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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

PRELIMINARY REGIONAL STUDY OF SURFACE RADIOACTIVITY IN THE BROKEN BAY—ILLAWARRA—KATOOMBA AREA

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ABSTRACT

Natural background radiation has been measured along typical road traverses in the environs of Sydney and Lucas Heights. Soil samples were taken and radioactive elements identified by gamma spectrometry.

The gamma-ray dose rates were in the range 20-40 mrad/year though higher and lower values were recorded.

The normal gamma-ray intensities at the surface were generally related to the nature of the underlying weathered rock formations. The characteristic dose rates are listed.

CONTENTS

1. INTRODUCTION

The safety organization associated with a nuclear research establishment must have a thorough knowledge of the geology of the environment of the establishment and especially the natural gamma-radiation intensity associated with the surface rocks and soils. This information gives a datum for radioactivity measurements related to site operations. An analysis of the gamma-radiation dose rates above various rocks and soils also provides information of purely geological interest.

A regional radiometric survey using carborne equipment has been carried out in the Sydney Basin along roads connecting with the A.A.E.C. Research Establishment at Lucas Heights. Soils from various points throughout the region were analysed by gamma-spectrometry to determine the proportions of gamma-emitting nuclides in them.

The detailed results obtained for the immediate environment of the Research Establishment are reported elsewhere (Duggleby et al. 1965) and this paper concentrates on the analysis of results of the survey over a wide area from the coast in the east to the Lett River in the west and from Maroota in the north to Robertson in the south.

2. THE GEOLOGICAL DISTRIBUTION OF GAMMA-EMITTING NUCLIDES

2.1 Naturally Occurring Radioactive Elements

The gamma-radiation intensity above the ground varies with rock type and associated soils, being due almost entirely to potassium and members of the uranium and thorium series. Gamma radiation from these elements is reduced to a negligible intensity by two or three feet of soil and hence it is the surface soil rather than the concealed bed-rock that determines the gamma-radiation intensity in soil covered areas.

The rates of weathering and solution differ among the various radioactive elements and these coupled with the wide range of half lives of the nuclides in the uranium and thorium series, lead to differences in relative concentrations of radioactive nuclides in the soils, compared with the parent rock types.

2.2 Potassium

Potassium, which occurs in most rock types, has a radioactive isotope of mass 40 and isotopic abundance of 0.0119 per cent. Eleven per cent of potassium 40 decays with a half-life of 1.3 x 10^9 years to argon 40 with the emission of a 1.46 MeV gamma photon, whilst the other 89 per cent decays by beta emission to calcium 40.

In igneous rocks the concentration of potassium varies roughly with the abundance of silica, the element being more prevalent in the acidic rocks such as granite than in the ultramafics such as peridotite. Rankama and Sahama (1950) showed that the large ionic radius of potassium and its twelve-fold co-ordination with respect to oxygen causes the element to be excluded from the early formed crystallates of magmatic differentiation and to become enriched in residual melts and solutions. Potassium concentrations range from 10 p.p.m. in peridotite, pyroxenite, and dunite to as much as 60,000 p.p.m. in granite (Ahrens 1954).

The potassium content of sedimentary rocks depends largely upon the relative amounts of feldspars, micas and clay minerals that partially constitute the mineral aggregate sediments. Thus shales and argillaceous sediments contain approximately 3 per cent potassium, sandstones 1 per cent, and limestones, being generally low in alkaline elements, about 0.1 per cent.

2.3 Thorium and Uranium Series

Uranium 238 (half-life 4.49 x 10^9 years) and thorium 232 (half-life 1.39 x 10^{10} years) and their daughter products are the other major contributors to the radioactivity of surface rocks and soils. Estimates of the average abundances (Fleischer 1953) range from 0.2 to 9 p.p.m. for uranium and from 7.3 to 20 p.p.m. for thorium, indicating that thorium is about 3 times as abundant as uranium. Estimates of the abundances of thorium and uranium in igneous rocks have been compiled by Adams et al. (1959) and are given in Table I. Their figures show a progressive increase in thorium and uranium contents from basic to acidic rocks and that high concentrations of uranium can be found in alkaline rocks.

The Th/U ratios for sedimentary rocks show much greater variability than for igneous rocks and Adams and Weaver (1958) have estimated that the ratios range from 0.2 to values greater than 21. The average values and ranges for thorium and uranium and the Th/U ratios for the more important sedimentary rocks are given in Table 2 (Adams et al. 1959).

Shales form about three quarters of all sediments (Pettijohn 1957) and generally have higher thorium and uranium contents than sandstone, orthoquartzites, and carbonate rocks. Black shales of marine origin often have an unusually high uranium content, whilst the thorium content is generally the same as in normal shales (Adams and Weaver 1958). This is because carbonaceous matter is particularly effective in precipitating uranium and is capable of absorbing large amounts of the element from solution.

In areas of intense lateritization, thorium- and radium-bearing minerals may be concentrated to a significant degree.

