GROUND FOLLOW - UP OF SOME RADIOMETRIC ANOMALIES AT JENGRE, PLATEAU STATE, USING GAMMA RAY SPECTROMETRY

BY

AHMED AMINU LAWAL

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DECLARATION

This is an original work carried out by the author under the supervision of Dr. Bala Bello Muhammad Dewu, of the Centre for Energy Research and Training, Ahmadu Bello University, Zaria.

This thesis has not been submitted in whatever form to any organisation or body for the award of any degree other than the Ahmadu Bello University.

All inclusions from the work of others have been duly acknowledged.

A. A. Lawal
(Author)

14-6-94
Date

CERTIFICATION

This thesis entitled; Ground Follow-up of some Radiometric Anomalies at Jengre, Plateau State using Gamma-ray Spectrometry; by Ahmed Aminu Lawal meets the regulations governing the award of the degree of Master of Science, Applied Geophysics of Ahmadu Bello University, Zaria, and is approved for its contribution of knowledge and literary presentation.

.....
Dr. B.B.M. Dewu
Chairman, Supervisory Committee

7th July, 1994
.....
Date

.....
Dr. M.N. Umego
Member, Supervisory Committee

6th July, 1994
.....
Date

.....
Prof. S.B. Ojo
Head of Department

07/07/94
.....
Date

.....
Prof. D. Mohammed
Dean, Postgraduate School

15/1/95
.....
Date

DEDICATION

This work is dedicated to my father, LATE ALHAJI AHMADU MOHAMMED LAWAL. May his soul rest in peace.

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ABSTRACT

The aero-radiometric' survey map of Lere (sheet 147) was studied with a view to selecting an area for detailed ground investigation to determine the radioelement potentials of the region. The map revealed several anomalies out of which the one with high uranium count, low potassium count and zero magnetic intensity occuring on flight line 32 was choosen for further ground investigation.

The ground spectrometric investigation was aimed at characterising the anomaly in terms of its radioelements content ie uranium, thorium and potassium. The investigation was particularly conducted to determine the uranium potentials of the anomalies detected in the region. Data was collected using a DISA-300 gamma ray spectrometer at stations spaced 50m apart. Analysis of data indicated that about 30% of the surveyed area could be characterised as an area of possible uranium mineralization.

Available data from uranium geochemistry was compared with the equivalent uranium concentrations calculated from the field gamma-ray spectrometric data. The comparison showed that the uranium concentrations in the area may be of low grade. Thus an independent geochemical analysis of the rock samples in the area need be carried out.

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CHAPTER ONE

INTRODUCTION

1.1 Preview

Geological and Geophysical Surveys in search of uranium deposits could be said to have started in Nigeria in 1947 when the mineral pyrochlore, containing substantial amount of uranium was discovered by the Geological Survey department in small granite bodies on the Jos Plateau. The occurrence of these granite bodies were surveyed in greater detail in 1949/50 by atomic energy division of the Geological Survey of Great Britain which carried out considerable laboratory analysis of the rock samples. These samples include core samples from 12 boreholes in the area altogether totalling 700m deep. The pyrochlore was found to contain about 3.3% U_3O_8 but extraction of the uranium from the mineral proved difficult (OECD & IAEA, 1979).

In 1969, an airborne radiometric survey covering 85,000 km^2 was undertaken by the International Resources Gooperation for ocean exploration of the United States. The survey covered two areas underlain by sediments of the Gundumi and Illo formations, Bima and Yolde formations in the then Sokoto, Bauchi and Borno divisions respectively. Though some areas with radiometric anomalies were identified, no ground

follow up was carried out (OECD & IAEA, 1979).

In 1973/74, the Geological Survey department contracted out the airborne gamma Spectrometer Surveying of four contigious areas;

1. Sokoto and Middle Niger area (Hunting)
2. Central North (Katsina - Jos) (Hunting)
3. Lower Benue and Adjoining Area (Fairey)
4. Upper Benue and Adjoining Region (Polservice)

These Surveys were completed and reports submitted in 1975/76. The Geological survey department commenced ground follow-up in 1976. This programme consisted of traversing identified areas with gamma spectrometers and scintillometers followed by detailed radiometric survey on grids, geological mapping, pitting, trenching and diamond drilling. Areas covered include about 20,000 km^2 in Sokoto State, 10,000 km^2 in Cross River and Benue States and 8,000 km^2 in the Niger and Benue Rivers confluence area of Northern Nigeria. No appreciable quantity of Uranium was found therefore no further drilling was carried out (OECD & IAEA, 1979).

In 1975, the Nigerian Mining Corporation carried out a feasibility study on the prospect of uranium mineralization in Nigeria. This was followed by a geochemical and reconnaissance ground traversing with scintillometers. A total area of 35,000 km^2 in north-eastern Nigeria was covered in

this programme. This programme was expanded in 1981 to include the Central area of Nigeria. Reconnaissance field work commenced in October, 1981. Readings were taken using total count scintillometers (ssp^2) and the results were contoured on a map of 1:100,000 Standard Sheets (Dada et al, 1982). In a report in 1979, the (OECD) expected an increase in the level of U exploration depending on the success of the efforts then. It however noted that the Federal Governments position on U exploration was not clear although a decree establishing the Nigerian Atomic Energy Commission (NAEC) (now Energy Commission of Nigeria (ECN) was promulgated. The need for such a commision necessarily means an increase in the area of U exploration/in the exploration of the radioelements to the industry/establishment. Also, the need for nuclear energy to play a prominent role in future energy supply was clearly demonstrated in the concluding report of the world Energy Conference (WEC) released in September 1978. All these mean that there is going to be an increase in the area of U exploration both locally and internationally.

In Nigeria, already, the initial stage in the large scale exploration for the radio-elements was launched when high sensitivity aero-radiometric surveys were carried out in 1975. The Survey covers the lower Benue area, the Middle Niger and the

Sokoto area conducted by Fairly Surveys Ltd. and Hunting Geology and Geophysics Ltd. respectively on behalf of the Federal Ministry of Mines and Power. Although intensive ground follow-up surveys have been carried out in some areas since 1977 (for example) the Nigeria Uranium Mining Company (NUMCO), the Nigerian Mining Corporation, the Geological Survey of Nigeria and by the Energy Research and Development Centre of the University of Ife), there is very little information on Uranium Occurrences in Nigeria. The little available information on uranium occurrences in Nigeria are mainly from individuals who have analyzed a few rock samples and uranium ores from some locations around the Nigerian Younger Granite province. However, the work of Uwah (1984) and Dewu (1986) who carried out detailed investigation of radiometric anomalies in the Sokoto Basin and Bisidhi areas of Sokoto and the Plateau States respectively, forms a very important step for a large scale exploration of U and allied minerals.

Only few ground radiometric surveys have been reported on the basement rocks of Nigeria. The present work is an investigation of an aeroradiometric anomaly on the basement complex of Nigeria using geophysical technique. The anomaly is contained in

Sheet 147 (aeroradiometric map of Lere). The map sheet was carefully studied to identify the anomaly patterns. Based on the preliminary study, an anomaly with high uranium and thorium contents was selected.

1.2 Uranium minerals and their occurrence

Uramium is an oxyphile element occuring in minerals of varying degrees of chemical complexity especially in association with the more acidic rocks of the lithosphere (Bowie, 1970). Economic Uranium deposits occur in both volcanic and plutonic rocks, in metamprphic rocks and in stratified and non stratified sedimentary rocks but the largest known reserves occur in sedimentary rocks (Dodson, 1972).

Uranium ore deposits can be classified into three major types - detrital, hydrogenic and Igneous - metamorphic. Although some igneous - metamorphic deposits form as primary concentrations, detrital and hydrogenic deposits formed as secondary concentrations at or near the surface of the earths crust are known. The uranium in these environments are believed to have been initially exposed to the surficial environment in felsic intrusive and volcanic rocks in concentrations generally less than 50 ppm. These are then concentrated in the present environment by secondary processes.

The classification of uranium deposits just like any other ore deposit is difficult in that it requires an interplay of genetic, geometric, mineralogical, petrographic, tectonic and chemical factors - some of which may be conflicting. The classification shown in Table 1.1 below is an attempt to reconcile these numerous factors so that their similarities may be emphasized.

Table 1.1 Types of important uranium Deposits (BOwie, 1970)

Type of Deposit	Characteristic Elements	Characteristic Minerals
IGNEOUS & METAMORPHIC Carbonatite	Nb, U, Th, Cu P, Ti, Z	Uranothorianite, pyrochlore betarite, peroskite, nicolite, chalcopyrite, Iemenite, apatite and Zircon.
HYDROGENIC Peralkaline Syenites	Nb, U, Th, Cu Pi, Ti, Zr	As in above
Pegmatitic	Th, U, Mo, Nb	Uraminite, Uranothorite molybderite, betafite allanite, fluorite.
Porphyritic	U, Th, Mo, Nb Ti, Zr	Uraminite, Uranothorite Monazite, Zircon, fluorite, sulphites.
DETRITAL Conglomerate	U, Th, Ti, Re Au	Uraminite, brannerite, Pyrite, monazite

The ores in both quadrivalent (U^{+4}) and hexavalent states (U^{+6}). The quadrivalent group which includes uraminite, Coffinite, and davidite are

generally black in colour, grading to brownish black and dark brown in the oxidized materials. Most uranium minerals occur as uranyl compounds. Natural uranium is present as U^{+4} in most sub-surface environment because the U^{+6} state is stable only under oxidising conditions (Rich et al., 1977).

Except in some shales and igneous metamorphic deposits, uranium is not found in sufficient quantity in the common rock types in the earths crust to be extracted economically. The average uranium in common rock - types is 3.5 ppm in felsic granites and 3 ppm in syenites (Uwah, 1984). The average crustal abundance of uranium is about 2 ppm (Rich et al, 1977). The relative abundance of Thorium and uranium in common rocks of the earth's crust and the abundance of Thorium and Uranium in minerals of igneous rocks are shown in Table 1.2 and Table 1.3. respectively.

Table 1.2 Average Relative abundance of Thorium and Uranium in various rock - Types (Adapted from Adams et al, 1954 and Parker and Ruzicka, 1979).

ROCK	THORIUM (ppm)	URANIUM (ppm)
Silicic intrusive	1 - 25	1 - 6
Silicic extrusive	9 - 25	2 - 7
Basic intrusive	0.5 - 5	0.3 - 2
Basic extrusive	0.5 - 10	0.2 - 4
Ultrabasic	low	0.001 - 0.03
Alkaline	low	0.1 - 30
Silicic Pegmatite	1 - 2	1 - 4
Clay and Shale	-	3.5
Limestone	-	2.2
Deep-Sea clays	-	1.3
Sandstone	-	0.45

Table 1.3 Thorium and Uranium in Minerals of Igneous rocks (Adams, et al 1954)

Mineral	Thorium (ppm)	Uranium (ppm)
ACCESSORY		
Allanite	(500 - 5000) (1000 - 2000)	(30 - 700) (? 100)
Apatite	(20 - 150) (50 - 250)	(5 - 50 (10 - 50 (?)
Epidote	50 - 500	20 - 50
Ilmenite		1 - 50
Magnetite	0.3 - 20	1 - 30
Monazite	25,000 - 200,000	500 - 3000
Sphene	100 - 600	100 - 700
Xenotime	low	500 - 35,000
Zircon	(100 - 2500) (50 - 4000)	(300 - 3,000) (100 - 6,000)
MAJOR		
Biotite	0.5 - 50	1 - 40
Hornblende	5 - 50	1 - 30
Potassium feldspar	3 - 7	0.2 - 3.0
Muscovite		2 - 8
Olivine	Low	0.01
Plagioclase	0.5 - 3.0	0.2 - 5.0
Pyroxene	2 - 25	0.01 - 40
Quartz	(0.5 - 6.0 (2.0	(0.1 - 50 (0.7

The lowest - grade ore deposits such as Rossing deposits contain approximately 240 g U_3O_8/t or approximately 325 ppm U. Some granites and syenites and their extrusive equivalent contain up to 50 ppm uranium with 'hot spots' to a few hundred ppm. In a few cases, peralkaline syenites locally contain up to 3000 ppm U.

1.3 Uranium mineralization in Basement Complex Rocks in Nigeria.

The Basement Complex rocks in Nigeria are exposed mainly in the northern, south-western and south-eastern parts of the country. Rahaman, (1976) recognized five petrological units within the Basement Complex of Nigeria namely;

i) migmatite gneiss complex

ii) slightly migmatized to non-migmatized para schists and meta-igneous rocks.

iii) Charnockitic rocks, metagabbros and pyroxene dionites.

iv) Older granites

v) unmetamorphosed dolerite dike and hypabyssal intrusives.

Limited geochemical studies on the basement rocks of South-western Nigeria indicate that the schists and quartzites have low uranium contents (average of 0.3 and 1.1 ppm U, respectively) (Rahaman & Oshin, 1984). The average uranium concentrations (average 3.4 ppm U) are also observed

in some metasediments and gneisses in the north-eastern part of the country. However, airborne radiometric survey has indicated a belt of uranium anomalies in the migmatite - gneiss complex stretching from Katsina-Ala to Dongo in the then North-Eastern Nigeria. These are believed to contain some uranium mineralization of economic importance (Rahaman & Oshin, 1984).

Studies carried out on the Older Granites from central and north-eastern Nigeria indicate possible U enrichment (Rahaman & Oshin, 1984). Preliminary geo-chemical work has also been carried out to assess the possibility of finding Uranium deposits in the Older Granite rock of north-east and south-west of Nigeria. Most of the analyzed samples from north-eastern Nigeria have less than 5 ppm U although higher uranium contents (10 ppm) are recorded in anatectic migmatites and porphyritic granites associated with anatectic migmatite. Examples of these are found around Mayo Belwa and Jalingo areas of Gongola State. Some pegmatites around Adada, north-east of Yola, contain as much as 72 ppm U. This value is about 18 times as much as the average concentration of uranium in normal granitic rocks and suggests a possible low grade uranium mineralization.

Ground gamma-ray spectrometric surveys along some traverses in the basement complex rocks in the Ife-Ilesha area of South western Nigeria did not

indicate any significant radiometric anomaly (Rahaman & Oshin, 1984). Similarly, geochemical studies show that granitic rocks in this area in general record normal average granitic uranium concentration. However, in the Erio, Aramoko area, one member of the Older Granite series (a coarse porphyritic granite) has been shown to contain as much as 30 ppm U. This may not be indicative of any uranium mineralization but suggests that the porphyritic granite may act as source rocks for continental sandstone type deposits (Rahaman & Oshin, 1984).

An interesting finding in the Basement Complex of Nigeria is the occurrence of uranium anomalies at the boundary between the Pre-Cambrian Basement Complex and the overlying Cretaceous sediments in places such as Kontagora, Wawa and Nasarawa. These areas of uranium anomaly may be further investigated for uranium potential (Rahaman & Oshin, 1984).

1.4 Radiometric Anomalies

The task of delineating a radiometric anomalous region involves an initial reconnaissance survey of the area. The purpose of this survey stage is to decide whether or not it is worth while to undertake a systematic gamma ray survey of the area in question. This decision can normally be made from a few tens of hours of relatively fast gross-count aero-survey at an altitude of 100 to 150 m. A fairly constant and low counts may indicate absence of uranium enrichment and

such areas can be eliminated for further surveys. This, however, does not mean that the area so eliminated are unfavourable for uranium exploration by other methods (Uwah, 1984).

In most systematic reconnaissance surveys, the total counts are analyzed and contoured to delineate areas of abnormally high radioactivity. These abnormally high radioactive areas are termed anomalous areas. The total counts which indicate anomalies are generally too erratic and variable to be contoured and they generally cover only a small area. In some cases, however, the anomalies cover sufficiently large areas to be contoured on large scale maps (Williams and Scherbastskoy, 1951).

Gamma ray spectrometry is used both in the reconnaissance and detailed surveys. The anomalies recognised from the Preliminary Surveys are of great practical importance for they may be an indication of deposits of radioactive ore.

