GEOLOGICAL SURVEY OF CANADA
COMMISSION GÉOLOGIQUE DU CANADA

PAPER 77-32

GEOLOGICAL INTERPRETATION OF AN AIRBORNE GAMMA-RAY SPECTROMETER SURVEY OF THE HEARNE LAKE AREA, NORTHWEST TERRITORIES

A.R. NEWTON
V.R. SLANEY

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

1978

GEOLOGICAL SURVEY
PAPER 77-32

GEOLOGICAL INTERPRETATION OF AN AIRBORNE GAMMA-RAY SPECTROMETER SURVEY OF THE HEARNE LAKE AREA, NORTHWEST TERRITORIES

A.R. NEWTON
V.R. SLANEY

1978

available by mail from

Printing and Publishing
Supply and Services Canada,
Hull, Québec, Canada K1A 0S9,

and

The Geological Survey of Canada
601 Booth St., Ottawa, K1A 0E8

or

Through your bookseller.

Catalogue No. M44-77/32
ISBN - 0-660-01530-7

Price: Canada: $3.50
Other Countries: $4.20

Price subject to change without notice

CONTENTS

Tables

Illustrations

Critical readers

R.L. Grasty
K.A. Richardson
J. Henderson

Authors' addresses

A.R. Newton
Geology Department
University of Capetown
Rondebosch, C.P.
South Africa 7700

V.R. Slaney
Geological Survey of Canada
Ottawa, Ontario

Original manuscript submitted: 1977 - 6 - 2
Approved for publication: 1977 - 6 - 24

GEOLOGICAL INTERPRETATION OF AN AIRBORNE GAMMA-RAY SPECTROMETER SURVEY OF THE HEARNE LAKE AREA, N.W.T.

Abstract

Airborne gamma radiation surveys are not easily correlated with published geological maps particularly in the swampy, lake-ridden, glaciated terrain of the western Canadian Shield. This study shows how large volumes of airborne data can be displayed in a simple format which provides both mapping and exploration geologists with information not easily obtained from the original data. Eleven lines or part-lines from a gamma-ray survey of the Hearne Lake area were chosen as test lines, and airphotos were used to identify outcrops of each rock type and the distribution of overburden, swamp and water along each line. Geological maps were used to locate the test lines and to provide a listing of the rock types in the area. With this information, it was possible to calculate the average radioelement characteristics of each rock type and to group the rock signatures into a number of rock classes. Nine rock classes plus water could be identified, although one of the nine also represents areas of swamp, and glacial overburden. A simple algorithm was developed by which each airborne survey data point was identified with whichever rock signature it most closely resembled. Use of this algorithm on the eight test lines resulted in a correct classification of two out of every three (63.3%) data points. When the classification process was extended to the whole survey area, many lithological units were shown to have rather variable radiation patterns. In a few cases, lithologically similar rocks from different parts of the survey area were shown to have different gamma-ray patterns. In other cases, spatially separated outcrops of the same rock unit are shown to have similar radiation characteristics. Zones of anomalously high radioactivity often cross lithological boundaries and may be considered useful indicators for uranium exploration. The techniques described are most usefully applied to those areas where the outcrop is extensive, where some form of geological map already exists, where there are airphotos at scales of 1:30 000 or larger, and where the gamma-ray survey lines are less than 2.5 km apart.

Résumé

Il est difficile d'établir une corrélation entre les levés aéroportés par spectrométrie gamma et les cartes géologiques publiées, en particulier dans le cas des terrains glaciaires marécageux et parsemés de lacs de l'ouest du Bouclier canadien. Dans la présente étude, on montre de quelle manière une grande quantité de résultats de levés aéroportés peuvent être présentés dans un format simple, et ainsi offrir aux géologues chargés de la cartographie et de l'exploration une information qu'ils n'auraient pu facilement tirer des données originales. On a choisi onze lignes ou segments d'un relevé gamma de la région de Hearne Lake comme lignes de référence, et utilisé des photographies aériennes pour identifier tous les types d'affleurements, et étudier la disposition de l'eau, des marécages et des terrains de couverture le long de chaque ligne. On a utilisé les cartes géologiques pour situer les lignes de référence et faire le bilan des types de roches de la région. A l'aide de cette information, on a pu évaluer les caractéristiques moyennes de radioactivité de chaque type de roche, et par groupement de leurs caractères distinctifs à répartir ces roches en certain nombre de classes. On a ainsi pu déterminer neuf classes de roches, l'eau mise à part; de plus, l'une d'entre elles décrit des zones occupées par des marécages et des terrains de couverture d'origine glaciaire. On a déterminé un algorithme simple, permettant d'établir une relation entre chaque point ayant fait l'objet d'un levé, et la désignation dont il se rapproche le plus. En employant cet algorithme sur les huit lignes de référence, on est parvenu à classer correctement deux points de données sur trois (63.3%). Lorsqu'on a étendu ce mode de classification à toute la région explorée, on a constaté que de nombreuses unités lithologiques manifestaient des caractères de radioactivité très variables. Dans certains cas, des roches de caractère lithologique semblable provenant de diverses parties de la région explorée présentaient une radioactivité gamma différente. Dans d'autres cas, des affleurements dispersés de la même unité rocheuse présentaient les mêmes caractères de radioactivité. Des zones à anomalies radioactives prononcées traversent souvent les frontières lithologiques, et pourraient probablement constituer d'excellents "indicateurs" pour la prospection de minéraux uranifères. Les techniques décrites conviennent surtout aux régions où les affleurements sont étendus, où des cartes géologiques ont déjà été établies, où l'on dispose de photographies aériennes à une échelle d'au moins 1/30 000, et où les lignes de relevés gamma ne s'écartent pas de plus de 1.5 km l'une de l'autre.

INTRODUCTION

The gamma-ray spectrometric method of aerial survey has undergone extensive development and testing in Canada over the past 9 years (Darnley and Fleet, 1968; Darnley, 1970(a), 1975). Between 1970 and 1976, airborne spectrometer surveys organized by the Geological Survey have covered 18,000 km^2 at 1 km line spacing, 935 000 km^2 at 5 km line spacing and another 800 000 km^2 at 25 km line spacing (Richardson, 1976). The Hearne Lake area is the only area to be flown at a line spacing of 2.5 km. While the original data are stored on magnetic tape they are made more generally available to the public through Open Files and Geophysical Series maps. The survey results are published as flight line profiles and as individual contour maps showing the distribution of potassium, equivalent thorium, equivalent uranium and total (integral) count rates as well as three ratio maps, eU/eTh, eU/K and eTh/K.

The data to be contoured are first smoothed to reduce statistical noise and to allow the automatic contouring program to work more effectively (Cameron et al., 1976).

The contour maps present a somewhat generalized view of the radioelement distribution which, more often than not, fails to reflect the distribution of rock types in an area. This is due not only to the rather poor spatial resolution of the contour maps but also to an irregular distribution and thickness of soil and glacial overburden, to the amount of moisture present in the overburden and to the presence of lakes and streams.

It was decided, therefore, to investigate an area in more detail to see whether or not there is any correlation between rock type and radioelement distribution, that is, to determine to what extent rocks have distinctive radiation signatures, and to find out whether any use could be made of such information for geological mapping or for uranium exploration.

Most airborne gamma radiation surveys are flown in order to outline areas of anomalously high radioactivity. Anomalous areas are easily recognized when radiation levels are appreciably higher than the values which characterize the rock types in the survey area. When the increase in radioactivity is more subtle, its significance may only be appreciated by comparing the increased radiation levels with the average radiation levels which characterize the host rock. The study of 'average' radiation levels and their variation from rock unit to rock unit and within each rock unit itself is seen to be at least as important to the exploration geologist as it might be to the mapping geologist.

Previously published studies have concentrated mainly on areas where there is a good correlation between spectrometric results and the known geology: Flanigan (1972), in Saudi Arabia, was able to separate basic rocks and marbles, intermediate rocks, alluvials, granodiorites and granitoids on the basis of both individual channels and total count Demnati and Naudy (1975), in Morocco, found that granite, rhyolites and phonolites, and an unconformity showed up well on total count, thorium and potassium. In both of these studies, aeromagnetic maps were also used, and provided useful supplementary and confirmatory evidence.