3. GEOLOGY OF THE AREA

Most of the area investigated in the radiometric survey is situated in the Sydney Basin which consists of Permo-Triassic sediments. The principal physiographic units (Figure 2) are :

(1) the Cumberland Plain,
(2) the Hornsby Plateau,
(3) the Blue Mountains Plateau,
(4) the Woronora Plateau,
(5) the Wianamatta Stillstand.

The dominant drainage system is that of the Hawkesbury River, and its tributaries.

Within the basin there are a number of structures including monoclines, warps, and smaller basins of which the largest is the Cumberland Basin. Marginal to, and underlying the Permo-Triassic sediments are Devonian and Silurian sediments intruded by granite, diorite, hornblendite and porphyry of Carboniferous age. Cappings of Tertiary basalt occur sporadically and numerous minor Tertiary intrusions including necks, dykes and a laccolith invade the younger sediments. Owing to the effects of weathering and solution, the rock formations are generally covered by characteristic soil developments. In many areas, however, transported Tertiary and Quarternary gravels and sands cover considerable areas.

The Triassic sequence consists of three units, namely the Narrabeen group at the base, the Hawkesbury sandstone and the Wianamatta group. The Narrabeen group comprises lithic sandstones, quartzose sandstone, conglomerates and red and grey shales. The Hawkesbury sandstone which occupies the immediate environment of Sydney is a quartz-rich glistening sandstone characteristically cross-bedded and containing only a small proportion of interbedded shale. The maximum thickness of the Hawkesbury sandstone is about 900 feet and it thins rapidly away from Sydney. The uppermost part of the sequence, the Wianamatta group, is mainly shale at the base but the upper half contains lithic sandstone. The Wianamatta group occupies a basin structure to the west of Sydney with the highest beds developed towards the south in the Camden-Picton area. The strata are non-marine in origin and conformable throughout, varying in thickness from a few hundred feet at the margin to more than three thousand feet under Sydney.

4. DESCRIPTION OF THE MONITORS

4.1 The Car-borne Monitor

The detecting element of the car-borne monitor used is a 3 inch diameter by 3 inch NaI (Tl) crystal coupled directly to a 3 inch photomultiplier tube (E.M.I type 9578A) enclosed in a mu-metal housing. The E.H.T. for the photomultiplier tube is supplied by an A.A.E.C. type 59 portable ratemeter (Fraser and Pryor 1964). The signals from the photomultiplier tube are fed to the ratemeter where they are amplified and displayed as a count-rate on a meter with scales up to 10,000 counts/second. The output from the ratemeter is fed to a clockwork-driven strip-chart Record recorder, so that the variations of count rate with time can be permanently recorded. The ratemeter is a transistorized instrument, internally powered by eight torch batteries, and therefore the whole monitor is portable and self contained.

Incorporated in each ratemeter is an amplifier with gains from 4 to 400 and a variable gate for pulses greater than a fixed voltage. One can adjust the amplifier and gate width to count the pulses from gamma photons in certain energy bands; for this survey they were adjusted with the aid of a small Co-57 source to count all gamma photons incident on the crystal with an energy greater than 0.11 MeV.

The crystal was mounted on a lead block in the near-side front mudguard of a Land Rover. The lead block was shaped so that the crystal was shielded from the Land Rover, but could "see" the ground along the side of the road. The

portable ratemeter and recorder were placed inside the vehicle and an operator marked the strip-chart when the vehicle passed pre-arranged landmarks.

4.2 The Gamma Spectrometer

The gamma-spectrometer, used for the analysis of the soil from selected sites, is a 5 inch diameter by 4 inch NaI (Tl) crystal viewed by a 3 inch photomultiplier tube feeding to a 512-channel Nuclear Data pulse-height analyser. The crystal is mounted in a steel room with 7 inch thick walls to attenuate the background radiation to negligible proportions.

The spectrometer has been in almost constant use since 1962 for the measurement of low levels of gamma activity in environmental samples and has been calibrated thoroughly for this use (Finn 1964).

Soil samples are placed in a "top-hat" re-entrant steel can fitting over the crystal so that a 1 inch thickness of sample surrounds the crystal on top and sides. The samples, each weighing 2 to 3 kg, are measured for periods of at least 40 minutes depending upon their activity. The pulse-height analyser sorts the pulses produced by the gamma photons according to their energies and results are obtained as numbers of counts per 10 keV channel.

To facilitate the interpretation of the gamma spectra of the soil samples, the spectrometer was further calibrated by spiking inactive soil samples with known quantities of aged refined thorium and uranium ores. The calibration for potassium had been carried out previously using solid potassium chloride.

5. THE SURVEY PROCEDURE

The 3 inch diameter by 3 inch NaI (Tl) crystal and associated electronic equipment was first taken by boat to the centre of a large expanse of freshwater where the only significant contribution to background would be from cosmic radiation. The count-rate recorded on the ratemeter was 15 counts/sec. When the crystal was mounted on the Land Rover at a point where the terrestrial background gamma-radiation was known to contribute a dose-rate of 41 mrad/year, the count rate was 180 counts/sec. Of this count-rate, 15 counts/second would be due to cosmic radiation and hence the sensitivity to terrestrial radiation was 4.0 counts/second per mrad/year.