Gamma ray spectrometric method does not measure uranium directly. The measurement is based on Bi-214 (one of the daughters in the U-238 decay series). Bi-214 may be separated from the uranium deposit if there are favourable conditions (for example presence of faults and joints) to enhance radon migration thereby causing disequilibrium in the U-238 decay chain. Therefore radiometric anomalies may not

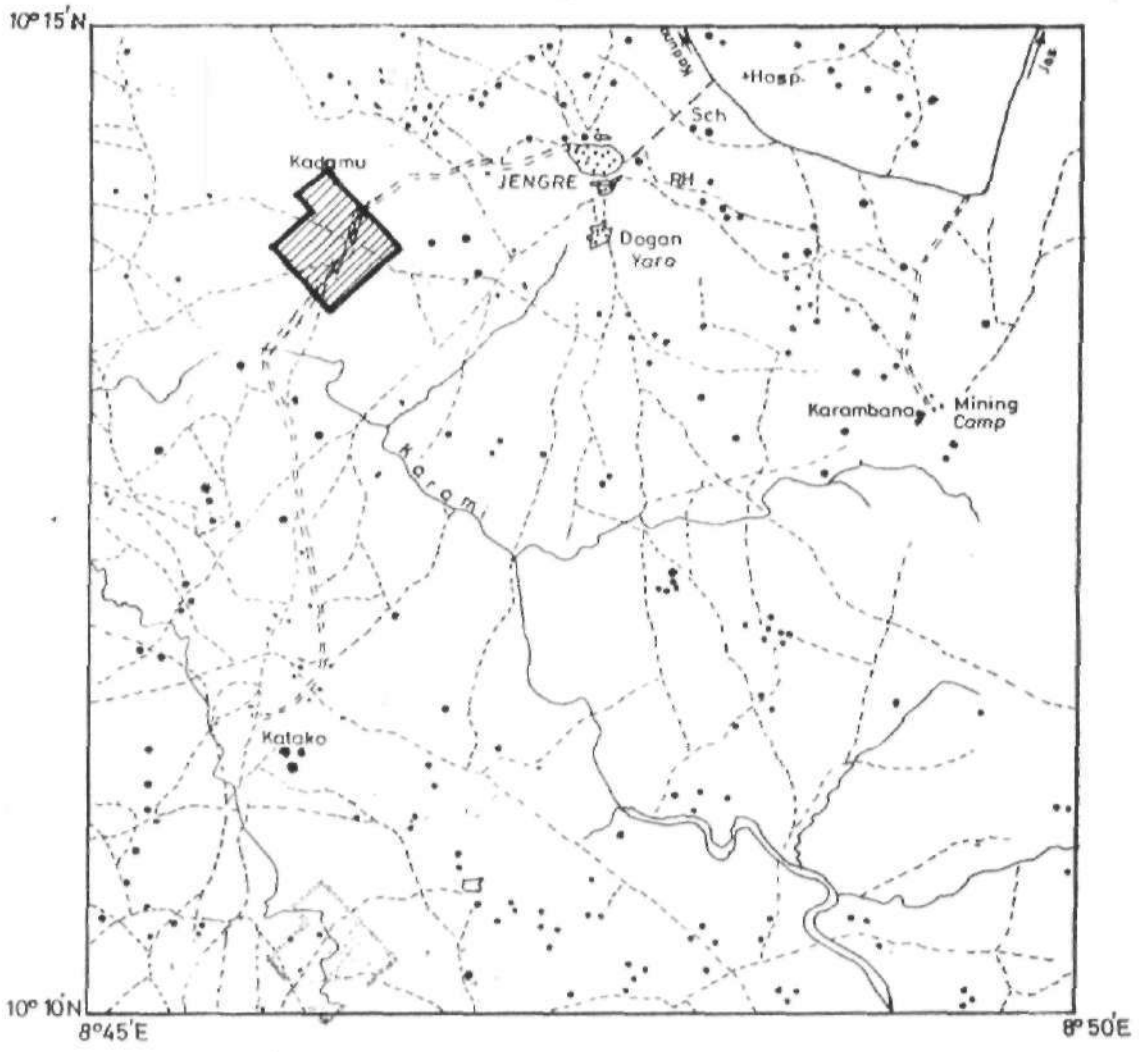
necessarily correlate with uranium mineralization (IAEA, 1980). Hence radiometric anomalies require thorough investigation before conclusions are made as to their economic importance.

1.5 Location and geology of the Area

The area is located in the South-eastern part of Lere (sheet 147) between latitudes 10° $10'$N and $10^{\circ}15'$N and longitudes $8^{\circ}45'$E and $8^{\circ}50'$E. It is near a village called Katako in Jengre L.G.A of Plateau state. There is a minor road from Jengre to the area of study (Fig 1.1). The area has some shrubs and scattered cultivations. It is devoid of waterways. The only water way is river Karami which passes through the landscape. Some outcrops are located just before the river towards Katako.

The area is within the crystalline basement adjoining the Jos Plateau. The geological sequence is made of plutonic and volcanic rocks belonging to pre Cambrian to lower Paleozoic age group.

The rocks comprise mainly of migmatites and gneisses which are all members of a single orogenic cycle (Fig 1.2). They are believed to have been formed largely from pre-existing gneisses by process of granitization (Buchanan et al, 1971). The migmatites occupy a large area but in general, exposure is limited and the few outcrops do not rise much above the surrounding relief. Petrologically, they are



L E G E N D

- Towns
- Huts, Villages
- Main Roads
- Secondary Roads
- Minor Roads
- Footpaths
- Hosp. Hospital
- Sch. School
- RH Rest House
- Study Area
- Rivers & Streams

FIG.1.1: LOCATION MAP OF THE AREA OF STUDY

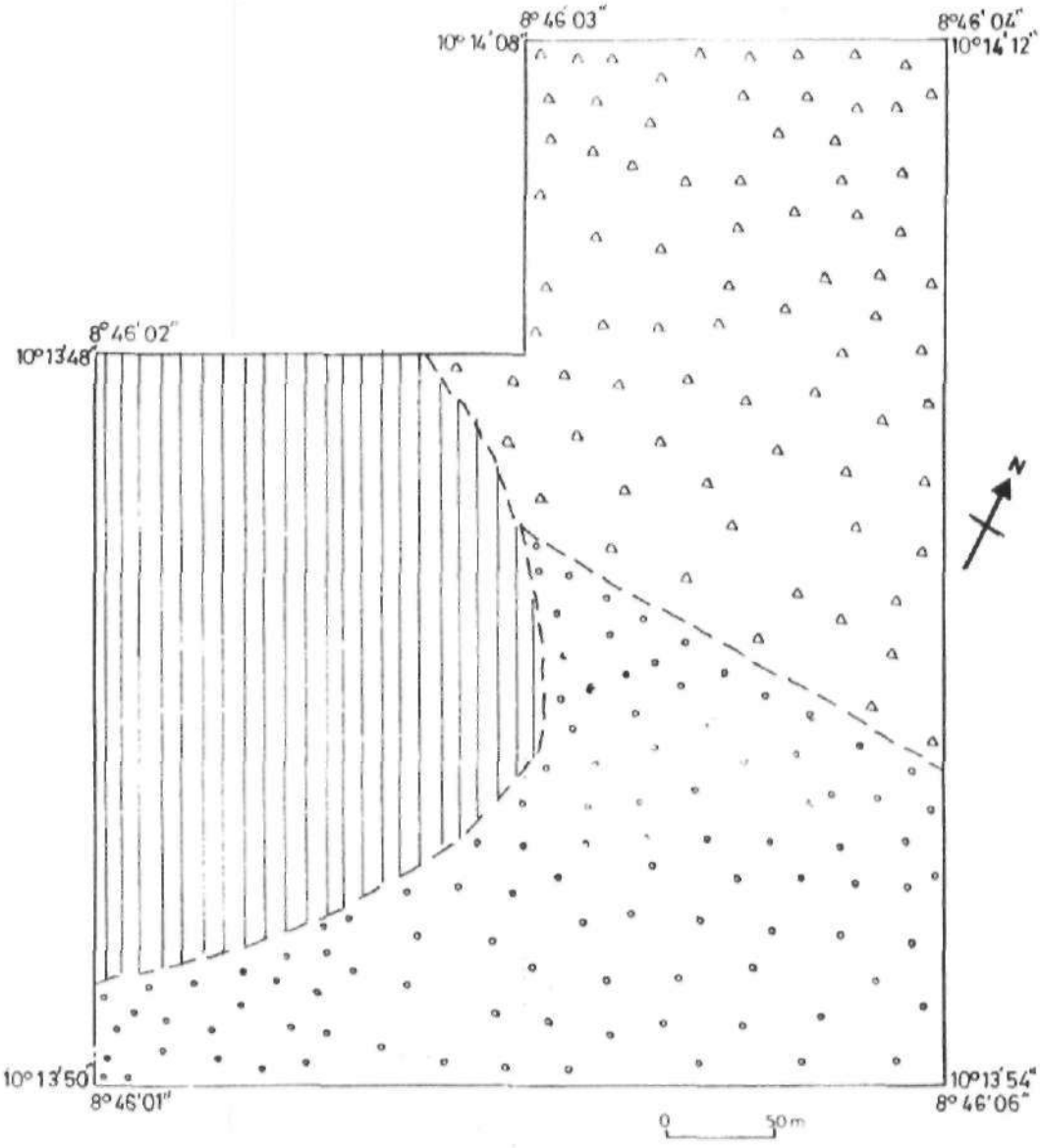


FIG.1.2: SURFACE GEOLOGY OF THE AREA OF STUDY
(After Buchanan et al 1971)

EXPLANATION

- Porphyroblastic gneiss (Medium and Coarse grained) including some Quartz and Feldspar
- Migmatites
- Hornblende biotite granite gneiss
- Geological boundary

made up of variable grain size. The gneisses are pre-dominantly of granodiorite composition but subordinate granitic or tonalitic phases also occur. The general texture is medium - grained and granoblastic with coarse porphyroblastic feldspar showing a variable and frequently localized occurrence. The gneisses are usually foliated (Buchanan et al, 1971). The rock types are covered with soil of varying texture.

1.6 Aim of the present survey.

The main aim of the present study is to carry out an investigation of an aeroradiometric anomaly identified on the aero-spectrometric map of Lere (Sheet 147) prepared by Hunting Geology and Geophysics (1976) in order to characterise the anomaly in terms of its radioelement contents. In particular, the investigation aims at determining the uranium potentials of such an anomaly. This is more so that the results of this study could be used in the interpretation of similar anomalies recorded in other areas of the basement complex of Nigeria.

CHAPTER TWO

PRINCIPLES OF RADIOACTIVITY AND RADIOMETRIC EXPLORATION METHODS

2.1 Principles of Radioactivity:-

The nuclei of some elements disintegrate spontaneously emitting energetic particles and electromagnetic radiation and in doing so are transformed into nuclei of other elements. The process of disintegration is called radioactivity and the elements that undergo such a process are called radioactive elements. The daughter elements may also be radioactive in their turn. The particles emitted are alpha (α) and beta (β) particles which are helium nuclei and electrons, respectively. The α- particles carry positive charge while the β- particles are unstable and carry negative charge. In the emission of these particles electromagnetic radiations are emitted. The electromagnetic radiation consists of gamma (γ) rays which are X-rays but of very short wavelength and therefore possess high energy. In addition to α, β and γ emission processes, there is also another type of nuclear transmutation called electron capture or K - capture. This is likewise an interaction between the nucleous and its extra nuclear electrons. It happens more frequently with electrons in the inner shells.

There are many naturally occurring radioactive elements and very many artificially produced ones. Natural radioactivity is confined principally to the

disintegration products of 3 elements namely; uranium, thorium and potassium. In addition to these, other naturally occurring radioactive isotopes are known. Examples of these include rubidium and the rare earth elements samarium and lutecium.

Whereas potassium undergoes a simple form of radioactive decay, the decay of uranium and thorium is complex and proceeds sequentially along a chain of disintegration. Each of the particles emitted during radioactive decay has its own characteristics and the gamma rays are characteristics of the elements which emit them. Natural sources of gamma radiation in rocks originate from uranium and thorium decay chain and the decay of potassium-40. The decay chains of uranium and thorium, and some of the gamma rays emitted by their daughters are shown in Table 2.1. All the three isotopes decay to a stable isotope of lead (Telford et al, 1976).

Each of the radioisotopes emits gamma radiation of characteristic energy and the gamma ray spectrum of a rock exhibits peaks of varying intensities corresponding to these characteristic energies. Figure 2.1 shows examples of such peaks for granite gneiss. About 11% of the natural potassium is K - 40 (half life = 1.3×10^9 yrs). It decays by electron capture to Ar-40 yielding gamma rays of energy 1.46 MeV. Gamma rays with this energy are used in gamma - ray

TABLE 2.1 RADIOACTIVE SERIES OF THORIUM AND URANIUM (Telford, 1976)

ELEMENT	ISOTOPE	HALF-LIFE	DECAY CONSTANT	RADIATION	γ-RAY ENERGIES (MeV)	Nº OF γ
Thorium	$_{90}Th^{232}$	1·4 x 10 yr	$1·58 \times 10^{-18}$	α, SF, γ	0·059	—
Radium	$_{88}Ra^{228}$	0·57 x 10yr	$3·3 \times 10^{-9}$	β, γ	0·03	>10
Actinium	$_{89}Ac^{228}$	6·1 hr	$3·1 \times 10^{-4}$	β, γ	0·06 - 0·97	5
Thorium	$_{90}Th^{228}$	0·91 x 10yr	$1·15 \times 10^{-8}$	α, γ	0·085-0·214	—
Radium	$_{88}Ra^{224}$	3·64 days	$2·2 \times 10^{-6}$	α, γ	0·24 - 0·29	—
Radon	$_{86}Rn^{220}$	51 sec.	$1·3 \times 10^{-2}$	α	0·54	—
Polonium	$_{84}Po^{216}$	0·16 sec.	4·3	α, γ	—	5
Lead	$_{82}Pb^{212}$	10·6 hr	$1·8 \times 10^{-5}$	β, γ	0·11 - 0·41	>10
Bismuth	$_{83}Bi^{212}$	60·6 min	$1·9 \times 10^{-6}$	β, γ	0·04 - 2·2	—
Polonium	$_{84}Po^{212}$	$0·3 \times 10^{-6}$ sec.	$2·3 \times 10^{6}$	α,	—	5
Thallium	$_{81}Tl^{208}$	3·1 min	$3·7 \times 10^{-3}$	β, γ	0·28 - 2·61	10
Lead	$_{82}Pb^{208}$	Stable			—	>10
Uranium	$_{92}U^{235}$	$7·1 \times 10^{8}$ yr	$3·1 \times 10^{-17}$	α, SF	0·07 - 0·33	>10
Thorium	$_{90}Th^{231}$	25·6 hr	$7·4 \times 10^{-6}$	β, γ	0·08 - 0·31	9
Protactinium	$_{91}Pa^{231}$	$3·4 \times 10^{4}$ yr	$6·5 \times 10^{-13}$	α, γ	0·29 - 0·36	>10
Actinium	$_{89}Ac^{222}$	2·16 x 10yr	10^{-3}	β, γ	0·09 - 0·19	4
Thorium	$_{90}Th^{227}$	8·2 day	$4·35 \times 10^{-7}$	α, γ	0·05 - 0·033	>10
Francium	$_{87}Fr^{223}$	22 min	$5·2 \times 10^{-4}$	β, γ	0·05 0·31	—
Radium	$_{88}Ra^{223}$	11·7 day	$6·16 \times 10^{-7}$	α, γ	0·03 - 0·45	—
Radon	$_{86}Rn^{219}$	4 sec.	0·17	γ	0·22 - 0·4	—
Astatine	$_{85}At^{219}$	54 sec.	$1·28 \times 10^{-2}$	α, β	—	—
Polonium	$_{84}Po^{215}$	$1·8 \times 10^{-3}$ sec	$3·8 \times 10^{2}$	β	—	—
Astatine	$_{85}At^{215}$	10^{-4} sec	$6·9 \times 10^{3}$	α	—	—
Bismuth	$_{83}Bi^{215}$	8 min	$1·44 \times 10^{-3}$	α, β	—	—
Bismuth	$_{83}Bi^{211}$	2·15 min	$5·35 \times 10^{-3}$	β, γ	0·35	4
Polonium	$_{84}Po^{211}$	0·52 sec	7·32	α, γ	0·56 - 0·83	—
Lead	$_{82}Pb^{211}$	36 min	$3·2 \times 10^{-6}$	α β, γ	0·85 - 0·83	—
Thallium	$_{81}Tl^{207}$	4·8 min	$2·4 \times 10^{-3}$	β, γ	0·89	—
Lead	$_{82}Pb^{207}$	Stable	—		—	—
Uranium	$_{92}U^{238}$	$4·51 \times 10^{9}$ yr	$4·9 \times 10^{-18}$	α, SF, γ	0·048	>10
Thorium	$_{90}Th^{231}$	24·1 day	$3·3 \times 10^{-2}$	β, γ	0·03 - 0·09	—
Protretimium	$_{91}Pa^{234}$	6·7 hr	$2·84 \times 10^{-5}$	β, γ	0·044 - 1·85	7
Uranium	$_{92}U^{234}$	$2·48 \times 10^{5}$ yr	$8·9 \times 10^{-14}$	α, SF, γ	0·053 - 0·118	4
Thorium	$_{90}Th^{230}$	8×10^{4} yr	$2·75 \times 10^{-10}$	α, γ	0·068-0·25	—
Radium	$_{88}Ra^{226}$	$1·622 \times 10^{3}$ yr	$1·35 \times 10^{-11}$	α, γ	0·19 - 0·64	—

