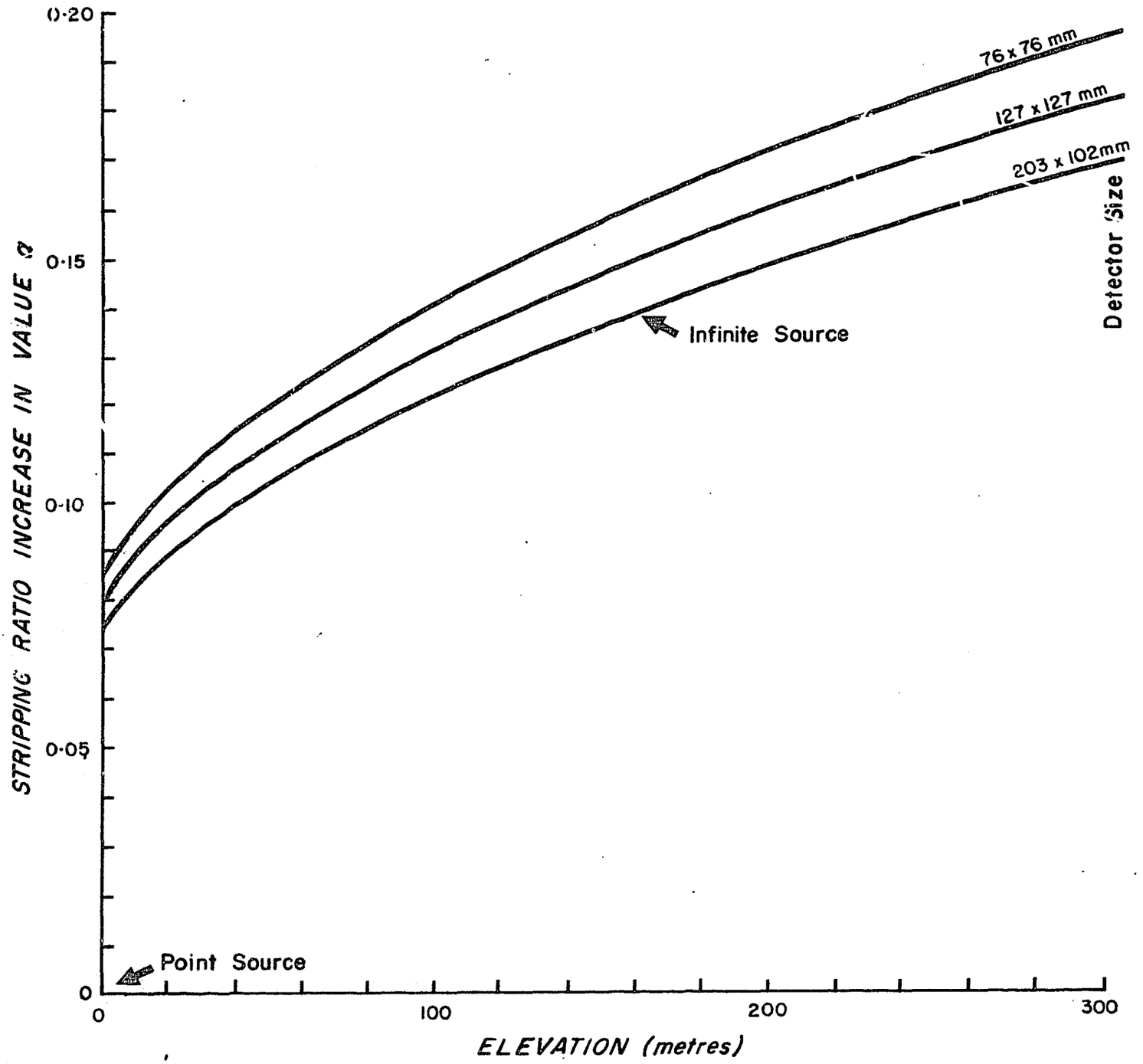

Fig. 10. Variation of stripping ratio α as a function of altitude for a homogeneous infinite source. (Reproduced, with permission, from Grasty, 1975a).

4.2 Conversion of airborne and ground data to element concentrations in the ground and to absolute units of surface radioactivity.

Two of the main objectives of airborne gamma-ray spectrometry should be:

(1) To relate airborne measurements to ground concentrations of potassium, uranium, and thorium.

(2) To determine surface radioactivity in standard absolute units. These should be micro-roentgens per hour (μR/h), or 'units of radioelement concentration' (ur) as recommended by the I.A.E.A. (I.A.E.A., 1976).

A method of achieving these objectives is to use a combination of calibration pads and test areas as outlined below:

1. Use calibration pads to determine stripping ratios and sensitivity constants for a ground spectrometer. (The ground spectrometer should have a detector with dimensions of at least 7.5 cm x 7.5 cm). This is done using the following equations:

$$C_2 = K_2 + \gamma U_3 + \beta TH_4 \qquad (1)$$

$$C_3 = U_3 + \alpha TH_4 \qquad (2)$$

$$C_4 = TH_4 + \varepsilon U_3 \qquad (3)$$

$$K_2 = S_K \text{ x (percent K)} \qquad (7)$$

$$U_3 = S_U \text{ x (ppm U)} \qquad (8)$$

$$TH_4 = S_{TH} \text{ x (ppm Th)} \qquad (9)$$

where C_2, C_3, and C_4 are the counts in channels 2, 3, and 4, respectively, after background subtraction.

S_K, S_U and S_{TH} are sensitivity constants which relate the corrected counts K_2, U_3 and TH_4 to the concentrations of radioelements in the pads.

Ten unknowns are included in the above equations. These are the four stripping ratios, three sensitivity constants, and three background values (these are not shown explicitly in the equations because the C values are the values obtained after background subtraction). If stripping ratio ε is neglected, because it is very small, then the remaining nine unknowns can be obtained from measurements on three pads containing known concentrations and different proportions of uranium, thorium, and potassium. If more than three pads are available, then a least-squares solution is possible. With the stripping ratios and sensitivity constants known, it is possible to calculate corrected count-rates and hence radioelement concentrations for areas away from the pads.

The above procedure can be used for airborne spectrometers parked over the top of pads, but the results obtained for stripping ratios would be only approximations to the values which apply at survey altitudes. Pad measurements would also be useful in monitoring the performance of airborne systems over a period of months or years.

2. Using a number of test areas, it is possible to establish correlation between airborne and ground radiometric data and approximate correlations with radioelement concentration in the ground surface. Darnley (1970) has shown that, provided similar areas are compared, it is possible to obtain a very good correlation between airborne and ground measurements. This is illustrated by Figure 11 of this report, which is reproduced from Darnley & Grasty (1971). It should be noted however that the airborne data have been corrected using ground level stripping ratios determined on the calibration pads. The height dependence of stripping ratios was probably not recognized at that time. The following scheme allows for this height dependence:

(a) Fly over the test area at normal survey altitude. Also determine height attenuation coefficients by flying at a number of different heights.

(b) Make ground spectrometer measurements on a grid pattern. This should be done using a spectrometer calibrated on calibration pads so that its stripping ratios and sensitivity constants are known.

(c) Collect surface samples of rock and/or soil for geochemical analysis to check the ground spectrometry.

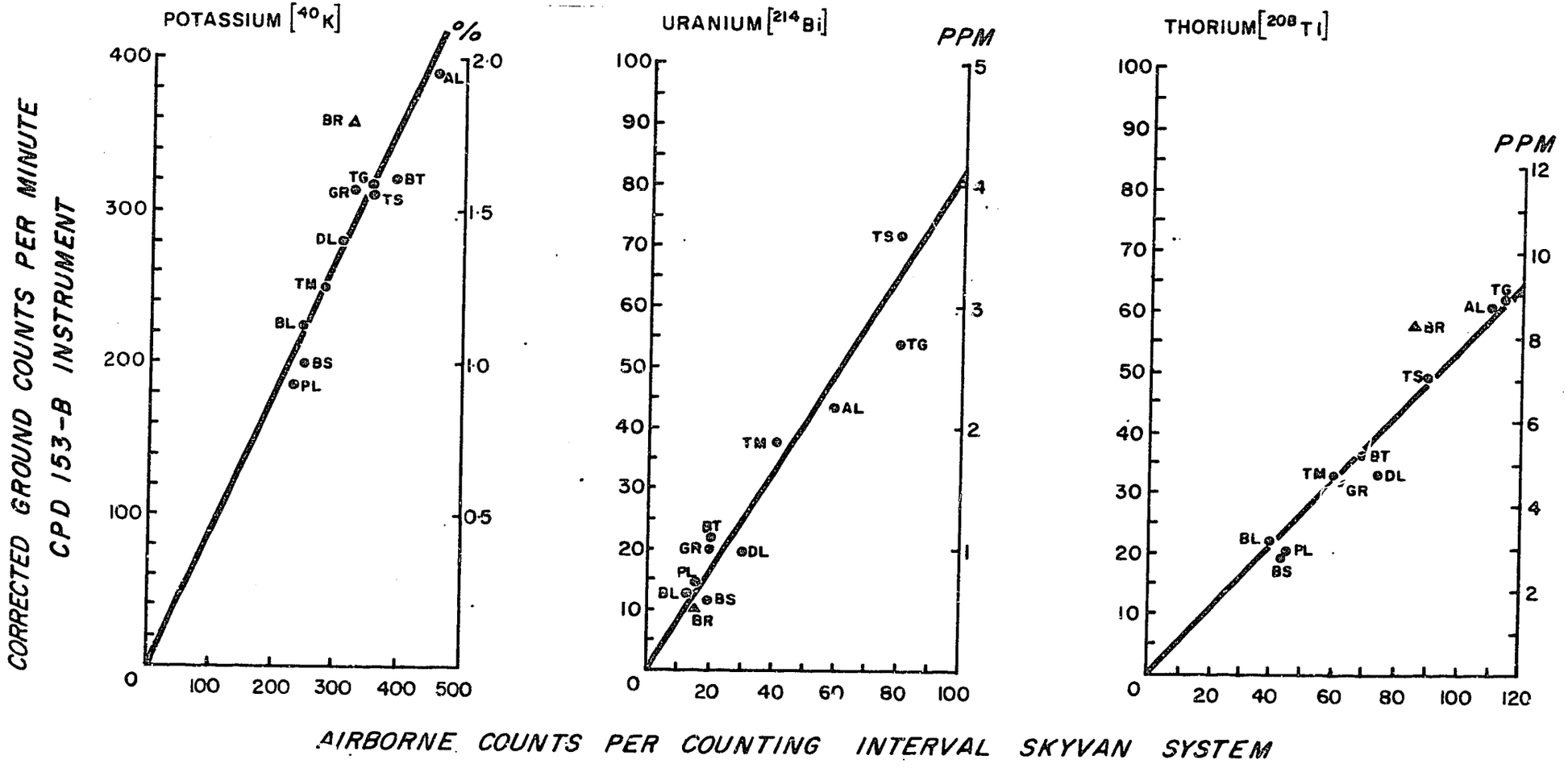

Fig. 11. Comparison of corrected ground and airborne count rates from the Skyvan system over ten different test sites in the Bancroft area (identified by initial letters) as well as Breckenridge test site (BR). (Reproduced, with permission, from Darnley & Grasty, 1971).

Combining equations 1,2,3,7,8 and 9:

$$C_2 = S_K \times (\text{percent K}) + \gamma S_U \times (\text{ppm U}) + \beta S_{TH} \times (\text{ppm Th})$$

$$C_3 = S_U \times (\text{ppm U}) + \alpha S_{TH} \times (\text{ppm Th})$$

$$C_4 = S_{TH} \times (\text{ppm Th})$$

Note that the C_i terms are the airborne measurements after background subtraction and height correction; the stripping ratios and sensitivity constants are the values required for the particular survey altitude.

The unknowns in these equations are the three stripping ratios and the three sensitivity constants. Two areas are required to provide the minimum amount of data to solve for the six unknowns. In order to generate linearly independent equations, the ratios of the radioelements in the test areas should be as different as possible. The radioelement concentrations for each area can be determined from steps (b) and (c) of the preceding scheme.

It is necessary to produce a detailed specification of test area characteristics. Charbonneau & Darnley (1970b) suggested that test areas should have the following characteristics:

(a) Reasonably homogeneous surface composition.
(b) Minimum length of 1 mile, minimum width ¼ mile.
(c) Flat surface with no obstacles to safe flying at low level along the major axis.
(d) Easily recognizable features to facilitate recognition from the air and permit accurate navigation.
(e) Reasonable access for ground measurements.

Test areas should, if possible, be close to a lake or the sea to facilitate accurate measurement of background.

3. To determine surface radioactivity in absolute units is relatively straightforward, and is necessary in order to compare the results from different areas and from different ground and airborne systems. It is very difficult to make valid quantitative comparisons without the use of

absolute units. A method of doing this is to use the ground spectrometer and calibrate it with a small radium-226 source. This produces a figure by which total-count measurements from a ground spectrometer can be converted to dose rate units (micro-roentgens per hour). The method is further described to Appendix 4. Some ground scintillometers (e.g. some of the Austral models) have meters graduated in this unit. Using the air-to-ground correlations established from test area measurements, it is then possible to convert airborne corrected total-count measurements to ground level radioactivity levels.

It is not necessarily suggested that maps should be produced in concentration units or absolute radioactivity levels, because it may not be possible to do this with sufficient accuracy. However, it would be very useful to have the necessary data to be able to provide approximate figures for concentrations and radioactivity levels.

The International Atomic Energy Agency held a special session on the calibration of gamma-ray spectrometers in Vienna, in December 1974. One of the main purposes of the session was to produce recommendations on calibration methods. These are described in I.A.E.A. Technical Report 174, published in 1976.

5. GEOLOGICAL APPLICATIONS AND INTERPRETATION OF AIRBORNE RADIOMETRIC DATA

Potassium, uranium, and thorium are all concentrated in the rocks and solutions of late stage magmatic differentiation. This produces preferential concentration in acid igneous rocks and their metamorphic and sedimentary derivatives. It is usual for the concentrations of these radioelements to vary together and to increase from basic rocks through to acidic rocks. Major variations in the relative concentrations of the radioelements are indicators of unusual geochemical conditions or processes and sometimes relate to mineralization. These variations are the source of the geological applications of radiometric measurement. Examples include:

1. Geological mapping
2. Uranium exploration
3. Bauxite exploration

4. Phosphate exploration
5. Beach sands exploration
6. Studies of porphyry copper deposits
7. Studies of hydrothermal alteration and hydrothermal mineralization
8. Studies of sedimentary processes

5.1 Geological mapping

Total-count and four-channel spectrometric surveys have been (and continue to be) used to assist geological mapping. The combination with aeromagnetic surveys is often very effective, because the radiometric data tend to emphasize the more acidic rocks, whereas the magnetic data tend to emphasize the more basic and ultrabasic rocks.

Examples of total-count data being used to assist mapping are included in Bowie & others (1958), Moxham (1958, 1963), Bates (1966), and Pitkin (1968). Essentially, the method of interpreting the data is to identify correlations between radioactivity and geology in areas of well-known outcrop and extend these into less well-known areas. Some problems are encountered, particularly in areas of extensive surface cover and if the data are in analog form, through the inability to allow fully for variations in ground clearance. Surface cover usually reduces the intensity of radioactivity detected by the airborne detector, and the results depend on whether or not this cover is derived in situ and, therefore, reflect the composition of underlying bedrock.

Four-channel spectrometric data have more potential for geological mapping because they contain more information on the geochemistry of the surveyed area. Subtle effects in the total-count channel data are often more clearly seen by variations in the other three channels. Additionally, the use of ratio data can overcome the surface cover problem, if it is locally derived and leaching has not occurred. Schwarzer & Adams (1973) show that the "spectrometric signatures" of bedrock are largely preserved in in-situ soils, thus making possible lithological identification and demarcation of contacts from airborne spectrometric data. Examples of the use of spectrometric data in mapping are included in Darnley & Grasty (1971), Grasty (1973), Demnati & Naudy (1975), and Wilkes (1975).

It is often important in interpreting radiometric data to have some knowledge of the range of radioelement content common for different rock types. Adams & others (1959) and Clark & others (1966) have collected this type of data from many sources, and produced useful syntheses showing typical ranges. The results presented by Clark are commonly referred to in other papers as the "Clark values" for particular rock types.

5.2 Uranium exploration

The search for uranium has provided much of the impetus for the development of airborne radiometric equipment. At an early stage it was realized that much time and money were being wasted following-up anomalies from total-count surveys, because many of them were not due to uranium. This led to the development of differential and integral spectrometers for airborne use. These provided information on the likely source of the anomalies, i.e. whether due to potassium, uranium, or thorium. Descriptions of the use of airborne radiometric techniques in uranium exploration are included in Pemberton (1969), Darnley (1973, 1975), Grasty (1975a), and Darnley & others (1975).

The key to radiometric interpretation in uranium search is the use of ratios. As stated earlier in this report, the radioelements potassium, uranium, and thorium generally vary together. In areas of uranium mineralization uranium is preferentially concentrated and, therefore, produces anomalously high uranium/thorium and uranium/potassium ratios. Figure 12 shows the anomaly recorded over the Koongarra uranium deposit, in the Alligator River region, NT, by the spectrometer system in aircraft VH-BMR during the 1972 BMR survey of that area. This clearly illustrates that with the equipment and settings used on that survey a uranium anomaly is characterized by:

(a) A high channel 3/channel 4 ratio (uranium/thorium)
(b) A channel 2/channel 3 ratio of about one
(c) Narrow, well-defined anomalies in channels 1, 2, and 3.

Characteristic (c) is not always seen, because the anomaly amplitude can be markedly reduced by material overlying the source of the radioactivity. This gives added importance to the use of ratios. In Figure 12 the data

have not been stripped. Lines have been drawn in to show the non-geological background levels. Everything above those lines is due to radiation from the ground. The horizontal scale is approximately 1 cm = 750 m.

Figure 13 is reproduced from Darnley (1975) and highlights the usefulness of ratio measurements. The two uranium anomalies would not have been identified from the integral (total-count) response; they may possibly have been selected from uranium response, but are much more clearly seen in the U/K and U/Th ratios. The example was obtained using the 50 000 cm^3 (3000 in^3) G.S.C. system.

Large surface indications of uranium can be found with simple instrumentation. However, it is now clear that it is necessary to be able to identify less obvious targets. This will require more sensitive (i.e. higher volume) detectors, careful survey operations, and better use of the data acquired.

5.3 Bauxite exploration

Certain bauxites contain amounts of uranium and/or thorium greater than the average for crustal rocks. Adams & Richardson (1960) investigated this and found that the uranium and thorium content depends on the source rocks; e.g. bauxites derived from nepheline syenites tend to have unusually high uranium and thorium content; bauxites derived from basic igneous rocks have very low radioelement content. Measurements on samples from many localities around the world have shown thorium contents in the range 5 to 131 ppm (average 49 ppm) and uranium in the range 1.5 to 21 ppm (average 11 ppm). To be economic, bauxite deposits have to be quite extensive (several km^2) and, therefore, can be sizable targets for airborne radiometric exploration. Horsfall & Wilkes (1975) showed that bauxites on the northern end of Cobourg Peninsula, NT, could be detected by their associated thorium response.