The three road routes were selected to cover as many different soils and rock types as possible (see Figures 1 and 2). Convenient landmarks every few miles along each route were determined in advance so that radioactive anomalies displayed on the charts could be plotted accurately on the maps.

Before setting out on each route the lower energy limit of the monitor was adjusted as follows: The photomultiplier E.H.T. was set at the value of 1200 V which gives the maximum range of adjustment of amplification over the normal background gamma-radiation spectrum. The gate width was adjusted to 20 per cent of the threshold voltage and a small Co-57 source (principal gamma energy = 0.122 MeV) was placed near the crystal and the amplifier of the ratemeter adjusted to give a maximum count rate. At this point the gate straddles the 0.122 MeV photopeak and hence the voltage is equivalent to an energy of 0.110 MeV. The gate width of the ratemeter was then set to infinity so that the ratemeter counted all gamma rays with energies greater than 0.11 MeV detected by the crystal. Before and after traversing each survey route the sensitivity of the instrument was checked with a 22.6 μCi radium source placed in a standard position near the crystal. The routes were followed at a steady speed of about 35 m.p.h. where possible so that each inch of chart represented about 500 yards travelled.

One constant error during the survey was the effect of the road surface on the true background due to the natural soil. This was investigated by placing the crystal on the side of the Land-Rover facing it towards the side and repeating a section of one route. The differences in the profile were only of the order of a few per cent and random in sign, illustrating that the road surface has approximately the same radioactivity as the average soil in this region.

One unavoidable error in carborne surveying is the variation of ground area "seen" by the detector as the vehicle passes through a cutting or along a ridge. This was allowed for as discussed in Section 6.1.

From time to time, and especially after long periods of dry or wet weather, readings were taken at a fixed site at Lucas Heights to determine the effect of soil moisture on the readings. These variations were found to be of a small order and generally less than 5% of the total dose recorded.

At selected points along the three routes, samples of soil were taken for later analysis by gamma spectrometry. These soil samples were selected on the basis of major changes in the character of the soil due to changes in the underlying rock types (either sedimentary or igneous) and also in certain areas where intense surface weathering and solution resulted in the development of laterites which are generally more radioactive than the associated soil development. Also as many areas are covered by transported Tertiary and Quarternary gravels and sands, which mask the radioactivity of underlying rock types, representative samples of these transported sedimentary deposits were also collected.

6. RESULTS OF THE SURVEY

6.1 Treatment of Results

The records of the variations in the level of gamma-ray intensity along the three routes are presented in Figures 3, 4, and 5.

The error due to change of solid angle subtended by the ground at the crystal as the vehicle passes through a cutting or along a ridge (Section 5) normally occurs over a short distance, so to correct for this and make the charts more amenable to interpretation, they were redrawn, reducing the horizontal scale by a factor of 25.

The count rate due to cosmic radiation was subtracted, and the dose rate due to radiation of terrestrial origin calculated and related to the surface geology. The analysis is shown in Tables 3 and 4. The gamma spectra of the soils from the selected sites were analysed in the following way:

Potassium in the soil was determined by reference to the size of the 1.46 MeV photopeak on the spectrum. Thorium with its daughter products, giving a much greater gamma radiation response than the uranium series, was next estimated using the prominent peaks at 0.91 and 0.97 MeV due to the presence of the daughter product, actinium 228. Finally any uranium present was estimated from the remainder of the spectrum after the potassium and thorium contributions had been removed.

The results of these measurements are given in Table 4. Formulae derived by O'Brien et al. (1958) relate the dose-rate one metre above the surface of the ground to the concentration of various radioisotopes in the ground. These were used to calculate a dose-rate above each rock type due to the isotope concentration in the grab sample, assuming that the sample is representative of the whole lithological unit. The resulting dose-rate is compared in Table 4 with the average dose rate measured over the unit with a carborne monitor. The degree of agreement gives an indication of how typical of the whole is each grab sample.

6.2 Discussion of the Results

From the detailed results shown in Tables 3 and 4, the following observations were made: The results of regional radiometric traversing show that the weathered outcrops of the different lithological units exhibit characteristic radiation dose-rates in the range of 20-40 mrad/year. However, the laterites at the Sebastopol trig. station and the granites and trachytes at the Lett River show higher radioactivity and the basalts fall below the range. In the townships of Bulli and Corrimal, high anomalous readings were recorded which were probably due to artificial causes, e.g. buildings.

The results of the gamma-ray spectrometry measurements show that the potassium contents of the samples have large variations about an average of 10700 p.p.m. The samples from the Tertiary alluvium, sands and gravels, laterite, basalts, and dolerites and the Quarternary alluvium have low concentrations, whilst those derived from the lithologic units containing large amounts of shale and argillaceous material have potassium contents of the order of several per cent. The carboniferous granite and Tertiary syenites also have potassium contents of this order.

The thorium contents of the soil samples analysed are generally in the range of 3 to 17 p.p.m. and average 10 p.p.m. The laterite sample has a relatively high thorium content of 37 p.p.m.