Richardson and Carson (1976) have correlated the regional distribution of eU with structural domains in the Canadian Shield of northern Saskatchewan. In the Elliot Lake

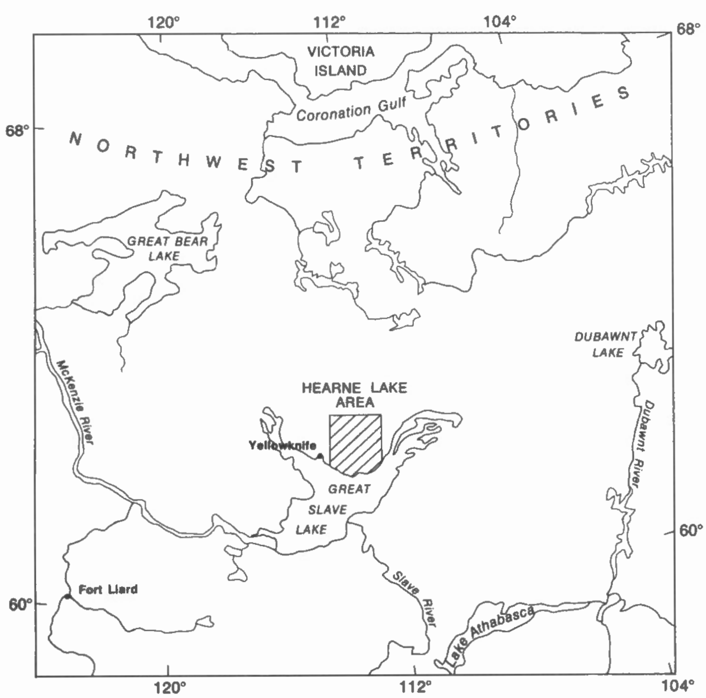

Figure 1. Location of Hearne Lake area

district of Ontario, Charbonneau et al. (1973) were able to distinguish Archean rocks and three formations of sedimentary rocks by their radioelement content.

Schwarzer and Adams (1973), in a low-altitude, high resolution helicopter survey in Oklahoma, found that by using cluster analysis techniques they could distinguish major soil types and that these were closely related to bedrock. This followed an earlier study (Schwarzer et al., 1972) in Puerto Rico, where differences in rock signatures were found, but were not tested by cluster analysis.

These studies suggested that it might be possible to establish radiometric signatures for different rock types within test areas, and to use these to identify the same rock types outside the test areas. Further, if a norm could be established for a particular rock type, it would be easy to define and delimit areas anomalous to that norm. This norm or signature was clearly something which had to be established with care, and preferably over exposed bedrock or where overburden was thin, since residual soils are rare over the greater part of Canada. To identify suitable segments of the spectrometer traverse lines, it would be necessary to use aerial photography. This was to be the main difference from previous studies, all of which included outcrop and overburden in defining rock signatures.

The area around Hearne Lake, some 45 km east of Yellowknife in the Northwest Territories (Fig. 1) was chosen as a test area for the following reasons:

1. It lies within the Canadian Shield, the environment most favoured for uranium exploration in Canada. Airborne gamma spectrometer profiles of the western half of the Shield showed the highest concentrations of radioelements between Yellowknife and Lake Athabasca (Darnley et al., 1970b).

2. A gamma-ray spectrometer survey with 2.5 km line spacing was completed in 1971 (Grasty and Richardson, 1972).

3. Colour airphotos flown by the Geological Survey (Slaney, 1971) are available at 1:15 000 scale as well as black and white photography at 1:20 000.

4. Topographic maps at 1:50 000 scale cover most of the area.

5. Rocks are exposed over 60-65 per cent of the region. A further 15-20 per cent consists of water and the remainder is overburden of glacial origin.

6. The area was originally mapped in 1937 and 1938 at 1:250 000 and was remapped between 1970 and 1973, to produce a draft map of the area (Henderson, 1976) which was made available at 1:125 000 scale.

The geology of the area will be described in detail in a forthcoming report by Henderson, but may be briefly summarized as follows (see Fig. 2). The stratigraphic sequence consists of Archean rocks of the Yellowknife Supergroup, comprising a thick unit composed of greywackes and mudstone, and a volcanic sequence which includes both acid and basic lavas and tuffs. The volcanics have a local distribution, being well exposed in the northeastern part of the study area where they occur near the base of the greywacke sequence.

A basal conglomerate is present in places, suggesting an unconformable relationship with underlying gneisses. A number of granitoid bodies, including granite, granodiorite, and adamellite, are intrusive into the Yellowknife rocks, and are surrounded by wide aureoles of metamorphism within which the sediments have been converted to schists. Deformation of the Yellowknife rocks has been severe and multiphase, including both pre-intrusive and syn-intrusive events. In the southeast there is a complex of alkalic intrusives including syenites, anorthosites and granite, which belong to a younger, probably Proterozoic, magmatic cycle (Davidson, 1972).

The region was glaciated in Quaternary times and is relatively free of glacial detritus.

The present day surface forms a peneplain which rises gently from a general level of 200 m above sea level in the southwest to 300 m in the northeast. The topographic relief in any part of the area rarely exceeds 100 m. The landscape consists of low rounded hills of bare rock separated by hollows floored with glacially derived material, often having an organic cover of peat or bog. Lakes are common and may occupy between 15 and 20 per cent of the area. Trees are sparse and poorly developed, the northern limit of tree growth being less than 60 km north of the test area. The peaty areas have a dense cover of sedges, shrubs, stunted willows and ephemeral plants. Drier areas are often covered with stunted pines which also grow from joints and fracture traces in the rock outcrops.

The Hearne Lake map-sheet was flown as part of the Yellowknife Survey (Grasty and Richardson, 1972) at a nominal height of 120 m above ground along 40 east-west oriented lines spaced 2.5 km apart. The average ground speed for the aircraft was 190 km per hour. While the survey was being flown, ground control points were plotted approximately 20 km apart along the flight line, onto a 1:250 000 scale topographic map. The X-Y co-ordinates of each control point were later measured manually from a similar map for merging with the digital geophysical data on magnetic tape.

The spectrometer, which has twelve 228.6 mm x 101.6 mm (9"x4") NaI(Tl) crystals, has been described on a number of occasions (e.g. Darnley, 1970a). For a review of the basic principles of the gamma-spectrometer, reference should also be made to Grasty (1976a).

For the Hearne Lake survey, the spectrometer had 4 channels set at 1.66-1.86 MeV for Uranium, 1.37-1.57 MeV for Potassium and 2.41-2.81 MeV for Thorium and a broad channel from 0.41 to 2.81 MeV for integral (or total) count. Individual readings were integrated over periods of 2.5 seconds. The output in counts per unit of time are recorded together with the principal flight parameters on magnetic tape.

In compiling the results of the survey, count values were corrected for background, for variations in the distance between the aircraft and the terrain, and for spectral stripping to produce profiles of count rates in each channel for each flight line proportional to equivalent uranium, potassium, equivalent thorium, and integral values together with eU/eTh, eU/K, and eTh/K ratios and a terrain clearance profile. Corrected count rates are presented without any smoothing except in the case of total count, where each 2.5 s count is the average of five 0.5 s readings, and the ratio values which are not calculated until sufficient data points are summed to give at least 100 counts in both the numerator and denominator channels (Grasty, 1972).

Contour maps are also provided for each of the four channels and the three ratios.

The work described in this paper made use of the more detailed profile data rather than the contoured data which undergo considerable smoothing in order to produce some coherence between the widely spaced flight lines.

It is of great importance to establish the source of the gamma-radiation being measured by the spectrometer: this is sometimes loosely called its "field of view".

Since each individual measurement is the average of an infinite number of sources over a 2.5 second count period care is necessary in interpreting the results. As the aircraft crosses from land to water, for example, even if the shore is orthogonal to the flight line, there is a transition zone between the level over land and that over water (Fig. 3). Where the flight line is oblique to the shore the effect is to produce a longer transition, while in the case of the shoreline being parallel to the flight line there is a general lowering of levels by an amount depending on the distance from the shoreline. Similar effects will occur in crossing a contact between two rock types having different radiation levels. Even given perfect exposure, it is clear that the recognition of an individual dyke or lithological unit will depend on its width, measured along the flight line, and the radiometric difference between the two rocks.

METHODS AND RESULTS

Establishing Rock Signatures

Eleven lines or part-lines were selected as test lines for detailed examination (Fig. 2) because they crossed 10 of the 12 major rock types known to be present within the survey area. Most of the rock types occurred at more than one location. At the beginning of the investigation, each of 24 lithological units, many of them identified as the same rock type, but spatially separated, were given a separate identification code. The radiometric profile data were studied at a common scale of 1:50 000, since this was the largest reasonable scale at which the profiles could be fitted onto available topographic sheets and because the scale was suitable for recording information from the aerial photographs (1:15 000 in colour; 1:20 000 monochrome).

The procedure eventually adopted was as follows:

1. Flight lines were transferred to the 1:50 000 topographic maps by replotting the fiducials from the original 1:250 000 scale flight maps. These fiducials are easily recognizable points approximately 20 km apart along each flight line which are plotted onto the topographic maps by the spectrometer operator during the survey. The flight lines were also transferred to airphotos.