5.4 Phosphate exploration

Uranium and phosphate are associated in many different types of deposit and minerals. There are about fifteen uranium minerals in which phosphate is present (e.g. autunite and torbernite) and uranium is commonly present as a minor constituent in phosphate minerals (e.g. apatite and

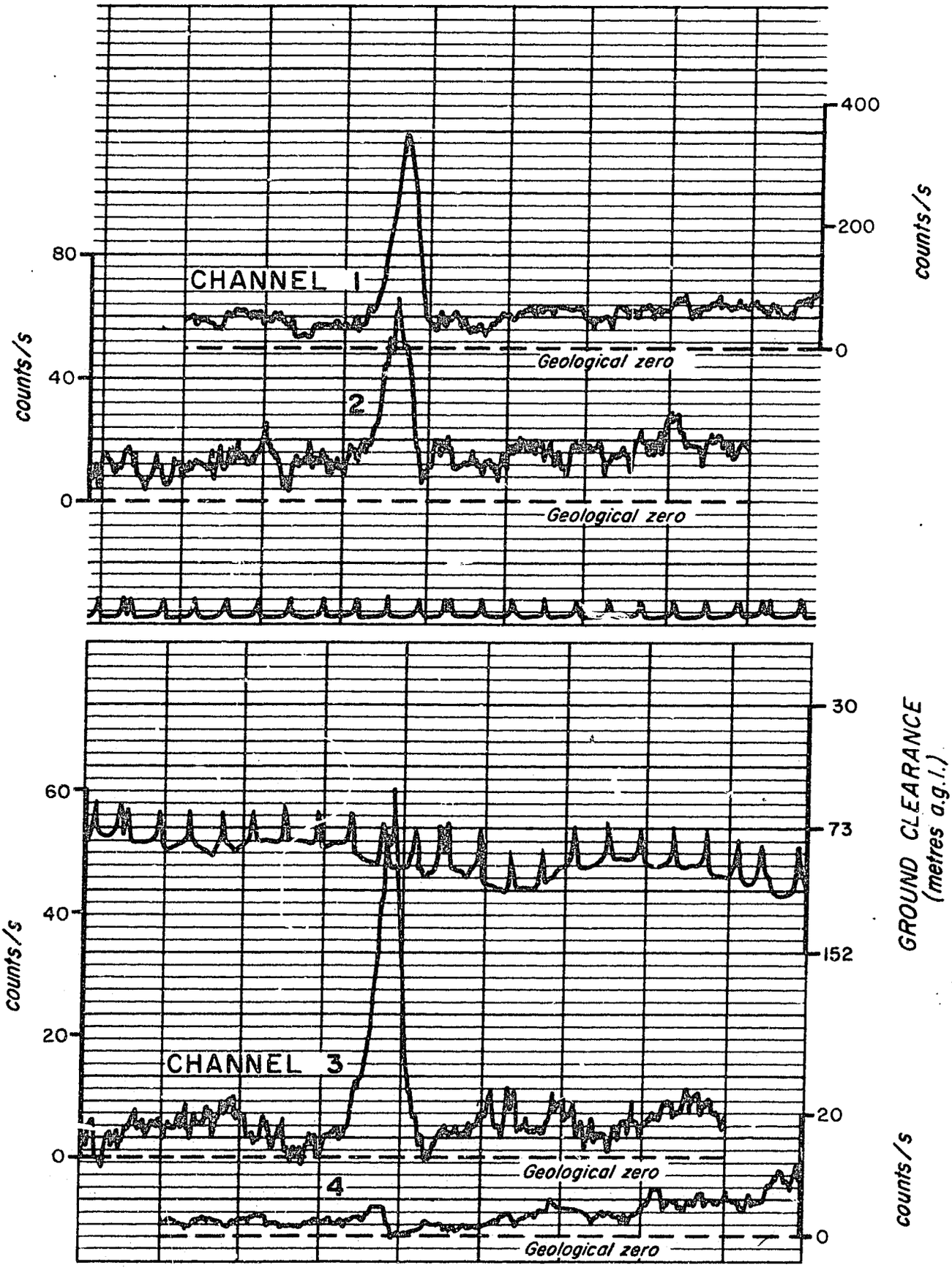

Fig. 12. Anomaly 2822/241 - Koongarra.

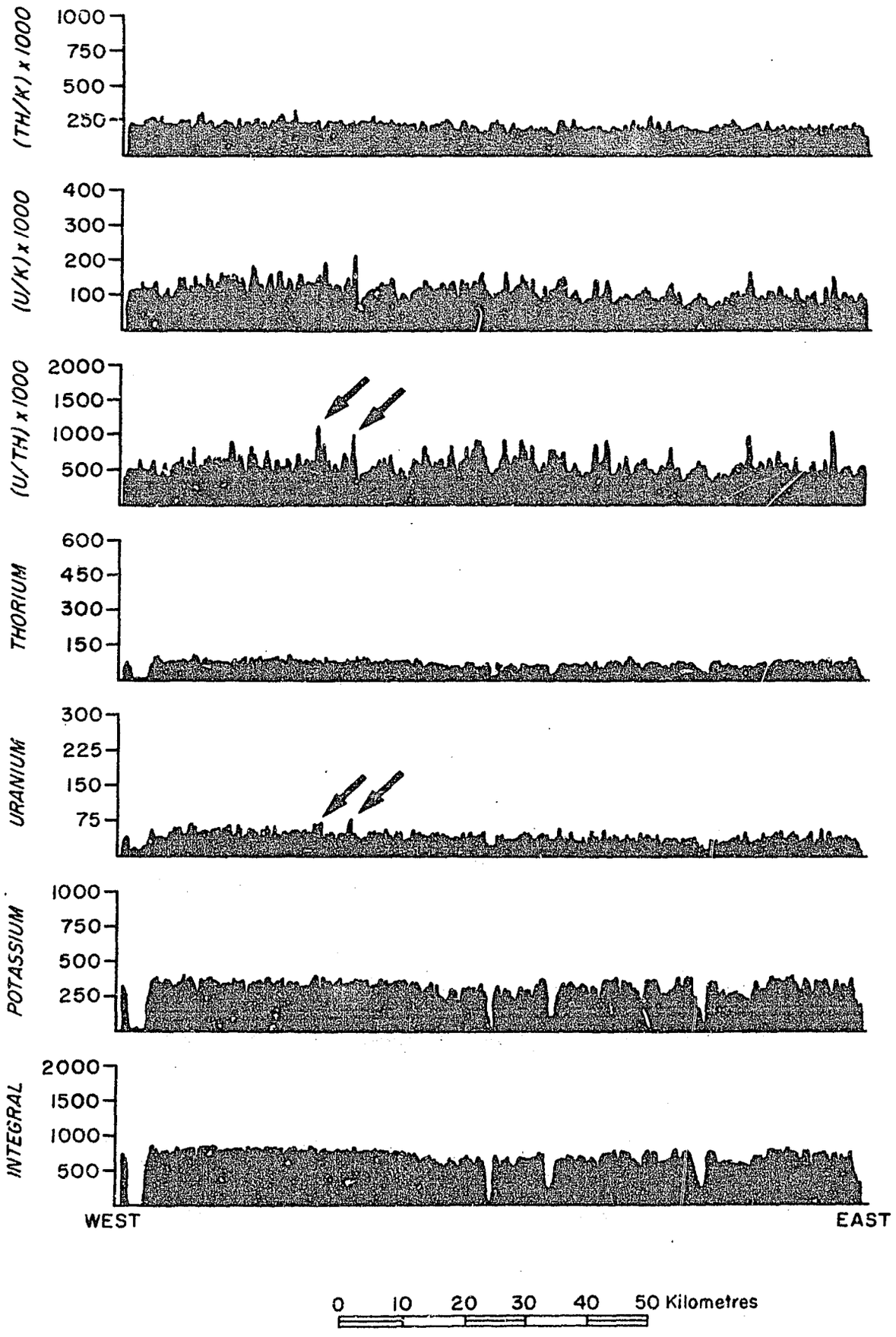

Fig. 13. Flight-line profile across part cf Prince Edward Island, Canada. (Reproduced, with permission, from Darnley, 1975).

xenotime). The unusually high uranium content of many phosphate rocks has been investigated by Cathcart (1956) and McKelvey (1956). The uranium content and high uranium/thorium ratios make possible radiometric exploration for phosphates. Examples of radiometric results over phosphates are included in Moxham (1960) and Waller & others (1971).

5.5 Beach sands exploration

Heavy minerals in beach sand deposits can, under favourable conditions, be detected by airborne radiometric survey. The requirements appear to be that monazite and/or zircon should be present in reasonable concentration and that they should be at or very close to the surface (probably within the top metre). There are a number of papers on the radioactivity of beach sands including Shirke & Chatterji (1958), Moxham (1960), and Adams (1969). Anomalous radioactivity is usually due to thorium, sometimes to uranium, and very rarely to potassium.

5.6 Studies of porphyry copper deposits

Davis & Guilbert (1973) investigated the distribution of potassium, uranium, and thorium in some porphyry copper deposits of Arizona and New Mexico. Their work, using ground measurements from an integral spectrometer, showed that potassium concentrations were higher in mineralized zones than in non-mineralized areas, by up to a factor of two, and showed a zonal distribution related to the ore deposits. Uranium and thorium distributions were irregular and of little value. It is suggested that the potassium content of some porphyry copper deposits may make airborne radiometric detection possible.

5.7 Studies of hydrothermal alteration and hydrothermal mineralization

Moxham & others (1965) presented results of ground spectrometry and chemical analyses from several copper and copper-lead-zinc deposits in the USA. These show that potassium concentrations increase in zones of alteration. Thorium concentrations remain unchanged, so that high potassium/thorium values are indicative of the zones of hydrothermal alteration.

Bennett (1971) presented some Canadian and Australian examples of airborne gamma-ray spectrometry over hydrothermal mineralization. Different examples show mineralization coincident with zones of high uranium/thorium or high potassium/uranium ratios. Anomalous indications of all these radioelements can define hydrothermal dispersion patterns.

5.8 Studies of sedimentary processes

Adams & Weaver (1958) reported results of uranium and thorium analyses of sedimentary rocks. These show a very wide range of thorium/uranium ratios from less than 0.02 to more than 21. Adams & Weaver showed that the ratio varies with sedimentary process and depositional environment. Thorium/uranium ratios for many oxidized continental deposit re above seven, whilst sedimentary rocks deposited in marine environments tend to have ratios considerably less than seven.

5.9 Other applications

Carbonatites and associated rare earth deposits often display anomalously high radioactivity. Radioactivity associated with oil and gas occurrences has been a subject of much controversy. Papers have been presented which show radiometric lows over hydrocarbon occurrences (e.g. El Shazly & others (1969)), whilst other papers present results showing high radioactivity over oilfields (e.g. Kellogg, 1957).

A non-geological use of airborne spectrometry is to measure snow thickness. This can be important in flood control when the snow melts, and has been used in the USSR (Kogan & others (1965)), USA (Peck & others, 1971), Norway (Dahl & Odegaard, 1970), and Canada (Loijens & Grasty, 1973).

5.10 Disequilibrium in the uranium and thorium series

Disequilibrium in the uranium-238 d thorium-232 series may cause problems in radiometric interpretation if daughter products before bismuth-214 and thallium-208, in the respective series, are removed. This is due to the radioactivity of these two daughters being used to determine uranium and thorium content respectively. Documentation of these two series is

provided in Figures 20 and 21 of Appendix 3 of this report. Adams & Gasparini (1970) stated that disequilibrium is rarely a problem in the thorium series, but occurs quite commonly in the uranium series. Rosholt (1959) described some examples of uranium series disequilibria from the USA. The main causes of disequilibrium in this series are the solubility of some of the early members of the series and the presence of the gas radon-222 in the series. Radon-222 has a half-life of 3.82 days. The effective life of radon-222 is about 24 days (6 half-lives) during which time it can migrate considerable distances either in solution in the ground or by escaping into the atmosphere. Further study is required to investigate more fully the implications of disequilibrium for radiometric interpretation.

5.11 Some interpretation techniques

The task in radiometric interpretation is to interpret and understand the radiometric data in geological terms. This requires study of geological maps together with radiometric data presentations to establish correlations between the two. If geochemical analyses of potassium, uranium, and thorium are available for rock and/or soil samples, these are also very valuable in the interpretation.

The interpretation of analog data is usually limited to selected anomalies, because of the difficulties of data handling. Definitions of anomalies have often been rather arbitrary and not always very useful, e.g. anomaly amplitudes specified as multiples of background, or multiples of statistical noise. Results quoted in terms of "background" are useless unless "background" is accurately and unambiguously defined. A simple terminology which overcomes this problem is shown in Figure 14. The non-geological contribution should always be subtracted and count rates specified relative to the geological zero level. With digital data, processing is usually much more comprehensive than for analog data, and it is possible to interpret more of the data and to make less distinction between anomalies and less anomalous areas.

Interpretation techniques commonly make use of data displays in addition to the normal presentation of profiles and/or contours. Two such techniques are the use of triangular diagrams and the use of cluster analysis. Triangular diagrams have been used in recent BMR Records (Tucker, 1975; Horsfall & Wilkes, 1975) in interpreting analog data. Their use

could straightforwardly be extended to processed digital data. Figure 15 illustrates the use of triangular diagrams with examples from Alligator River, NT.

Data points on the triangular diagrams are calculated as follows:

(1) Subtract non-geological contributions from the count rates in channels 2, 3, and 4.

(2) Express each of these as a percentage of their sum, e.g.

$$\text{percentage count rate channel 2} = \frac{\text{Channel 2 count rate} \times 100\%}{\text{Sum of count rates in channels 2, 3, and 4}}$$

(3) Plot the points on the diagram.

The data used need not be restricted to peaks of anomalies; any data along the flight-lines can be used. Diagram (a) in Figure 15 is the master diagram used to assess the main source contributing to the radioactivity. The divisions within the diagram are closely related to the stripping ratios for the equipment and settings used. Other divisions can be readily used to suit the user. Two advantages of this type of data display are:

(a) Ratios between all three channels can be handled simultaneously.

(b) Positions on the diagrams are affected only to a small extent by departures in ground clearance from the standard flying height.

In the interpretation of the Alligator River data the triangular diagram method was used to classify the anomalies and interpretation maps produced as illustrated in Figure 16.

The use of cluster analysis as a tool in radiometric interpretation has been described by Schwarzer & Adams (1973). This reference also shows the use of histograms of fully corrected data expressed as radioelement concentrations for different rock types. In this use of cluster analysis, potassium, uranium, and thorium data are merged and used to produce groupings of similar rock types.

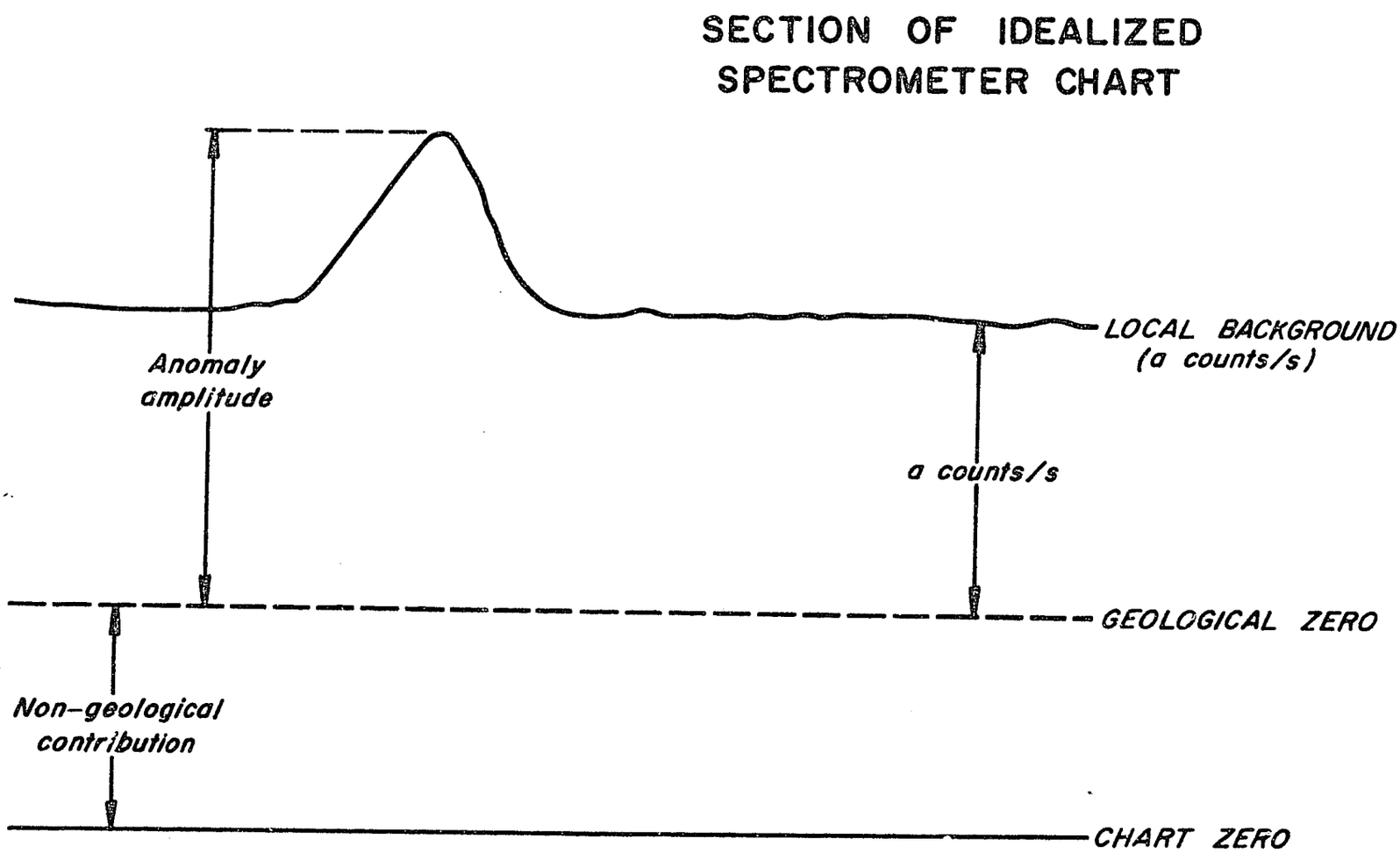

Fig. 14. Diagram to illustrate use of background terminology as used in this report.