The uranium contents of the soil and weathered rock samples are of a low order and are generally less than 0.5 p.p.m. although a concentration of 2 p.p.m. is found in the granite sample.

6.3 Validity of Results

The radiometric profiles show many sharply defined localized variations in gamma-ray intensity superimposed on broad regional trends. It would seem at first that the radioactivity data obtained from the survey could be used in a straight-forward manner to locate contacts between the various geological units of contrasting radioactivity. This is not possible generally for although the geological contacts are usually relatively sharp the boundaries at the surface are mostly obscured by soil development and weathering. The attendant processes result in a redistribution of the radioactive materials masking the radioactivity of the underlying unweathered geological formations.

The main field effects are due to:

(1) Weathering and solution,
(2) The absorption of gamma radiation in various media,
(3) The effect of soil cover and vegetation,
(4) Man-made effects, e.g. buildings etc.

Hence we cannot attempt detailed geological interpretation using the radiometric data alone. The validity, extent and quality of extrapolated and inferred radiation intensities are restricted owing to the wide separation of traverses.

The gamma spectrometry results for potassium and thorium can be taken to be accurate to ± 10 per cent. for samples measured, the results for the uranium series contribution being less accurate because of the comparatively small gamma contribution from the series. However, it is important to realize that the samples were random surface samples taken as representative of a very large area, and uniformity of the radioactive isotope concentrations throughout the geological area is unlikely.

The results should therefore be regarded as preliminary ones only, illustrating the survey method and providing a basis for more detailed investigations in the future.

7. CONCLUSION

The car-borne gamma-radiation monitor and the gamma spectrometer, used to make a preliminary radiometric survey of the environs of Sydney, give reasonably consistent results despite the modifying effects of weathering, topography, and masking by transported soils. Throughout the region the concentration of uranium in the soil is very low, being generally less than 0.5 p.p.m. The presence of significant concentrations of thorium in lateritized Hawkesbury sandstone and of higher than average dose-rates in the Lett River and Hartley area, and the low dose-rates over the Tertiary basalt of the Mt. Wilson region are worthy of note.

The results are in general agreement with the average values and ranges for potassium, thorium, and uranium determined elsewhere by previous investigations reported in the literature.

8. ACKNOWLEDGEMENTS

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TABLE 1.

THE ABUNDANCES OF THORIUM AND URANIUM IN IGNEOUS ROCKS*

Rock type	Thorium in p.p.m.	Uranium in p.p.m.	Th/U ratio
Acid intrusive	1-25	1-6	2-6
Acid extrusive	9-25	2-7	4-7
Basic intrusive	0.5-5	0.3-2	3-4
Basic extrusive	0.5-10	0.2-4	3-7
Ultrabasic	Low	0.001-0.03	-
Alkaline	-	0.1-30	Variable
Pegmatite	1-2	1-4	0.4-1.5

TABLE 2.

THE ABUNDANCES OF THORIUM AND URANIUM IN SOME SEDIMENTARY ROCKS*

Rock type	Thorium in p.p.m.		Uranium in p.p.m.		Th/U Ratio	
	Average	Range	Average	Range	Average	Range
Common shale	12±1	2-47	3.7±0.5	1-13	3.8±1.1	1-12
Orthoquartzite	1.7 ±0.1	0.7-2.0	0.45±0.5	0.02-0.6	4.0±0.8	1.8-5.8
Black shales	-	2.8-28	-	1.4 -80	-	0.07-12
Carbonate rocks	1.7±0.7	0.1-7	2.2±0.1	0.1 -9	1.0±0.3	0.1-6.5

* Adams, J.A.S., Osmond, J.K., Rogers, J.W. (1959). - The geochemistry of thorium and uranium. Physics and Chemistry of the Earth. Vol. 3 (Ahrens, L.H., Press, F., Rankama, K., Runcorn, S.K. eds.) p.298 Pergamon Press.

TABLE 3. THE GEOLOGICAL FORMATIONS AND ASSOCIATED SURFACE DOSE-RATES ALONG THE THREE ROUTES COVERED BY THE CAR-BORNE SURVEY