2. An interpretation of the airphotos was made along the flight lines using the geological map (Henderson, 1976) for control. Thus, contacts between different lithological types, areas of outcrop, of swamp, water and of heavy vegetative growth suggesting the presence of fairly well drained glacial material, were all indicated on the traverses. The aim of this interpretation was to subdivide the ground underlying the flight lines into terrain units which might have different radiation characteristics. The results of the photointerpretation were then transferred to the 1:50 000 topographic maps.

3. Computer prints of the radiometric profile maps were produced for the test lines at a scale of 1:50 000. It was not always easy to correlate the fiducials on these radiometric profiles with the same fiducial points plotted on the topographic maps because of the evident discrepancies between the two that locally reach 1.5-2.0 cm (or 750-1000 m on the ground). In most cases the mismatches were probably due to variations in speed and flight direction of the aircraft between ground control points (the fiducials). In addition, since the original flight control for the airborne survey was plotted on 1:250 000 maps, all inaccuracies in the recording or transfer of fiducial points were enlarged five-fold when the flight lines were replotted at 1:50 000.

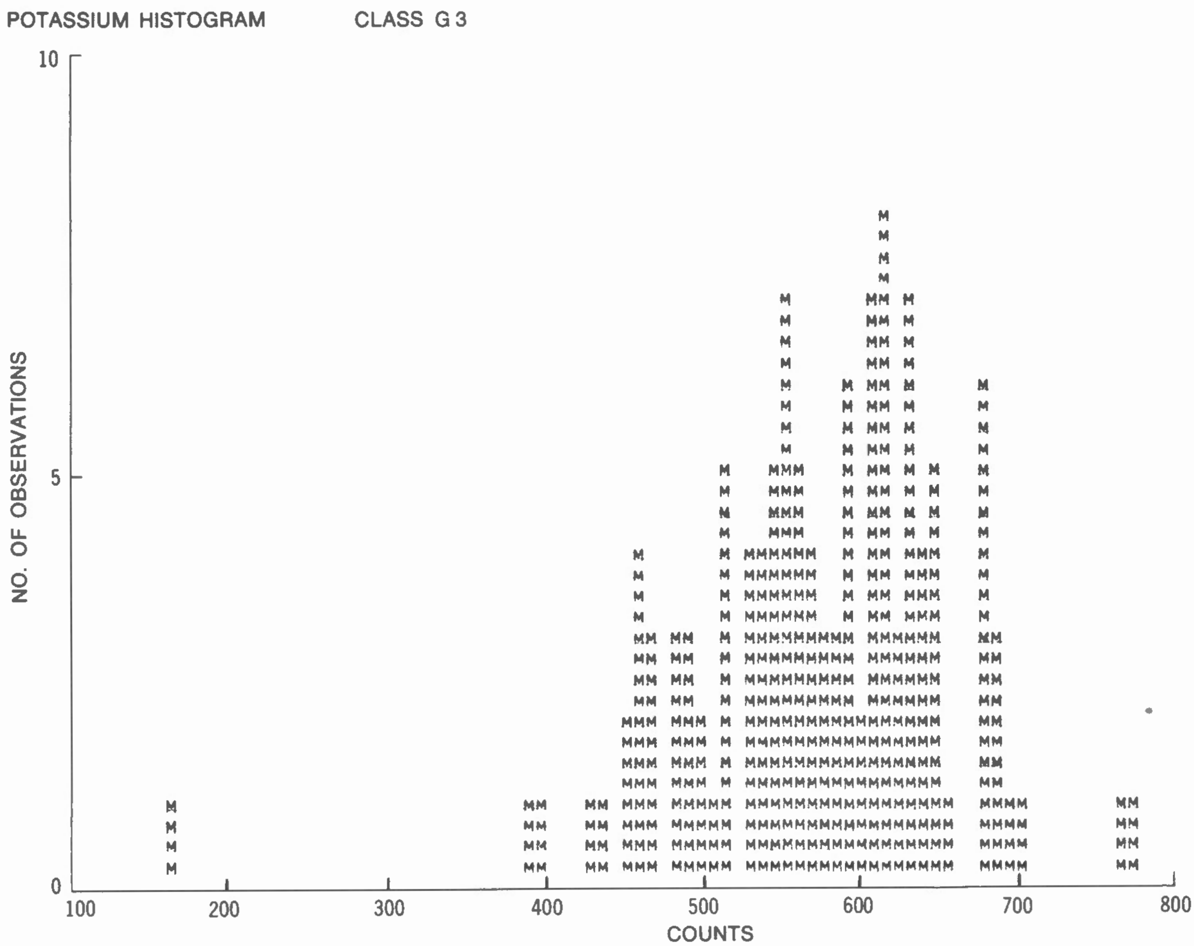

Figure 4. Histograms of selected rock types

4. The next stage of the investigation was to note, on the radiometric profiles, those portions of the profile which represented areas of exposed rock. Then the location and identity of each profile segment as recorded on a computer card. Means and standard deviations for each element in each rock type were computed from these segments. Histograms (Fig. 4) and signature diagrams (Fig. 5) were also generated to show the range of radiation values as a function of frequency for each element. The histograms provide visual indication of the homogeneity of the rocks sampled and can also be used to indicate whether the sample was large enough to be representative.

The question of the minimum number of readings (or length of line) necessary to give a representative sample of a rock type is not easily answered. By averaging different sized groups of readings along a number of traverses it was found that a minimum sample size of about 20 readings (3.3 km of traverse) was sufficient to represent most rock types. Because of this, seven of the original test line rock spectra were excluded from further analysis on the grounds that they were not properly represented within the test lines.

To find out whether in fact there was any significant difference between the radiometric spectra acquired in the above fashion and spectra acquired (with far less difficulty) without excluding areas of water, swamp and deep overburden, a second set of 'unselected' data was obtained for each rock from the same test profiles.

With the inclusion of data from areas of swamp and open water, there is an average decrease in the means in all three channels, of about 20 per cent, and an average increase of 35 per cent in the standard deviations. Under these conditions it will be much more difficult to group the rock units into mutually distinguishable classes.

Grouping of Rock Signatures

The next stage was to find out the range in variation of the radiometric signatures so that spectra showing similar characteristics might be grouped together and separated from those with dissimilar characteristics. By combining spectra into larger groups, it was hoped to distinguish a fewer number of litho-radiation units with greater reliability.

Three approaches were tried, an empirical one, a statistical one based on clustering techniques and a semi-statistical one. The statistical approach using clustering (based on Anderberg, 1973; Lefkovitch unpubl. ms., 1975; Davis, 1973) was not very satisfactory since it provided no obvious groupings. This is presumably due to the large degree of overlap between the data sets. The empirical approach was carried out by comparing on a light table, each of the 17 spectral signatures, and grouping together those signatures which seemed most similar in character. In this way, the 17 initial signatures were reduced to 8 fairly distinct radiation classes plus a 'water' class. The weakness of this method is that because of the large number of alternatives being considered, it was not feasible to recalculate group means and standard deviations every time a spectrum was considered for addition to a group.

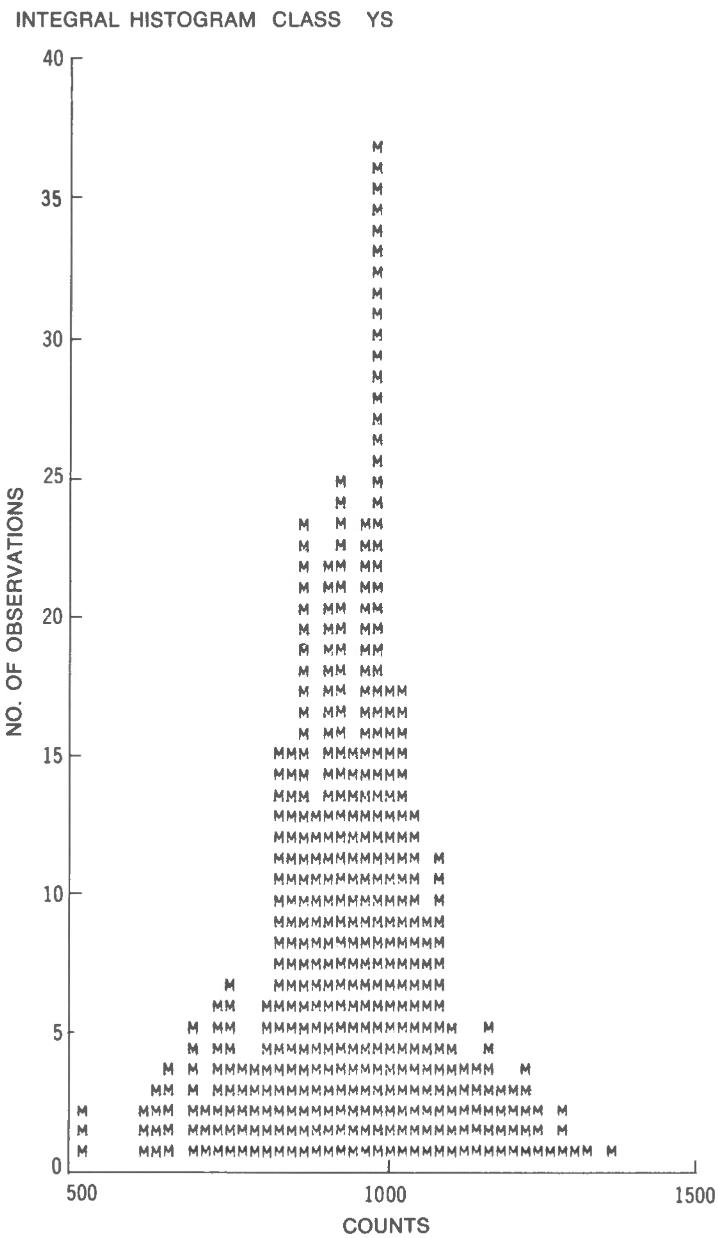

Figure 4 (cont'd.)