TABLE 2·1 Contd·

ELEMENT	ISOTOPE	HALF-LIFE	DECAY CONSTANT	RADIATION	γ-RAY ENERGIES(MeV)	Nº OF γ
Radon	$_{86}Rn^{222}$	3·82 day	$2·02 \times 10^{-6}$	α, γ	0·19 - 0·64	–
Polonium	$_{84}Po^{218}$	3·05min	$3·8 \times 10^{-3}$	β	–	–
Astatine	$_{85}At^{218}$	1·35sec	0·51	β		>10
Radon	$_{86}Rn^{218}$	0·03sec·	–	–	0·61	–
Bismuth	$_{83}Bi^{214}$	19·7min	$5·85 \times 10^{-4}$	β, γ	0·45 - 2·43	>10
Polonium	$_{84}Po^{214}$	$1·64 \times 10^{-4}$sec	$4·2 \times 10^{3}$	α	–	–
Lead	$_{82}Pb^{214}$	26·8min	$4·3 \times 10^{-4}$	α, β, γ	0·05 - 0·35	–
Lead	$_{82}Pb^{210}$	24 x 10yr	$1·05 \times 10^{-9}$	β, γ	0·047	–
Bismuth	$_{83}Bi^{210}$	5 day	$1·58 \times 10^{-6}$	β, γ	0·79	–
Polonium	$_{84}Po^{210}$	$1·38 \times 10^{2}$yr	$5·7 \times 10^{-8}$	α, γ	0·3- 0·75-1·1	–
Thallium	$_{81}Tl^{210}$	1·3 min	$8·85 \times 10^{-3}$	β, γ	–	–
Lead	$_{82}Pb^{206}$	Stable	–	–	–	–

SF — Spontaneous Fission

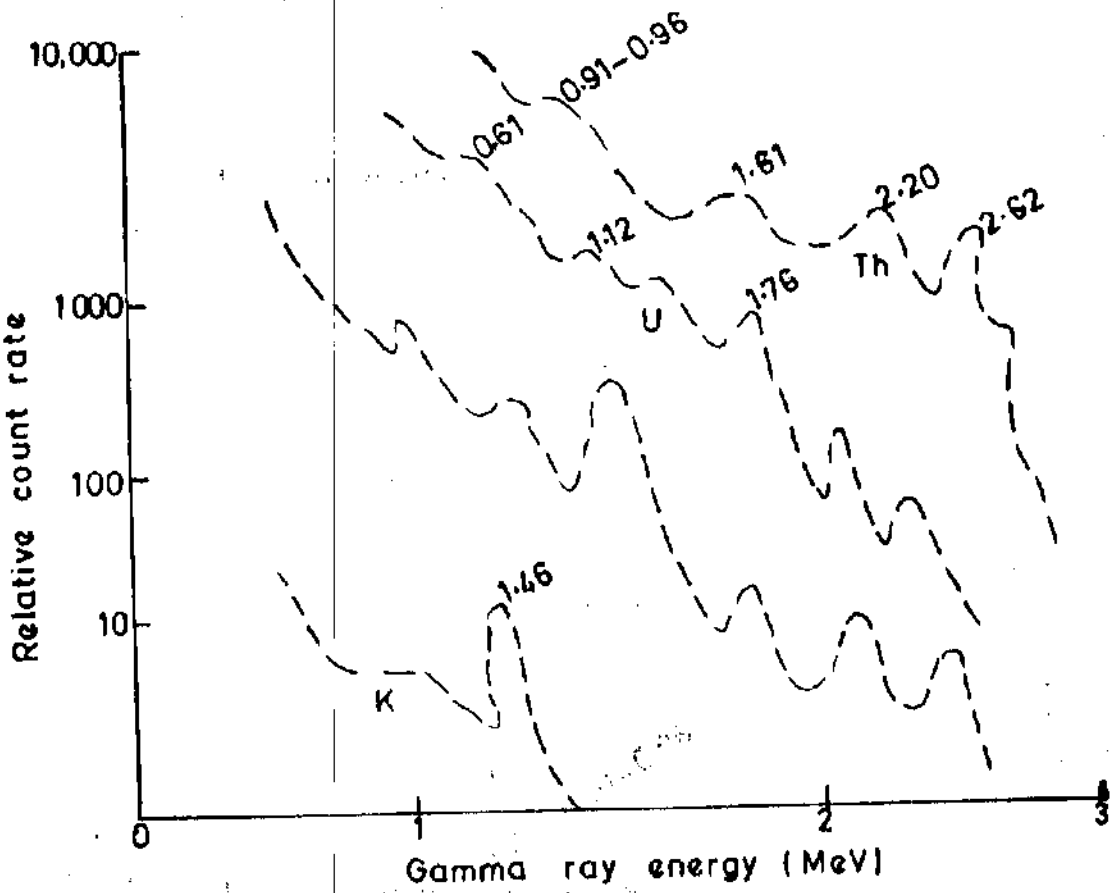


FIG. 2.1: SPECTROGRAMS OBTAINED FROM K U AND Th SAMPLES ON GRANITE GNEISS (After Doig, 1968)

spectrometry to detect and measure natural potassium in crustal rocks. Due to the relative low abundance of K - 40 in natural potassium, the intensities of the 1.46 MeV gamma rays are low (Figure 2.1).

Each of the decay chains of the U-235 and U-238 has an intermediate nuclide of atomic number 86, which is a gas under normal condition decaying by alpha (α) emission to a solid daughter, Radium, (Table 2.1). These are Rn-222 in U-238 and Rn-219 in U-235. The most promising radiation characteristic is that of Ra-234 which has an energy of 0.001 MeV, but this is present at a very low intensity (Doig, 1968). Of particular importance in gamma ray spectrometry is the decay of Bi-214 to PO-214 in the U-238 series. This decay yields several gamma rays of various energies. The 1.76 MeV gamma rays following this decay are normally used in gamma ray spectrometry in the determination of uranium in crustal rocks. The combination of the 1.76 and 1.12 MeV gamma rays emitted by Bi-214 has been used for uranium measurements (Uwah, 1984).

The decay chain of thorium is complex as shown in Table 2.1. Of particular interest in γ - ray Spectrometry is the decay of Tl - 208 to Pb - 208 by gamma emission. This decay results in the emission of 2.62 MeV gamma rays and is the highest gamma ray energy in the thorium decay series.

The 2.62 MeV peak is pronounced and free from interference (Figure 2.1) and is therefore considered as the most suitable for thorium concentration measurements in geological samples using gamma-ray spectrometry (Dewu, 1986).

2.2 Radiometric Exploration Methods

Radiometric method is a geophysical technique dependent on a property of the radioelement. As earlier stated, there are many naturally occurring radioactive elements in the earths crust, but only uranium, thorium and potassium are of importance for exploration purposes. This is because they emit strong gamma radiations and they occur in relatively large abundance in the natural environment. Also, these elements occur together in most rocks, and their ratios can be used to aid in such exploration works. The rest are either so rare or so weakly radioactive to make any significant contribution to the natural environment. Therefore, for uranium exploration purposes they are not considered important. For example, the abundance of Te - 130 in the crust is only about 0.017 ppm, a concentration much below the limit of detection of most of the analytical instruments currently available. Also, the possibility of the occurrence of transuranic elements such as Pn-239, Pu-244 and Np-237 which could contribute to the natural radiation environment is not certain. The importance of U, Th and K in contributing to the total heat budget

of the earth is generally recognised. The fact that these elements are sources of heat means that geothermal heat measurements can be employed for the determination of the abundance of the radio-elements within the earth's crust.

There are basically two radiometric survey techniques, the ground and the aero-radiometric surveys. Aero-radiometric Survey can normally be recommended in circumstances where the terrain is not easily accessible and/or large areas need to be prospected/covered. The technique becomes particularly advantageous because other geophysical techniques can be carried out simultaneously. The aero-radiometric surveys are superior to ground surveys for regional reconnaissance work because large areas can be covered in a relatively short time but there is always the danger of missing important targets because of uneven coverage. There are numerous documented cases of anomalies that were missed by an airborne survey owing to too wide a flight line spacing or rugged terrain which could have prevented the aircraft from maintaining a satisfactory ground clearance (Reedman, 1979). For example a uranium deposit consisting of a number of veins just produced a single large airborne anomaly whereas a ground survey with a high density of sampling points defined the individual vein sources as a series of separate anomalies.

For reconnaissance surveys, gross counts may be adequate to delineate areas of higher than normal radioactivity. However, where the contribution due to the individual radioelement is required, spectrometric surveys are employed. In this technique, individual contribution due to U, Th and K are obtained in addition to the Total count. Determination of the radioelement concentration can then be made assuming the decay series to be in secular equilibrium.

2.3 Concept of Equilibrium and U - Series Disequilibrium.

When a radioisotope decays, producing a radioactive daughter whose half-life is shorter than that of its parent, a condition of radioactive equilibrium will eventually be attained in which the daughter product is decaying as rapidly as it is being produced. The activity of the resultant mixture decreases at the same rate as that of the parent, ie it is determined by the half-life of the parent. This type of equilibrium condition is referred to as secular equilibrium. In this case, the daughters can attain 99% equilibrium with their parents. The time required for the daughter activity to reach 99.9% equilibrium will be approximately ten times the half life of the daughter (Dewu, 1989).

The decay of U-238 to its stable daughters, Pb-206 and Th-232 to Pb-207, involves nineteen and eleven daughters, respectively. If none of these

daughters is removed out of the series, sometimes after the formation of a U or Th bearing crystal, a state of equilibrium is reached, whereby the loss of a daughter due to its decay is made up by the decay of the preceeding parent. This occurs where the half-life of the parent is much larger than the half-life of the daughter. If one of the daughters is taken out of the system, however, disequilibrium is established, and the nuclides above the one which has been lost become proportionally more enriched in the series. Similarly, the nuclides developed from the decay of the lost daughter are depleted in the series. If the nuclide which has been lost has a short half-life then equilibrium is restored within a short time. On the other hand, the loss of nuclide with a long half-life will mean that the series takes a long time to regain equilibrium (Dewu, 1989). Due to the exponential character of radioactive decay, the nuclides in a decay series approach their equilibrium values assymptotically so that 100% equilibrium is never achieved.

The U-238 decay series contains a number of daughters with very long half-lives. U-234, Th-230 and Ra-226 which are members in this series, have half-lives of 4.5×10^5 years, 8×10^6 years and 1622 years, respectively, so that it will take approximately 10^6 years for the U-238 series to attain secular equilibrium. Thus, a loss of U-234 from the series

means that a period not less than 10^6 years will be required before 99% equilibrium between the members in the series is restored. In the Th-232 decay series, however, the longest - lived daughter, Ra-228 has a half-life of just 6.7 years so that equilibrium is restored within a relatively short period of time should a member be lost from the decay series. This makes the assumption of secular equilibrium in the Th-232 decay series safer than for the U-238 series (Dewu, 1989).

Disequilibrium is a serious problem in the use of simple gamma-ray spectrometers for U and Th determinations because both analyses are based on daughters which are far down the decay series. To obtain correct abundances requires the existence of equilibrium between the daughters and parents: Bi-214 with U-238 and Tl-208 with Th-232. In the Th-232 decay series, this requirements is, however, largely met in natural environments because of the relatively short half-lives of the members in the series, the longest being Ra-228 ($t_{\frac{1}{2}}$ = 6.7 years), which attain 99% equilibrium in less than 45 years. (Dewu, 1989). In addition, its gaseous daughter, Rn-220 ($t_{\frac{1}{2}}$ = 54.5 sec) is short lived, and can all decay before it ever gets the chance to escape from its parents. The U-238 series, however, contains a number of very long-lived daughters (U-234, Th-230, Ra-226), and loss of any one of these will mean a much longer period is needed for

re-establishment of equilibrium. Of serious concern also is the half-life of its gaseous daughter, Rn-222 ($t_{\frac{1}{2}}$ = 3.8 days) which is sufficiently long for it to survive to be transported to considerable distances away from its parent (Dewu, 1989).

Apart from U-238 and U-234 fractionation, U-238 has also been found separated from its other daughters in natural environments. Of importance in disequilibrium studies are the relationship with and between Ra-226, Pa-231, Rn-222, Pb-210 and Po-210. Whereas fractionation between U-234 and U-238 may be due to physical processes such as alpha recoil, fractionation between U-238 and its other daughters is better explained by the difference in chemical properties. Ra, in particular, has been found to be more soluble in water than either U or Th and can thus be removed by moving water from the sites of its deposit. Titayeva et al. (1973) reported excess Ra-226 over Th-230 and U-238 in soils and sediments. This was attributed to either the deposition of Ra-226 as absorbed ions onto clay minerals and organic matter, or preferential leaching of U-238. Ra-226 is also associated with oil field brines and deposits from hot springs (Rosholt, 1959). Chemical fractionation preferentially enriching Pa-231 relative to Th-230 in Mn nodules has also been reported by Gascoyne (1977). High Pa-231 in high grade black U minerals was reported by Rosholt (1959).

Rn isotopes, being gases are easily removed from members in the decay series, and may be the most important cause of disequilibrium in the U-238 decay series in environments favourable to Rn diffusion. Rn is also soluble in water and can therefore, be transported in aqueous solution. Also, Rn loss can produce artificial disequilibrium during sample preparation for U analysis (Dewu, 1989).

The need to assume secular equilibrium in four-channel gamma-ray spectrometry is a most important drawback in the use of the method for U exploration. This is because many factors may cause disequilibrium to occur, especially in the U decay series as discussed above. The development of secular equilibrium in the decay series is further complicated due to the difference in geochemical behaviour of the various daughters in each series. As discussed above, physical properties are also important because of the presence of gaseous daughters, Rn-222 and Rn-220 in the U-238 and Th-232 decay series, respectively.

Methods to determine the existence of equilibrium in the U-decay series from gamma spectrometric data and chemical analysis have been suggested. Comparison of the results of chemical analysis and the determination of equivalent uranium (eU) from gamma spectrometry is one of such methods. However, any conclusion reached from such methods much be treated with caution because of the possible complexity of the disequilibrium

which may occur in the U-decay series. For example such comparison may be found to show a linear relationship between chemically determined uranium (cU) and (eU) in samples where Bi-214 is not in equilibrium with U-238 (Dewu, 1993).

Indeed, at best, these methods can only be used to make an assessment of the equilibrium condition of the U decay series. Precise determination of disequilibrium can best be achieved by other methods such as the α - spectrometric methods (Dewu, 1989).

CHAPTER THREE

FIELD GAMMA RAY SPECTROMETRIC TECHNIQUE.

3.1 Principles of Gamma Ray Spectrometry

The radiometric technique most useful in the detection and assessment of radioactive elements is the gamma ray spectrometry. It involves the detection of gamma rays of varying energies of scintillations or solid state detectors. The scintillations are amplified, sorted out and stored as energy spectra by single or multi channel height analyzers. The spectral data can then be analysed to yield abundance of the individual radio-elements.

There are three major techniques of gamma-ray spectrometry namely multi channel, threshold (integral) and window. Multichannel Spectrometry involves obtaining Count rates from the full spectrum in a series of discrete channels. Threshold spectrometry, such as used in this work involves summing the counts from the spectrum in a series of overlapping steps by varying the energy threshold at which counting commences. The preferred gamma-spectrometric method of assaying Th, U and K consists of simultaneous gamma ray counting in three energy intervals or "windows" each of width of about 250 to 300 KeV and centred at 2.62, 1.76 and 1.46 MeV, respectively. This is the window type spectrometry and is the most commonly used in most airborne, ground surveys and laboratory analysis (Lovborg et al., 1979). It involves measuring the count rates only from portions

of the spectrum encompassing the photo peaks of interest. An energy window has to be selected to register particular gamma rays. The threshold gamma ray spectrometer is an instrument that transforms incident gamma ray radiation into a visual readout like all analogue spectrometers. It essentially consists of

a) A large scintillation detector having high resolution.

b) An extremely stable high voltage supply

c) An amplifier and a pulse height selection circuit

d) A digital or analog display of the count rate with two or more energy bands each characteristic of a natural radioelement.

e) A digital or analog display of the gross-count.

f) A timing circuit

g) A battery supply.