Portion of Route	Weathered Geological Formations Traversed, and Comments	Dose Rate due to Radioactivity in mrad./yr.
	ROUTE 1	
Lucas Heights	Hawkesbury sandstone (Rh)	38-41
Helensburgh turn-off (Princes Highway)	Localized thick layers of thorium-bearing laterite near Sebastopol trig. station	41-68
Helensburgh turn-off-1ml N of Stanwell Park	Hawkesbury sandstone (Rh)	34-41
1 ml N of Stanwell Park-Wombarra	Narrabeen group (Rn)	38(av)
Wombarra-Corrimal	Upper coal measures (PcU)	34(av)
In Bulli	Built up area	Anomalous readings up to 71
In Corrimal	Built up area	Anomalous readings up to 62
Corrimal-Shellharbour	Gerringong volcanics (PmU)	41(av)
	Extensive areas of Quaternary alluvium (QAl)	30(av)
	Weakly radioactive areas in Quarternary alluvium (due to monazite sand or Gerringong volcanics?) near bridge across entrance to Lake Illawarra	Anomalous readings up to 60
	Reading on bridge (over seawater)	3
Shellharbour-Albion Park	Gerringong volcanics (PmU) with patches of Quaternary alluvium (QAl)	26(av)
Albion Park-Robertson	Quaternary alluvium (QAl) Gerringong volcanics (PmU) Upper coal measures (PcU) Narrabeen group (RN)	Each 26(av)
	Weathered basalt (TV)	19(av)
Robertson-Bowral	Wianamatta group (RWL)	23-26
	Basalt (TV)	15(av)
	ROUTE 1 (Continued)	
Bowral-Picton	Weathered Tertiary Trachyte (near Bowral) (TeS)	38(av)
	Wianamatta group (RWL) and Hawkesbury sandstone (RN)	30-34
Picton-Camden	Wianamatta group (RWL)	30(av)
	Patches of Quaternary alluvium (QAl)	28(av)
Camden-Narellan	Quaternary alluvium (QAl)	24(av)
Narellan-X-roads near Liverpool	Wianamatta shale (RWL) and Quaternary alluvium (QAl)	26(av)
Liverpool-Lucas Heights	Tertiary sand and clay beds (Ts) (near Liverpool)	19-26
	Wianamatta group (RWL)	30(av)
	Hawkesbury sandstone (Rh) (near Lucas Heights)	30-34
	ROUTE 2	
Liverpool-Cabramatta	Quaternary alluvium (QAl)	26(av)
Cabramatta-Parramatta	Wianamatta group (RWL)	26-30
Parramatta-Baulkham Hills	Hawkesbury sandstone (Rh)	26(av)
Baulkham Hills-Glenorie	Wianamatta group (RWL) (predominantly) and an exposure of Hawkesbury sandstone (Rh)	30(av)
Glenorie-Maroota-Cattai	Hawkesbury sandstone (Rh) (predominantly)	36(av)
	Patches of Wianamatta shale (RWL)	30(av)
	Tertiary sands and gravel (Tg)	32(av)
	Quaternary alluvium (QAl) (Little Cattai Creek)	23-30
Cattai-Pitt town	Hawkesbury sandstone (Rh) (near Cattai)	30(av)
	Quaternary alluvium (QAl)	30(av)
	Tertiary sands and silts (Ts)	39(av)
	Tertiary gravels (Tg)	38(av)

(Continued...)

(Continued...)

Portion of Route	Weathered Geological Formations Traversed, and Comments	Dose Rate due to Radioactivity in mrad|yr.
	ROUTE 2 (Continued)	
Pitt town-Cranebrook-Penrith	Tertiary sands and silts (Ts)	26-30
	Gravel beds (Tg) (near Londonderry)	26-30
	Wianamatta group (RWL)	26-34
Penrith-Mulgoa	Quaternary alluvium (QAl)	26(av)
Mulgoa-Liverpool	Wianamatta group (RWL)	26-34
	ROUTE 3	
Liverpool-Penrith	See route 2.	See route 2.
Penrith-Mt. Victoria	Quaternary alluvium (QAl) and patches of Tertiary sands (Ts)	30(av)
	Hawkesbury sandstone (Rh)	36(av)
Mt. Victoria-Hartley	Narrabeen group (RN)	36(av)
	Hawkesbury sandstone (Rh) and Upper Coal Measures (PcU)	34(av)
	Upper Marine Series (PmU)	41-64
Hartley-Hampton	Lower Carboniferous granite (Clg)	71(av)
	Small patches of Upper Marine Series (PmU) and an intrusion of rhyolite (possibly lower middle Devonian (Dr))	60(av)

TABLE 4. AVERAGE MEASURED DOSE-RATES FROM TERRESTRIAL GAMMA-RADIATION OVER EACH LITHOLOGICAL UNIT AND THE CORRESPONDING THEORETICAL DOSE-RATES CALCULATED FROM THE CONCENTRATIONS OF GAMMA-EMITTERS OBTAINED BY GAMMA-SPECTROMETRY OF SOIL SAMPLES