The method eventually adopted was semi-statistical based on the computer algorithm which was developed to allocate each unknown reading to which ever spectral signature the reading most closely resembles. The algorithm itself is described in the next section. It will be recalled that the test line data had already been classified as to rock type, and swamp and water, using aerial photographs and available geological maps, and that this information was now included on the computer tape with the test line data. By applying the classification algorithm to the test line data it was possible to construct a crosstabulation table (Table 1) which showed how many data points were correctly classified and how many were not; the table also showed where the wrongly classified data were being allocated. The way in which the crosstabulation table was used to group the spectra is described as follows: the first classification of the test line data was carried out with 17 rock signatures. The rock type with the lowest percentage of correctly classified values was then combined with the rock type with which it was closely identified. The next run, therefore, consisted of 16 spectral signatures, and once again, the rock with the most misidentified points was chosen to be combined with that which it most closely resembled. New sets of means and standard deviations were calculated for each new grouping. In this way the number of spectra was reduced one by one, until a stage was reached at which all the rock classes were being classified with similar success. Using this technique, the 17 Hearne Lake spectra were grouped into 9 radiation classes (plus water) with 63.3 per cent of the readings being correctly classified into one or other of these classes. Table 1 is the final crosstabulation table, and shows the classification accuracies of the nine signatures used to carry out the classification of the whole survey area.

The eight groups selected using the empirical technique were also tested using the crosstabulation method and were found to give 61.3 per cent success. This confirmed the advantages of the semi-statistical approach although the differences in the two methods was not as great as might have been expected.

The classifying algorithm developed to group the rock signatures used the potassium, uranium and thorium count channels only. It was found by experiment that the classification accuracy could be improved only marginally by introducing the total count channel and by applying different weightings to the potassium, uranium and thorium channels. Consequently, in the approach described here, only the three radiolements were utilized and were given equal weighting.

Table 3 provides a listing of the original 17 rocks from which radiation data were obtained for spectral analysis. The figure also shows how the spectra were finally grouped together.

Table 2 lists the means and standard deviations for each of the 9 final spectral classes. These are the values used for the computer classification of the total survey area.

The degree of separation between the classes is shown graphically in Figure 6, which presents the means and standard deviations taken from Table 2, and plotted in the form of the three ratios, Th/U, U/K and Th/K. The Th/U ratio plot is the most interesting of the three in that it shows that the thorium and uranium channels by themselves are able to separate most of the classes. They do not separate YS from G8 and from G3, for which, as the Th/K plot shows, the third element, K, is required.

Classification Algorithm

The function of the algorithm is to allocate each data set in the whole survey to whichever rock class it most closely resembles.

The method adopted can be visualized in terms of a three dimensional plot using potassium, uranium and thorium as the principal axes. Each rock type can be described by a point representing the three means for that rock, while the standard deviations are represented by lines centred on the mean point and parallel to the three axes. Thus at the 1σ level, a rock will be represented by a triaxial ellipsoid with axes of length $2\sigma(K)$, $2\sigma(U)$, and $2\sigma(Th)$. An unknown set of readings is represented by a point in space, at varying distances (in terms of standard deviation) to the centroids of the ellipsoids representing each of the different rocks. The unknown value is allocated to the rock type represented by the nearest ellipsoid centroid. To provide equal weighting to the different channels, the distances to the centroids of the ellipsoids are measured in terms of their respective standard deviations.

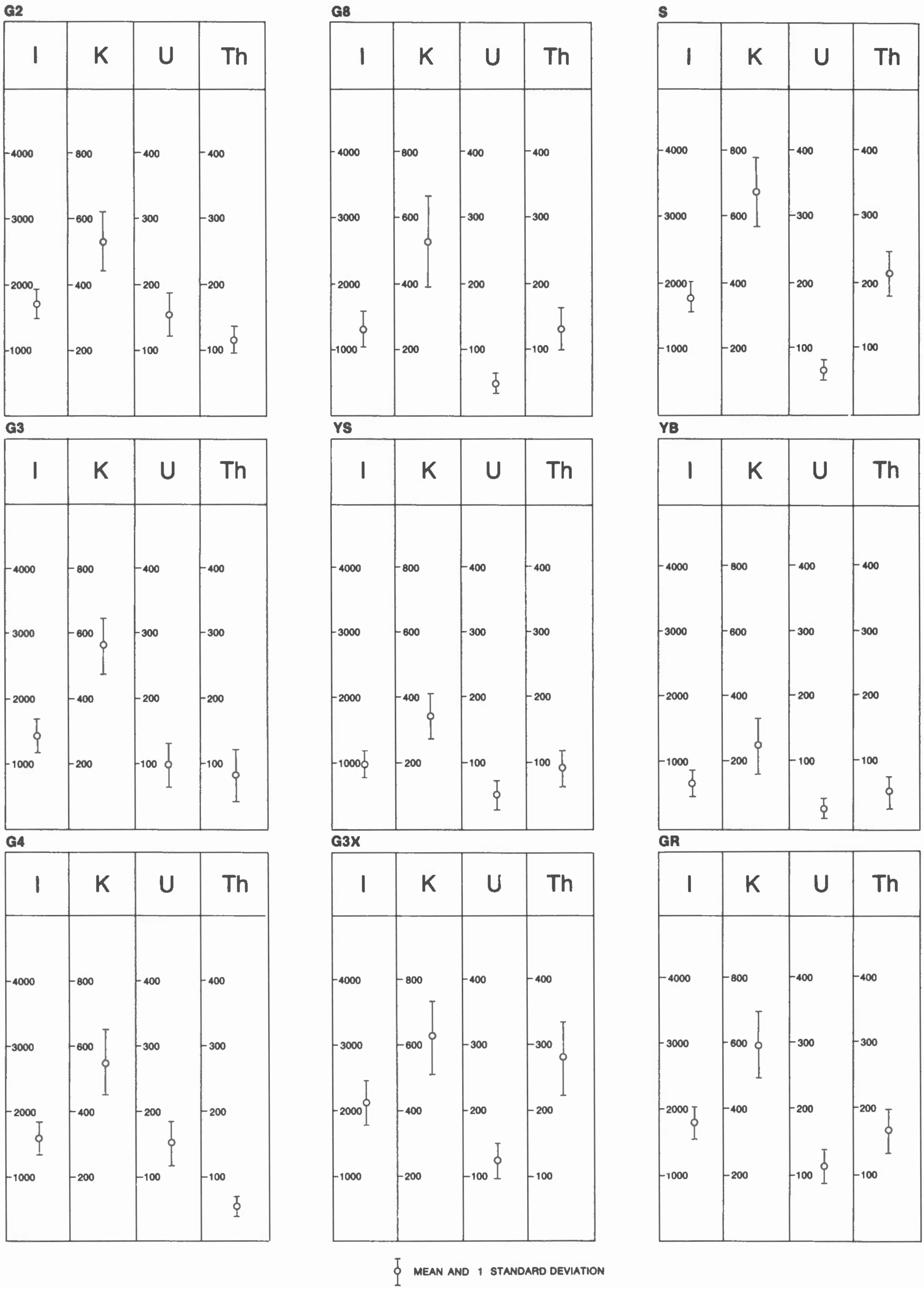

Figure 5. Spectral signature diagrams

Table 1

Classification efficiency by use of crosstabulation table of rock spectra

	Distribution of wrongly classified readings											
	G2	G8	S	G3	YS	YB	G4	G3X	GR	Total values	Number wrong	Percent correct
G2	0	0	0	4	1	0	0	0	3	29	8	72.4
G8	0	0	1	0	2	2	0	0	1	20	6	70.0
S	0	3	0	0	0	0	0	1	1	12	5	58.3
G3	21	12	0	0	14	2	12	0	31	229	92	59.8
YS	8	159	1	33	0	241	2	1	44	1286	489	62.0
YB	0	0	0	0	14	0	0	0	0	65	14	78.5
G4	0	0	0	5	0	0	0	0	0	16	5	68.7
G3X	0	1	1	0	1	0	0	0	3	41	6	85.4
GR	0	0	2	4	2	0	0	4	0	37	12	67.6