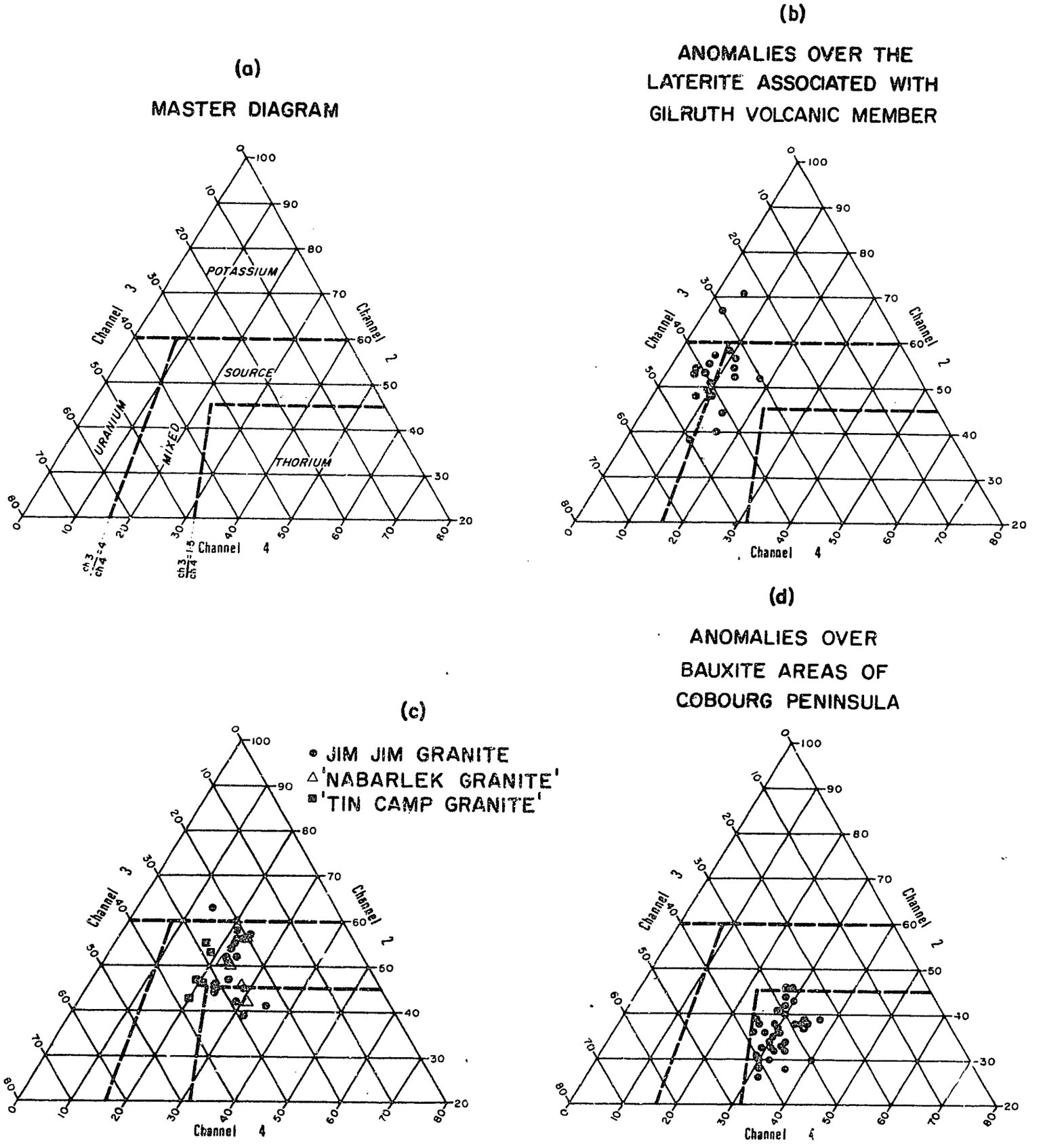

Fig. 15. Examples of the use of triangular diagrams for interpretation (from Alligator River 1972 survey).

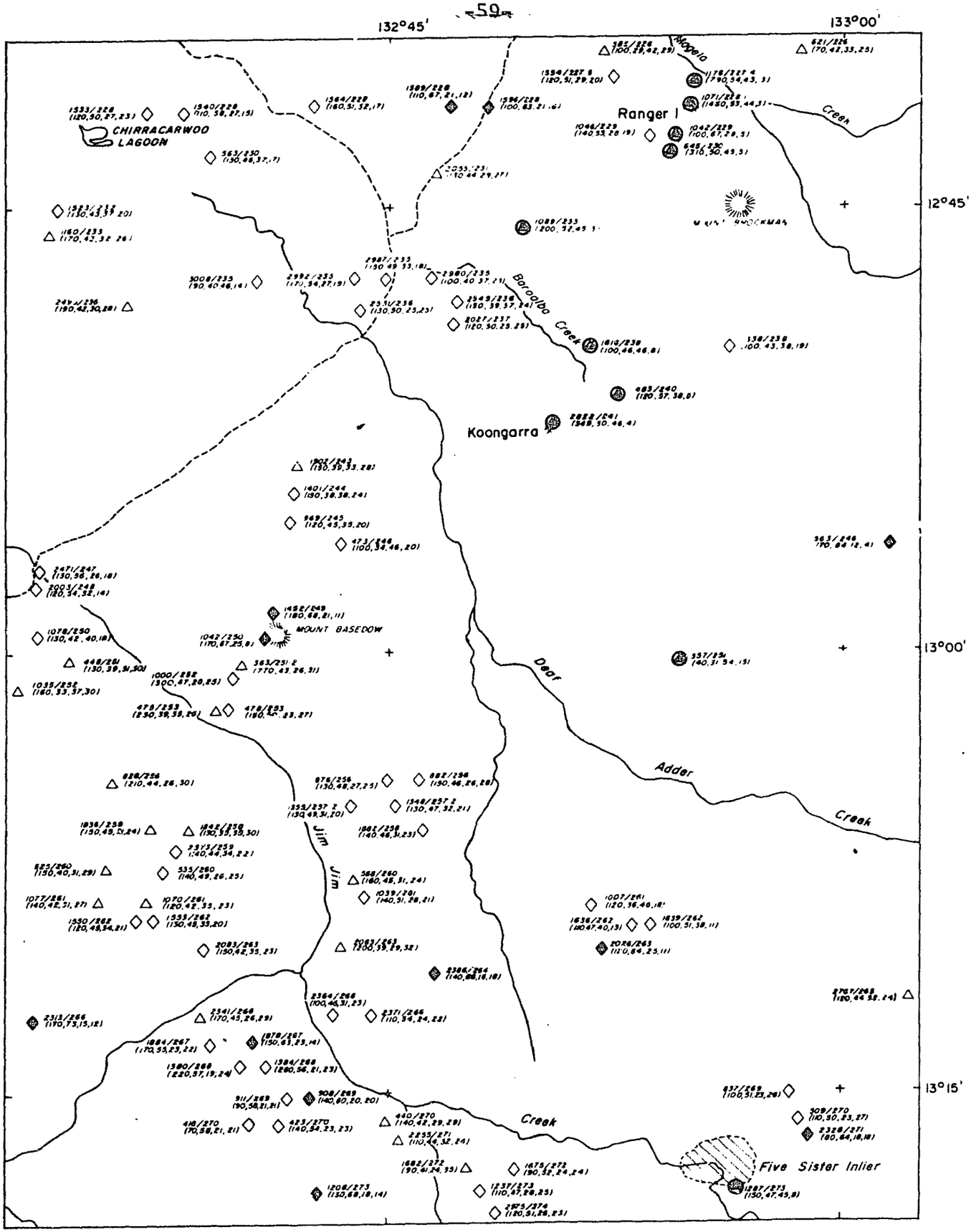

Fig. 16. Reduced scale version of part of an interpretation map from

6. GROUND SPECTROMETRY AND GEOCHEMICAL ANALYSIS

The number of published papers on ground spectrometry is relatively small. The following provide a summary of the state of the art: Adams & Fryer (1964), Doig (1968), Løvborg & others (1969), Killeen & Carmichael (1970), and Løvborg (1973).

During the course of the gamma-ray project, ground spectrometry was investigated in the Alligator River and Arunta Block areas of the Northern Territory. In each area rock samples were collected from sites where ground spectrometry was used. Samples have been measured as follows:

Alligator River samples

potassium by atomic absorption
uranium by gamma analysis, X-ray fluorescence (XRF) and delayed neutron analysis
thorium by gamma analysis and XRF

Arunta samples

potassium by atomic absorption
uranium and thorium by XRF

Some of the results from these areas and conclusions from them are presented below.

6.1 Alligator River area

Ground spectrometer measurements were made in this area in 1973 using a McPhar TV-5 integral spectrometer with a sodium iodide detector of 4.4 cm diameter and 5.1 cm thickness. Most measurements were acquired by counting over periods of 2 or 3 minutes. Results of uranium and thorium determinations using ground spectrometry, laboratory multichannel gamma-ray spectrometry and X-ray fluorescence are presented in Table 7. This table also includes measurements of uranium content obtained by delayed neutron analysis at Lucas Heights (Australian Atomic Energy Commission).

TABLE 7. COMPARISON OF URANIUM AND THORIUM ANALYSES BY GROUND SPECTROMETRY, LABORATORY GAMMA ANALYSIS, XRF, AND DELAYED NEUTRON ANALYSIS (DNA) (URANIUM ONLY)

Sample Number	Rock Type	URANIUM ANALYSES (ppm)				THORIUM ANALYSES (ppm)		
		Ground Spec.	Lab. Spec.	XRF	DNA	Ground Spec.	Lab. Spec.	XRF
GR 36	Laterite	4	54	29	42	1	30	9
GR 40	Laterite	<1	37	32	12	6	28	19
GR 45	Laterite	14	215	203	194	2	85	9
GR 46	Laterite	4	<4	4	5	1	<4	4
GR 48	Laterite	5	60	29	24	3	25	3
GR 49	Laterite	5	<4	6	4	5	<4	3
JJ 447	Phyllite	16	68	40	38	2	30	20
JJ 448	Basic volcanic	1	<4	4	2	1	<4	11
JJ 428	Granite	2	22	10	11	6	67	38
Ho 126	Laterite	3	41	17	17	2	37	17
Ho 127	Laterite	2	22	18	16	2	24	14
Ho 128	Laterite	2	23	16	16	1	43	18
GR 35	Laterite	5	39	28	25	1	22	8

These results show that the ground spectrometer analyses did not compare well with the other methods. This is believed to be due to the following reasons:

(a) The ground spectrometer used was temperature sensitive and the energy calibration drifted badly, even though considerable effort was made to keep the instrument properly calibrated; about 30 percent of all measurements made were calibration measurements.

(b) The stripping ratios provided by the manufacturer were determined using small hand-held sources. These are not the correct values for field use.

(c) Sampling problems. The TV-5 probe was used standing on flat areas of outcrop. It responds mainly to a small circular area surrounding the probe. Further work is necessary to determine what representative sampling (rock sample collection) is required to give equivalent information.

The uranium and thorium analyses determined by laboratory gamma analysis and XRF are shown in Figure 17. This shows that in nearly all measurements the gamma analyses were considerably higher than the XRF analyses. The uranium analyses were about 70 percent higher and the thorium analyses higher by at least 50 percent and in many cases considerably more. Samples with high uranium content and high uranium/thorium ratios (as determined by XRF) were generally shown by gamma analysis to have much higher thorium content and consequently much lower uranium/thorium ratios.

The uranium analyses obtained from XRF and delayed neutron analysis (here abbreviated to DNA) gave very good agreement as is illustrated by Figure 18. The sample data used in this figure are from samples from the Alligator River and Cloncurry areas. Good linearity and consistency are obtained for the range 3-6000 ppm. The delayed neutron method is described in Appendix 5 of this report. Recent work (Løvburg & others, 1976) indicates that it may also be possible to obtain thorium analyses by delayed neutron analysis using fast neutrons.

The accuracy of the laboratory gamma analyses can probably be considerably improved by modification of techniques used in measurement and data reduction. Some suggestions which could improve the accuracy are:

(1) The use of higher-energy peaks. Current BMR analyses have used the low-energy part of the spectrum (less than 400 KeV). The spectra are much simpler in the region above 1 MeV and, though longer counting periods may be required, the improvement in accuracy should justify this. Various authors (Adams & others, 1958; Bunker & Bush, 1966, 1967; Løvborg, 1975)

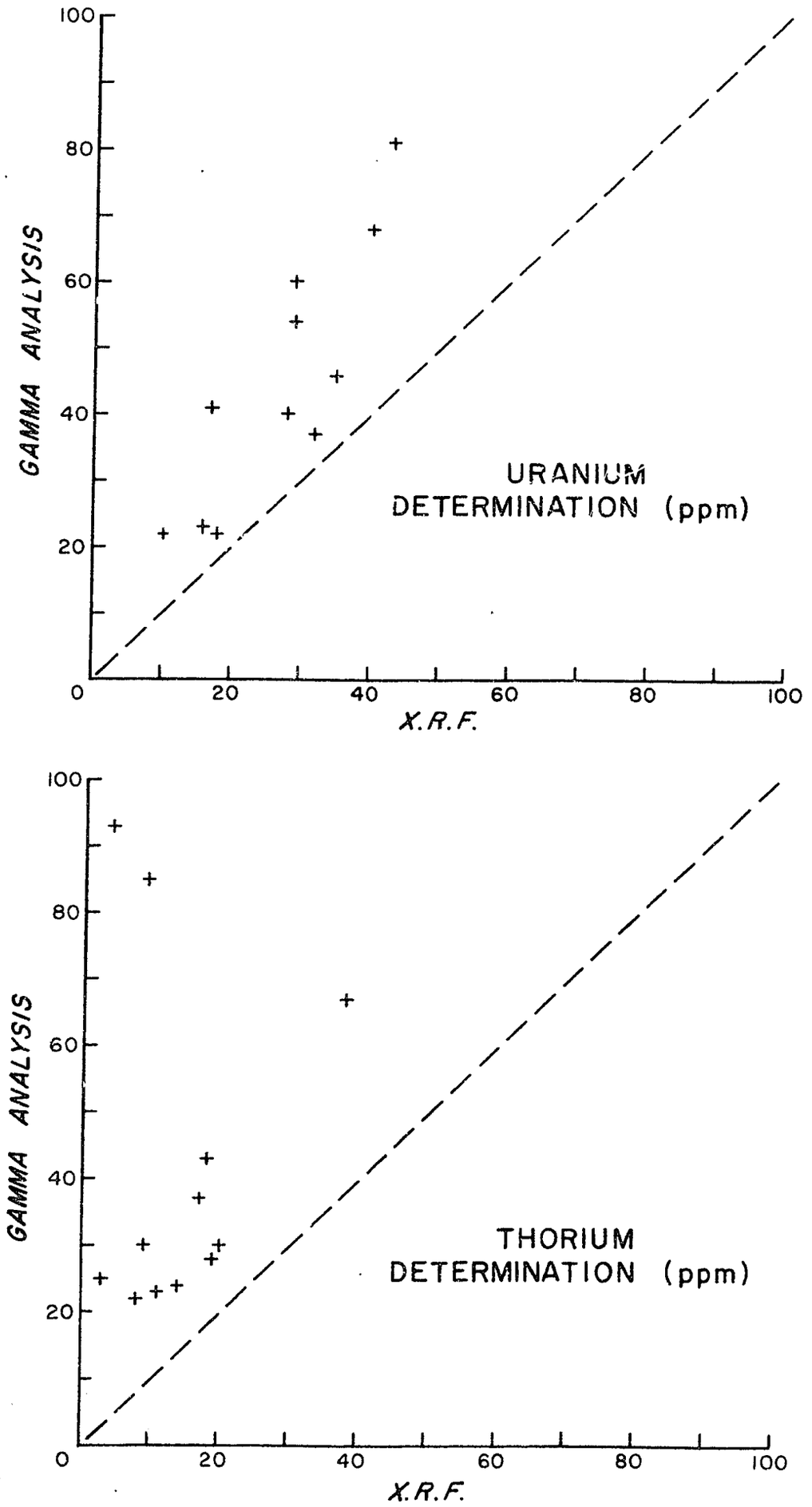

Fig. 17. Comparison of uranium and thorium analyses by gamma analysis and X-ray fluorescence (XRF).

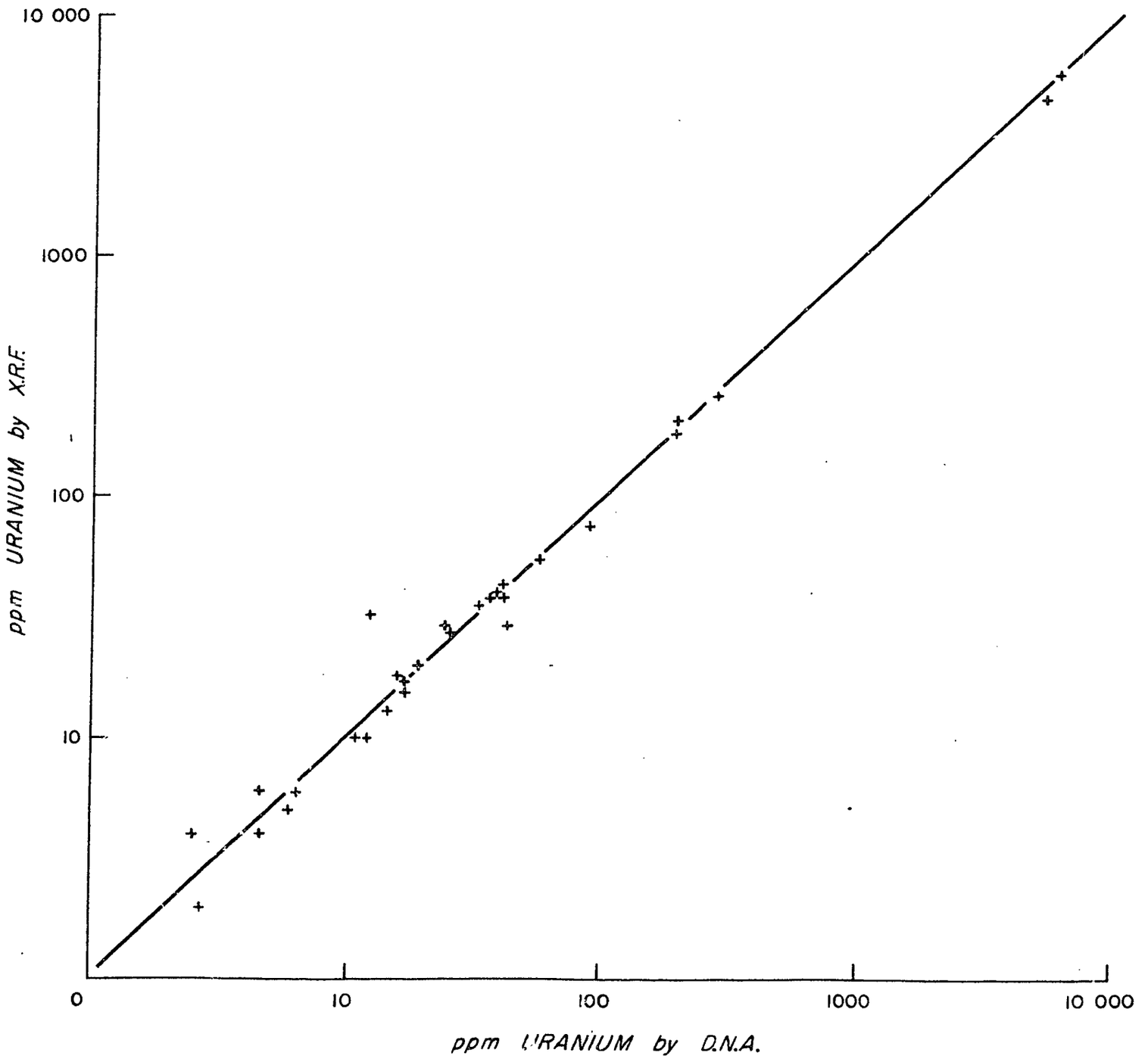

Fig. 18. Comparison of uranium analyses by X-ray fluorescence (XRF) and delayed neutron analysis (DNA).

have described the use and results of using the 1.46 MeV peak for potassium, 1.76 MeV peak for bismuth-214 (uranium-238 series) and 2.62 MeV peak for thallium-208 (thorium-232 series). To check the state of equilibrium or disequilibrium it will be necessary to use the lower-energy peaks as described by Mero (1960).

(2) The use of thinner sample containers to reduce the self-absorption within the sample. The measurements reported here generally used about 2 cm thickness of material and a sample weight of 100-250 grams.

(3) Investigation of correction factors as a function of sample density and different energies. Bunker & Bush (1966, 1967) show graphs of correction factors as functions of energy and density.