The detector is a thallium activated sodium iodide (NaI (Tl)) scintillation detector accompanied by a photomultiplier, coupled to a single or multichannel pulse height analyzer which stores the accumulated counts and delimits discrete portions of the gamma ray energy spectrum. The electronics of the spectrometer system are normally adjusted so that the spectrum encompasses gamma-ray - energies from the region of a few tenths of KeV up to 3-4 MeV. This energy region contains many characteristic gamma rays

of the U-238 and Th-232 decay series as well as the single gamma ray at 1.46 MeV of K-40. The sodium iodide crystal converts gamma rays into faint flashes of light whose brilliance is proportional to the energy level of the gamma radiation measured. These light flashes are detected by a high gain photo-multiplier tube, amplified and fed to a specialized circuitry (pulse height analyzer) which accepts only those signals above a selected energy or threshold setting. This setting is equivalent to the light flash intensity related to the known gamma ray spectrum of the radioactive elements. The signals are then registered in a frequency counts circuit as counts per unit time, and presented numerically on an illuminated digital display. The frequency or signal count rate displayed is the intensity of all gamma ray energy above a selected threshold setting. The digital readout therefore, is essentially a summation or 'integral' measurement. A block diagram of such spectrometers is as shown in Figure 3.1.

A typical gamma ray energy spectrum in the range covered by the threshold spectrometer is shown in Figure 3.2. The gamma ray peaks at 2.62 MeV, 1.76 MeV and 1.46 MeV can be readily distinguished.

The spectrogram also includes the normal effects of gamma ray energies other than those three which are of primary interest. Among those other energies include compton scatterring, cosmic rays and the

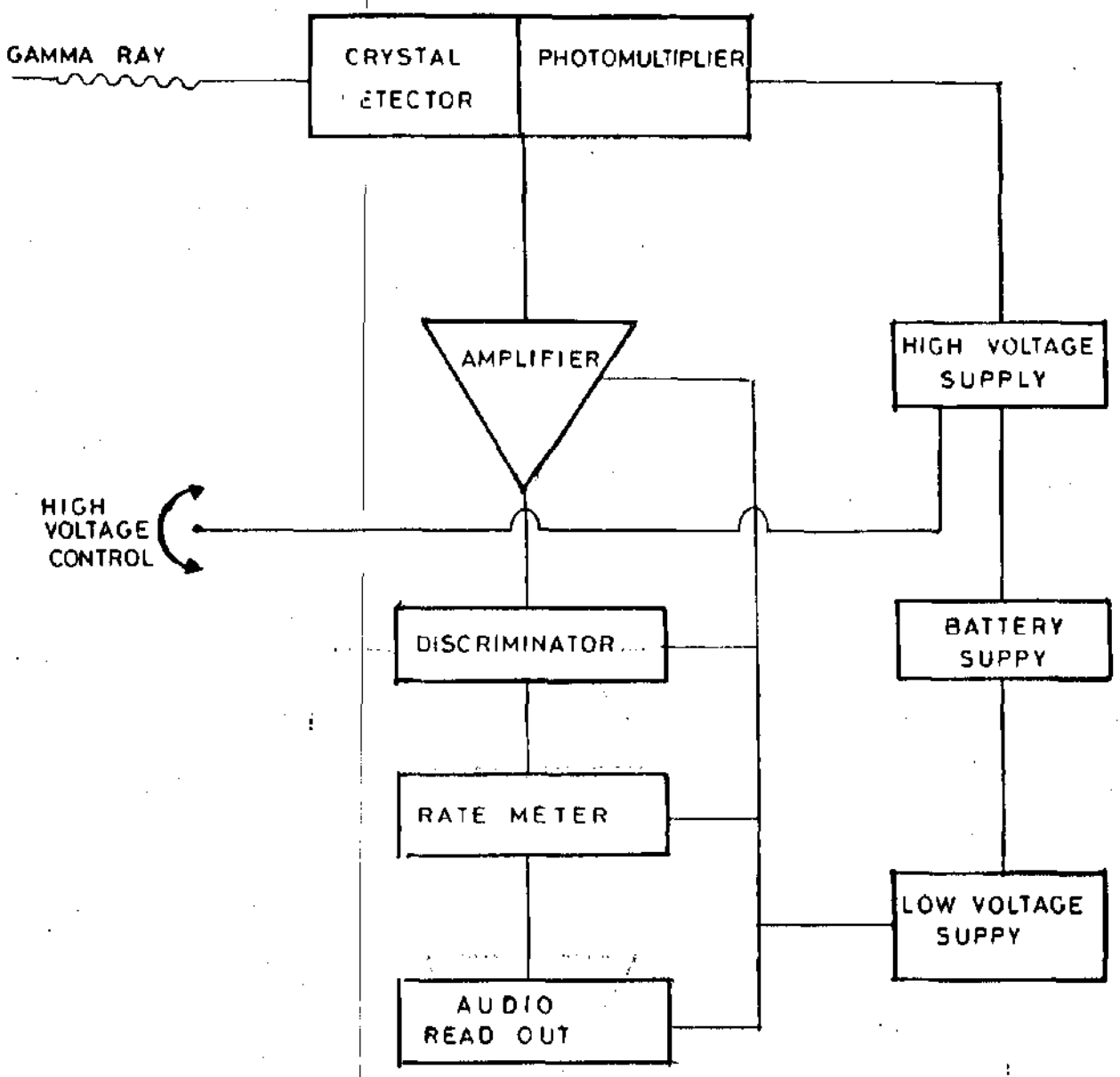


FIG. 3·1: BLOCK DIAGRAM OF A THRESHOLD GAMMA RAY SPECTROMETER

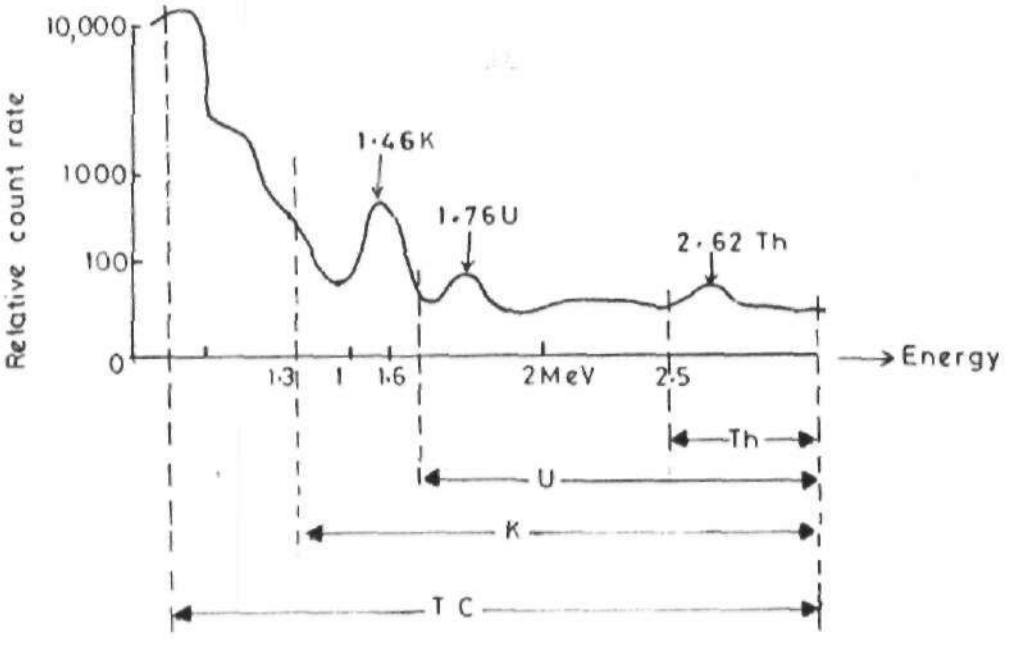
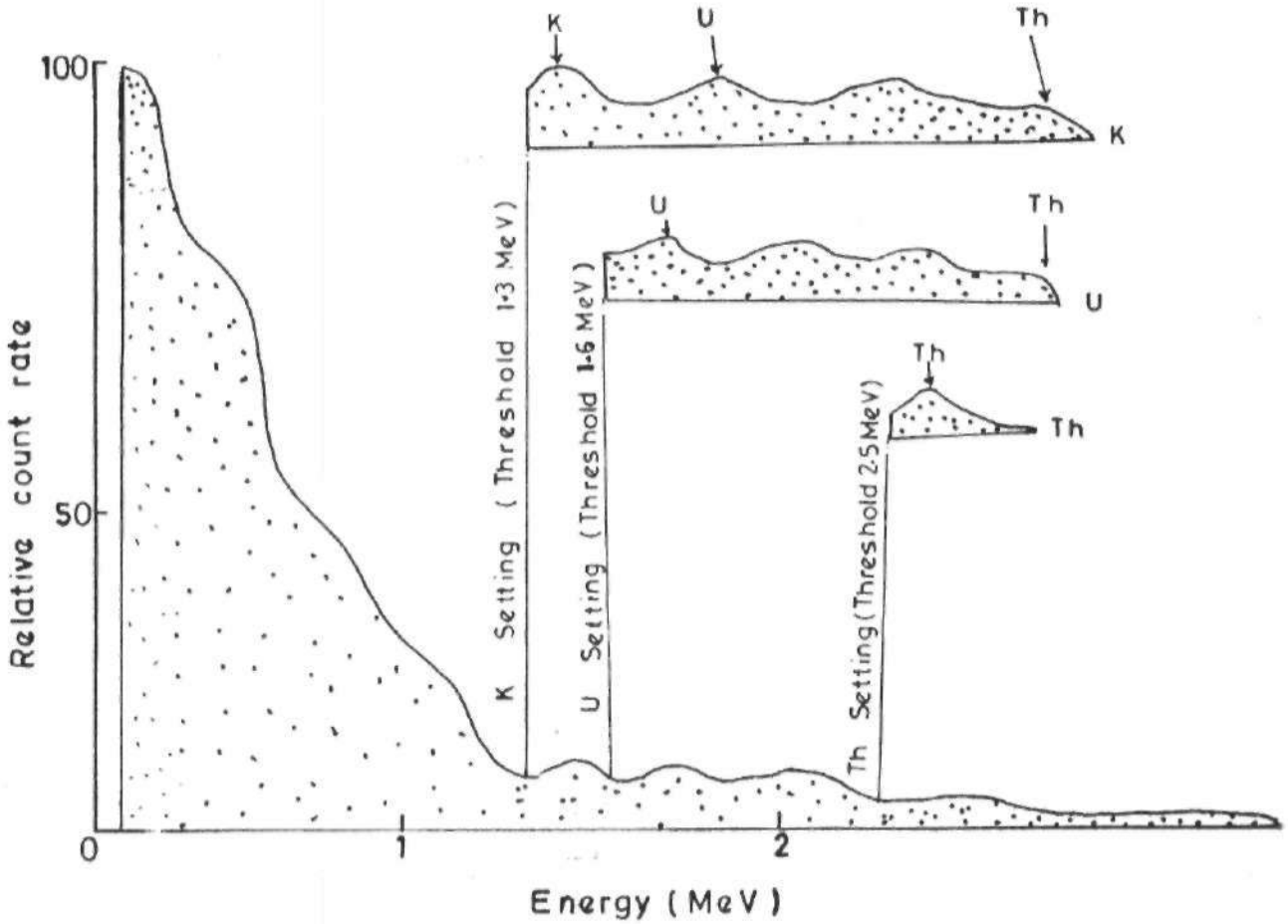


FIG.3.2:GAMMA RAY SPECTOGRAM FOR NATURAL ROCKS
(Geometrics, 1984)

gamma rays from other isotopes in the natural environment, which comprises a complex radioactive 'decay series with spectral peaks throughout the spectrum. Compton scattering is secondary gamma ray radiation at a lower energy produced by the primary gamma ray radiation. Cosmic rays are extra-terrestrial high-energy radiation whose contribution amounts to less than 10% of the total radiation (Geometrics, 1984).

The measurement of each element or gamma ray component involves the measurement of the intensity of all energies in the spectrum above a certain "threshold" setting. What is measured is a single number representing the total number of counts within that portion of the spectrum which can be expressed more or less by the area under the curve within each threshold setting as illustrated in Figure 3.3.

In order to normalize the response of different instruments used in Gamma ray spectrometric measurements it is necessary to use a standard reporting unit. First, to be universal, this unit must be practical and meaningful to the largest number of geoscience users whilst at the same time possessing acceptable scientific validity (IAEA, 1976). Since measurements of natural radioactivity are made in order to obtain information on the radioelement composition of rocks, the units



FIG·3·3: RELATIONSHIP OF COUNT RATE TO THRESHOLD SETTING

should

i) relate as directly as possible to radioelement concentration.

ii) under specified condition provide identical results in a direct comparison of radiometric with chemically determined values.

iii) not be subject to confusion with any other unit.

Furthermore, it's required that a consistent code should be adopted in order to distinguish estimations of abundance based on observation of the radioelement under investigation (IAEA, 1976).

Estimations of abundance based on a direct measurement of a property of a radioelement should be indicated by the element name or a symbol alone, thus percent potassium, parts per million uranium and parts per million thorium. When the measurement is based on a decay product, for example the use of a gamma emission of Bi-214 to estimate an abundance of uranium, then the term 'equivalent' or symbol 'e' should precede the element name or symbol, thus equivalent uranium or eU.

Measurements of Gamma ray spectrometric survey are currently being reported in terms of

(a) Counts per unit time (counts/second or counts/min)

(b) Microroentgens per hour (μR/h)

(c) Equivalent uranium (eU)

(d) Millivolts (mV)

(e) American Petroleum Institute gamma-ray Units (API Units) for bore-hole logging

(f) Multiples of background.

(g) Bequerel/gramme.

Only a small number of institutions have reported gamma-ray spectrometric data in terms of element concentration. The majority of air borne and ground surveys have based their reporting on count rates because now all modern radiometric instruments for field work are graduated in counts per unit time and are calibrated such that the individual radioelement (U, Th and K-40) concentrations can be calculated from the field readings.

The results of Gamma ray spectrometric survey of an area can be presented in any one or all of the following ways

i) a contour map showing areas of equal count rates

ii) a contour map showing areas of equal radioelement concentration, (%K) for potassium K and parts per million (ppm) for thorium and uranium, or

iii) a contour map showing areas of equal uranium to thorium ratios (U:Th) or Uranium to potassium ratio (U:K) or (Th:K).

Based on some analysis, areas of possible radio-element importance can be delineated in such presentation.

Gamma ray spectrometers are used in both airborne and ground gamma ray spectrometry. It should however be emphasised that much primary uranium prospecting will continue to be carried out on the ground, especially where aeroradiometric surveying is

impracticable for financial or other reasons. As an increasing percentage of the world's uranium resources must be sought in areas with sparsely developed road systems, most ground surveying will have to take place on foot with or without transportation support. Consequently, the light weight portable gamma spectrometers which are commercially available today, much of which have been improved are very suitable for this sort of work.

3.2 Data Processing

Field gamma-spectrometric surveying is a strong technique from which guidance on the nature of radioactive anomalies can be obtained. It's major advantages have been mentioned in the preceeding sections. It is therefore important that in view of the investment in equipment and manpower required for this type of work that the assay values obtained are permanently saved in an easily retrievable form (Lovborg, 1973).

Having obtained the spectrometric data, necessary corrections are then applied so as to obtain counts rates which are in proportion to the radioelement concentrations. The results could then be expressed in terms of concentration of the radioelements measured.

The procedure for estimating concentration of the three radioelements, K, U and Th depends on the type of spectrometer used. For a threshold spectrometer

such as the one used in this work, the relationship between the count rates and the element concentration is such that the concentration in parts per million (ppm) is directly proportional to the background corrected and stripped count rate (Uwah, 1984). Suppose the background readings in c/s in the thorium, uranium and potassium thresholds are Th_{bc}, U_{bc} and K_{bc} respectively, then

$$Th\ (ppm) = K_1\ (Th_c - Th_{bc}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.1$$

$$U\ (ppm) = K_2\ (U_c - U_{bc}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.2$$

$$K\ (\%) = K_3\ (K_c - K_{bc}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ 3.3$$

where K_1, K_2 and K_3 are the sensitivity constants of the spectrometer for the Th, U and K channels respectively.

Also, because of the interference of thorium in the uranium counts and thorium and uranium in the potassium counts, stripping ratios have to be incorporated into the above equations. This is because in determining potassium for example, the energy threshold used is 1.46 MeV, that is all gamma rays with energy above 1.46 MeV are counted. And since on this range, both the gamma rays emitted by the decay chains of uranium and thorium are present, then a means has to be found for correcting for their presence. Similarly, in measuring uranium, the threshold energy used is 1.76 MeV, so the only interference is from the gamma rays from thorium decay series and this must be accounted for. But in the measurement of thorium, the

energy threshold is set at 2.62 MeV hence there is no interference from any of the gamma rays from either potassium or uranium. Therefore in terms of the stripping ratios, the concentration equations become

$$Th\ (ppm) = K_1\ (Th_c - Th_{bc}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

$$U\ (ppm) = K_2\left[(U_c - U_{bc}) - S_1\ (Th_c - Th_{bc})\right] \quad \ldots\ldots (3.5)$$

$$K(\%) = K_3\left[(K_c - K_{bc}) - S_2(U_c - U_{bc}) - S_1(Th_c - Th_{bc}) - S_3(Th_c - Th_{bc})\right] \quad \ldots\ldots\ldots\ldots (3.6)$$

where S_1, S_2 and S_3 are the stripping constants.