$D_{Th} = 2.79\ S_{Th}$ mrad|yr

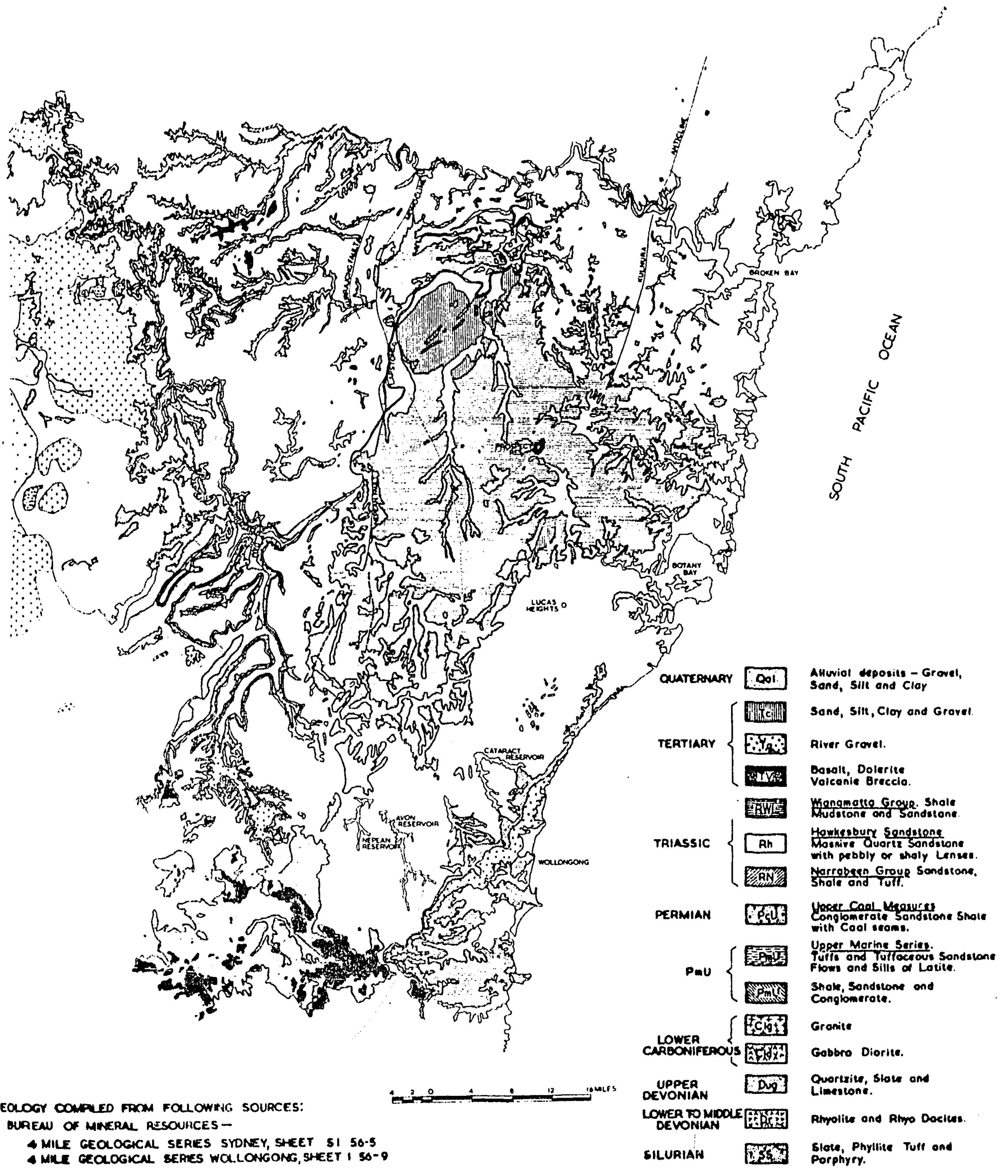
$D_U = 5.79\ S_U$ mrad|yr

$D_K = 1.33 \times 10^{-3}\ S_K$ mrad|yr

where D_i = dose-rate

S_i = concentration in p.p.m.

Sample No.	Sampling Locality	Geological Classification	Contents in p.p.m.			Theoretical dose-rate (mrad|yr) due to				Average dose-rate (mrad|yr) over whole unit
			Th	U	K	Th	U	K	Approx. Total	
1	Waterfall	Hawkesbury sandstone (Rh)	7	<0.5	4500	19	<3	6	28	40
2	Nr. Sebastopol trig. station	Lateritized Hawkesbury sandstone (T)	37	<0.5	<1000	103	<3	<1.3	107	41-68
3	Stanwell Park	Narrabeen group (RN)	4	<0.5	16400	11	<3	22	36	38
4	Russelvale	Upper Coal Measures (PcU)	12	0.5	5000	33	3	7	43	34
5	Lake Illawarra	Quaternary alluvium (QAl)	3	0.5	3100	8	3	4	15	30
6	Shellharbour	Gerringong volcanics (PmU)	4	<0.5	14400	11	<3	19	33	26
7	Robertson	Tertiary basalts (TV)	6	<0.5	< 2000	17	<3	<3	17-23	19
8	Bowral-Mittagong	Tertiary trachyte (TeS)	8	<0.5	28300	22	<3	38	63	38
9	Picton	Wiannamatta group (RWL)	10	0.5	8700	28	3	12	43	30
10	Penrith	Quaternary alluvium (QAl)	10	0.5	4200	28	3	6	37	26
11	Prospect	Tertiary basalt (TV)	5	<0.5	11100	14	<3	15	32	-
12	Lett River	Lower Carboniferous granite (Clg)	11	2	44000	31	12	59	102	71
13	Hartley	Upper Marine Series (PmU)	17	<0.5	23000	47	<3	31	81	41-64
14	Hartley Vale	Upper Marine Series (PmU)	10	<0.5	12200	28	<3	16	47	41-64
15	Hartley Vale	Coal and torbanite series from Upper Marine Series (PmU)	14	0.5	7600	39	3	10	52	41-64
16	Mt. Wilson	Tertiary basalt and dolerite (TV)	7	<0.5	2200	20	<3	3	26	-
17	Richmond	Tertiary sand and clay (Ts)	4	<0.5	3800	11	<3	5	19	28
18	Maroota	Tertiary river gravel (Tg)	9	<0.5	1300	25	<3	2	30	32