Potassium analyses have been obtained using the Atomic Absorption method. This is relatively straightforward and appears to produce satisfactory results. The lower limit of detection with the BMR equipment is about 0.01 percent potassium (by mass).

6.2 Arunta area

Ground spectrometer measurements were made and rock samples collected during the 1975 Arunta Project (Mutton, Shaw & Wilkes, in prep.) in the 1:250 000 Sheet areas of Mount Liebig and Mount Rennie. The ground spectrometer used was an Exploranium DISA-400A with a 7.6 x 7.6 cm sodium iodide detector for which stripping ratios and sensitivity constants were determined on the Geological Survey of Canada test pads at Ottawa. Measurements were made with the detector 60 cm above the ground. A computer program GSPEC has been written to handle ground spectrometry data and has been used to process the Arunta results. Appendix 7 gives details of this program.

Table 8 shows the results of potassium, uranium and thorium determinations obtained by ground spectrometry, and by laboratory analysis of rock samples from the sites where spectrometry was done. The spectrometry used counting times of 3 or 4 minutes. Error figures quoted correspond to $\pm$ 1 standard deviation based on errors from counting statistics. No allowance has been made for inaccuracies in the knowledge of background levels, stripping ratios and sensitivity figures. The results show that:-

1. The ground spectrometry measurements for potassium have underestimated the potassium concentration. On average the values derived from spectrometry are 70 percent of the values derived from atomic absorption analysis of rock samples.

2. About 70 percent of the uranium measurements agree to within ± 2 ppm. However it should be noted that the range of uranium concentrations is very restricted.

3. About 53 percent of the thorium analyses agree within ± 20 percent.

In most cases only one sample was analysed per spectrometry site hence some of the differences between laboratory measurements and ground spectrometry are due to inadequate sampling.

TABLE 8

RADIOELEMENT ANALYSES FROM GROUND SPECTROMETRY AND LABORATORY ANALYSIS

Sample Number	Rock Type	Laboratory analysis			Ground spectrometry		
		K %	U ppm	Th ppm	K %	U ppm	Th ppm
1000	granite	3.06	4	22	1.52 ± 0.07	2.1 ± 0.4	21.5 ± 0.8
1003	granodiorite	3.15	4	23	2.68 ± 0.09	0.6 ± 0.5	23.0 ± 1.0
1004	granodiorite	3.18	3	20	2.64 ± 0.09	1.7 ± 0.5	23.5 ± 1.0
1005	granodiorite	3.28	4	20	2.58 ± 0.09	3.1 ± 0.5	19.6 ± 0.9
1006	granodiorite	3.12	ND	11	1.98 ± 0.09	2.3 ± 0.5	20.4 ± 0.9
1007	sandstone	ND	2	18	0.0 ± 0.08	5.0 ± 0.6	28.3 ± 1.1
1008	granodiorite	3.16	4	21	2.35 ± 0.09	1.6 ± 0.4	17.6 ± 0.9
1011	dolerite	0.58	ND	ND	1.13 ± 0.07	0.6 ± 0.4	11.5 ± 0.7
1012	tonalite	2.29	ND	ND	1.67 ± 0.09	1.4 ± 0.5	13.0 ± 0.9
1016	gneiss	3.90	ND	25	2.23 ± 0.08	1.5 ± 0.4	11.3 ± 0.7

TABLE 8 (Continued)

Sample Number	Rock Type	Laboratory analysis K %	U ppm	Th ppm	Ground spectrometry K %	U ppm	Th ppm
1017	amphibolite	2.59	4	16	1.57 ± 0.08	1.4 ± 0.4	14.5 ± 0.8
1018	granite	3.31	4	17	2.50 ± 0.16	4.2 ± 0.9	19.3 ± 1.6
1019	gneiss	4.29	6	21	1.92 ± 0.08	1.7 ± 0.4	16.4 ± 0.9
1022	tonalite	2.71	ND	13	2.06 ± 0.08	2.6 ± 0.5	15.8 ± 0.8
1023	tonalite	3.30	ND	19	2.39 ± 0.09	1.3 ± 0.5	21.1 ± 1.0
1024	tonalite	2.94	4	14	2.54 ± 0.09	1.9 ± 0.5	19.0 ± 0.9
1025	tonalite	2.81	ND	15	2.75 ± 0.09	1.3 ± 0.5	19.1 ± 0.9
1026	tonalite	3.22	3	19	2.29 ± 0.09	1.4 ± 0.5	21.1 ± 1.10
1027	granodiorite	2.96	4	16	2.16 ± 0.08	1.6 ± 0.4	17.3 ± 0.9
1030	gabbro	0.07	ND	ND	0.01 ± 0.05	0.0 ± 0.3	4.1 ± 0.6
1031	hornfels	0.16	ND	7	0.31 ± 0.05	0.9 ± 0.3	5.6 ± 0.5
1032	hypersthene norite	0.13	ND	ND	0.08 ± 0.04	0.0 ± 0.2	2.0 ± 0.4
1037	hypersthene norite	0.11	ND	ND	0.0 ± 0.04	0.5 ± 0.2	2.7 ± 0.4
1062	conglomerate	1.74	ND	8	2.53 ± 0.08	2.2 ± 0.4	23.3 ± 0.9
1063	sandstone	0.75	ND	4	0.32 ± 0.05	0.3 ± 0.3	4.5 ± 0.5
1067	dacite	2.11	4	17	2.18 ± 0.09	3.8 ± 0.5	18.2 ± 0.9
1070	gneiss	4.08	8	36	2.70 ± 0.11	1.8 ± 0.7	49.1 ± 1.4
1071	granite	4.83	10	41	3.32 ± 0.12	4.4 ± 0.8	57.4 ± 1.5
1072	granite	4.26	7	37	2.82 ± 0.13	5.4 ± 0.8	38.2 ± 1.6
1090	granodiorite	3.25	3	23	2.19 ± 0.09	3.9 ± 0.5	22.7 ± 1.0
1091	gneiss	6.40	9	100	3.24 ± 0.12	3.2 ± 0.8	63.4 ± 1.6
1092	adamellite	3.06	2	21	2.01 ± 0.08	2.2 ± 0.5	18.3 ± 0.9
1094	granite	2.91	4	23	2.26 ± 0.09	3.5 ± 0.5	19.6 ± 0.9
1095	granodiorite	3.33	ND	10	2.70 ± 0.16	3.1 ± 0.9	20.6 ± 1.6

TABLE 8 (Continued)

Sample Number	Rock Type	Laboratory analysis K %	U ppm	Th ppm	Ground spectrometry K %	U ppm	Th ppm
1100	gneiss	3.27	3	21	2.37 ± 0.08	3.3 ± 0.4	21.1 ± 0.8
1107	gneiss	0.73	ND	15	0.26 ± 0.06	1.1 ± 0.4	16.3 ± 0.9
1136	granite	5.04	4	28	3.37 ± 0.11	3.4 ± 0.6	30.6 ± 1.1
1140	gneiss	5.84	3	12	2.16 ± 0.09	0.9 ± 0.4	6.8 ± 0.7
1142	gneiss	1.97	ND	13	1.44 ± 0.08	1.9 ± 0.4	15.0 ± 0.8
1145	gneiss	2.75	ND	18	2.67 ± 0.09	0.9 ± 0.5	24.6 ± 1.0
1148	gneiss	4.75	2	40	3.28 ± 0.12	4.2 ± 0.7	46.4 ± 1.4
1151	gneiss	3.40	ND	12	2.30 ± 0.09	1.7 ± 0.5	27.2 ± 1.1
1152	gneiss	3.40	ND	23	1.99 ± 0.11	0.0 ± 0.7	59.4 ± 1.6
1157	soil	2.15	ND	12	1.69 ± 0.12	1.1 ± 0.6	8.9 ± 1.1
1163	gneiss	4.11	2	32	2.61 ± 0.12	1.2 ± 0.7	30.0 ± 1.4
1164	gneiss	4.18	3	27	2.71 ± 0.17	0.9 ± 1.0	32.8 ± 2.0
1165	gneiss	3.43	ND	18	2.75 ± 0.10	1.3 ± 0.6	37.3 ± 1.3
1166	mylonite	2.47	3	21	1.72 ± 0.09	1.5 ± 0.6	34.1 ± 1.2
1168	gneiss	3.67	8	45	2.67 ± 0.13	3.5 ± 0.8	42.7 ± 1.6
1184	schist	3.75	ND	18	2.13 ± 0.10	1.3 ± 0.5	18.0 ± 1.1
1185	quartzite	0.81	ND	6	0.98 ± 0.07	1.3 ± 0.4	11.2 ± 0.7
1189	migmatite	4.16	3	24	3.08 ± 0.10	1.2 ± 0.5	24.7 ± 1.0
1198	gneiss	3.23	ND	8	3.39 ± 0.15	0.8 ± 0.6	11.3 ± 1.2
0100	sand	2.38	2	10	1.82 ± 0.09	1.1 ± 0.4	8.8 ± 0.8
0501	tonalite	3.50	5	26	2.52 ± 0.09	2.3 ± 0.5	18.9 ± 0.9
0509	adamellite	3.35	3	15	2.61 ± 0.09	0.3 ± 0.4	19.8 ± 0.9
0510	adamellite	2.89	4	24	2.65 ± 0.09	3.4 ± 0.5	22.0 ± 1.0
0511	quartzite	4.55	ND	7	2.15 ± 0.08	1.5 ± 0.4	16.2 ± 0.8

ND: non-detectable detection limits 2 ppm for uranium and thorium
0.01% for potassium

6.3 Conclusions

1. X-ray fluorescence appears to be quite satisfactory for measuring the uranium and thorium content of rock samples. Good agreement was obtained between uranium measurements made by XRF and delayed neutron analysis. Important samples can be sent to AAEC for delayed neutron analysis and results obtained within about two weeks at a reasonable price.

2. Ground spectrometry with a suitable spectrometer can produce approximate uranium and thorium determinations in the field, but not with high accuracy. Potassium analyses from ground spectrometry are not of sufficient accuracy to be particularly useful. If higher accuracy is required, differential scanners should be used with the spectrometer, as described in I.A.E.A. Technical Report 158 (1974). To produce reliable ground spectrometry data the ground spectrometer should meet at least the following criteria:

(a) The energy levels of each window should not drift by more than a few percent over the range of operating temperatures. In Australia this is about 0-45°C. Differences up to 20°C during any one day are frequently encountered.

(b) The instrument should be calibrated on test pads and the calibration repeated at regular intervals during its working life.

(c) Detector dimensions should be at least 7.6 cm (diameter) x 7.6 cm (height).

3. Laboratory gamma analysis has not proved satisfactory in our experience at BMR. Experience in other laboratories indicates that gamma analyses can be achieved with higher accuracy than we have achieved.

4. Potassium determination on rock samples using Atomic Absorption appears to be quite satisfactory, but no independent checks have been done to verify this during the course of this project.

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The following material has been reproduced from published sources with the permission of the publishers as listed here.

Figure 1. American Geophysical Union.
2. American Geophysical Union.
3. University of Chicago.
8. Department of Energy, Mines and Resources, Canada.
9. Geological Survey of Canada.
10. Society of Exploration Geophysicists.
11. Canadian Institute of Mining and Metallurgy.
13. Geological Survey of Canada.

Table 2. International Atomic Energy Agency.

Appendix 1. Canadian Mining Journal.
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APPENDIX 1

CHARACTERISTICS OF SOME COMMERCIALLY AVAILABLE AIRBORNE AND GROUND SPECTROMETERS

TABLE 9. CHARACTERISTICS OF AIRBORNE GAMMA-RAY SPECTROMETERS AVAILABLE FOR PURCHASE.

(Reproduced, with permission. from Hood, 1976)

MANUFACTURER (Country)	MODEL DESIGNATION	NO. & SIZE OF NaI(Tl) Detectors inch diam X length (Volume in cu.in.)*	TYPE OF SPECTROMETER D - Differential I - Integral (Ch-Channel)	RANGES cps/cpm=counts per second/minute (K = 1000) (M = 1000K)	TIME CONSTANT IN SECONDS OR COUNTING TIME	RECORDING OUTPUT	SIGNAL PROCESSING	POWER REQUIREMENTS (v = volts) (w = watts)
Abem — Atomenergi (Sweden)	Geospectrometer 1511	One 10x5 temp. regulated (393 cu.in.)	D or I up to 8Ch, plug-in pulse-height selectors Type 4128-3 windows Type 4129 - 1window	Thumbwheel selection 4128 0-899 counts per sampling period 4129 0-9999 counts per sampling period	0.1-99 sec. or min. each channel	Paper tape punch or 10-Ch. analog	Automatic or manual program	220V, 50Hz 100W 24/28VDC, 125W
Alpha Nuclear (Canada)	AGSS-T	Up to four 6x4 (452 cu.in.)	D or I 1 Ch.	50,100,200,500, 999 fullscale analog with X1,X10,X100 multipliers	Count times — 1,2,3,5,8,10, 20,30 sec or min	HP 7155 recorder	Single Channel analyzer	Internal batteries plus 12 to 24VDC. 110VAC at 12W
	DGRS-1002	Up to 15 6x4 (1696 cu.in.)	D or I 4 Ch	All Ch-100 to 25.6K cps	1,2,5,&10 sec for all Ch. Analog only	Analog		24V DC 40W
Exploranium (Canada)	DIGRS-3001	Up to 30 6x4 temp. reg. (3393 cu.in.)	D or I 4 Ch	All Ch.- 100 to 16 Kcps	Analog 1,2&5 sec each Ch Digital-0.1 to 99 sec in 1 sec intervals	Digital BCD, 5 digits/Ch. & 4 Ch analog		24VDC 60W
	GR-800	Up to 5000 cu.in using 6x4 or rectangular xtals	D or I 256 Ch Programmable selection	TC Ch-100 to 100Kcps K,U&Th Ch — 100 to 10Kcps	Programmable sampling rate from 0.1 sec to 100 sec in 0.1 sec intervals	4 Ch analog & BCD digital, HP Bussline	Programmable processing & outputs	24VDC 60W
Inax (Canada)	287B	One or more 9x4 temp. regulated (254 cu.in.)	D 128 or 1024 Ch 4 integration regions	Digital 1-10^4 counts for integral 1-10^3 for others	1 to 10 sec count time. Automatic for U/Th ratio	6 Ch Analog or digital		28VDC or 115VAC 40W
McPhar (Canada)	AU-4	Up to four 6x4 (452cu.in.)	I 4 Ch	TC Ch-30K to 3Mcps KCh-3K to 300Kcps U Ch-1K to 100Kcps Th Ch-300 to 30Kcps	1,2,3,4,5,sec	6 Ch analog		24/28VDC
	SPECTRA I	Up to 36 6x4 temp regulated and/or spectrum stabilized (4072cu.in.)	D or I 4 Ch	Digital-1Mcps Analog-100,200,500, 1K,2K,5K, 10K 20K,50Kcps	0.1 to 9.9 sec selectable	4 Ch analog or digital DTL or TTL		24/28VDC 50W
	SPECTRA II	Up to 36 6x4 temp reg. and/or spectrum stabilized (4072cu.in.)	Digital multichannel 256,512,1024 Ch 4 Ch analog	Same as Spectra I	Same as Spectra I	Same as Spectra I	Programmable Scan per Ch	24/28VDC 75W
Scintrex (Canada)	GAM-2	All Scintrex spectrometers are compatible with the following sensors: GSA-61:one 6x4 GSA-62:two 6x4 GSA-64:four 6x4 GSA-77:seven 6x4 Any of these sensors can be combined The GSA-64 and GSA-77 models are temp.-controlled	D or I 4Ch	All channels-30,100, 300,1K,3K,10Kcps	0.5,1,2or5sec each channel	4 Ch analog	Ratemeter output	12/24VDC or 110/220VAC 8W
	GAM-2S		D or I 4 Ch	Same as GAM-2	Same as GAM-2	4 Ch analog	Analog Compton Ratio outputs such as U/Th optional	12/24VDC or 110/220VAC 8W
	GAD-4		D or I 4 Ch analog version	100,1K,10K,100Kcps	1,3,10,30, 100,300,1000 or 3000 sec.	4 Ch analog	Compton stripping	10-30VDC
			4 Ch digit. outputs	N/A		Bit parallel, digit Serial BCD coded	N/A	
	GAD-5		D or I 4 Ch ratemeter outputs	Same as GAM-2	Same as GAM-2	Same as GAM-2	Same as GAM-2	12/24VDC 110/220VAC 30W
			4 Ch digital outputs	N/A	0.1,0.2,0.4,1,2,4 10,20,40,100 sec.	3 decades & range DTL/TTL compatible	N/A	

* 1 in^3 = 16.38 cm^3

TABLE 10. CHARACTERISTICS OF SCINTILLATION COUNTERS AND SPECTROMETERS AVAILABLE FOR GROUND RADIOMETRIC PROSPECTING.
(Reproduced, with permission, from Hood, 1976)