For the determination of these constants, sites with known U, Th and K concentrations and where U and Th decay series are in equilibrium are required. Such sample sites must have an aerial radius of about 1m and extend to a depth of about 10cm. The instrument manufacturers use calibration pads for the determination of these constants. However, as the electronic components in the instrument age, these constants change and need to be checked regularly. Where calibration pads are not available, values supplied by the manufacturers have to be used. This is one further problem in gamma-ray spectrometry in developing countries in particular. Because of this factor, the effects due to drift caused by environmental factors such as temperature, and the fact that secular equilibrium is assumed in these computations, the abundance of the elements are reported as equivalent of the elements (eU or eTh) and not as absolute values.

3.3 Field Procedure

Ground gamma-ray spectrometry was employed for the collection of spectrometric data in this study. The area investigated measures 450 m by 1 km (about 2 km from river Karami which was previously identified in the aero-radiometric survey map of the area) (Figure 3.4). For the measurements, nine profiles were considered. Five of these profiles were each 1 km long and the remaining four 700 m long each. The station spacing on each profile is 50 m. The stations were established such that points outside the area delineated as anomalous from the aero-survey were considered. This is to look at the anomaly under study entirely because ground displacements of such anomalies have been reported (Dewu, 1986).

A DISA - 300 gamma ray spectrometer manufactured by Exploranium, a division of Geometrics was used for the measurements. The spectrometer is fitted with NaI(Tl) scintillation detector of 5.1 cm in diameter and 5.1 cm thick. The detector is coupled to a high gain photomultiplier tube. Because of the temperature/ drift characteristics of the photomultiplier tube, the spectrometer was calibrated every day before the start of the measurements during the course of the survey. For this, the spectrometer is provided with ^{60}Co calibration source. The procedure for taking readings involved placing the spectrometer on the ground at each station and readings taken for each window. The

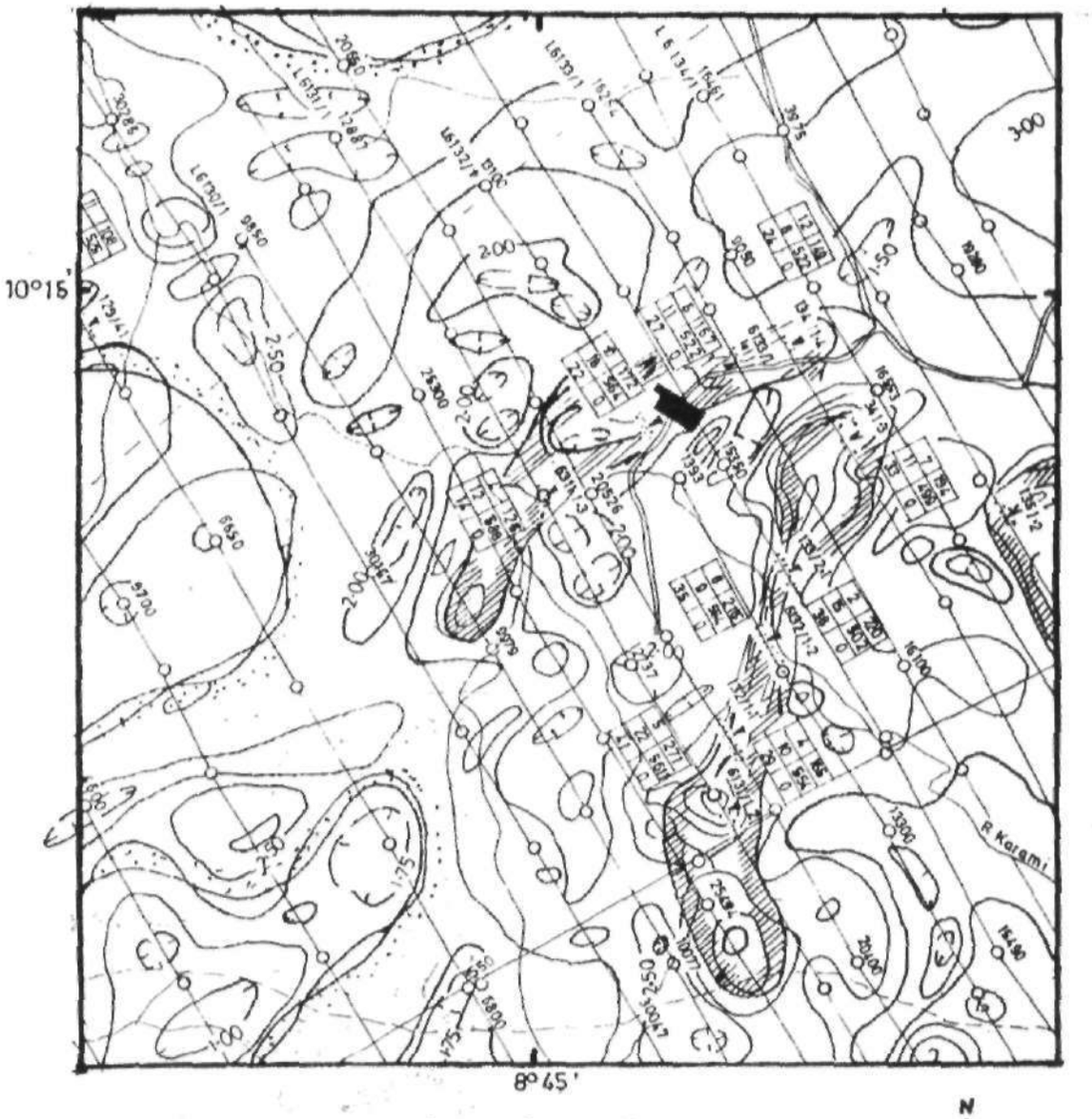


FIG 3.4: RADIOMETRIC MAP OF LERE SHOWING THE STUDY AREA

windows are T/C for total count, K + U + Th for potassium count, U + Th for uranium count and Th for thorium count. Typically, it takes about 15 - 20 minutes to take readings from the four channels at a station.

Because of the sum total effects of cosmic rays, atmospheric radioactivity, and the radioactivity of the measuring system, background readings were taken and subtracted from each corresponding channel count rate. This was done by taking readings with the spectrometer over known very low radioactive areas. From the aero-radiometric map studied, areas around Saminaka have low radioactivity. Background readings were therefore taken at Krosha - Saminaka three times and the average of the three was calculated and used for this work. The background readings were taken a day before starting the survey, six days after beginning the survey and a day after the Survey was completed. Average values of the background are 1220 cpm for T/C, 1026 cpm for K, 428 cpm for U and 146 cpm for Th, respectively.

3.4 Data Reduction

The counts obtained from gamma spectrometric measurements have to be converted to element concentrations to be meaningful. The concentration equations (3.4), (3.5) and (3.6) are used to convert the count rates to relative surface concentrations. The

sensitivity constants and stripping ratios for the spectrometer are

K_1 = 7.5 cpm/ppm

K_2 = 20.5 cpm/ppm

K_3 = 154 cpm/ppm

S_1 = 0.62

S_2 = 0.68

and S_3 = 0.83

(Geometrics, 1984)

Using the above constants, equation (3.4) (3.5) and (3.6) become

$$eTh\ (ppm) = \frac{Th_c - Th_b}{7.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.7)$$

$$eU\ (ppm) \quad \frac{(U_c - U_b) - 0.62\ (Th_c - Th_b)}{20.5} \quad \ldots\ldots\ldots\ldots \quad (3.8)$$

and

$$K(\%) = \frac{(K_c - K_b) - 0.68(U_c - U_b) - 0.62(Th_c - Th_b) - 0.83(Th_c - Th_b)}{154} \quad \ldots\ldots(3.9)$$

The above relations were used to determine equivalent Th, U and K concentrations eTh, eU and K(%) respectively. These concentrations for all the sample points along profile 1 is given in Table 3.1, while that for profiles 2 - 9 are given in the Appendix.

TABLE 3.1

EQUIVALENT Th , U AND K CONCENTRATIONS

PROFILE 1

STN	e_{Th} (ppm)	e_U (ppm)	K (%)	e_U : e_{Th}
1	132.7	83.1	4.4	0.62
2	139.9	71.0	6.6	0.51
3	125.0	79.1	6.3	0.63
4	104.5	61.0	3.6	0.58
5	075.0	37.4	1.7	0.50
6	082.7	33.2	1.9	0.40
7	080.3	37.4	2.9	0.46
8	092.8	50.4	2.0	0.54
9	130.8	61.6	4.4	0.47
10	123.7	65.0	6.5	0.52
11	113.3	65.8	4.0	0.58
12	143.1	64.5	7.0	0.45
13	142.8	68.9	6.5	0.48
14	139.6	65.5	6.7	0.47

CHAPTER FOUR

DATA ANALYSIS AND INTERPRETATIONS

4.1 Analysis of Data

In chapter three, the method of data collection was discussed. Treatment of data to obtain element concentrations from counts were also detailed in the same chapter. In this chapter, the results obtained are going to be analysed to characterise U and or Th occurrence in the area surveyed. The concentrations of uranium, eU, Thorium, eTh and potassium K(%) determined from the spectrometer readings using equation (3.7) (3.8) and (3.9) are given in Table 3.1 and in the Appendix In order to actually characterise the anomaly considered in terms of its radioelement contents, the contour maps of Total Count (Figure 4.1), frequency distribution curve, (Figure 4.2), uranium concentrations contour map, (Figure 4.3), thorium concentrations contour map, (Figure 4.4), Potassium concentrations contour map, (Figure 4.5) and the ratio of uranium to thorium concentrations contour map, (Figure 4.6) were drawn.

The total count contour map can be used to delinate areas of sources of radiations (radioactive source areas). This can be achieved by determining a reference background count, the peak intensity (the highest contour value) of the source of radiation and the half maximum, which is the contour midway between some reference background and the peak intensity of the source of radiation. The contact between lithologic units in this procedure is considered to be

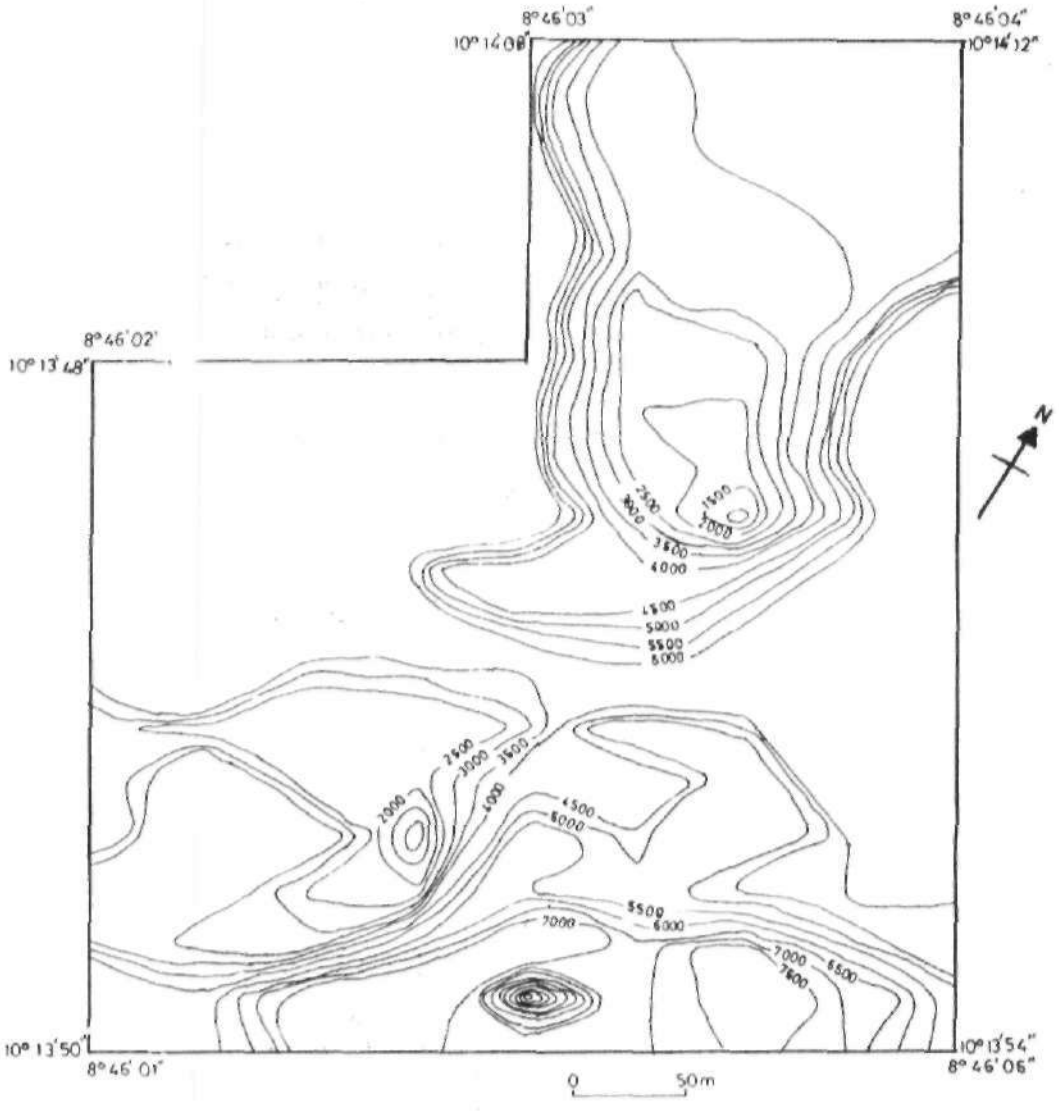


FIG. 4.1: CONTOUR MAP OF TOTAL COUNT. (Contour interval = 500 C / S)