GEOLOGY COMPILED FROM FOLLOWING SOURCES:
BUREAU OF MINERAL RESOURCES –
4 MILE GEOLOGICAL SERIES SYDNEY, SHEET SI 56-5
4 MILE GEOLOGICAL SERIES WOLLONGONG, SHEET I 56-9

FIGURE 1. MAP OF THE SURFACE GEOLOGY IN THE AREA COVERED BY THE SURVEYS

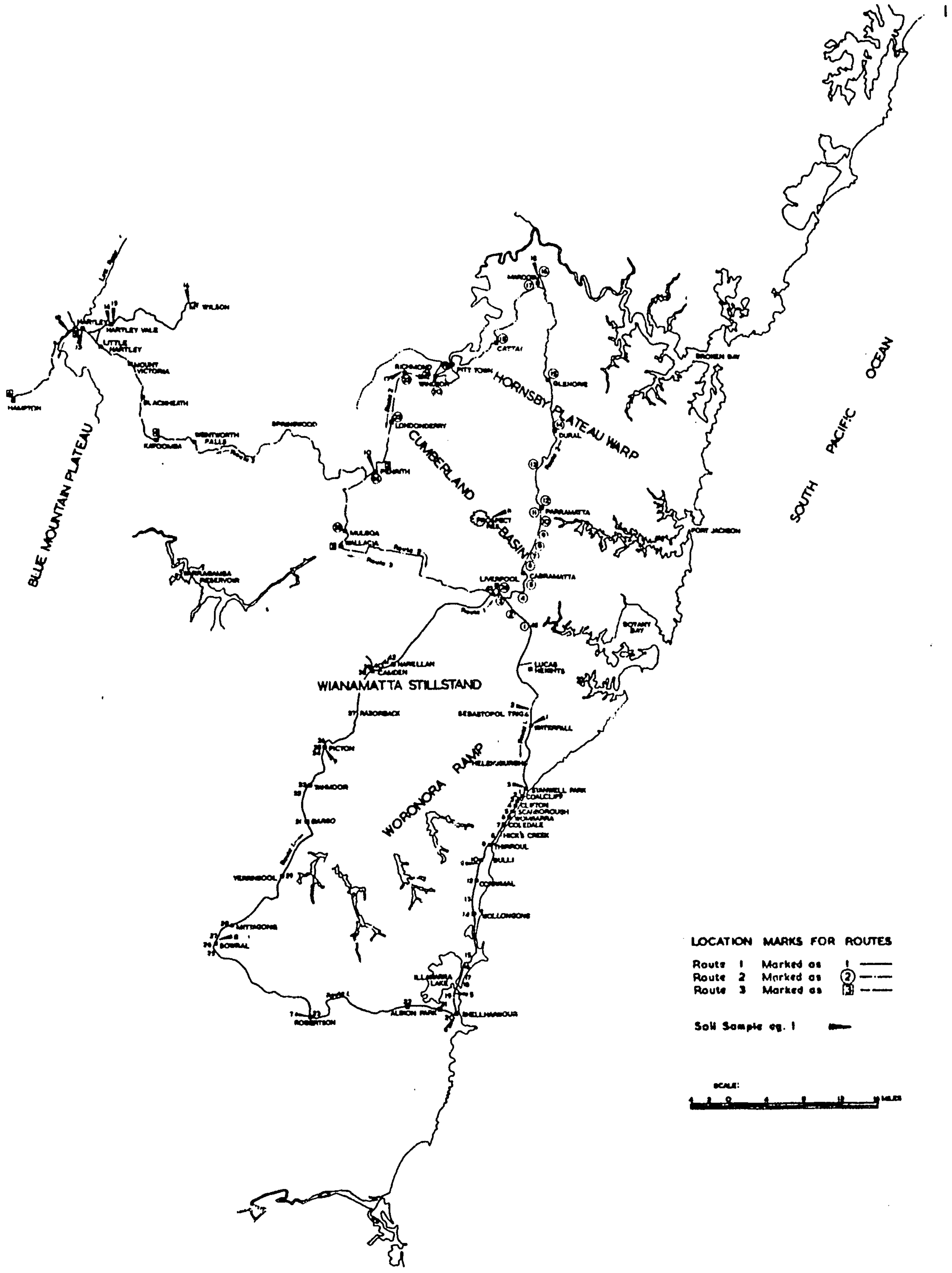