MANUFACTURER (Country)	MODEL D-Differential Sp-Spectrometer	SCINTILLATION CRYSTAL (Inch diameter X thickness) NaI(Tl) (Volume in cu.cm.)	RANGES (cps or cpm = counts per second or minute) (K = 1000 M = 1000K)	TIME CONSTANT IN SECONDS	POWER SOURCE	WEIGHT IN KILOGRAMS	REMARKS
ABEM — Atomenergi (Sweden)	Geospectrometer 1501 (4 channel Sp)	5x6 (1931 cu.cm)	Ch 1-300,1K,3K,10Kcps Ch 2-30,100,300,1Kcps Ch 3-30,100,3001Kcps Ch 4-30,100,300,1Kcps	Ch 1-1,2.5, 5&10sec Ch 2,3,4-2.5, 5,10,20sec	12/24V 110/220V 50/60 Hz 50W	57 kg inc 5 Ch recorder	Alarm contact on Ch 1 For vehicle mounting
Austral Exploration Services (Australia)	SG-2	1x1 (13 cu.cm)	30,100,300,1K,3K, 10Kcps	3&15 sec	C cells	2 kg	Total count settable alarm
	GDS-12 (Sp)	2x2 or larger (103 cu.cm)	30,100,300,1K, 3K,10Kcps	3&15 sec	D cells		Continuous threshold Recorder output
Elsec (UK)	Type 751 (4 Channel Sp)	2x2 or 3x3 (103 or 348cu.cm)	10,30,100,300, 1K,3K,10Kcps	2 to 20 sec	Nicad batteries	4.5 kg	Digital readout & servo stabilization
Exploranium (Canada)	GRS-101 Analog Scintillometer	1.25x1 (20cu.cm)	100,300,1K,3K, 10 Kcps		2 D cells	1.2 kg	3 pos threshold alarm
	GR-310 (Sp)	2x2 (103cu.cm)	Digital display in cps Also analog ranges - 100,200,400,800, 16K,3.2K,6.4K, 12.8Kcps	0.5,1,1.5& 2 sec	12 D cells	3.6 kg	Adjustable threshold alarm. Analog O/P Single Ch differential Sp
	GR-410 (4 Channel D. Sp)	3x3 (348cu.cm)	Digital display in cps. Also analog ranges - 100,200,400,800, 1.6K,3.2K,6.4K, 12.8Kcps	0.5,1,1.5 and 2 sec	12 D cells	3.6 kg console 3.4 kg detector	Analog O/P. Automatic isotope gain control. Adj threshold alarm
	DISA-300 (Sp)	2x2 (103cu.cm)	Digital numeric display in cps	1,2,4,6,8, 10,20&30 secs or minutes	12 D cells	3.2 kg	Selectable single Ch integral unit with sample period alarm
	DISA-400A (4 Channel D. Sp)	3x3 or larger (348cu.cm)	Digital display in cps. Also analog ranges 100,200, 400,800,1.6K,3.2K, 6.4K,12.8Kcps	1,2,5 and 10 sec	12 D cells	3.2 kg console 3.4 kg detector	Analog O/P
Inax (Canada)	153	3x3 (348cu.cm)	1 to 10Mcps	15,30 sec 1,2 min	Ag-Zn batteries	10.5 kg	Digital display
	192 (Sp)	3x3 (348cu.cm)	1 to 10Kcps	0.3 to 30sec	Ag-Zn batteries	10.9 kg	Single channel Digital
	290 (Sp)	2x2 (103cu.cm)	30 to 240Kcpm	0.01 to 60sec automatic	Mn-Alkaline cells	1.8 kg	Digital alarm
McPhar (Canada)	TC-33A	1x1.25 (16cu.cm)	100,300,1K,3K, 10Kcps	Preselected	2 C cells	1.3 kg	Pistol grip
	TV-1 (Sp)	1.25x1 (20cu.cm)	100,1K,10K,100K cpm	1&10 sec	2 C cells	1.4 kg	3 pos threshold
	Spectra-44 (4 Channel Sp)	3x3 (348cu.cm)	Digital 2-9999cps Analog-100,200,400, 800,1.6K,3.2K,6.4K &12.8cps	Digital-1sec to 30 min Analog-1,2,5 & 10 sec	12 D cells	1.9 kg console 3.1 kg detector	Simultaneous count Sequential readout Digital alarm
Scintrex (Canada)	BGS-1SL	1.5x1.5 (43cu.cm)	30,100,300,1K, 3K,10Kcps (1cps=2.5x10^{-4}mR/hr)	Long on 30 &100 cps	4 D cells	2.2 kg	Audio alarm with variable threshold
	GIS-3 (Integral Sp)	2x2 (103cu.cm)	10,30,100,300, 1K,3K,10Kcps (1cps=2.0x10^{-4}mR/hr)	1 or 3 secs	4 D cells	3.6 kg	Single Ch with preset thresholds. Variable threshold audio alarm
	GAM-1 (D. Sp)	2x2 (103cu.cm)	30,100,300,1K, 3K,10Kcps (1cps=2.0x10^{-4}mR/hr)	1,3 or 10sec	6 D cells	4 kg	Integral or differential energy analysis. Audio alarm
	GAD-1 (D. Sp)	2x2 (103cu.cm)	30,100,300,1K, 3K,10Kcps (1cps=2.0x10^{-4}mR/hr)	1,3 or 10sec	6 D cells	3.7 kg	Same features as GAM-1 plus digital counting & display
	GAD-4 (4 Channel Sp)	Various sensors for various applications	100,1K,10K or 100Kcps on 4 Ch	1,3,10,30,100, 300,1K,3K digital count times	8 D cells	3 kg	All features of GAD-1 plus 4 Ch operation A&D outputs

APPENDIX 2

INTERNATIONAL ATOMIC ENERGY AGENCY (I.A.E.A.) RECOMMENDATIONS ON AIRBORNE GAMMA-RAY SPECTROMETERS.

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AIRBORNE GAMMA-RAY SPECTROMETERS

I. GENERAL INTRODUCTION

I-1. Application

In spite of the relatively high cost per line km adequate airborne gamma-spectrometry surveys yield a high cost effectiveness. The total expenditure to fly, map, evaluate and select sites for additional exploration by this method compares favourably with other methods. Spectral data, when well evaluated, greatly reduce the amount of high-cost ground checking required to assess the survey results. This field effort is a necessary part of the survey and often costs more, per km^2 or per anomaly, than the airborne survey, including data reduction.

There are three primary objectives or applications. These are:

(a) To discover and evaluate large areas which may be favourable for additional exploration and to do so in a minimum time with a limited staff and with a high degree of reliability.

(b) To locate and identify subtle anomalies often associated with economic deposits and which can lead to their discovery.

(c) To support the primary geological mapping of large areas, particularly when these are difficult of access on the ground. Systems of adequate sensitivity are able to determine the relative concentrations of uranium, thorium and potassium in typical country rock and the lithologies can often be identified and mapped by means of their characteristic radioelement concentrations or diagnostic abundance ratios between these elements.

I-2. Advantages

(a) Airborne gamma-ray spectrometers, in combination with altimeter and navigational or flight path recovery instruments, can provide rapid evaluation of broad and often inaccessible areas at a relatively low cost per unit area.

(b) Except for areas of very high relief, the method is applicable to moderately developed land and to remote inaccessible areas with poor trafficability.

(c) The method senses a large area and therefore provides a representative sample.

(d) The per cent coverage can be predetermined by selection of flight-line spacing and complete radiometric coverage can be achieved; this is very difficult to accomplish with most low-cost surface surveys.

(e) The spectrometric capability identifies and measures the relative concentration of potassium and the uranium and thorium series (eq U, eq Th);

it can also identify radiation contributed by fall-out of artificial radio-isotopes. It therefore provides data for evaluation of geochemical environment studies.

(f) If statistically valid data are collected, then isotopic ratios, e.g. U/Th, U/K, and Th/K, can be mapped. In contrast to total-count measurements, the ratio values are only slightly influenced by absorbers such as soil moisture and vegetation and are not appreciably affected by variations in ground clearance (often a problem in rough terrain).

(g) Survey results pinpoint areas of interest thus concentrating expensive groundwork where it is most effective.

(h) The method lends itself to efficient production of profiles, maps and statistical evaluation by computers.

I-3. Disadvantages or limitations

(a) Adequate systems require large capital investment and time to develop the factors and methods for data reduction, analysis, and presentation. (Software for computer processing, statistical analysis, and presentation formats is nearly as important as the data acquisition instruments.)

(b) Although cost per unit area is usually less than for a comparable ground survey, the greatly reduced time required to complete the survey and evaluation may result in a large expenditure in a single budget period. Breaking the survey into several small projects is more costly and generally less satisfactory.

(c) Except for very limited systems, the spectrometer is generally larger and heavier than gross-count systems and requires a larger aircraft and crew.

(d) Operational data collection and analysis requires more technical knowledge and experience. Equipment is complex and requires maintenance by highly trained personnel.

(e) Areas of high topographic relief are often difficult or impossible to survey because of aircraft limitations and because of the drastic variations in sample geometry.

(f) Lack of local airfield and service facilities for the aircraft, the system, and the crew greatly increases the cost.

(g) The method, as in gross-count gamma surveys, is not highly sensitive to small nearly 'point' sources because the gamma intensity, measured at the detector, represents an average intensity for a broad area; point source anomalies are effectively diluted by the much larger sample.

(h) The airborne detector responds to gamma rays which mostly originate in the upper 15 to 30 cm (6 to 12 in) of the ground; buried concentrations have little to no direct effect; overburden and soil moisture have great influence; and weathering may deplete or enrich the near surface materials and cause significant secular disequilibrium between gamma emitting isotopes and parent uranium or thorium.

II. GENERAL DESCRIPTION OF THE INSTRUMENT OR SYSTEM

An airborne gamma-ray spectrometer system generally consists of:

(a) A number of high resolution, thermally insulated, sodium iodide detectors

(b) A spectrometer assembly which generally includes pulse amplifier and shaping electronics, pulse-height (energy) analysers such as several differential single-channel analysers (SCA) one for each energy band or window to be recorded, or a multichannel analyser (MCA) or an analog-to-digital converter (ADC), and computer-type memory to accumulate, store and manipulate data

(c) In-flight data display such as multichannel analog strip chart record, digital display, and CRT spectrum presentation

(d) Recording system which may include one or more methods such as multi-pen analog strip chart, magnetic or punch-tape digital recorder

(e) A radar altimeter

(f) Flight-path recovery system which may include photographic or video tracking camera and/or Doppler navigation equipment.

III. MINIMUM PERFORMANCE REQUIREMENTS

III-1. Overall operating performances

The system, when operated under normal survey conditions of altitude, speed and moderate relief, should be capable of:

(a) Mapping the relative equivalent concentration of U, Th and K in broad areas of typical rocks and soils

(b) Distinguishing the relative abundance of anomalous concentration significantly greater than normal rock levels

(c) Reliably detecting relatively small variations in gross gamma intensity which represent small anomalous concentrations of radioelements in a line or nearly point-source configuration.

Specific minimum requirements of a system depend on a number of factors which must be optimized to achieve the primary objectives of the survey; major interrelated factors include altitude, aircraft speed, sensitivity, energy resolution, ground resolution (area of single measurement) and requirements or emphasis to be placed on statistically significant ratios of natural radioisotope abundance.

III-2. TEMPERATURE LIMITATIONS

The equipment, with the possible exception of the detectors, is operated in the controlled environment of the aircraft. An operating temperature range from 5 to 40°C is adequate. The equipment when not in use should withstand temperatures in the range from -40°C to +55°C (-40°F to +131°F) without damage.

III-3. SENSITIVITY

Requirements for sensitivity depend on the objectives of the survey and the topographic and geological conditions. The effective sensitivity of the survey system is its capability to reliably resolve small but significant variations in abundance of radioelements along the survey path. Statistical reliability limits the minimum detectable variation and is proportional to the square root of the number of diagnostic gamma rays counted; greater statistical reliability can be achieved by increasing the volume of the detector and/or increasing the sampling (or averaging) period. Resolution of local variations in abundance along the flight line is decreased if the sampling or counting time is increased. Therefore, the effective sensitivity of the system can be measured in terms of the number of diagnostic gamma rays recorded per unit distance travelled by the aircraft.

Factors which determine the system sensitivity are:

(i) total sensitivity of the detector to diagnostic gamma rays; this is controlled principally by the volume, composition and energy resolution of the detector
(ii) degree to which available energy bands in the spectrum are utilized
(iii) amount of undesirable 'background' from contamination in the detector system and aircraft
(iv) speed (velocity) of the aircraft (metres or feet per second)
(v) flight height (terrain clearance)

The dominant factors are crystal volume and velocity of the aircraft. Therefore, the ratio V/v, where V is the volume of the NaI(Tl) detector and v is the aircraft velocity in m/s, provides a fair indication of the counts per unit distance travelled by the aircraft and is a reasonable measure of effective sensitivity of the system.

Objectives of a survey may be divided into two general categories, each having minimum requirements for system sensitivity.

(a) Sensitivity requirements for limited-objective surveys

(1) Limited objectives may include:
(i) direct prospecting, often depending on the gross or total count, to discover mineralized occurrences of the major natural radioelements (K, U, Th)

(ii) to qualitatively identify the principal radioelement causing significantly anomalous gamma-ray intensities attributed to mineralized localities

(iii) to establish the normal relative abundance of K, U and Th in major rock units which are exposed over broad areas

(2) Sensitivity required for the limited objectives, listed above, is significantly less than that required to achieve the comprehensive objectives which are amenable to sensitive gamma spectrometry surveys because:

(i) little dependence is placed on single measurements of eq K, eq U or eq Th for detailed mapping

(ii) the principal element is only qualitatively identified at significantly anomalous localities

(iii) relative normal average abundance in large areas can be determined by extending the counting time or averaging a series of adjacent measurements, with an acceptable reduction in ground resolution. An effective sensitivity ratio, $V/v \geq 0.1$ (where V is the volume of the detector in litres and v is the aircraft velocity in m/s), is generally adequate for limited objective surveys. For example: a 7.42 l NaI(Tl) detector, such as 4 (6×4 in) crystals, and an aircraft speed of 200 km/h or 55.6 m/s yields a V/v ratio of 0.13; the aircraft travels 167 m in 3 s of counting or resolving time and assuming a typical abundance of about 2 ppm eq U or 4 ppm eq Th, the indicated concentrations can be measured with a statistical reliability of about ± 50% (at the 90% confidence level) at a flight height of about 100 m.
When the system is operated in the integral mode to take advantage of gross or total count rates for detailed mapping, the lower discriminator should be set no higher than 0.2 MeV. Preferably the system should operate on a noise free stable gain plateau to obtain optimum low counting statistics at short counting times.

(b) Sensitivity requirements for comprehensive objective surveys

(1) Comprehensive objectives, which are generally most effective, may include:

(i) detailed quantitative mapping of the apparent abundance of major natural radioelements (K, U and Th) in the near-surface rocks and soils

(ii) mapping the abundance ratios (U/K, U/Th, Th/K) which are relatively independent of modifying parameters, e.g. surface geometry, various absorbers such as soil moisture and vegetation, and percentage of outcrop. The abundance ratios are frequently more indicative of lithologic units or geologic-geochemical environments than intensity alone

(iii) statistical evaluation and correlation of radioelement abundances and abundance ratios to geological features in order to detect and evaluate subtle but significant low-contrast anomalies which may be obscured by normal variations in lithology, geometry and surface absorbers

(2) Sensitivity required to achieve these or similar comprehensive objectives is about 7- to 10-fold greater than for the less demanding limited objectives. The effective sensitivity ratio, V/v, should therefore be at least 0.7 and preferably near 1.0 for best results. For example, a V/v ratio of 0.72 can be obtained using either 40 l of detector in an aircraft flying 200 km/h (124 mile/h) or 20 l of detector and a velocity of 100 km/h (mile/h). This emphasizes the advantage of slow-flying aircraft and that the aircraft is really an important part of the system.
If recognition and mapping a variation in abundance of 20% in one of the radioelements is significant to the comprehensive survey, then the variations caused by counting statistics alone should be maintained at a lesser percentage. In general, the standard deviation of single measurements should not exceed about 15% and, preferably, the statistics should not be greater than 20% at the 90% confidence level. This requires 65 or more net (corrected) counts in a single measurement and, for surveys of typical areas, containing perhaps 2.5 - 3 ppm U, will require a combination of detector volume multiplied by seconds of counting time of about 120 litre seconds. If, for example, the allowable distance travelled during a single measurement is established as 165 m and the aircraft velocity is 200 km/h (55.5 m/s) then the counting time cannot exceed 3 s and, to achieve the desired 120 litre · seconds sensitivity, will require about 40 litres of NaI(Tl); the volume can, of course, be decreased proportionally if a slower aircraft is used or if the allowable distance travelled during a measurement is increased.

III-4. Operating life

There is no significant limitation because the system is powered from the aircraft and the minimum expected life of the detectors and electronics is at least several years.

III-5. MTBF

Except for minor adjustments in the field by the operator the MTBF should be 30 working days, unless accidentally damaged.

IV. SPECIFICATIONS AND DESIRABLE FEATURES OF THE MAJOR COMPONENTS OF THE INSTRUMENT OR SYSTEM

IV-1. Detector assembly

The minimum dimension of the crystal(s) should be 10 cm. Energy resolution of the detector system as a whole should not be more than 14% (FWHM). All photomultiplier tubes should be matched or adjusting electronics provided to assure a common pulse-height energy response from all detectors.

Detector systems should exhibit great short-term stability which may be achieved by using near constant temperature housings, temperature

compensating components, and regulated HV supply. Systems may employ manual or automatic gain stabilization based on a low energy isotopic source, suitable LED, or stabilized light pulser. These devices may be omitted if data reduction methods include frequent periodic or continuous spectral calibration using the natural spectra from multichannel analyser records. Drift in count rate in an 8 h period by non-stabilized systems should be less than ± 2.5% of the mean count rate.

IV-2. Measuring electronics

Summing amplifier. Most systems employing multiple detectors require a summing amplifier to combine the output from the several detectors. This should permit the gain of each detector to be balanced to achieve required system energy resolution (< 14% FWHM), and should provide switches to switch detectors in or out of the circuit. The baseline shift and gain changes must be less than 1% at 10 000 counts/s or else compensation circuits must be incorporated. (Systems employing ADC and computer for in-flight pulse-height and analysis will require a multiplexing for multiple detectors and adequate storage to accumulate, process, and combine spectra from the several detectors.)

Pulse-height selection. Energy discrimination can be accomplished using one or more of the following instruments: (1) a multichannel analyser (MCA), (2) an ADC and small computer, and/or (3) several differential single-channel analysers (SCA) — one for gross count and one for each of the energy windows to be measured. Variable threshold (integral) analysers are generally unsatisfactory for continuous sensitive radioelement mapping.

An MCA system should provide at least 100 channels and 200 to 400 are desirable if spectra are to be displayed on either a CRT or plotter to monitor calibration; differential non-linearity should be less than 2% over the top 98% of the energy range; apparent energy shift should be less than 1% at count rates up to 5×10^4 counts/s and drift (at constant temperature) less than 1% or 2 channels/d.

A multiple SCA system requires a differential SCA for each energy window to be monitored, generally four or more. Accuracy of setting, in terms of MeV, should be within 1% and the accuracy and stability of window width within 5%.

Counting loss of an MCA system should not exceed 20% at rates of 10^4 counts/s and loss due to dead time in SCA systems should be less than 10%.

Instrumental error of the system should not exceed ± 5% at standard operating conditions.

Data accumulators. Measurements of gamma intensity and energy can be accumulated in a ferrite core memory of an MCA or computer, by a digital rate meter (automatically recycled scaler), or analog rate meter. It is desirable to provide selectable accumulation or response times (2 time constants) to optimize counting statistics and ground resolution which are a function of aircraft speed, height, and sensitivity (volume) of the detector(s). The distance travelled during a measurement period should be minimized to achieve maximum ground resolution. Thus,

for example, similar ground resolution can be obtained by flying at 100 km/h and collecting for 5 s or flying 200 km/h and collecting data for 2.5 s. Generally the distance travelled during a single measurement should not exceed about 160 m (528 ft, or 0.1 mile) and the product of ground speed (km/h) and seconds of counting time should rarely exceed 500; this can be achieved by counting or response times of 5 s at 100 km/h or by counting 2.5 s at 200 km/h; selectable times should range from 0.5 to 2 s for the gross or total count data and from 1 to 10 s for the spectral data. Data collected using short periods of accumulation can be averaged or summed during data processing to improve statistics but with impaired ground resolution; systems providing corrected and averaged data in real time are desirable although post flight compilation is acceptable.

Altimeter. All gamma intensity data must be corrected for variations in height (ground clearance). A radar altimeter having an accuracy of ±5% over the range 15 to 300 m (50 to 1000 ft) is required. A value for ground clearance can be averaged for the same period as each gamma-ray measurement or should be obtained near the midpoint of the measurement. The time constant should not exceed 2 s and should respond nearly equally fast to upslope and downslope changes. Output from the altimeter must be compatible with digital recorders and/or in-flight computer and with the analog chart recorder if height-corrected data are not obtained in real time. All height values must be correlated with corresponding gamma measurement.

Track recovery. Track (flight path) recovery can be accomplished by one or more of the following: (1) a photographic tracking camera, (2) a TV/video tape camera, (3) a Doppler radar, or (4) an inertial guidance system. The latter two, though expensive and requiring frequent maintenance and testing, are desirable for large areas lacking frequent and easily identifiable ground control features. Automatic entry of fiducial points which co-ordinate the tracking data with the radiometric measurements is required, e.g. event marker on analog records and digital values in the tape record format. The records should be documented at least each kilometre if an optical method is used and at least each fifth measurement period if Doppler or inertial methods are used. More frequent tracking records may be desirable if topography or geology necessitates irregular flight lines. When properly operated, a system using one or more of these or equivalent track recovery methods should establish the flight path and position of each gamma-ray measurement with sufficient accuracy to assure that no more than 10% of the mapped position of the data points will differ from the true location on the flight line by more than 1/2 of the prescribed distance between measurements along the flight line or more than 1/2 the prescribed distance between flight lines.