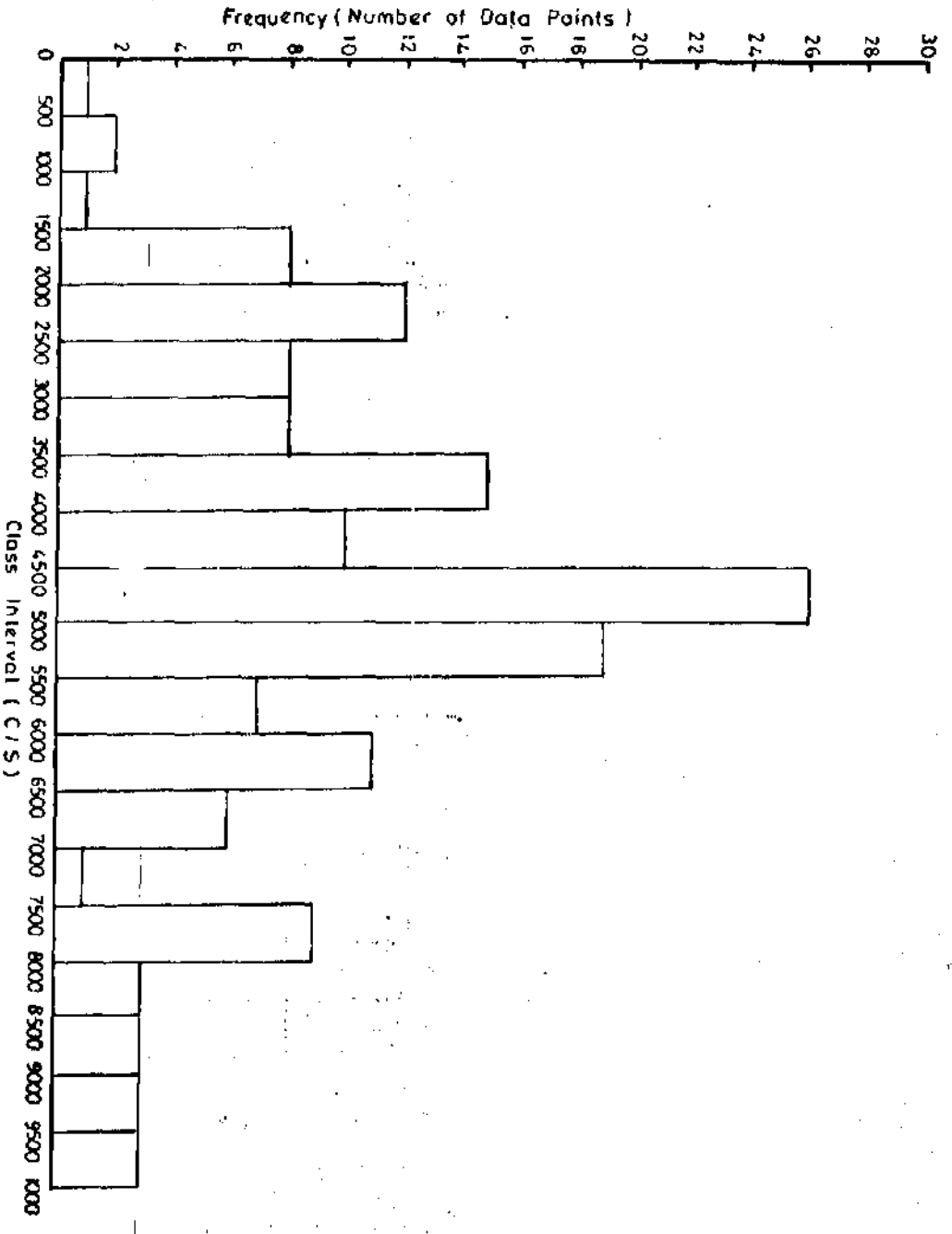


FIG. 4.2: FREQUENCY DISTRIBUTION CURVE

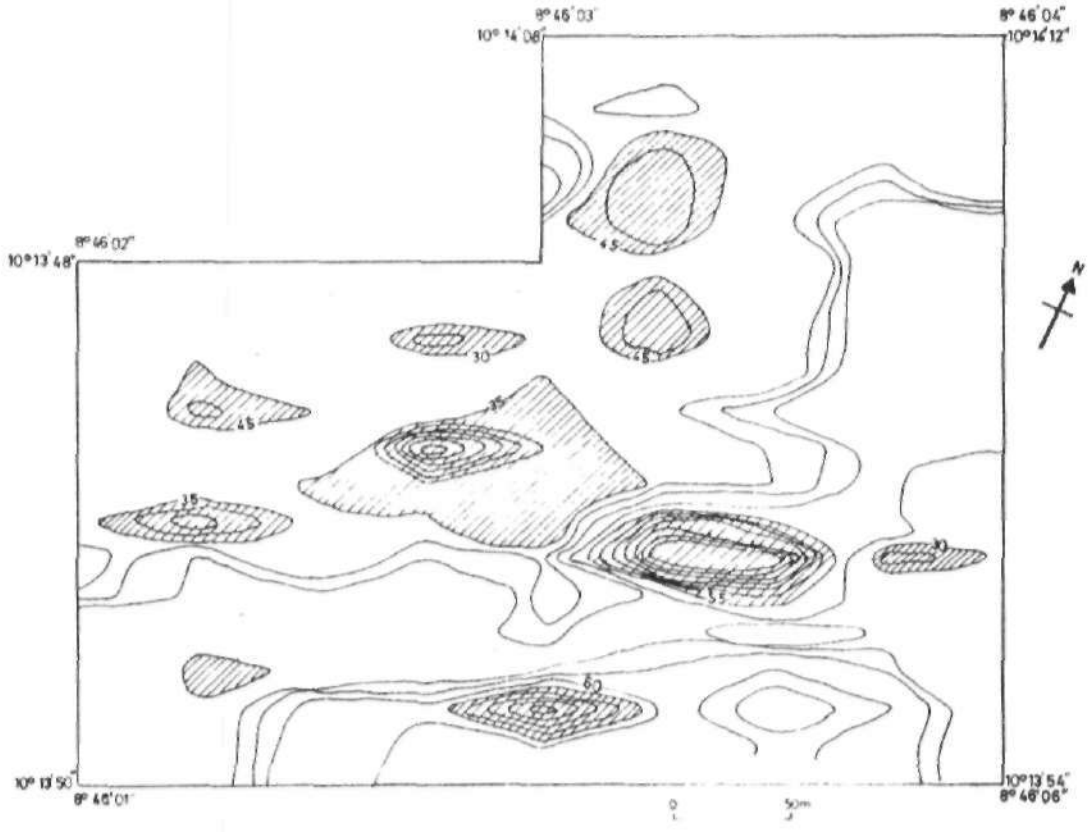


FIG-4-3; CONTOUR MAP OF EU SHOWING AREAS OF EU ANOMALIES (Contour interval = 5ppm)

EXPLANATIONS

Areas of EU < 25ppm

Areas of EU > 25ppm

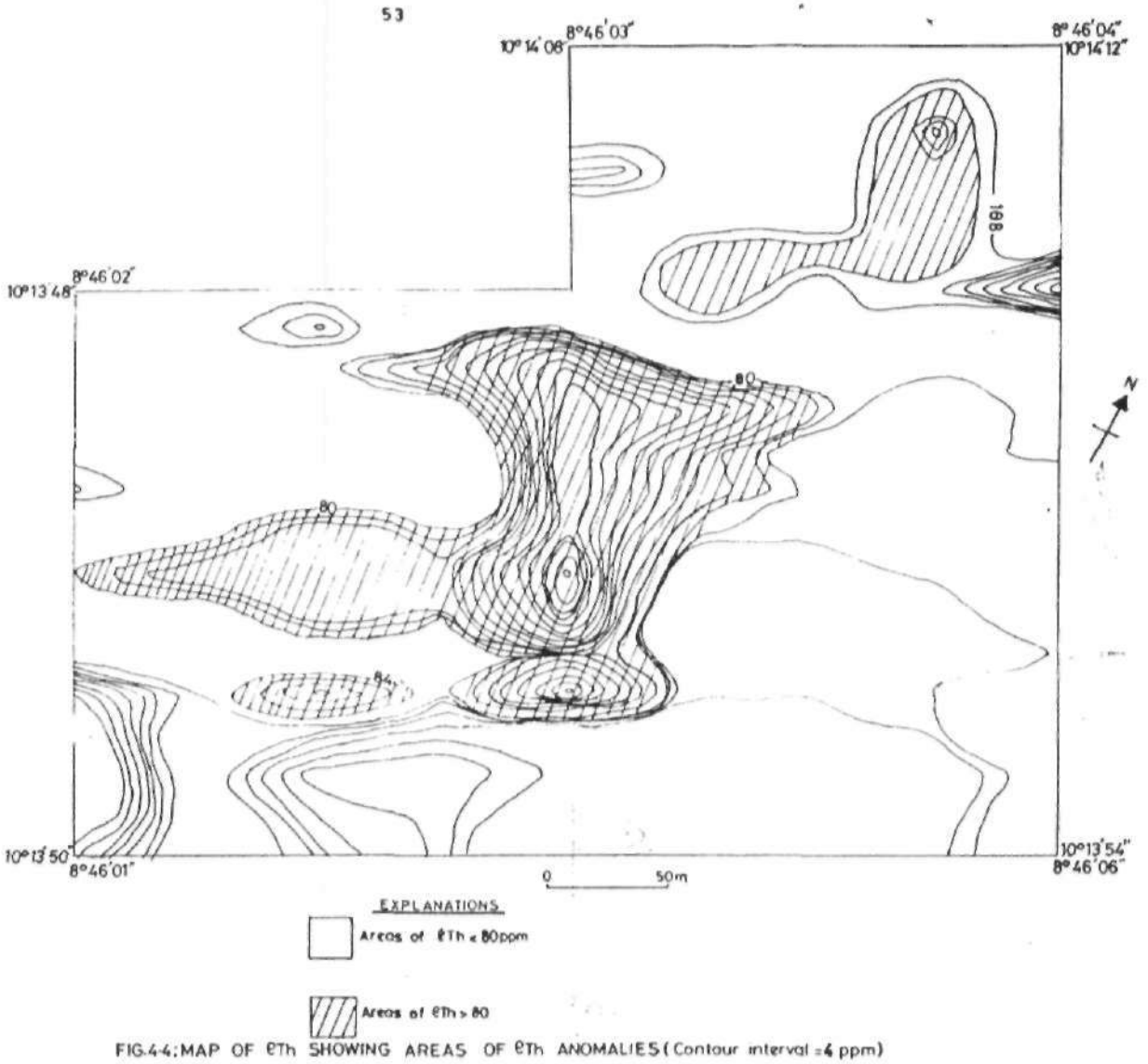


FIG.4-4: MAP OF ϱTh SHOWING AREAS OF ϱTh ANOMALIES (Contour interval = 4 ppm)

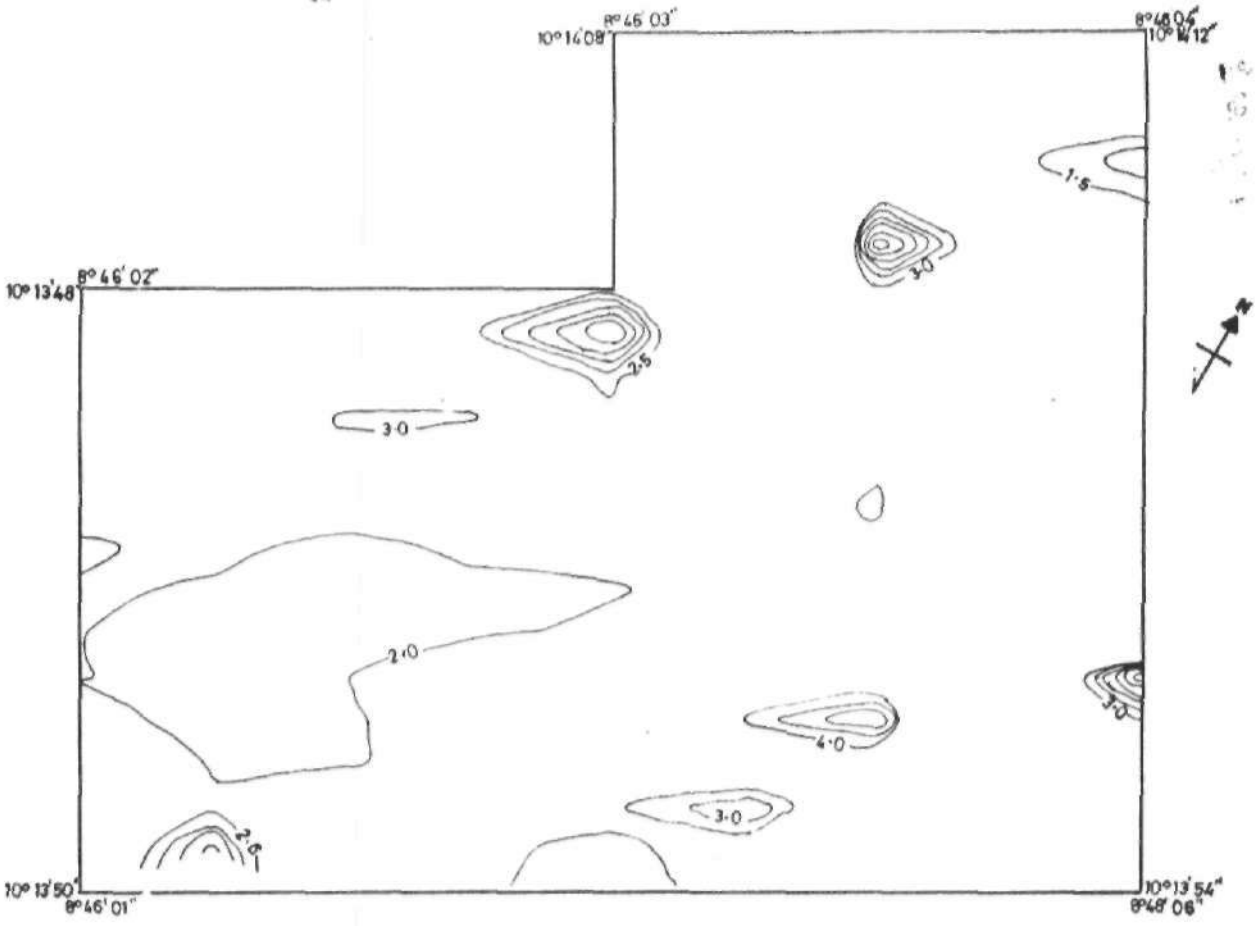


FIG.4.5 : MAP OF K (%) . Contour interval = 0·5%

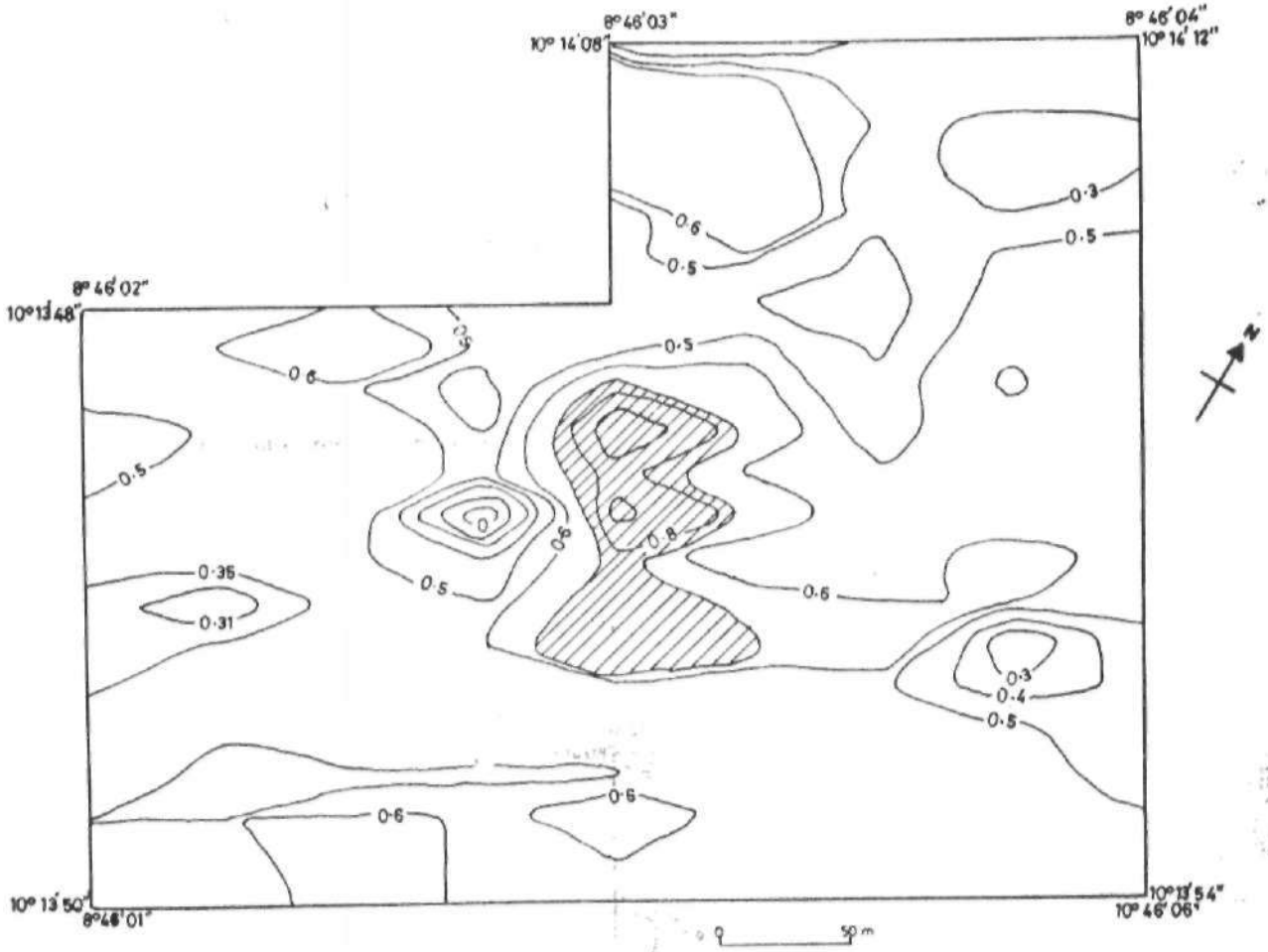


FIG. 4.6: CONTOUR MAP OF eU : eTh SHOWING AREAS OF eU : eTh ANOMALIES

EXPLANATIONS

Areas with eU : eTh < 0·7

Areas with eU : eTh > 0.7
(areas of probable Uranium mineralization)

the contour at the half-maximum. In this study, the reference background was deduced using a frequency distribution curve (Figure 4.2). It is a normal distribution curve. The mode gives a count of 4500 c/s and this is taken as the reference background for the area.

The total count map (Figure 4.1) shows that anomalous gamma ray counts occur at the north-eastern, southern and in the south-eastern parts of the study area. For the anomaly at the north-eastern part of the area, the peak intensity (the highest contour value) is 6000 c/s. The reference background was found to be 4500 c/s, hence the half maximum is approximate areas of the source of radiation which produce this anomaly is bounded by the 5500 c/s contour line. For the anomaly at the Southern part, the peak intensity is 5000 c/s contour. Similarly for the anomaly at the South-eastern part, the peak intensity is the 6500 c/s. The half maximum is then the 5500 c/s contour line. These areas of sources of radiations are shown in Figure (4.7).