Elements K U Th

Table 2

Means and Standard Deviations of spectral classes

	Potassium (%)		eUranium (ppm)		eThorium (ppm)	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
G2	4.0	0.7	7.1	1.5	13.0	2.4
G8	4.0	1.1	2.3	0.7	14.6	3.6
S	5.0	0.8	3.1	0.8	23.7	3.6
G3	4.2	0.7	4.6	1.5	9.5	4.2
YS	2.5	0.5	2.3	1.0	10.2	3.2
YB	1.9	0.6	1.2	0.8	5.9	2.8
G4	4.1	0.7	7.0	1.6	6.2	1.5
G3X	4.7	0.8	5.6	1.2	31.3	6.3
GR	4.4	0.8	4.9	1.2	18.0	3.8

Conversion factors used to convert instrument counts are as follows:
1%K = 134 counts, 1 ppm eU = 22 counts, 1 ppm eTh = 9 counts

Table 3

Grouping of Rock Types

Rock Type	Initial Identification	Final Grouping
Wedge Lake muscovite-biotite granite	G3X	G3X
Hornblende syenite (southeast Igneous Complex)	S	S
Redout Lake granite	GR	GR
Matonabee Point muscovite-biotite granite	G2	G2
Detour Lake South biotite-muscovite granite	G4	G4
Duncan Lake muscovite-biotite granite	G3	G3
Caribou Lake leuco-adamellite	G7	
Blatchford Lake granite	G8	G8
Acid Volcanics, Yellowknife Supergroup	YA	
Greywackes, mudstones, schists, Yellowknife Supergroup	YS	
Gabbro	B	
Southwest Granodiorite	G1	YS
Southwest Granodiorite (northeast Portion)	G1A	
Ross Lake granodiorite and mixed gneisses	G5	
Morose Lake muscovite-biotite, adamellite	G6	
Anorthosite	AN	
Basic Volcanics, Yellowknife Supergroup	YB	YB
Tumpline Lake granodiorite	G3C	
Water	W	W

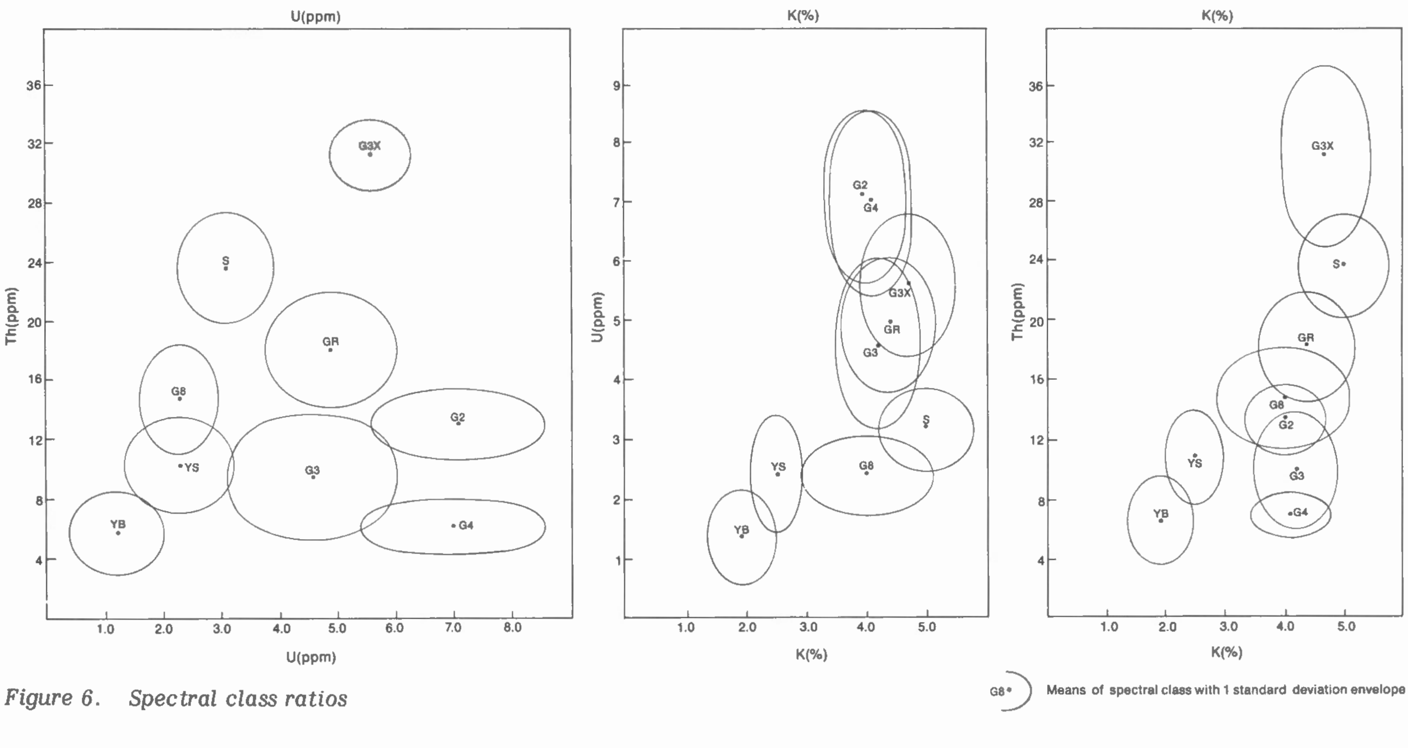

Figure 6. Spectral class ratios

For each radiation measurement, the distance, D, from the mean value of each rock class is given by:

$$D^2 = \left(\frac{K - \bar{K}}{\sigma K}\right)^2 + \left(\frac{U - \bar{U}}{\sigma U}\right)^2 + \left(\frac{T - \bar{T}}{\sigma T}\right)^2$$

where $\bar{K}$, $\bar{U}$, and $\bar{T}$ are the mean potassium, uranium and thorium concentrations and σK, σU and σT the standard deviations for each rock class. K, U and T are the radiation measurements of the unknown data point which will be allocated to the rock class for which D is a minimum.

In practice, the procedure adopted was to evaluate D according to the equation:

$$D = \mathrm{Abs}\left(\frac{K - \bar{K}}{\sigma K}\right) + \mathrm{Abs}\left(\frac{U - \bar{U}}{\sigma U}\right) + \mathrm{Abs}\left(\frac{T - \bar{T}}{\sigma T}\right)$$

which provided reasonably satisfactory results.

RADIATION PATTERNS IN THE HEARNE LAKE SURVEY AREA

Once the spectral classes had been defined and checked against the test lines, the entire survey area was classified and the results printed out in map form at a scale of 1:50 000. At this scale, the map takes up nearly 4 m^2 (40 square feet) and is too bulky to be included with this report. Portions of it, with lakes and geology added, are included as Figures 7.1, 7.2.

Figure 8 is a simplified version of the computer classified map reduced to 1:250 000 scale, and this is the map that is discussed in this section of the report.

A geology map at 1:250 000 scale, based entirely on Henderson's compilation (1976) is included as Figure 2 for comparison with the radiation map.

The radiation characteristics of the rocks of the Hearne Lake area are discussed under five general headings. The first four of these refer to the igneous complexes which are found in the northwest, southwest, southeast and northeast quadrants of the survey area. The fifth heading refers to the Yellowknife Supergroup, which lies between and around the igneous complexes.

Northwest Igneous Complex

This complex consists of two larger, elongate plutons, the Duncan Lake and Sparrow Lake granites, and four smaller plutons, Prestige Lake, Wedge Lake, Scott Lake and Hidden Lake, which lie along the eastern flanks of the main granite masses. The easternmost tip of another large granite mass lies just within the survey area at the southwestern shores of Prelude Lake. All of these plutons are described as muscovite-biotite granites (Henderson, 1976).

The Duncan Lake - Sparrow Lake plutons, crossed by 7 test lines, together constitute the type area for class G3.

Class G3 is characterized by moderately high K values (mean 4.2%) moderate eU values (4-6 ppm mean) and the lower end of the intermediate range of eTh values (9.5 ppm mean) (see Table 4).

Excluding the scattered YS values, which are considered to represent higher energy classes attenuated by the inclusion of lakes within the field of view, and YB values believed to be mainly areas of moist overburden, this pair of granite plutons shows marked variations in its radiation pattern.