IV-3. Data output

Types of output. Several forms of output from the gamma spectrometer, altimeter, track recovery, and ancillary equipment are required or desirable. These may include uncorrected or corrected analog and digital data which should be displayed and recorded.

Chart recorder. A multitrace strip chart recorder is essential even if digital data is being recorded as well, either to record analog data or to monitor records in real time. Parameters being recorded should be selectable and might, for example, include: (1) raw (uncorrected) radiometric data — gross or total —, two or more differential energy windows from SCA or MCA, (2) radiometric data corrected in-flight in real time for ground clearance and Compton scatter (stripped) and possibly one or more abundance ratios, (3) altimeter record, if uncorrected data is recorded, and (4) auxiliary geophysical parameters such as magnetics or RF. Digital systems will require digital to analog converters.

The recorder should be of the servo-system type, or equivalent, capable of operating when subjected to typical vibration and g levels during flight. Four or more traces (channels) are required (up to 7 channels desirable). Chart speed (time drive) should be selectable; typical values are 0.5, 1, and 2 mm/s (about 1, 2 and 5 in/min); minimum channel width (full-scale pen travel) is 5 cm.

Digital tape recorders. Because of the need to process a large volume of data, preferably in real time, digital systems are almost essential for continuous sensitive spectrometric mapping. Digital systems require adequate storage or buffer to assure that read-out and recording will not inhibit data collection for more than 0.5 s.

Systems using a limited number of energy windows and ancillary equipment may employ punch (perforated) tape recorders; speed of 60 to 120 characters/s are necessary; standard tape and codes such as one-inch, 8 level ASCII, compatible with common data processing equipment are recommended.

Systems employing multichannel analysis and a number of auxiliary inputs such as altimeter, along-track-cross-track Doppler data, magnetometer, or other geophysical parameters, require the greater speed of magnetic tape recording. Recorders should be incremental type, fast start-stop, either reel or cassette; tapes should be compatible or convertible to interface with common medium to large computers. Half-inch tape, 7 or 9 track, relatively low packing such as 200 - 800 bits per inch, odd parity is currently desirable.

Manual entry to digital recorders is required to identify data and co-ordinate measurements with tracking control points.

If the system is to be used in an area remote from a computer, a tape-reader and display should be available to monitor or periodically check data accumulation; in-flight retrieval is desirable.

IV-4. Power supply

The system including ancillary equipment generally receives primary power from the aircraft. Requirements depend on type of system and may range from 500 to 1500 VA including digital recorders, CRT display, computer etc. The specified voltage, frequency, and maximum power for each item and the system should be clearly stated including need for regulation or filtering.

IV-5. Size and mass (weight)

Size and mass (weight) depend on the type of system, sensitivity, sophistication of read-out, recording and on-line real-time corrections, and method to evaluate ^{214}Bi in the atmosphere. Limited sensitivity equipments are usually in the range 100 - 200 kg (220 - 440 lb) whilst the high sensitivity systems for comprehensive surveys may weigh 500 - 700 kg (1100 - 1600 lb). Detectors must be positioned to minimize absorption effects of changing fuel levels and to meet positioning and loading requirements of the aircraft. A central control panel, including monitoring displays for the whole system, must be conveniently located for the operator although the sensors and much of the electronics can be remotely located to meet loading requirements. Palletized systems for sensors, electronics, and control console are desirable, to permit rapid installation and removal from aircraft.

IV-6. Moisture resistance

Systems designed to mount detectors externally, as in some helicopter applications, require rainproof detector housings, cables, and connectors. Generally, however, sensitive sophisticated systems are mounted inside the aircraft and need meet only requirements of humidity.

IV-7. Shock

The system should be mounted in a manner that protects against vibration and shock and which meets regulations for safe tie-down in the aircraft.

IV-8. Accessories

(a) A complete set of manuals for each of the component instruments including test and maintenance instructions, recommended calibration and operating procedures.

(b) Set of test sources, a few microcuries each of low, medium and high energy gamma emitting isotopes, to check energy resolution, spectrometer calibration.

(c) Though not a true accessory, a number of computer software (programs) will be required to process and evaluate the survey data. These, including factors for height correction, stripping of Compton scattering, statistical analysis and formating displays, maps and profiles are of nearly equal importance as the data collection instrumentation.

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APPENDIX 3

URANIUM-238 AND THORIUM-232 DECAY SERIES AND SPECTROGRAMS

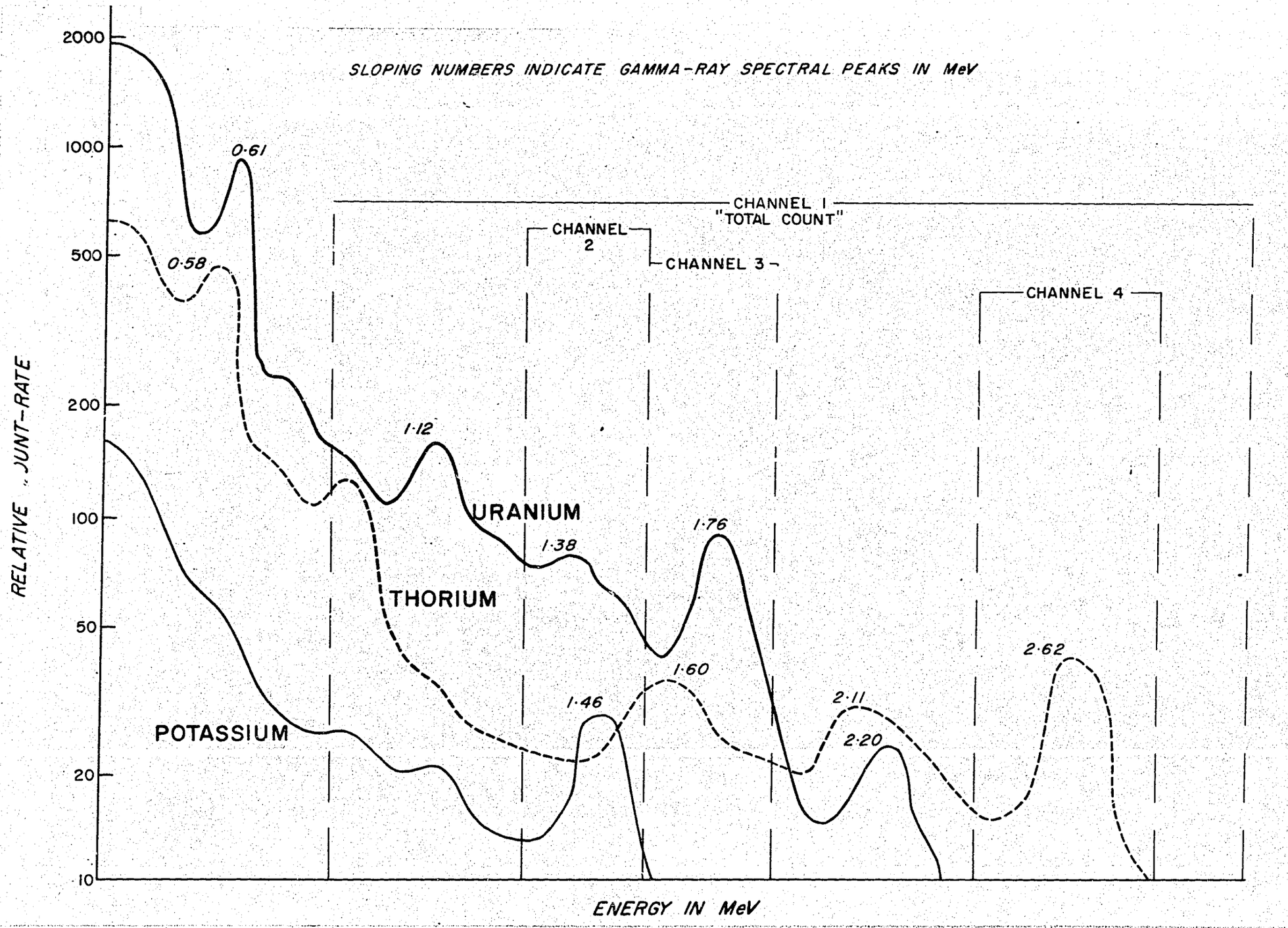
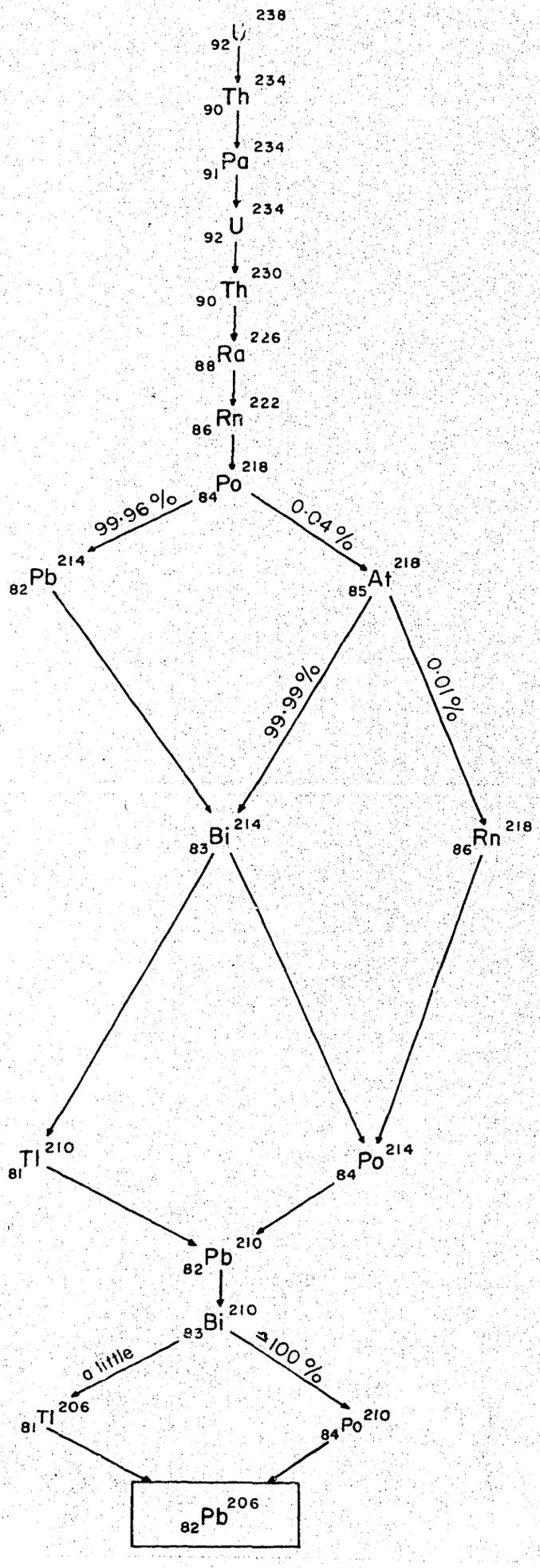
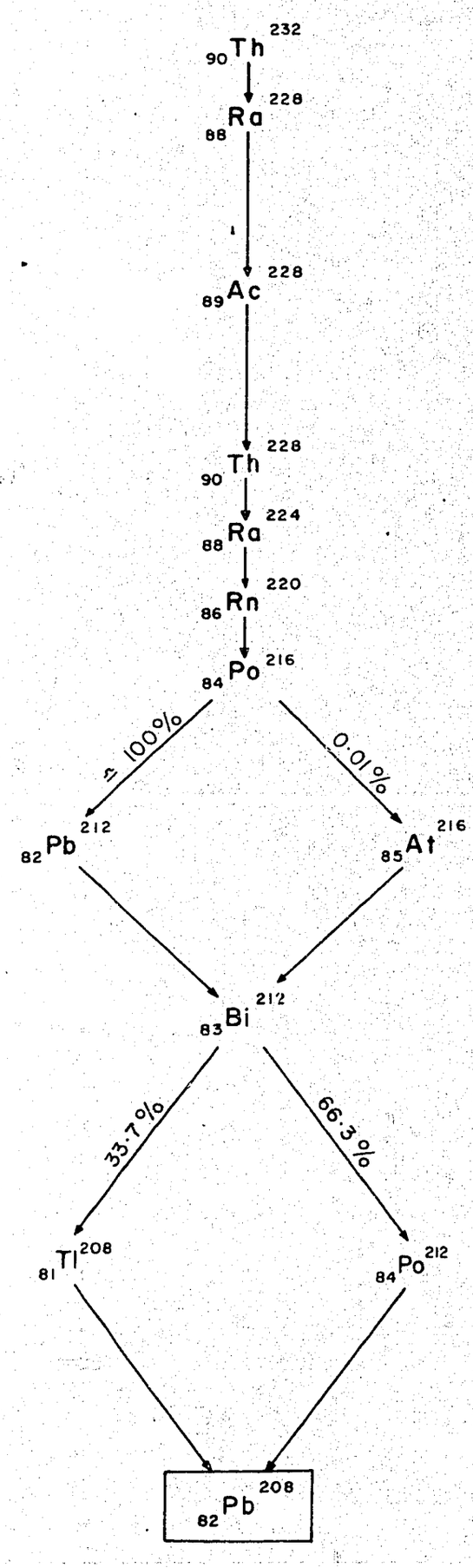


Fig. 19. Typical gamma-ray spectrograms for potassium, uranium and thorium.



NUCLIDE	½ LIFE	γ ENERGIES (MeV)
U^{238}	$4{\cdot}5\times10^{9}$ yr	
Th^{234}	24·1 days	0·09
Pa^{234}	1·18 min	1·01 , 0·77
U^{234}	$2{\cdot}5\times10^{5}$ yr	0·05
Th^{230}	8×10^{4} yr	
Ra^{226}	1622 yr	0·19
Rn^{222}	3·82 days	
Po^{218}	3·05 min	
Pb^{214}	26·8 min	0·35 , 0·29 0·24 , 0·05
At^{218}	≙ 1·5 s	
Bi^{214}	19·7 min	2·43, 2·20, 2·12 1·85 , 1·76, 1·73 1·51 , 1·42 , 1·38 1·28 , 1·24, 1·16 1·12 , 0·94, 0·81 0·77 , 0·61
Rn^{218}	0·02 s	
Tl^{210}	1·32 min	
Po^{214}	1×10^{-4} s	
Pb^{210}	19·4 yr	0·05
Bi^{210}	5 days	
Po^{210}	138·3 days	
Tl^{206}	4·23 min	
Pb^{206}	Stable end product	

Fig. 20. Uranium-238 decay series.



NUCLIDE	1/2 LIFE	γ ENERGIES MeV
Th^{232}	1.41×10^{10} yr	0.06
Ra^{228}	6.7 yr	
Ac^{228}	6.13 h	1.64, 1.59, 1.10 1.04, 0.97, 0.91 0.46, 0.41, 0.34 0.23, 0.18, etc
Th^{228}	1.9 yr	0.08
Ra^{224}	3.64 days	0.24
Rn^{220}	54.5 s	
Po^{216}	0.16 s	
Pb^{212}	10.6 h	0.30, 0.24 0.18, 0.12
At^{216}	$\simeq 3 \times 10^{-4}$ s	
Bi^{212}	1.01 h	1.81, 1.61 1.34, 1.04 0.83, 0.73
Po^{212}	3×10^{-7} s	
Tl^{208}	3.1 min	2.62, 0.86 0.76, 0.58 0.51, 0.28 0.25
Pb^{208}	Stable end product	

Fig. 21. Thorium-232 decay series.

APPENDIX 4

CALIBRATION OF SPECTROMETERS IN ABSOLUTE UNITS, USING RADIUM-226

The sensitivity of total-count channels of spectrometers can be measured by using a small radium-226 source. This is done by positioning the source at different distances from the detector and measuring the count rate at each distance. The dose rate D at any source-to-detector distance d is given by the equation:

$$D = \frac{KC \times 10^{-1}}{d^2}$$

where D is dose rate in microroentgen per hour; K is the K factor for the source used; C is the source strength in microcuries; d is source-to-detector distance in metres.

Count rate R is related to dose rate by:

$$R = BD + bg$$

where B = sensitivity figure; bg = background count rate.

Hence a plot of count rates against $1/d^2$ has a gradient of $BKC \times 10^{-1}$. For radium-226, K = 8.25. A typical source strength to be used is 25 microcuries. From the gradient measurement with K and C known, a value for B is determined. The units of B are counts per second per microroentgen per hour. A typical value for a 7.6 x 7.6 cm detector is 12 counts per second per microroentgen per hour. Values obtained from two 15 x 10 cm detectors are shown in Figure 4 (section 2.2) of this report.

APPENDIX 5

THE DELAYED NEUTRON METHOD OF DETERMINING URANIUM CONTENT IN ROCK SAMPLES

Uranium-235 is the only commonly occurring nuclide which undergoes fission with thermal neutrons. Some of the fission products decay to other nuclides, which themselves may decay by further neutron emission. These delayed neutrons have half-lives of up to 55 seconds, and their detection provides a highly specific analysis for uranium without the complication of disequilibrium problems. Samples are submitted, either finely crushed, or as liquid, in 10 cm^3 plastic containers. A typical sequence is:

1. Irradiation in a reactor for 60 seconds.

2. Immediate transfer to a counter chamber, which contains five boron trifluoride neutron detectors; counting continues for 40 seconds.

Uranium determinations are made by comparison with standard sources. This service is offered in Australia on a commercial basis by the Australian Atomic Energy Commission using their MOATA reactor at Lucas Heights, NSW.

Full details of this method have been given by Green & others (1974).

APPENDIX 6

RESULTS OF EXPERIMENTAL AIRBORNE INVESTIGATIONS MADE DURING 1975, USING THE VH-BMG SYSTEM WITH TWO 15 x 10 cm DETECTORS

1. Background measurements at different altitudes

Airborne tests to investigate the variation of background gamma radiation as a function of altitude were made on two days during the 1975 Darwin-Katherine survey, using Twin-Otter VH-BMG. The information from these tests was used to estimate the most suitable height for flying background runs during routine surveys, and to determine the correspondence between these high-level measurements and background measurements made at survey altitudes over lakes.

(a) On 24/9/75 measurements were made during a transit flight from Katherine to Darwin. At intervals during the flight, data were printed out on the NCR thermal printer and altitudes read from the pilot's barometric altimeter. Figure 22 is a plot of the total-count variation. This is very similar to Figure 3 of section 2.1 of this report and shows a minimum at about 1100 m (3500 ft) above sea level. It seems probable that the background component steadily decreases with decreasing altitude and that the background at the survey altitude could be deduced by extrapolation of the curve CD. Radiation recorded from the ground is evident over the section AB. This suggests that a height of 2000 ft (above ground) is probably too low for making background measurements. The ground elevations along the flight path were in the range 200-600 ft above sea level so that the minimum in the curve corresponds to a ground clearance of approximately 3000 ft. Thin cloud was present at about 7500 ft for most of this flight.

(b) On 16/10/75 more detailed tests were performed over Darwin River Dam, south of Darwin. In these tests, repeated runs were made over the water and over a strip of adjoining land. Each run comprised about 2 miles over water and two miles over land. Runs were made at 100 ft intervals from 200 to 700 ft and 500 ft intervals from 1000 to 5000 ft. Cloudbase was at about 4500 ft. All these elevations and those which follow are relative to ground level. Table 11 summarizes the data obtained. These were used to compare background measurements at different heights over the land and water, and also to determine attenuation coefficients from the low-level runs over

the land section. These latter results are described in chapter 2 of this appendix. From Table 11 it can be seen that radiation from the ground is detected up to at least 2000 ft. Background levels over the water increase with increasing height. Minimum figures from the runs over the land occur at 3000 ft (using total-count and potassium channel data) which would appear to indicate optimum ground clearance for routine background measurements. However, total-count and potassium channels measurements at this height are still approximately 10 percent higher than measurements over the water at 500 ft. The backgrounds at 2000 ft were approximately 25 percent too high. The percentage differences for the uranium and thorium channels are higher but the count rates are very low and the differences are of the order of one count per second.