In order to determine on which rock type these anomalous radioactivity readings occur, the geology of the area Figure (1.2) was compared with the Total Count map (Figure 4.1). This was done by superimposing the geological map of the area on the Total Count map. The resulting map (Figure 4.8) shows that the anomalies occur in all rock types in the area suggesting that

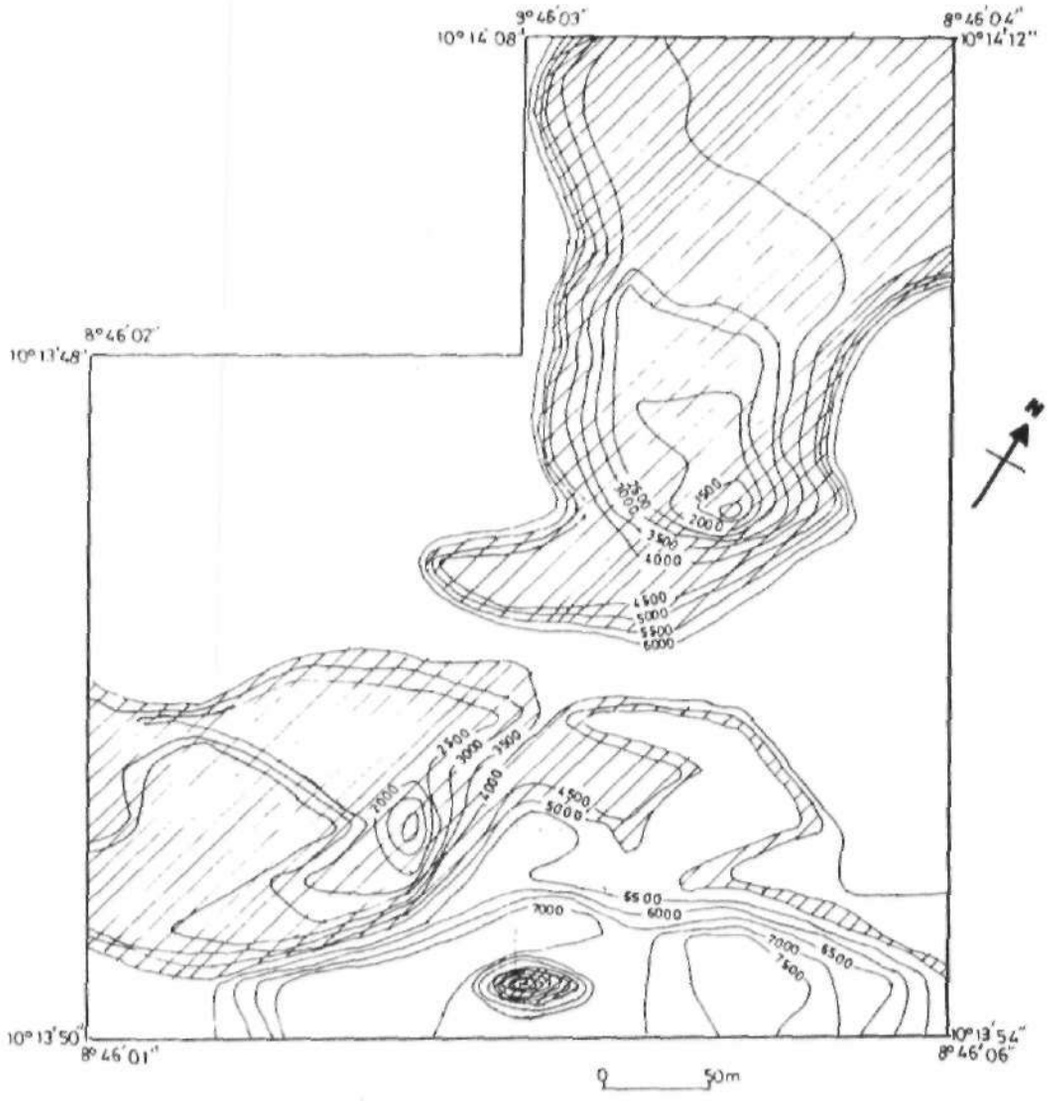


FIG.4.7: CONTOUR MAP OF TOTAL COUNT SHOWING AREAS OF SOURCES OF RADIATIONS
(Contour interval : 500 C/S)

EXPLANATIONS

Areas of sources of radiations

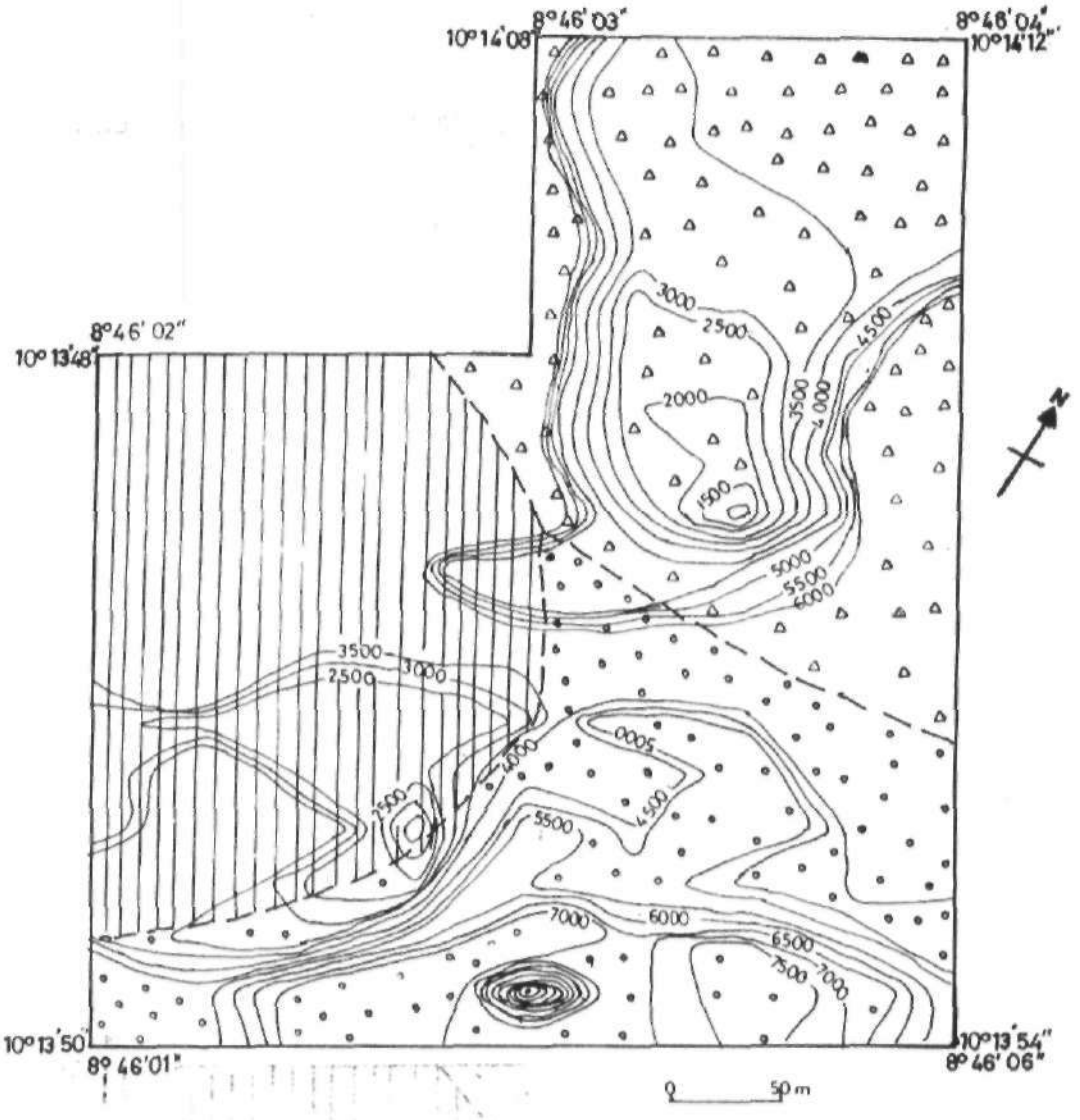


FIG-4.8: GEOLOGY SUPERIMPOSED ON TOTAL COUNT MAP

EXPLANATIONS

- Porphyroblastic gneiss(medium and coarse grained) including some Quartz and feldspar
- Hornblende biotite granite gneiss
- Migmatites
- Geological boundary
- 1000 Contour intervals

the radiation could have originated from the soil cover. This may be the case because all the common rock types in the area and the soils derived from them contain a significant amount of the naturally radioactive elements.

The mineral potentials of the anomalies reflected on the Total Count map were assessed by thorough analysis in order to delineate areas of radioelement anomalies. This was done by statistical analysis, determining threshold values (upper limit of normal background values) of eU, eTh and eU: eTh. Frequency distribution tables were drawn from which the mean and the standard deviation from the mean were calculated using standard statistical formula (Tables 4.1 - 4.3).

For class intervals with equal size C, the median obtained by interpolation is given by

$$\text{median} = L_1 + \left\{\frac{(N/2 - (\sum f)_i)}{f_{\text{median}}}\right\}$$

where L_1 = lower class boundary of the median class (ie the class containing the median)

N = Number of items in the data

$(\sum f)_i$ = Sum of frequencies of all classes lower than the median class)

(Spiegel, 1981).

f_{median} = frequency of median class

C = size of median class interval.

The 90% confidence interval for the mean values

TABLE 4.1

FREQUENCY DISTRIBUTION TABLE

CLASS INTERVAL eU (ppm)	Li (ppm)	FREQUENCY (fi)	CUMMULATIVE freq.	$fi(Li-\bar{L})^2$
0 - 4.5	0	1	1	585.64
5 - 9.5	4.75	0	1	0
10 - 14.5	9.75	1	2	208.80
15 - 19.5	14.75	1	3	89.30
20 - 24.5	19.75	15	18	297.04
25 - 29.5	24.75	11	29	3.33
30 - 34.5	29.75	12	31	369.63
35 - 39.5	34.75	23	54	2559.95
40 - 44.5	39.75	18	72	4352.44
45 - 49.5	44.75	14	86	5912.23
50 - 54.5	49.75	16	102	10444.84
55 - 59.5	59.75	8	110	7466.42
60 - 64.5	59.75	12	122	15165.63
65 - 69.5	64.75	13	135	21375.93
70 - 74.5	69.75	3	138	6224.41
75 - 79.5	74.75	3	141	7665.91
80 - 84.5	79.75	2	143	6171.60
85 - 89.5	84.75	2	145	7332.60
90 - 94.5	89.75	1	146	4296.80

TABLE 4·2

FREQUENCY DISTRIBUTION TABLE

CLASS INTERVAL ^{238}U / ^{232}Th	Li(ppm)	FREQUENCY (fi)	CUMMULATIVE freq.	$fi(Li-\bar{L})^2$
0 — 0·09	0	1	1	0·4225
0·10 — 0·19	0·095	2	3	0·6160
0·20 — 0·29	0·195	7	10	1.4491
0·30 — 0·39	0·295	17	27	2.1424
0·40 — 0·49	0·395	40	67	2.6010
0.50 — 0.59	0·495	38	105	0·9129
0.60 — 0·69	0·595	22	127	0·0665
0.70 — 0·79	0·695	11	138	0·0222
0·80 — 0·89	0·795	7	145	0·1472
0·90 — 0·99	0·895	3	148	0·1801
1·00 — 1·09	0·995	2	150	0·2380
1·10 — 1·19	9·095	1	151	0·1980
1·20 — 1·29	1·195	0	151	0
1·30 — 1·39	1.295	1	152	0·4160

TABLE 4.3

FREQUENCY DISTRIBUTION TABLE

CLASS INTERVAL (Th (ppm)	Li (ppm)	FREQUENCY (fi)	CUMMULATIVE freq.	fi (Li - $\bar{L}$)^2
20.0 - 29.9	19.95	2	2	9814.00
30.0 - 39.9	29.95	6	8	21636.01
40.0 - 49.9	39.95	3	11	7515.01
50.0 - 59.9	49.95	2	13	3208.00
60.0 - 69.9	59.95	22	35	19866.05
70.0 - 79.9	69.95	24	59	9648.06
80.0 - 89.9	79.95	28	87	2828.07
90.0 - 99.9	89.95	25	112	0.06
100.0-109.9	99.95	13	125	1287.03
110.0 - 119.9	109.95	14	139	5527.03
120.0 - 129.9	119.95	4	143	3588.01
130.0 - 139.9	129.95	5	148	7980.01
140.0 - 149.9	139.95	6	154	14970.01
150.0 - 159.9	149.95	0	154	0
160.0 - 169.9	159.95	2	156	9786.00

(L) was obtained from the equation

$$L = \bar{X} \pm \frac{1.645\ S}{\sqrt{N}} \sqrt{\frac{N_p - N}{N_p - 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

where $\bar{X}$ = estimate of the true mean

S = standard deviation

N_p = Total number of stations in the field.

and the standard deviation (S) is given by

$$S = \sqrt{\frac{(F_i(L_i - L)^2}{N - 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

where L_i = Lower limit of the class intervals

The median can be taken as the mean, hence $\bar{X}$ in (4.2) can be replaced by $\bar{L}$ ie

$$L = \bar{L} \pm \frac{1.645\ S}{\sqrt{N}} \sqrt{\frac{N_p - N}{N_p - 1}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

The threshold value L_B was taken as the upper range of equation (4.4) That is

$$L_B = \bar{L} + \frac{1.645\ S}{\sqrt{N}} \sqrt{\frac{N_p - N}{N_p - 1}} \quad \ldots\ldots\ldots\ldots\ldots (4.5)$$

The values of eU, eTh and eU: eTh exceeding their threshold values were considered anomalous (Dewu, 1986). Details of this for the individual elements is given in the proceeding section.

4.2 Geochemical Considerations

Geochemical techniques have been used in exploration programmes for many years. The techniques have been used in mineral exploration by chemical analysis of samples collected as a means of delineating areas of interests in terms of mineral ore potential or

as a follow-up to surveys by other techniques. Geochemical techniques have found application in the later stages of exploration simply because gamma ray techniques have found application in the later stages of exploration simply because gamma ray techniques are faster and cheaper. Gamma ray surveys in U explorations have limitations especially when they are carried out in granitic terrains. Often only qualitative interpretation is possible from such determinations. This is partly because the measurements are based on one of the daughters in the decay series and the U decay series frequently is not in radioactive equilibrium. Also, even a thin overburden can absorb gamma rays when radioactivity occurs so that deposits may not be detected during routine surveys. Therefore, at a certain stage in an exploration programme the need to use geochemical investigations becomes necessary.

The basic principles of geochemical investigations in the earth sciences concern the determination of the relative abundances of elements and then relating such abundances to the physico - chemical conditions in the immediate environment of investigation. In recent years, considerably improved detection limits for most of the elements have increased the reliability of chemical analysis and hence the application of geochemical techniques. Uranium in geological samples, for example can now be detected within the part per billion (ppb) range (Dewu, 1989).

There are several analytical techniques in geochemistry. A major decision to be taken prior to the start of routing sampling is that of determining whether samples should be analysed in the field or at a home laboratory. This will depend on the analytical method to be employed the availability of local facilities and personnel and the requirements of the field scientist in relation to follow up investigations. The commonest practice at present is to undertake all analysis at a home laboratory although field laboratories have proved successful in some circumstances. Analytical techniques currently available include

i) Fluorimetric
ii) Gamma spectrometry
iii) X - ray fluorescence
iv) Colorimetry
v) Neutron activation analysis
vi) Atomic absorption spectroscopy
vii) Chromatography

The Fluorimetry is the most important method used for the analysis of uranium because it is extremely sensitive for example in waters as little as 0.2 ppb uranium can be detected, and in rocks 1ppm is easily attainable (Levinson, 1974).

The average chemical abundances of thorium and uranium in various igneous rock types are shown in Table 1.2 . The table shows that in general, the thorium and uranium contents of igneous rocks increase

with increasing acidity or silica content. Thus, the average thorium and uranium contents of basic intrusive rocks are only about one quarter of those given for granites. Ultrabasic rocks are exceptionally low in both elements, and their determination in these rocks is particularly difficult (Adams et al, 1954).

Many studies have shown that thorium and uranium in intrusive rocks are concentrated in accessory minerals, either as separate grains or as inclusions in which most of the reported thorium and uranium contents of both major and accessory minerals fall.

The average abundances shown in Table 1.3 shows that accessory minerals apparently contain much of the thorium and uranium in silicic intrusive rocks. It is possible that the thorium and uranium apparently incorporated in the various major minerals of the rocks (Plagioclase, pyroxene and others) are actually concentrated in submicroscopic grains of accessory minerals.