Duncan Lake

The northern edge of this granite, where it borders Duncan Lake, consists of a 2-5 km-wide strip of class GR (high thorium). GR values also occur at the northeast margin of the granite and close to the edge of the granite in the southeast. Scattered occurrences of G4 with or without G2 (both high uranium classes) are found around most of its borders mostly within 5 km of the edge of the pluton.

Sparrow Lake

The outer margin of this wedge-shaped pluton, like that of Duncan Lake, is clearly recognizable by the change to higher count radiation classes. The boundaries follow those of the geological map (Fig. 2) very precisely except in those few areas where it is obscured by surficial deposits. A circular area of class GR occupies most of the central part of this pluton, as well as its southwestern corner. G2 (high uranium) occupies parts of the margins of the pluton in the north and in the east. Radiometrically, the southeastern part of the pluton is most interesting because of the extensive occurrence of class G4 (high uranium).

Prestige Lake

The Prestige Lake granite consists very largely of GR (high thorium) values.

Wedge Lake

Wedge Lake is radiometrically distinct from all the other granites in the entire survey area. While the granite is not large in area, three test lines cross it and it is the type area for class G3X. G3X is recognized by very high total counts, and by high values in all channels, in K (4.7%), eU (5.6 ppm) and eTh (31.3 ppm). In the whole of the northwestern granites outside of the Wedge Lake pluton only one reading is classified as G3X. This one reading is found in the Prestige Lake pluton.

Day Lake

Day Lake is a small pluton consisting of scattered G4 (high uranium) and G3 values.

Hidden Lake

Hidden Lake pluton is mostly obscured by overburden except for a 1 km-wide rim at the northern and eastern margins of the intrusion which is classified as G3.

Prelude Lake

Southwest of Prelude Lake, the granite is classified almost entirely as G4 (high uranium).

Southwest Igneous Complex

The greater part of the southwestern quadrant of the survey area is occupied by granitic rocks intrusive into the sediments of the Yellowknife Supergroup. The granitic rocks were not subdivided on the early (Henderson and Joliffe, 1941) published map. On the latest map (Henderson, 1976), the area is also mapped as granodiorite, except for that part between Campbell Bay and Matonabee Point in the southwest, and is described as a muscovite-biotite granite similar in character to the plutons in the northwest of the survey area.

Radiometrically, the Southwestern Granodiorite is indistinguishable from the greywackes and schists of the Yellowknife Supergroup which surround it to the north, east and south. For this reason, most of the main body of the granodiorite and all of the associated plutons to the east (which were originally designated 'G1') have been grouped into class YS. There are three unusual features in the radiation patterns of the Southwestern Granodiorite:

1. The southeast portion of the main granodiorite body is differentiated from the rest, because of the large number of G8 and GR values, and the sprinkling of G3 values all of which indicate a generally higher level of radioactivity in this area.

Table 4

A comparison of YS, YB and G8 classes in the Yellowknife Supergroup and the Southwestern Granodiorite

	1	2	3	4	5	6	7	8	9	10
K mean	2.5	2.4	2.4	2.0	2.6	2.5	2.2	4.0	3.1	3.1
standard deviation	0.5							1.1		
U mean	2.2	2.2	1.8	1.7	2.1	2.3	1.8	2.3	2.1	2.6
standard deviation	0.8							0.7		
Th mean	10.0	8.1	12.2	6.2	8.0	11.7	5.8	14.6	15.0	15.2
standard deviation	3.1							3.6		

1	YS	Class	Test Lines	Average of 797 values
2	YS	Line 37 east	Yellowknife Supergroup	Average of 21 values
3	YS	Line 28 east	Yellowknife Supergroup	Average of 15 values
4	YB	Line 37 east	Yellowknife Supergroup	Average of 26 values
5	YS	Line 41 west	S.W. Granodiorite	Average of 44 values
6	YS	Line 26 west	S.W. Granodiorite	Average of 31 values
7	YB	Line 41 west	S.W. Granodiorite	Average of 37 values
8	G8	Class	Test Lines	Average of 14 values
9	G8	Line 28 east	Yellowknife Supergroup	Average of 18 values
10	G8	Line 26 west	S.W. Granodiorite	Average of 25 values

2. South of a poorly defined line drawn from Hearne Lake in the east, passing through Defeat Lake to Great Slave Lake in the west, G8 values occur scattered in equal numbers throughout both the Southwestern Granodiorite and the sediments of the Yellowknife Supergroup. The incidence of G8 values appears to increase towards the south. The nature of this apparent change in the chemical composition of the rocks is indicated in Table 4. North of Hearne Lake, both the Southwestern Granodiorite (column 5) and the Yellowknife sediments (column 2) have very similar radioelement concentrations. Southwards from Hearne Lake the granodiorite (column 6) and the sediments (column 3) both classified still as 'YS', show a parallel increase of 3 to 4 ppm in thorium content. Locally the granodiorite (column 9) and the sediments (column 10) have been classified as class G8, and these rocks average 7 to 8 ppm thorium and 0.5 to 0.6% potassium higher than similar rocks (but class YS) north of Hearne Lake. This zone, containing higher thorium and potassium concentrations, includes both granodiorites and the Yellowknife Supergroup sediments; it also crosses, almost at right angles, major structures and metamorphic boundaries in the Yellowknife sediments. Its geological significance remains unknown.

3. Nine minor occurrences of class G3 lie within the southern part of the main granodiorite, mostly near its eastern and western margins. G3 represents a level of radioactivity distinctly higher than YS or G8 and may well represent small intrusions of granite.

The muscovite-biotite granite at Matonabee Point is crossed by one test line and represents the type area for class G2, characterized by somewhat lower potassium (4.0% mean) and higher thorium (13 ppm mean) than most other granites, but its high uranium content (7 ppm mean) makes it unusual. The rock itself consists predominantly of G2 (56%) with scattered G3 (20%) GR (12%) and YS (12%) values.

Southeast Plutonic Complex

The western portion of this igneous complex between Caribou and Great Slave lakes is described by Davidson (1972) as an adamellite. The rock is crossed by two test lines and is the type area for class G7 which was later grouped into the extended G3 class. G3 (see Table 4) is characterized by intermediate values in all channels, with means of 4.2% K, 4.6 ppm eU, and 9.5 ppm eTh. The western adamellite is not homogeneous radiometrically. While G3 values predominate, especially in the central area, occurrences of G4 and G2 are prominent in the south and G2 at the northern limits of the intrusion. Both G2 and G4 are defined in part by mean uranium values close to 7 ppm.

Immediately east of the adamellite, there is a dyke-like gabbro, 3 to 4 readings wide where it is intersected. Where recognized, it is classified as 'YS'.

The gabbro is bounded to the east by three nearly rectangular rock units. The northernmost is described by Davidson (1972) as a mélange of syenite and granite, and is represented radiometrically by a mixture of G3, G8 and YS values. The middle unit is anorthosite and is characterized by YS with scattered G8 values. The southernmost rectangle is underlain by syenite with one small central intrusion of anorthosite. Although this syenite occupies a small area it is crossed by one test line on which the radiation characteristics appeared sufficiently unusual for the rock to be taken as the type area for class S. This class has high total count readings, and is recognized by very high potassium (5.0% mean) and thorium (23.7 ppm mean) and intermediate levels of uranium (3.1 ppm mean).

After the whole survey area was classified it became evident that the one test line crossing this syenite does not truly represent the rock itself but is part of a zone of anomalously high radioactivity which follows the northern shores of the East Arm of Great Slave Lake and includes both the southern edge of the syenite and the southern parts of Blatchford Lake Granite to the east of the syenite. Away from the anomalous line, the normal syenite is represented by a mixture of YS and G8 values.

The next rock to the east is an alkalic granite which extends from Blatchford Lake to Great Slave Lake. This rock is the type area for class G8, a class defined by mean potassium 4.0%, mean uranium 2.3 ppm, and 14.6 ppm mean thorium.

The 1:50,000 scale computer classified map shows that the granite too, is inhomogeneous. The northern half of the granite is represented by G8 with scattered G3, GR and YS values. Most of the remaining area of granite is represented by class YS, with scattered G8 values. The southernmost line, sub-parallel to the shore of Great Slave Lake, is quite different and represents an extension of the anomalous G3X, GR, G8 zone which also occurs in the syenite to the west.

The core of the Blatchford Lake granite is a sub-circular intrusion of alkalic syenite. The syenite is represented by G8 with minor G3, GR and YS values and is identical in radiation characteristics to the northern part of the Blatchford granite. One portion of the syenite, a one mile section of line 26 near the northwest margin, is unusual because of a short sequence of G3X values. This section includes the area described by Davidson (1972) as brecciated siliceous rock containing mildly radioactive fluorite.