From the results of sections (a) and (b) it appears that 2000 ft is definitely too low for routine background measurements and that 3000 ft would be more suitable. Backgrounds measured at the latter height would be about 10 percent higher than low level measurements made over water. Further detailed tests are recommended to investigate measurements from the altitude range 2500-3500 ft to determine the optimum ground clearance.

2. Measurements of height attenuation coefficients

(a) The low-level runs over land at Darwin River Dam were used to determine attenuation coefficients. Figures 23 and 24 show log-linear plots of accumulated counts as a function of ground clearance. The accumulated counts plotted were the counts accumulated over 41 seconds minus 41 seconds of accumulated background from the measurements over water. The slopes of the lines indicate the values of the attenuation coefficients (μ) obtained, which were as follows:

total-count channel	$\mu = (5.4 \pm 0.2) \times 10^{-3}\ m^{-1}$
potassium channel	$\mu = (5.4 \pm 0.2) \times 10^{-3}\ m^{-1}$
uranium channel	$\mu = (5.2 \pm 0.3) \times 10^{-3}\ m^{-1}$
thorium channel	$\mu = (5.1 \pm 0.5) \times 10^{-3}\ m^{-1}$

the errors quoted are $\pm$ 1 standard deviation

TABLE 11. VARIATION OF MEAN COUNT RATES AS A FUNCTION OF GROUND/WATER CLEARANCE

Nominal Ground Clearance (feet)	Total-Count Channel		Potassium Channel		Uranium Channel		Thorium Channel	
	Over Land	Over Water	Over Land	Over Water	Over Land	Over Water	Over Land	Over Water
200	136.5 ± 2.3	34.0 ± 0.5	28.4 ± 0.8	7.2 ± 0.3	14.9 ± 0.4	3.6 ± 0.2	9.3 ± 0.4	1.4 ± 0.1
300	139.1 ± 3.0	35.8 ± 0.6	29.2 ± 0.9	6.7 ± 0.2	16.2 ± 0.4	3.9 ± 0.2	11.2 ± 0.5	1.6 ± 0.1
400	114.1 ± 1.6	35.6 ± 0.6	24.1 ± 0.5	7.4 ± 0.2	13.2 ± 0.5	4.0 ± 0.2	9.1 ± 0.3	1.6 ± 0.1
500	108.7 ± 1.4	37.3 ± 0.4	21.9 ± 0.5	7.9 ± 0.2	12.0 ± 0.3	4.0 ± 0.2	8.2 ± 0.1	1.6 ± 0.1
600	92.7 ± 1.3	38.3 ± 0.5	19.2 ± 0.4	7.7 ± 0.3	10.8 ± 0.3	4.4 ± 0.2	6.0 ± 0.3	1.6 ± 0.1
700	90.1 ± 1.1	37.0 ± 0.5	18.0 ± 0.5	7.4 ± 0.2	10.1 ± 0.3	4.3 ± 0.2	6.0 ± 0.3	1.4 ± 0.1
1000	66.2 ± 0.8	38.0 ± 0.6	13.8 ± 0.3	7.6 ± 0.3	7.7 ± 0.4	4.2 ± 0.2	4.2 ± 0.2	1.6 ± 0.1
1500	50.1 ± 0.8	40.2 ± 0.5	10.6 ± 0.4	8.9 ± 0.2	5.6 ± 0.2	5.0 ± 0.2	2.5 ± 0.2	1.8 ± 0.1
2000	46.1 ± 0.9	38.4 ± 0.6	10.6 ± 0.3	8.3 ± 0.2	5.3 ± 0.3	4.6 ± 0.2	2.3 ± 0.2	1.7 ± 0.1
2500	43.2 ± 0.9	40.5 ± 0.6	8.9 ± 0.3	8.4 ± 0.3	4.3 ± 0.3	5.0 ± 0.2	2.3 ± 0.2	1.8 ± 0.1
3000	41.0 ± 0.9	40.7 ± 0.6	8.6 ± 0.3	8.4 ± 0.3	4.9 ± 0.3	4.6 ± 0.2	2.2 ± 0.2	1.7 ± 0.1
3500	43.9 ± 0.9	42.0 ± 0.7	8.9 ± 0.5	9.1 ± 0.3	5.2 ± 0.3	5.2 ± 0.2	2.0 ± 0.2	1.8 ± 0.1
4000	42.0 ± 0.6	42.9 ± 0.7	9.1 ± 0.4	8.7 ± 0.3	5.3 ± 0.3	4.6 ± 0.2	1.8 ± 0.2	1.9 ± 0.1
4500	43.1 ± 0.6	41.5 ± 0.5	8.7 ± 0.4	9.0 ± 0.3	4.7 ± 0.3	4.4 ± 0.2	2.0 ± 0.2	1.9 ± 0.1
5000	43.3 ± 0.6	40.7 ± 0.5	9.2 ± 0.3	8.4 ± 0.3	5.1 ± 0.2	4.7 ± 0.2	2.2 ± 0.2	1.8 ± 0.1

N.B. - errors quoted are ± 1 standard deviation
all units are counts/sec.

tests made over Darwin River Dam, N.T. 16.10.75

(b) Similar measurements were made during the Beach Sands Survey, northern NSW, 1975, over a small dump of heavy minerals which represents a small-area source (less than 30 m x 30 m). Unfortunately only three runs were made so that the results deduced are only approximate. Figure 25 shows the results obtained which yield approximate figures for effective attenuation coefficients as follows:

total-count channel	$\mu = 11.3 \times 10^{-3}\ m^{-1}$
potassium channel	$\mu = 11.2 \times 10^{-3}\ m^{-1}$
uranium channel	$\mu = 8.2 \times 10^{-3}\ m^{-1}$
thorium channel	$\mu = 13.1 \times 10^{-3}\ m^{-1}$

Errors are probably of the order $\pm 2 \times 10^{-3}\ m^{-1}$. It is interesting to see that the attenuation coefficients are higher than those obtained for the broad-source measurements reported in (a) and that the potassium channel and uranium channel coefficients are significantly lower than that for thorium. This is to be expected since the predominant source of radioactivity in the dump is thorium. The high thorium content produces more scatter into the uranium and potassium channels so that the count-rate fall- with increasing altitude in those channels is less rapid; hence the lower coefficients.

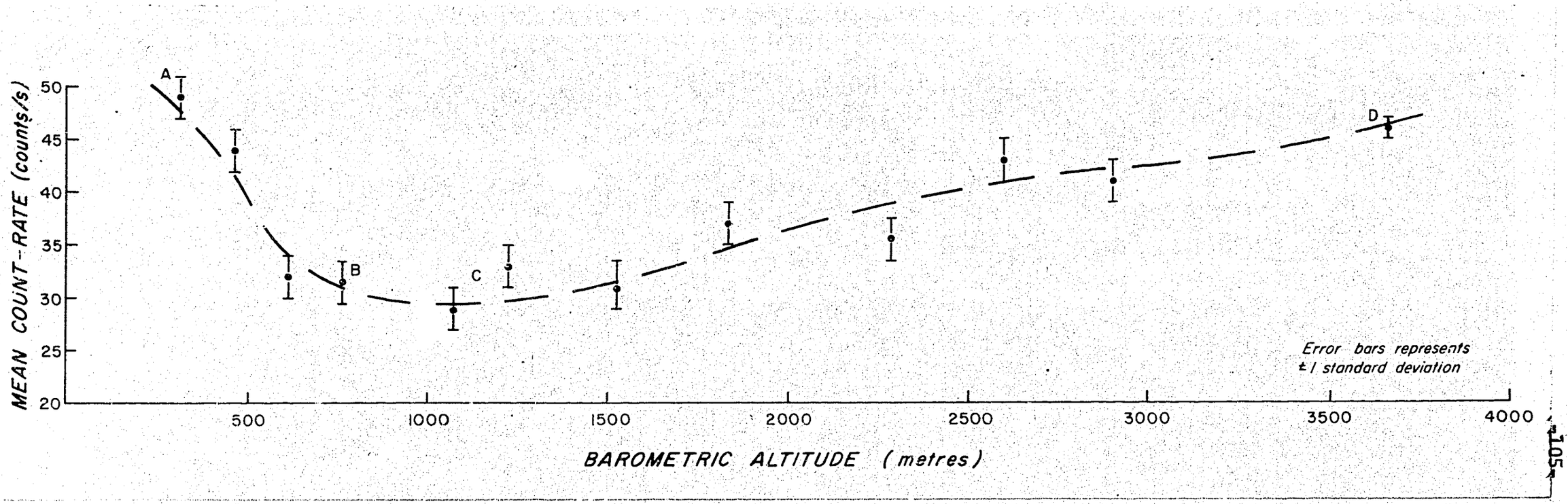
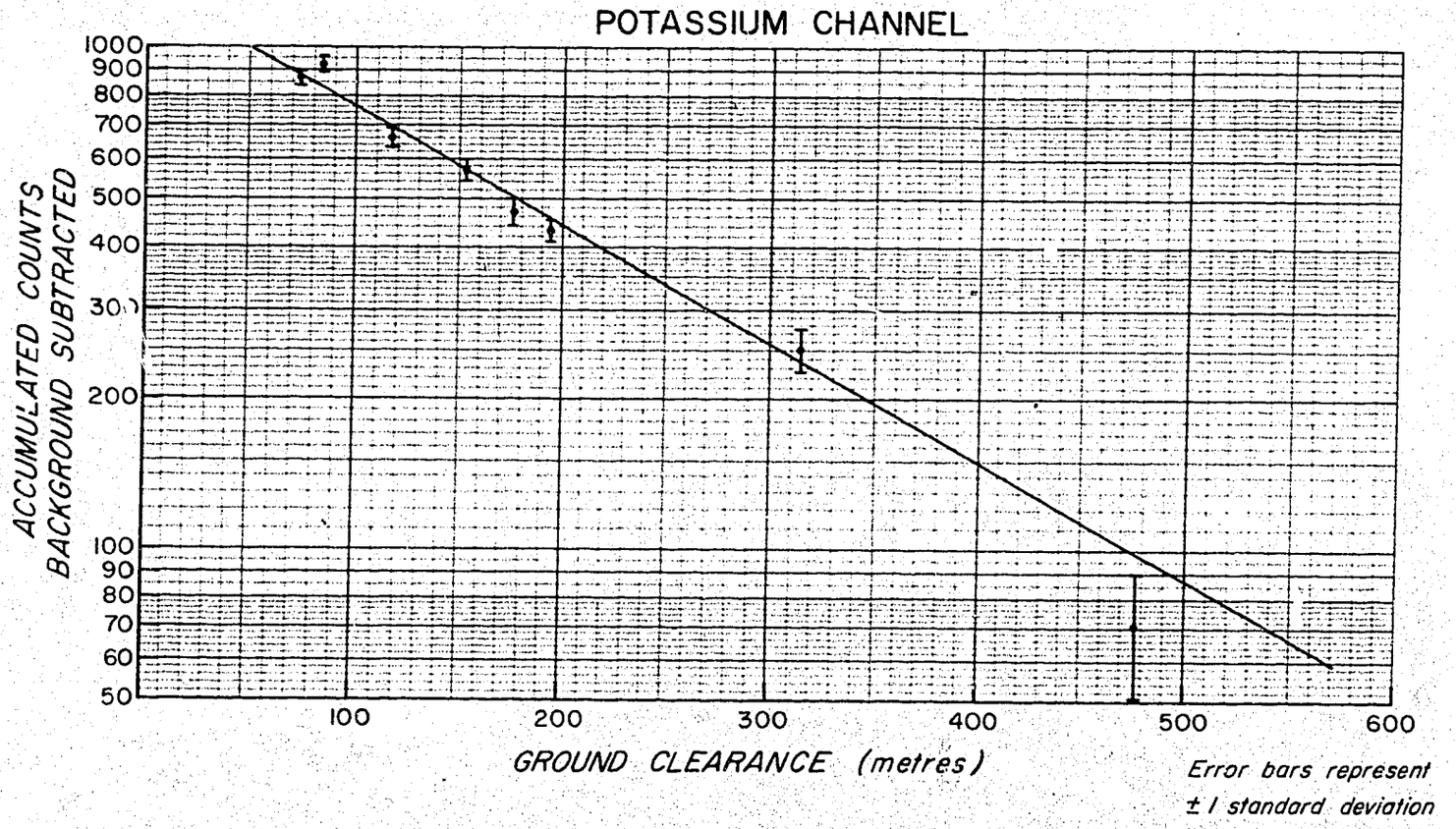


Fig. 22. Variation of total-count radioactivity as a function of barometric altitude (24.9.1975).



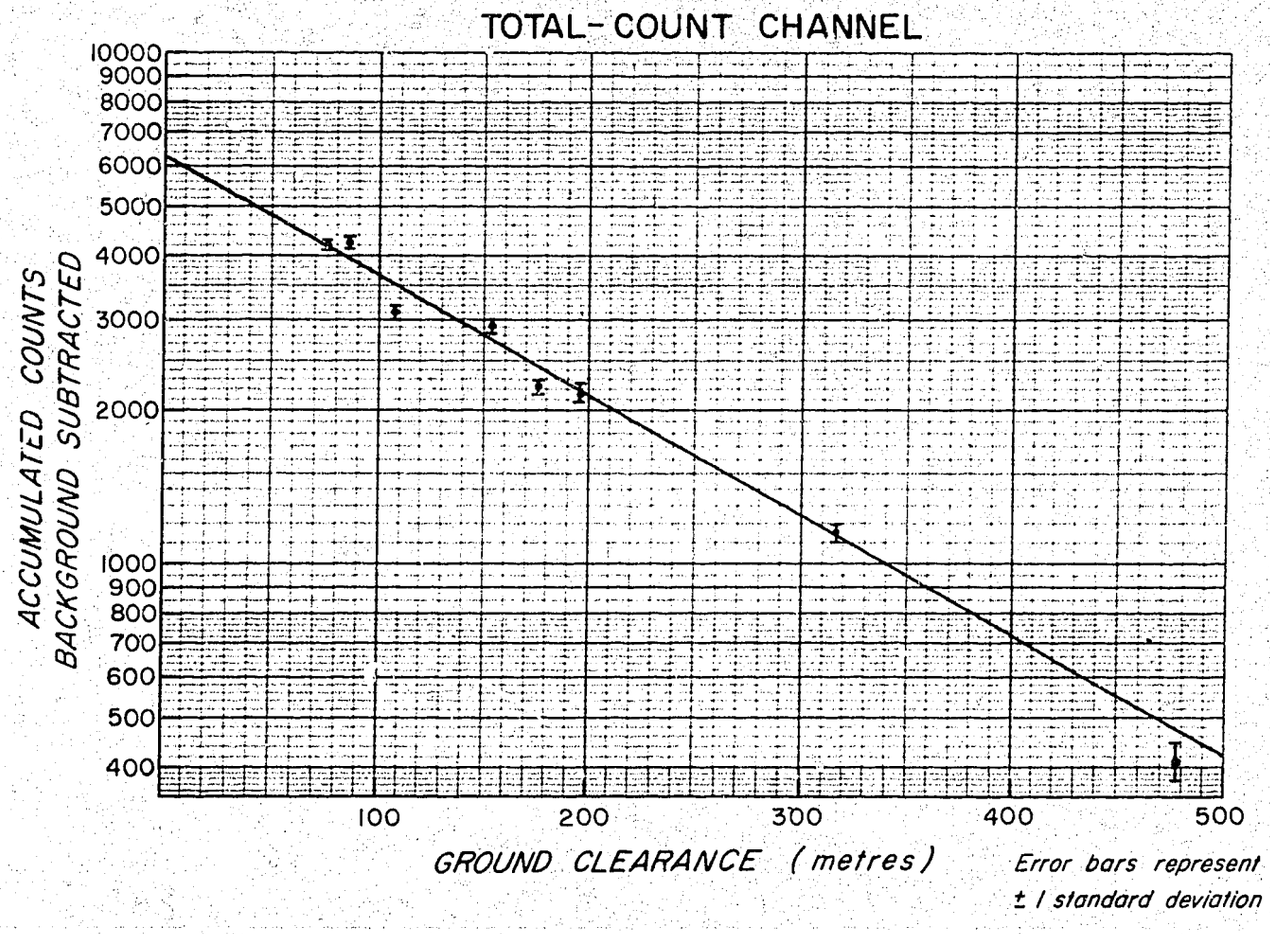


Fig. 23. Accumulated counts as a function of ground clearance - potassium and total count.

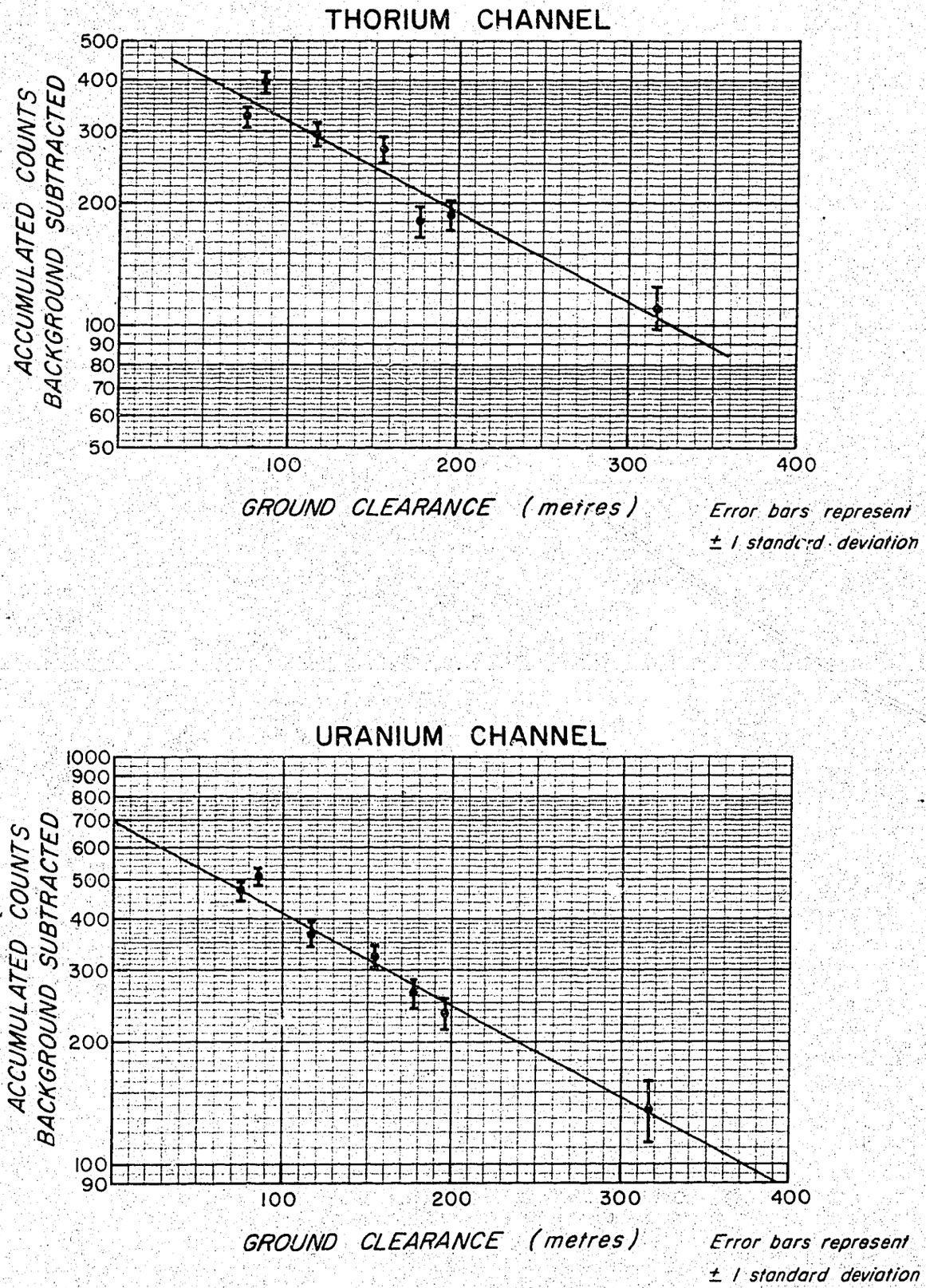


Fig. 24. Accumulated counts as a function of ground clearance - thorium and uranium.