The ground gamma-ray spectrometric data in this study indicates that the equivalent uranium concentration ranges from 0 to 88.1 ppm and equivalent thorium concentrations ranges from 23.1 ppm to 147.1 ppm. These results show an above average concentrations of uranium and thorium in igneous rocks compared with known standard concentrations in these rocks (Table 1.2). This may suggest possible low grade uranium mineralization as the uranium and thorium may be concentrated in grains of the accessory minerals (Table 1.3). However, the average

concentrations are believed to increase with a decrease in the age of intrusions. Therefore if the samples contain as much uranium and thorium as suggested by the gamma-ray spectrometric data, an independent laboratory analysis of rock samples from the area need be carried out.

4.3 Interpretations of Data

Methods of determining thresholds from statistical data are detailed above. This is used to analyse U concentrations as determined in this study. Using equations (4.1), (4.3) and (4.5) and Table 4.1, the threshold value of eU was found to be

$$L_B = 24.18 + 0.18$$

$$L_B = 24.4 \text{ ppm} \simeq 25 \text{ ppm}$$

Those areas where eU concentration exceeded 25.0 ppm were considered as areas of anomalous eU concentrations. From the above analysis, it can be seen that uranium anomalies occur in the western, central part and the South-eastern part of the surveyed area. There are also smaller anomalies spread all over the area. Thus about thirty percent of the area is uranium anomalous (Figure 4.3). Areas outside the anomalous zones were also surveyed to see if some anomalies were missed during the aero-radiometric survey. From the distribution of U anomalous zones in the area surveyed (Figure 4.3), it can be seen that uranium anomalies could be found outside areas delineated as thorium anomalous zones as shown on the aero-radiometric map of the area.

Generally, the relative abundances of U, Th and K remain relatively constant over a wide range of rock types (Darnley, 1973). In order to actually characterise the U content, the ratio eU: eTh was therefore used. From the point of view of economic potential, the most promising areas of uranium mineralization are those areas of coinciding eU and eU:eTh anomalies (Darnley 1973). Using Table 4.2 and the set of equations above, the threshold value of eU : eTh was found to be

$$L_B = 0.65 \pm 0.03$$

$$L_B = 0.68 \text{ ppm}$$

From this value, only the anomaly in the central portion (Figure 4.6) can be considered anomalous. Comparing this with eU anomalies, the most probable areas of uranium mineralization were mapped out in Figure 4.9. Also, some of the uranium anomalies are coincident with anomalies on the Total Count map. This may indicate uranium enrichment in the area generally.

The contour map of thorium concentrations is as shown in Figure 4.4. The map shows that there are well defined eTh anomalies in the area. Again using Table 4.3 and equation (4.1), (4.3) and (4.5), the threshold value was found to be

$$L_B \simeq 80 \text{ ppm}$$

All areas bounded by the 80 ppm contour line and above are considered anomalous. This indicated that the central part and the Southern part of the surveyed area

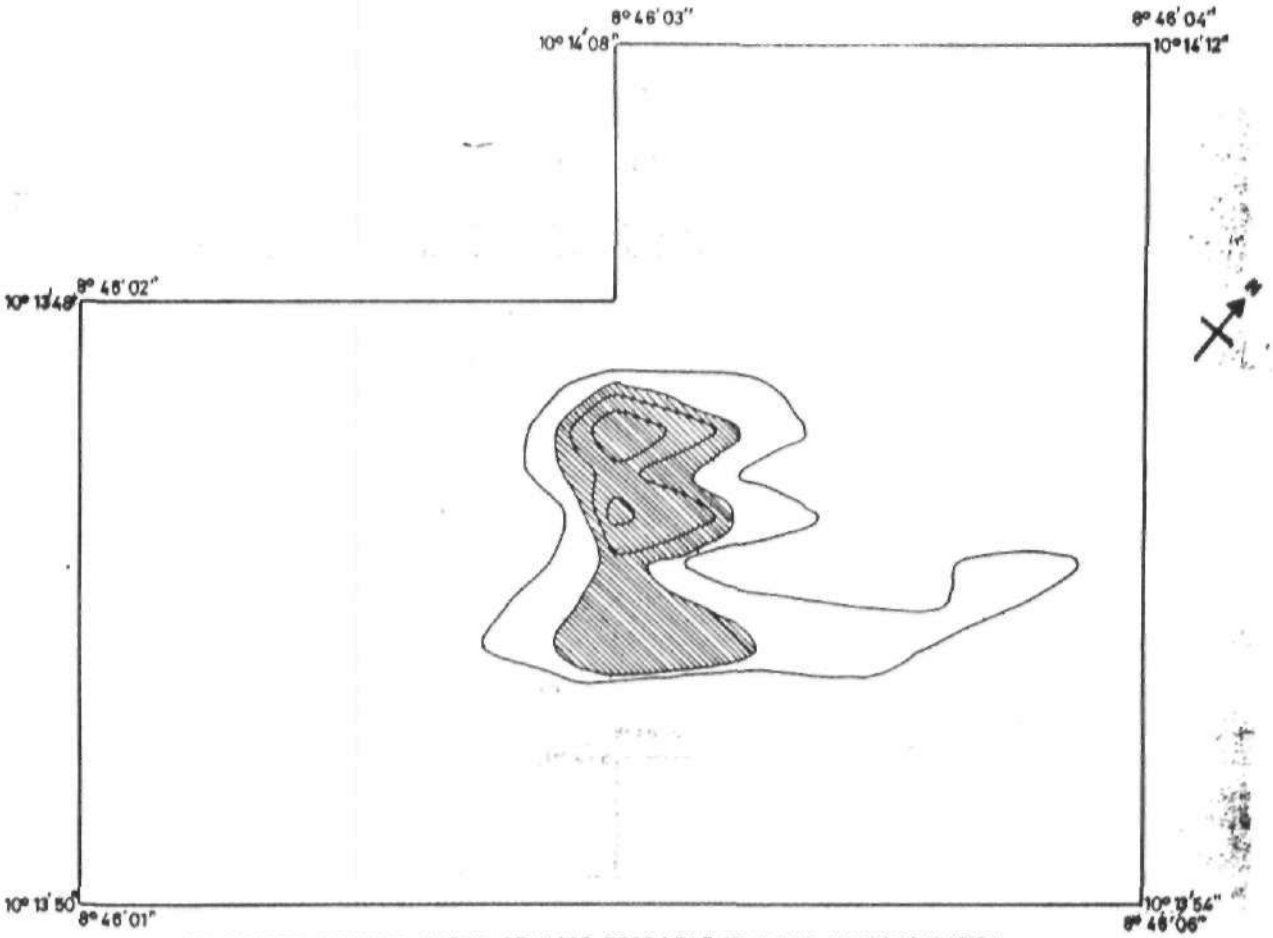


FIG.4.9: MAP SHOWING AREAS OF MOST PROBABLE URANIUM MINERALIZATION

EXPLANATIONS

Areas of conicident eU and eU : eTh anomalies

are thorium anomalous. Thus about fourty percent of the area surveyed is thorium anomalous. Areas outside the anomalous zone investigated were devoid of thorium anomalies. These results agree with the findings of the aero-radiometric survey. In most cases, areas of high eTh concentrations coincided with areas of high eU concentrations. These are mainly areas of exposed outcrops.

Figure 4.5 shows the contour map of potassium concentrations. The map shows that potassium anomalies are absent in the area surveyed, though potassium concentrations were as high as 10% in some stations. In some of the points however, K(%) was not detected or K values were insignificant.

CHAPTER FIVE

DISCUSSIONS AND CONCLUSIONS

5.1 Discussion of Results

The contour map of the Total Count (Figure 4.1) reveals some anomalies. The sources of radioactivity in the area surveyed were identified from this map. Some of these sources correspond with areas of eU and eTh anomalies. From these analyses and the computed values of the individual elements concentrations, uranium and thorium were identified as the main sources of radioactivity in the area surveyed. The contribution of potassium is also significant because at some stations, extremely high K values were recorded even though in most of the stations its concentration is negligible.

The contour maps of the individual elements and the contour map of eU:eTh also reveal some anomalies. One of the anomalies on the eU:eTh map is coincident with eU anomalies. This same anomaly is also coincident with some eTh anomalies (Figure 4.6). From the analyses of eU and eU:eTh contour maps, the most probable areas of uranium mineralization constitute about 20% of the total area surveyed. These are areas of coincident eU and eU:eTh anomalies and occur on all the rock types of the area. Results of eTh anomalies also show that about 40% of the area is thorium anomalous. It must be stressed that these results were obtained assuming secular equilibrium in the U and Th decay series. The problems disequilibrium pose in simple

four-channel gamma - ray spectrometry can not be over emphasised.

5.2 Conclusions and Recommendations

Using a portable four-channel gamma ray spectrometer, ground gamma ray spectrometric technique was used to determine the concentrations of U, Th and K for the area surveyed. The results obtained show that thorium concentrations are greater than the uranium concentrations. Potassium concentrations also could be as high as 10% though in most stations, it is negligible. In conclusion, the presence of uranium, thorium and potassium can be inferred from this study. The study has also shown that there is preferable enrichment of uranium to the other two elements in the area. From the foregoing discussions, the study has thus proved the possibility of the existence of uranium mineralization in the area. The only problem is determining the nature of the uranium ore, the ore grade, its mode of occurrence and the viability of it recovery.

As a follow-up to this study detailed geochemical studies can be carried out to determine the uranium concentrations and study equilibrium precise position in the uranium decay series. If need be, detailed studies can also be carried out to determine the nature of the uranium ore and its grade. Diamond drill holes can also be sunk at some of the areas delineated as areas of most probable uranium mineralization to confirm the possibility or otherwise of uranium mineralization in the area.

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7 APPENDIX

Equivalent Th, U and K Concentrations along Profiles 2-9

Profile 2

STN	^{e}Th (ppm)	^{e}U (ppm)	K (%)	^{e}U : ^{e}Th
1	072.	38.8	0.8	0.53
2	073.4	37.9	2.6	0.51
3	067.3	29.3	1.6	0.41
4	082.5	43.6	1.3	0.53
5	081.6	46.2	4.5	0.57
6	090.7	47.3	3.9	0.53
7	066.5	21.0	1.2	0.31
8	085.6	47.1	3.5	0.55
9	119.4	54.7	6.2	0.45
10	082.9	38.4	3.3	0.46
11	091.2	43.7	4.0	0.48
12	079.5	46.9	3.8	0.59
13	076.3	46.1	3.9	0.60
14	092.0	44.3	2.7	0.48

Profile 3

STN	e_{Th} (ppm)	e_{U}(ppm)	K(%)	$e_{U} : e_{Th}$
1	95·8	68,5	6·3	0·71
2	112.0	69.4	6·0	0·62
3	36·7	38,0	1·8	0·44
4	64.3	51·9	1·7	0·80
5	92·3	47.4	1·8	0·51
6	61·2	28·9	1·8	0·47
7	64.1	37.5	0·7	0·58
8	63·8	33,3	0·6	0·52
9	104·2	63.7	4·7	0.61
10	73·4	45·2	3·2	0·61
11	78·2	52.5	2·9	0·67
12	82·7	43·5	3·8	0.52
13	63·0	53·7	3·4	0·85
14	75·3	47.0	3·7	0·62

Profile 4

STN	e_{Th} (ppm)	e_U (ppm)	K (%)	$e_U : e_{Th}$
1	101·9	56.5	3·8	0·55
2	103.7	61.7	5·3	0.59
3	94·4	45.1	3.0	0·47
4	81.6	50.1	3·9	0·61
5	147·1	74.7	7.0	0·50
6	73·9	44·9	1·4	0·60
7	70·2	35.7	0·6	0·51
8	78·2	32.0	3·3	0·41
9	116·2	0	13·0	0
10	89.1	41.5	2·6	0·46
11	93·6	37·9	3·0	0·40
12	65·5	22·3	4·0	0·34
13	91·2	42·1	2·5	0·46
14	90·2	41·8	3·2	0·46

Profile 5

STN	eTh (ppm)	eU (ppm)	K (%)	eU : eTh
1	83·8	59·8	3·1	0.71
2	94.2	88·1	4.1	0.93
3	103.2	50.6	3·8	0.49
4	46.8	41.6	3.9	0.88
5	68·9	36.7	3·0	0·53
6	28·5	39.7	3·0	1·39
7	23.1	23.5	1·7	1·01
8	34.8	26.9	3.0	0·77
9	31·9	29·7	3·1	0.93
10	31·6	26·9	2·2	0·85
11	34.6	35.2	2·8	1·01
12	39.9	31·0	2·1	0·78
13	83.0	34,5	0	0·41
14	84·3	31·6	2·5	0.37
15	85·4	42·3	1.6	0·49
16	83·8	26·9	5·2	0.32
17	41·8	32.5	5·3	0·78
18	55·9	40·7	0·6	0·72
19	34·3	39.0	7·2	1·13
20	63·8	20·8	4·2	0·32

Profile 6

STN	e_{Th} (ppm)	e_{U} (ppm)	K (%)	$e_{U}:e_{Th}$
1	104·8	51.5	4.6	0·49
2	110·9	59·8	3.0	0.54
3	99·2	55.6	5·5	0·56
4	90·2	47·9	4·0	0.53
5	97.6	46·5	2·4	0·47
6	116·5	93·3	8·5	0·80
7	104·8	71·8	4.0	0·68
8	80.9	35·8	3·5	0.44
9	66.0	50·3	3·4	0·76
10	63·6	37·7	2·1	0.59
11	47·6	35·3	0	0·74
12	92·0	58·8	8·0	0·64
13	96	53·7	6·0	0.56
14	128.2	40.0	10·2	0.31
15	116·2	61.9	14.0	0·53
16	66.2	63.7	2.7	0·96
17	56·6	51.4	11.0	0·91
18	58·2	38·9	10·5	0·67
19	60·4	40·5	6·2	0·67
20	92·3	25.0	4·1	0·27

Profile 7

STN	e_{Th}(ppm)	e_{U}(ppm)	K(%)	$e_{U}:e_{Th}$
1	110·9	67·6	4·8	0·61
2	130·9	75·2	6·5	0·57
3	118·1	65·9	5·0	0·56
4	90·1	40·3	2·4	0·45
5	116·5	61·8	5·1	0·52
6	107·2	86·6	0·8	0·81
7	96·3	55·0	0·3	0·57
8	84·3	40·3	2·4	0·48
9	84·3	39·3	1·7	0·46
10	99·2	51·6	2·4	0·52
11	70·7	30·3	0	0·43
12	79·8	27·8	1·3	0·35
13	76·3	21·0	2·6	0·27
14	87·5	17·0	3·2	0·19
15	142·8	35·8	0	0·25
16	84·0	30·4	3·0	0·36
17	60·1	21·7	5·3	0·36
18	86·4	42·3	4·9	0·49
19	87·0	36·7	5·4	0·42
20	99·0	41·8	0·8	0·42

Profile 8

STN	e_{Th}(ppm)	e_{U}(ppm)	K(%)	$e_{U}:e_{Th}$
1	94·7	60·8	3·5	0,64
2	114·0	65·3	1·7	0,57
3	89·6	53·5	1·7	0,60
4	86·7	46·4	11·2	0,53
5	143·3	43·3	6·4	0·30
6	100·3	20·0	0·7	0·20
7	83·5	53·0	0	0·63
8	76·3	52·8	1·4	0·69
9	119·4	52·1	10·9	0·43
10	104·3	65·8	2·5	0·63
11	101.6	67·1	4·0	0·66
12	78·2	67·4	9·4	0·86
13	90·4	65·8	7·2	0·76
14	102·9	63·1	6·8	0·61
15	113·6	61·5	5·1	0·54
16	161·5	48·0	0	0·30
17	142·8	34·0	1·7	0·24
18	160·6	21·5	2·0	0·13
19	108·3	84·0	6·4	0·77
20	90·4	55·4	8·7	0·61

Profile 9

STN	e_{Th}(ppm)	e_{U}(ppm)	K (%)	e_{U};e_{Th}
1	77.9	37.0	1.0	0.47
2	71.5	36.0	1.4	0.50
3	63.1	22.7	1.0	0.36
4	61.7	21.3	3.0	0.34
5	84.3	38.5	0.1	0.46
6	60.9	32.0	9.5	0.52
7	64.9	29.4	0.2	0.45
8	67.8	27.6	9.5	0.40
9	116.8	51.3	10.0	0.44
10	65.7	22.2	0.2	0.34
11	68.9	21.4	1.2	0.31
12	81.6	28.6	0	0.35
13	88.8	36.4	0	0.41
14	129.5	64.0	4.0	0.49
15	93.6	72.7	6.8	0.78
16	71.5	12.0	1.5	0.17
17	73.7	21.0	0.7	0.28
18	74.2	21.6	2.2	0.29
19	73.1	27.5	2.5	0.37
20	79.0	24.4	3.1	0.31