Buckham Lake Granite

Henderson (1976) described this rock as a muscovite-biotite granite similar in character to Duncan Lake granite. While the edge of the granite is well defined by sharp increases in radiation levels, the rock itself appears to be subdivided fairly evenly between three radiation classes, G2, G4 and G3. Since G2 and G4 are characterized by high uranium values, the intrusion clearly merits further investigation.

Northeast Igneous Complex

This area was described by Davidson (1972) and the results of his fieldwork were incorporated into Henderson's (1976) compilation.

The core of this complex, centering on Morose Lake, is described as a massive muscovite-biotite adamellite. The rock is crossed by three test lines and is the type area for class G6, which was later grouped into the enlarged YS because of the nearly identical radiation characteristics of the two classes. Radiometrically the rock appears to be variable. The overall radiation pattern consists of YS (45%) with scattered G8 (16%), G3 (19%) and GR (15%) values. There are two areas of distinctly anomalous values:

1. At the eastern boundary there is a wedge shaped zone of G2 and GR values which passes from the Morose Lake adamellite into an adjacent area of younger adamellite and mixed gneiss.

2. South of Languish Lake there is an area of mixed GR and G3X values.

Enveloping the Morose Lake adamellite to the west, southeast and east are a series of migmatites and diorites often cut by swarms of basic dykes now sheared to amphibolite. The western portion of this mixed gneiss is known as the Ross Lake granodiorite.

The Ross Lake granodiorite is the type area for class G5 which was later grouped into the extended YS class.

Excluding areas classified as YB (largely overburden) the greater part of the gneiss (64%) is recognized as YS with sparsely scattered G8 (8%) values. The remainder of the gneiss is made up of four zones of higher radiation classes.

1. At the northern limit of the survey area there is a zone of mixed G2, GR and G3 values which extends for more than 5 miles along 2 adjacent lines. The southern tip of an adamellite intrusion also crosses these two lines, and the G2, GR, G3 association passes unchanged from the mixed gneiss into the adamellite.

2. The G2, GR, G3 association appears again in a closely similar situation in the eastern portion of the mixed gneiss where it borders the Morose Lake adamellite.

3. The western zone of mixed gneiss includes a somewhat irregular band of mixed G8 and GR values traceable from line 61 in the north, south to Victory Lake.

4. South of Victory Lake the Ross Lake gneisses develop different radiation characteristics and are classified as a complex of G3, G2 and GR. The continuation of these gneisses northeast of Turnback Lake includes a few G3X (the highest radiation category) as well as G3, G2 and GR values.

Redout Lake Granite underlies most of the southern portion of the main igneous complex. This granite is described by Davidson (1972) as being structurally complex and highly variable in composition, a feature that is reflected in the character of its regional gamma radiation pattern. The rock is crossed by two test lines which produced average values so distinctive as to become the type area for class GR (potassium mean 4.4%, uranium mean 4.9 ppm, thorium mean 18 ppm). On the computer classified map, the Redout granite appears as a complex of G3 (27%), GR (20%), G2 (20%) and G3X (5%) values. There are also a large number (27%) of YS values most of which occur around a series of lakes and are considered to originate through the attenuation of radiation from rocks with class G3 or higher, levels of activity.

The G3X values found at the north end of Detour Lake and at the south end of Redout Lake are considered particularly interesting because of the very high radiation characteristics of this class.

From Detour Lake, a spine of foliated muscovite-biotite gneiss extends southwards from the main igneous complex into the surrounding rocks of the Yellowknife Supergroup. Two test lines cross the Detour Lake granite which represents the type area for class G4.

The rock is distinctive because of its intermediate potassium mean (4.1%) combined with a high uranium mean (7 ppm) and a low thorium mean (6.2 ppm).

In the final classification, the northernmost half of this rock is predominantly G3 (32%) while the southern half (which included the two test lines) is largely class G4 (26%). Minor amounts of G2 (9%) and GR (6%) are also scattered throughout the granite. A significant number of YS values (21%) are also present, and are believed to be due to the attenuation by water of areas of higher radioactivity. A small, nearly circular intrusion of granite lying west of the main body, was also mapped by Davidson (1972) as Detour Lake granite, an association which is confirmed by the preponderance of G4 with minor G3 values.

Two other separate biotite granodiorite plutons are recorded to the east and northeast of the igneous complex. Only YS and YB values occur in the area of these plutons which would suggest that from radiation characteristics alone, the two plutons are more closely related to the southwestern granodiorites than to the rocks of the northeastern igneous complex.

Yellowknife Supergroup

This consists of three main lithological units. At the base of the sequence, basic and acid volcanics are found, overlain by a very extensive series of greywackes, mudstones and schists.

Basic Volcanics are found only in the northeast quadrant of the survey area. They are best exposed in a zone up to 6 km wide which follows the northwest edge of the northeast igneous complex. Other occurrences around the southern and southeastern edges of the complex are smaller in size and occur in such complex structures that they are difficult to distinguish with any degree of confidence on the airphotos.

The northwestern exposure of basic rocks is crossed by two test lines and is the type area for the class YB. Class YB is recognized by low values in all channels (potassium mean = 1.9%, uranium mean = 1.2 ppm, and thorium mean = 5.9 ppm). The basic rocks here are remarkably homogeneous on the total classification map. Only two YS values occur within the main zone of basic volcanics.

Most other basic rocks that might be considered to fall into this category – basic dykes in the northwest of the survey area and a gabbro intrusion west of Defeat Lake, are not recognized on the total classification map, almost certainly because outcrops are too small.

Class YB is of special interest because in the total classification map it is found to represent not only basic rocks but also most of the area overlain by surficial materials and swampy ground. As such the class is found throughout the map area and within the boundaries of all the rock types. YB is believed to represent surficial materials because whenever such materials are found, moisture fills the interstices between mineral grains, pebbles or boulders and this attenuates radiation to a uniformly low level in all channels.

YB is considered more important as an indicator of surficial materials, than as an indicator of the presence of basic volcanic rocks, since the latter have such limited distribution within the survey area.

Acid Volcanics of the Yellowknife Supergroup occur around the southern and southeastern margins of the northeast igneous complex. These rocks are now characterized as class YS and as such they are indistinguishable from the surrounding mudstones and greywackes of the Yellowknife Supergroup.

Greywackes, mudstones and schists of the Yellowknife Supergroup underlie about 40 per cent of the study area. Most of the test lines cross these rocks which represent the type area for class YS. Class YS as originally defined has been grouped together with 7 other classes (see Table 3) because of close similarities in the radioelement signatures. The extended YS, with a potassium mean of 2.5%, uranium mean of 2.3 ppm and thorium mean of 10.2 ppm (Table 2) is now a 'holdall' class representing all rocks with modest to fairly low values in all channels.

Radiometrically the sediments are notably homogeneous. No distinction can be made between unaltered greywackes and amphibolite facies nodular schists. YB values occur very extensively throughout the area but as explained elsewhere, these are considered to represent areas of moist overburden, swamps or the inclusion of standing water in the field of view of the survey aircraft.

There are also a few small areas within the sediments where higher radiation classes occur. Three of these lie close to Campbell Lake. Another is found west of Hearne Lake and others occur along the south shore of Prelude Lake and at Upland Lake. Each of these areas is presumed to indicate the presence of small granitic intrusions. None of these features are found on Henderson's (1976) compilation.

South of Hearne Lake, G8 values occur, at first sporadically, but increasingly in number towards the south. This represents a regional increase of 1 to 2 ppm thorium and 0.5 to 1% potassium when compared with the sediments north of Hearne Lake.

CONCLUSIONS

A number of rocks have been distinguished by their airborne gamma radiation signatures, however the reliability with which they are recognized depends very much on the uniformity of the radioelement concentrations in each rock, on the presence and composition of the overburden, and on the presence of water, both free-standing and within the overburden.

The capability of an airborne spectrometer system to distinguish rock types also depends on the absolute levels of radioactivity in each rock type. Where low levels of radiation predominate rocks are difficult to separate and must be grouped into 'holdall' spectral classes. With increases in the level of activity it becomes possible to separate individual rocks by their radioelement characteristics.

Areas of alluvium or of glacial overburden can be separated from areas of outcrop. This is possible because of the high moisture content commonly found in most areas of glacial and alluvial material, and in organic debris. Rocks with gamma radiation signatures similar to that of overburden do occur (e.g. gabbro and anorthosite) but these, rather fortunately, have a limited distribution within the Hearne Lake area.

The advantages to be derived from a digital analysis of the basic airborne spectrometric data are believed to justify the additional work involved, because:

1. Much higher spatial resolution is possible. The contoured maps of the radiometric survey are smoothed by a process which affects many adjacent points. Profiles are not smoothed but they are more difficult to work with when a two dimensional, regional, analysis is desired. The definition of boundaries on the computer classified maps is limited by the counting time of the airborne spectrometer system and by the accuracy with which the location and speed of the aircraft is known during the survey.