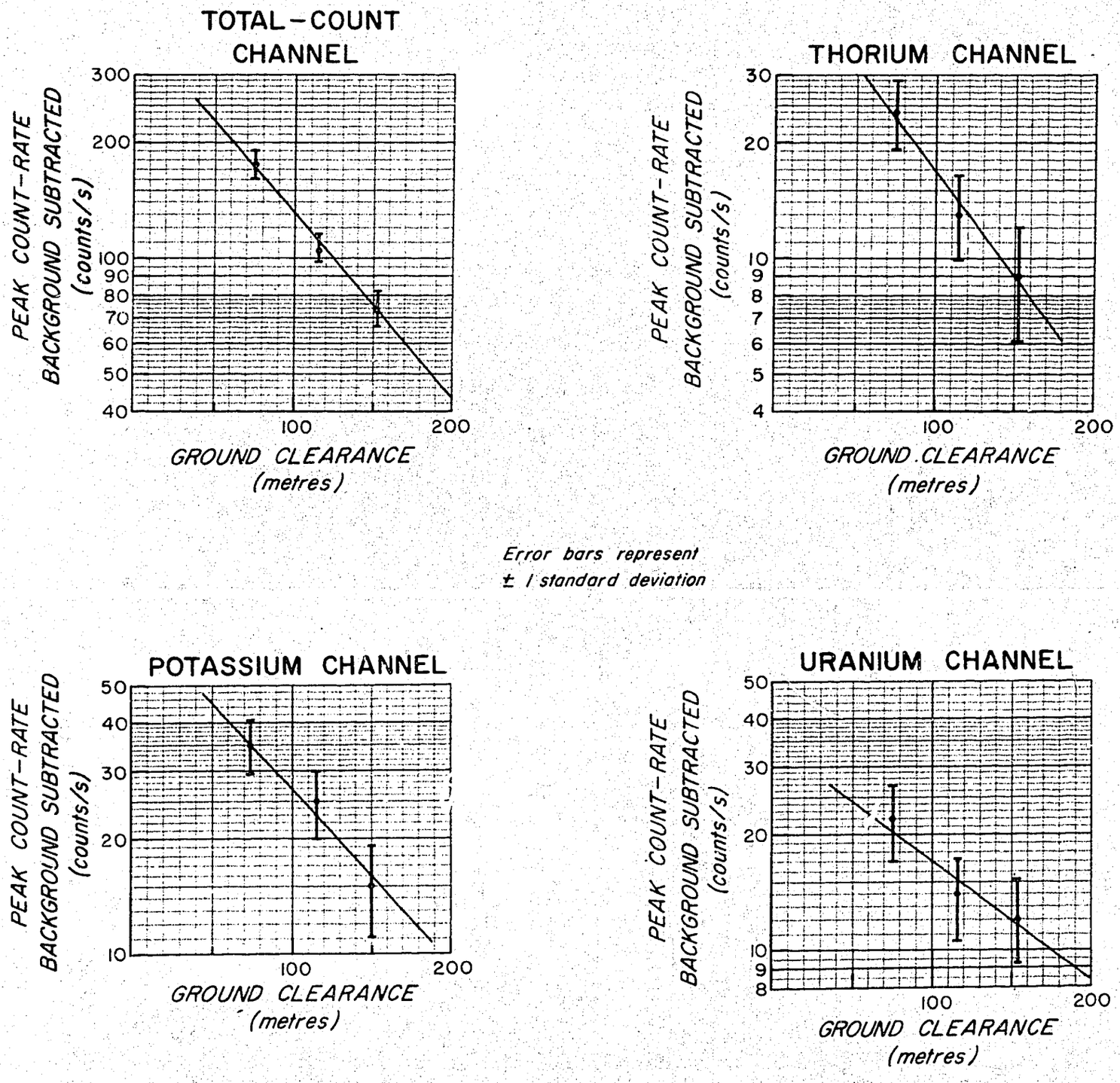


Fig. 25. Count rates as a function of ground clearance for 'point source'.

APPENDIX 7

PROGRAM GSPEC FOR PROCESSING GROUND SPECTROMETRY DATA

Program GSPEC

This program was written in 1975 by P.G. Wilkes, to process ground spectrometry data using CSIRO's C.D.C. 7600 computer in Canberra. The program performs the following:

1. Conversion of total-count data to the absolute units of dose-rate, microroentgens per hour (μR/hr). No background is subtracted for total-count data; hence the dose-rate figures include a non-geological component which is usually in the range 2-5 μR/hr.

2. Background subtraction for channels 2, 3, and 4.

3. Spectral interaction corrections.

4. Conversion of corrected data to equivalent concentrations of potassium (in percent), uranium (in ppm), and thorium (in ppm).

5. Radioelement ratio calculations; U/Th, U/K, and Th/K.

   N.B. The ratios involving potassium have been multiplied by 10^4 and this should be remembered when using the output of this program.

6. Statistical calculations on corrected data, dose-rate, and ratios.

This appendix provides input requirements, program listing, and sample output.

Input requirements

A. Job control language (J.C.L.) cards.
B. Program cards as in the program listing.
C. Data cards.

The structure of the data cards is as follows:

Card 1 : Background counts in counts per minute for channels 2, 3, and 4. These are BGDK, BGDU, and BGTH. (Format is 3F10.1).

Card 2 : Total-count conversion figure TOTCON. For BMR's Exploranium spectrometer (DISA-400A) this figure is 660 counts per minute per microroentgen per hour. (Format is F10.1).

Card 3 : Stripping ratios STRIPA (alpha), STRIPB (beta), STRIPG (gamma). (Format is 3F10.2).

Card 4 : Sensitivity constants (SENSK, SENSU, SENSTH) to convert corrected count rates to element abundances. (Format is 3F10.2).

Card 5 : Identifier card. IDENT = 1 for individual station data.
IDENT = 3 for traverse data.
IDENT = 2 for no more data.

The identifier card controls part of the printout heading; the number or name of the traverse is printed out if traverse data are being processed. (Format is I1).

Card 6 : Traverse number or name NTRAV (Format is 1X, 8HTRAVERSE, 2X, A5). This card is not used if IDENT $\neq$ 3.

Card 7 : Number of stations, or number of stations per traverse, NSTAT. (Format is I5).

Card 8 to NSTAT + 7 inc. These cards contain the radiometric data for each station. One card per station is used and contains STAT (station number or name), NRAWTOT, NRAWK, NRAWU, NRAWTH (accumulated counts in channels 1, 2, 3 and 4 respectively) and TIME (accumulation time in minutes). (Format is A10, 4I10, F10.2).

Card NSTAT + 8 : Identifer card. IDENT = 1 if more station data follow.
IDENT = 3 if more traverse data follow.
IDENT = 2 if no more data follow.

Additional radiometric data cards if required.

Additional notes

1. In the printout "SD" represents one standard deviation.

2. If the processing produces any negative values for corrected data these are shown in the printout of corrected data/min, but are set to zero in subsequent calculations of corrected data, abundances and ratios. If the denominator in the ratio calculations is zero, the printout shows -1.00 for that ratio and its standard deviation (SD).

```
      PROGRAM   GSPEC(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      LIN=5
      LOT=6
    1 FORMAT(1H1,30X,38HGROUND SPECTROMETER DISA 400A ANALYSIS////)
    2 FORMAT(3F10.1)
    3 FORMAT(F10.1)
    4 FORMAT(3F10.2)
    5 FORMAT(3F10.2)
    6 FORMAT(I1)
    7 FORMAT(A5)
    8 FORMAT(1X,8HTRAVERSE,2X,A5,/)
    9 FORMAT(I5)
   10 FORMAT(1X,*   STATION  TIME UNCORRECTED DATA /MIN     DOSE   SD
     1   CORRECTED DATA /MIN       ABUNDANCES                    RATIOS*)
  101 FORMAT(1X,*              MINS                              RATE
     1K    SD     U  SD    TH  SD     K      U      TH    U/TH     SD     U/K   S
     1D     TH/K    SD*/)
   11 FORMAT(A10,4I10,F10.2)
   12 FORMAT(1X, A10,F6.2,I7,3I5,3X,2F5.2,I6,I4,I5,I4,I5,I4,F6.2,2F6.1,1X
     1,2F6.3,F7.2,F5.2,F8.2,F5.2/)
   13 FORMAT(1H1)
   14 FORMAT(11X,*CONSTANTS USED*/)
   15 FORMAT(11X,*BGDK*,F8.1,8X,*BGDU*,F7.1,9X,*BGDTH*,F6.1,/)
   16 FORMAT(11X,*ALPHA*,F8.2,7X*,BETA*,F8.2,8X,*GAMMA*,F7.2,/)
   17 FORMAT(11X,*SENSK*,F8.2,7X,*SENSU*,F7.2,8X,*SENSTH*,F6.2,//)
      WRITE (LOT,1)
      READ (LIN,2) BGDK,BGDU,BGDTH
      READ (LIN,3) TOTCON
      READ (LIN,4) STRIPA,STRIPB,STRIPG
      READ (LIN,5) SENSK,SENSU,SENSTH
      WRITE(LOT,14)
      WRITE(LOT,15) BGDK,BGDU,BGDTH
      WRITE(LOT,16) STRIPA,STRIPB,STRIPG
      WRITE(LOT,17) SENSK,SENSU,SENSTH
  100 READ (LIN,6) IDENT
      IF(IDENT.EQ.1)GO TO 110
      IF(IDENT.EQ.2)GO TO 140
      READ (LIN,7) NTRAV
      WRITE (LOT,8) NTRAV
  110 READ(LIN,9)NSTAT
  120 WRITE (LOT,10)
```

```
      WRITE(LOT,101)
      DO 130  I=1,NSTAT
      READ (LIN,11) STAT,NRAWTOT,NRAWK,NRAWU,NRAWTH,TIME
      RAWTOT=FLOAT(NRAWTOT)
      RAWK=FLOAT(NRAWK)
      RAWU=FLOAT(NRAWU)
      RAWTH=FLOAT(NRAWTH)
C     CONVERT TO COUNTS PER MIN AND SUBTRACT BACKGROUNDS
      A=RAWK/TIME
      B=RAWU/TIME
      C=RAWTH/TIME
      E=A-BGDK
      F=B-BGDU
      G=C-BGDTH
C     CALCULATE DOSE RATE
      D=RAWTOT/TIME
      DOS=D/TOTCON
C     PERFORM ENERGY STRIPPING
      THCOR=G
      NTHCOR=THCOR +0.5
      IF(THCOR.LT.0.0)THCOR=0.0
      UCOR=F-THCOR*STRIPA
      NUCOR=UCOR +0.5
      IF(UCOR.LT.0.0)UCOR=0.0
      POTCOR=E-UCOR*STRIPG-THCOR*STRIPB
      NPOTCOR=POTCOR +0.5
      IF(POTCOR.LT.0.0)POTCOR=0.0
C     STATISTICS OF  CORRECTED  DATA
      SDOS=(SQRT(RAWTOT))/(TIME*TOTCON)
      STHCOR=(SQRT(RAWTH))/TIME
      NSTHCOR=STHCOR +0.5
      SUCOR=SQRT(RAWU/TIME**2 +(STRIPA**2)*(STHCOR**2))
      NSUCOR=SUCOR  +0.5
      SKCOR=SQRT(RAWK/TIME**2 +(STRIPB**2)*(STHCOR**2)+(STRIPG**2)*(SUCO
     1R**2))
      NSKCOR=SKCOR +0.5
C     CONVERSION TO ELEMENTAL ABUNDANCES
      PCENTK=POTCOR/SENSK
      PPMK=10000.0*PCENTK
      PPMU=UCOR/SENSU
      PPMTH=THCOR/SENSTH
```

```
C       CALCULATION OF RATIOS AND THEIR STATISTICS
        IF(PPMU.EQ.0.0.AND.PPMTH.EQ.0.0)GO TO 300
        IF(PPMTH.EQ.0.0)GO TO 300
        UTHRAT=PPMU/PPMTH
        SUTH=(SQRT((SUCOR/SENSU)**2 +((PPMU*STHCOR)/(PPMTH*SENSTH))**2))/P
       1PMTH
        GO TO 301
  300 UTHRAT=-1.0
        SUTH=-1.0
  301 IF(PPMU.EQ.0.0.AND.PCENTK.EQ.0.0)GO TO 302
        IF(PCENTK.EQ.0.0)GO TO 302
        UKRAT=PPMU/PCENTK
        SUK=(SQRT((SUCOR/SENSU)**2 +((PPMU*SKCOR)/(PCENTK*SENSK))**2))/PCE
       1NTK
        GO TO 303
  302 UKRAT=-1.0
        SUK=-1.0
  303 IF(PPMTH.EQ.0.0.AND.PCENTK.EQ.0.0)GO TO 304
        IF(PCENTK.EQ.0.0)GO TO 304
        THKRAT=PPMTH/PCENTK
        STHK=(SQRT((STHCOR/SENSTH)**2 +((PPMTH*SKCOR)/(PCENTK*SENSK))**2))
       1/PCENTK
        GO TO 305
  304 THKRAT=-1.0
        STHK=-1.0
  305 CONTINUE
C       ROUND UNCORRECTED DATA TO NEAREST INTEGER
        NA=A +0.5
        NB=B +0.5
        NC=C +0.5
        ND=D +0.5
        WRITE (LOT,12) STAT,TIME,ND,NA,NB,NC,DOS,SDOS,NPOTCOR,NSKCOR,NUCOR
       1,NSUCOR,NTHCOR,NSTHCOR,PCENTK,PPMU,PPMTH,UTHRAT,SUTH,UKRAT,SUK,THK
       1RAT,STHK
  130 CONTINUE
        WRITE(LOT,13)
        GO TO 100
  140 STOP
        END
```

GROUND SPECTROMETER DISA 400A ANALYSIS

CONSTANTS USED

BGDK	75.0	BGDU	18.0	BGDTH	13.0
ALPHA	.65	BETA	.70	GAMMA	1.10
SENSK	222.77	SENSU	18.62	SENSTH	8.20

STATION	TIME MINS	UNCORRECTED DATA/MIN				DOSE RATE	SD	CORRECTED DATA/MIN					
								K	SD	U	SD	TH	SD
560780A	10.00	18305	1373	405	325	27.74	.06	878	15	184	7	312	6
560790A	10.00	14283	1182	273	250	21.64	.06	831	13	100	6	237	5
560800A	10.00	10256	788	203	162	15.54	.05	512	11	88	5	149	4
560820A	10.00	8276	442	176	114	12.54	.04	196	9	92	5	101	3
570760A	10.00	11384	906	242	216	17.25	.05	588	12	92	6	203	5
570780A	10.00	16814	1295	311	353	25.48	.06	903	14	72	7	340	6
570790A	10.00	13629	1104	292	235	20.65	.06	731	13	130	6	222	5
570800A	10.00	13867	1126	274	288	21.01	.06	774	13	77	6	275	5
570810A	10.00	10603	982	168	156	16.07	.05	745	12	57	5	143	4
577807A	10.00	14623	1083	280	314	22.16	.06	725	13	66	6	301	6
578811A	10.00	14207	1024	283	280	21.53	.06	662	13	91	6	267	5
579820A	10.00	10955	959	198	170	16.60	.05	688	12	78	5	157	4
580780A	10.00	15661	1346	274	358	23.73	.06	995	14	32	7	345	6
580790A	10.00	12364	906	268	238	18.73	.05	559	12	104	6	225	5
580800A	10.00	13365	970	287	260	20.25	.06	602	13	109	6	247	5
580830A	10.00	13683	843	253	314	20.73	.06	514	12	39	6	301	6
587818A	10.00	11471	821	227	253	17.38	.05	520	12	53	6	240	5
590790A	10.00	19715	1385	435	525	29.87	.07	859	16	84	8	512	7
590800A	10.00	10053	833	187	205	15.24	.05	574	11	45	5	192	5
590820B	2.00	13127	1206	248	225	19.89	.12	881	29	92	13	212	11
590830A	6.00	10664	772	255	196	16.16	.06	439	15	118	8	183	6
591809A	10.00	11769	814	251	256	17.83	.05	486	12	75	6	243	5
600780A	10.00	9733	810	175	181	14.75	.05	565	11	48	5	168	4

ABUNDANCES			RATIOS						STATION
K	U	TH	U/TH	SD	U/K	SD	TH/K	SD	
3.94	9.9	38.0	.260	.011	2.51	.11	9.65	.24	560780A
3.73	5.4	28.9	.186	.012	1.45	.09	7.75	.21	560790A
2.30	4.7	18.2	.260	.017	2.06	.13	7.93	.27	560800A
.88	4.9	12.3	.400	.025	5.61	.38	14.04	.78	560820A
2.64	5.0	24.7	.201	.013	1.88	.12	9.37	.29	570760A
4.05	3.9	41.4	.094	.009	.96	.09	10.22	.24	570780A
3.28	7.0	27.1	.258	.014	2.13	.11	8.25	.23	570790A
3.47	4.1	33.6	.123	.010	1.19	.10	9.66	.25	570800A
3.34	3.1	17.4	.176	.016	.92	.08	5.21	.17	570810A
3.25	3.5	36.8	.096	.010	1.09	.11	11.30	.29	577807A
2.97	4.9	32.5	.151	.011	1.65	.12	10.93	.30	578811A
3.09	4.2	19.1	.219	.016	1.36	.09	6.19	.19	579820A
4.46	1.7	42.0	.041	.008	.38	.08	9.41	.21	580780A
2.51	5.6	27.4	.204	.013	2.23	.14	10.91	.33	580790A
2.70	5.8	30.1	.194	.012	2.16	.13	11.14	.33	580800A
2.31	2.1	36.7	.058	.009	.91	.15	15.89	.48	580830A
2.33	2.8	29.2	.097	.011	1.21	.14	12.52	.38	587818A
3.86	4.5	62.4	.072	.007	1.17	.11	16.19	.37	590790A
2.58	2.4	23.4	.103	.012	.93	.11	9.08	.28	590800A
3.96	4.9	25.8	.192	.029	1.25	.18	6.52	.39	590820B
1.97	6.4	22.3	.285	.020	3.23	.23	11.34	.52	590830A
2.18	4.0	29.7	.136	.011	1.85	.15	13.60	13	591809A
2.53	2.6	20.5	.126	.014	1.02	.11	8.09	.26	600780A