2. Areas with similar radioelement characteristics are easily recognized. This is very difficult to do with the contoured maps of the Hearne Lake survey.

3. It is also possible to explore far more complex relationships between the different channels of data when using a computer; the alternative is to overlay large numbers of contoured maps and profiles on a light table.

4. The location and magnitude of zones of anomalous radiation are also more easily recognized on the digital classification.

Gamma spectrometer surveys should not be studied in isolation. Aerial photographs are an essential part of the process, but other geophysical techniques, in particular airborne magnetic maps, provide additional, often essential, information for the analysis of the radiation data. Airphotos are essential to determine the degree of exposure of the rock types and the extent and nature of overburden and vegetative cover. Photographs may also provide precise evidence of the position and extent of rock contacts, whether previously mapped or not, which will guide the choice of rock categories for investigation.

Airborne magnetic maps have not been described in this report although the maps are available and were in fact consulted during the investigation. They do provide information not otherwise available from the radiation data; in particular the locations of gabbroic intrusions, basic volcanics and dykes, and internal structures in some granitic bodies. Clearly much more will be achieved by combining gamma ray analysis with airborne magnetics, than by studying each component alone.

One of the main difficulties encountered in this investigation was the uncertainty regarding the precise flight track of the aircraft between ground control points. This planimetry problem has undoubtedly affected the correlation of the airphoto analysis with the test line radiation data, which also means that the averages and standard deviations of the rock classes have also been affected.

The techniques developed in this study are best applied to areas where outcrops are extensive and overburden minimal, and would include the northwestern parts of the Canadian Shield and some of the Arctic Islands. A geological map is essential; the more detailed the map, the better the radiometric analysis will be. Airphotos are needed at scales of 1:30 000 or larger, preferably acquired at the same time of year as the gamma-ray survey. The gamma survey line spacing should be less than 2.5 km; again, the closer the lines the better the results will be.

It is recognized that a great deal more work needs to be done to establish the methodology described in this report. Certainly there is a need to extend the study to other types of terrain, in particular to sedimentary sequences with simple structures, to areas with a variable cover of glacial material but with fewer lakes and marshy ground, and to areas with known radioactive anomalies. Most important of all, there is also a need to investigate the relationships between the radiation classes established in this study, and the rock types which they are thought to represent.

ACKNOWLEDGMENTS

Mrs. Barbara Elliott was responsible for writing the computer programs used in this study. The authors would also like to thank other members of the Radiation Methods Section of the Geological Survey, in particular J.M. Carson, R.L. Grasty and K.A. Richardson, with whom they have had many discussions and from whom they received much good advice. They also thank A. Fabbri of the Geomathematics Section of Geological Survey for help with the statistical analysis of the data.

REFERENCES

Anderberberg, M.R.
1973: Cluster analysis for applications; New York and London, Academic Press, 359 p.

Cameron, G.W., Elliott, B.E., and Richardson, K.A.
1976: Effects of line spacing on contoured airborne gamma-ray spectrometry data; Paper IAEA-SM-208/2, in Exploration for Uranium Ore Deposits, p. 81-92, International Atomic Energy Agency, Vienna.

Charbonneau, B.W., Richardson, K.A., and Grasty, R.L.
1973: Airborne gamma-ray spectrometry as an aid to geological mapping, township 155, Elliot Lake area, Ontario; in Report of Activities, Pt. B, Geol. Surv. Can., Paper 73-IB, p. 39-47.

Darnley, A.G. and Fleet, M.
1968: Evaluation of airborne gamma-ray spectrometry in the Bancroft and Elliot Lake areas of Ontario, Canada; 5th Symp. Remote Sensing Envir., Ann Arbor, Mich., p. 833-853.

Darnley, A.G.
1970a: Airborne gamma-ray spectrometry; Can. Min. Metall. Bull., v. 63, p. 145-154.

Darnley, A.G., Grasty, R.L., and Charbonneau, B.W.
1970b: A Radiometric Profile Across Part of the Canadian Shield. Geol. Surv. Can., Paper 70-46.

Darnley, A.G. and Grasty, R.L.
1971: Mapping from the air by gamma-ray spectrometry; Can. Inst. Min. Met., Spec. Vol. 11, p. 3-12.

Darnley, A.G.
1975: Geophysics in uranium exploration; in "Uranium Exploration '75", Geol. Surv. Can., Paper 75-26, p. 21-31.

Davidson, A.
1972: Granite studies in the Slave Province; in Report of Activities, Geol. Surv. Canada, Paper 72-1A, p. 109-115.

Davis, J.S.
1973: Statistics and data analysis in geology; New York, John Wiley and Sons, 550 p.

Demnati, A. and Naudy, H.
1975: Gamma ray spectrometry in central Morocco; Geophysics, v. 40, p. 331-343.

Flanigan, V.J.
1972: Gamma radiation; an aid to geologic mapping on the Arabian Shield, Kingdom of Saudi Arabia, Proc. 2nd Int. Symp. Natural Radiation Environment, Houston, p. 667-697.

Forgy, E.W.
1965: Cluster analysis of multivariate data; Efficiency versus interpretability of classifications, Biometric Soc. Meetings, Riverside, California (Abstract in Biometrics v. 21, no. 3, 768).

Gower, J.C.
1966: Some distance properties of latent root and vector methods used in multivariate analysis; Biometrika v. 53, no. 3/4, p. 325-338.

Grasty, R.L.
1972: Airborne gamma spectrometry data processing manual; Geol. Surv. Can., Open File No. 109.

Grasty, R.L. and Richardson, K.A.
1972: Gamma-spectrometer survey of an area north of the Great Slave Lake and the islands of the East Arm of the Great Slave Lake, Northwest Territories; Open File Report No. 124, 7 maps and profiles, Geol. Surv. Can.

Grasty, R.L.
1976a: Applications of gamma radiation in remote sensing; in Remote Sensing for Environmental Sciences, ed. E. Schanda, Springer-Verlag, New York.

1976b: The "field of view" of gamma-ray detectors - a discussion; in Report of Activities, Geol. Surv. Can., Paper 76-1B, p. 81-82.

1976c: A calibration procedure for an airborne gamma-ray spectrometer; Geol. Surv. Can., Paper 76-16.

Henderson, J.F. and Joliffe, A.W.
1941: Geology of Beaulieu River, N.W.T.; Geol. Surv. Can. Map 581-A, 1 inch to 4 miles.

Henderson, J.B., Cecile, M.P., and Kamineni, D.C.
1972: Yellowknife and Hearne Lake map areas, District of Mackenzie; in Report of Activities, Geol. Surv. Can. 72-1A, p. 117-119.

Henderson, J.B.
1976: Yellowknife (85J) and Hearne Lake (85I) map areas, District of Mackenzie, N.W.T.; compiled at 1:125,000, Geol. Surv. Can., Open File 353.

Jancey, R.C.
1966: Multidimensional group analysis; Aust. J. Botany, v. 14, no. 1, p. 127-130.

Killeen, P.G., Hunter, J.A., and Carson, J.M.
1971: Some effects of altitude and sampling rate in airborne gamma-ray spectrometric surveying; Geoexploration, v. 9, p. 231-34.

Killeen, P.G., Carson, J.M., and Hunter, J.A.
1975: Optimizing some parameters for airborne gamma-ray spectrometric surveying; Geoexploration, v. 13, p. 1-12.

Lefkovitch, L.P.
1975: Hierarchical clustering from principal coordinates; an efficient method for small to very large number of objects (unpubl. manuscript).

Richardson, K.A.
1976: Canada's Uranium Reconnaissance Program; in Uranium Geophysical Technology Symposium (Abstract), Bendix Corp., Grand Junction, Colorado, Sept. 14-16, 1976.

Richardson, K.A. and Carson, J.M.
1976: Regional uranium distribution in northern Saskatchewan; Symposium on Uranium in Saskatchewan, Sask. Geol. Soc., Spec. Pub. 3, p. 27-50.

Schwarzer, T.F., Cook, B.G., and Adams, J.A.S.
1972: Low altitude gamma-spectrometric surveys from helicopters in Puerto Rico as an example of the remote sensing of thorium, uranium and potassium in soils and rocks; Remote Sensing Environ., v. 2, p. 83-94.

Schwarzer, T.F. and Adams, J.A.S.
1973: Rock and soil discrimination by low altitude gamma-spectrometry in Payne Co., Oklahoma; Econ. Geol., v. 68, p. 1297-1312.

Slaney, V.R.
1971: Colour aerial photography of Hearne Lake (85I) and Yellowknife (85J) map sheets; Geol. Surv. Can., Open File 100.