FIGURE 2. THE ROUTES OF THE CAR–BORNE SURVEYS AND LOCATIONS OF SAMPLING POINTS

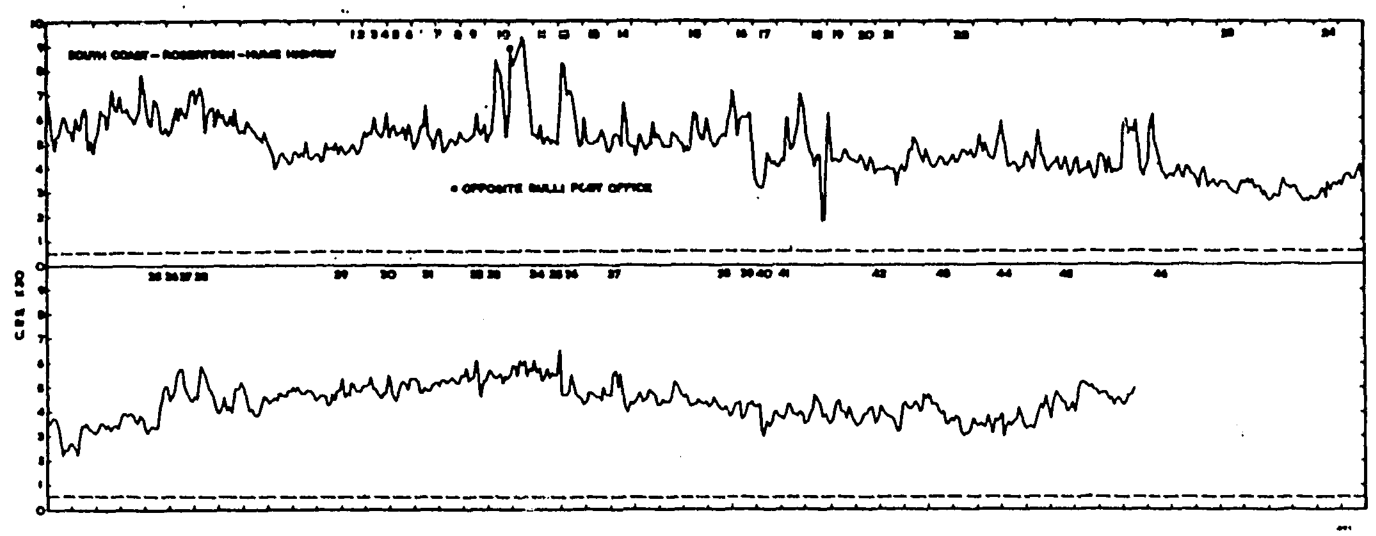


FIGURE 3. VARIATION OF SURFACE GAMMA DOSE RATE ALONG ROUTE 1

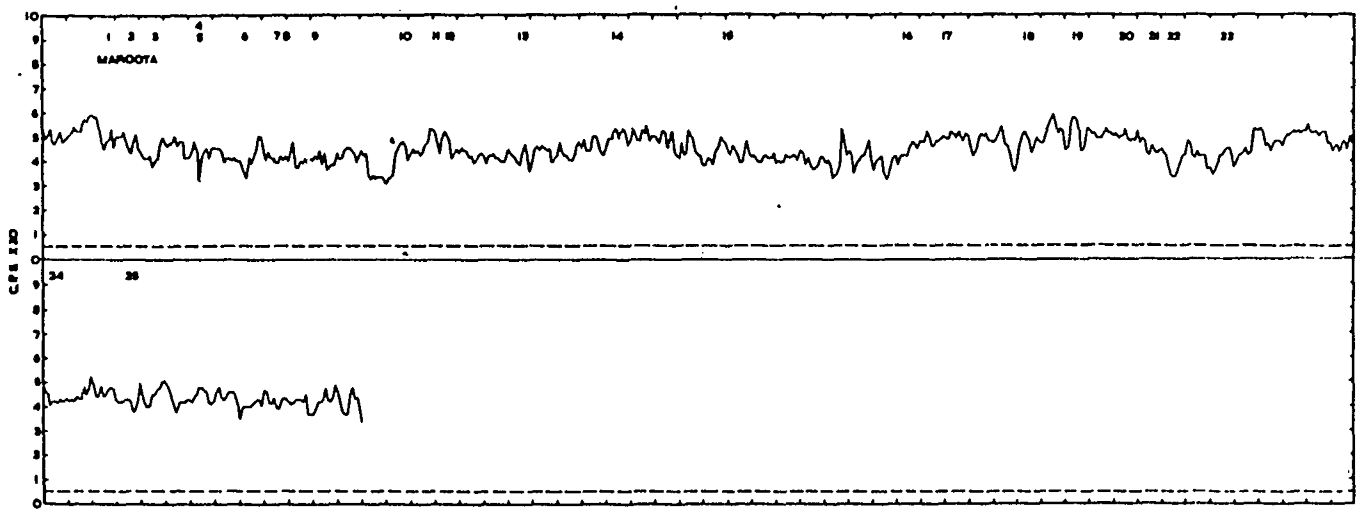


FIGURE 4. VARIATION OF SURFACE GAMMA DOSE RATE ALONG ROUTE 2

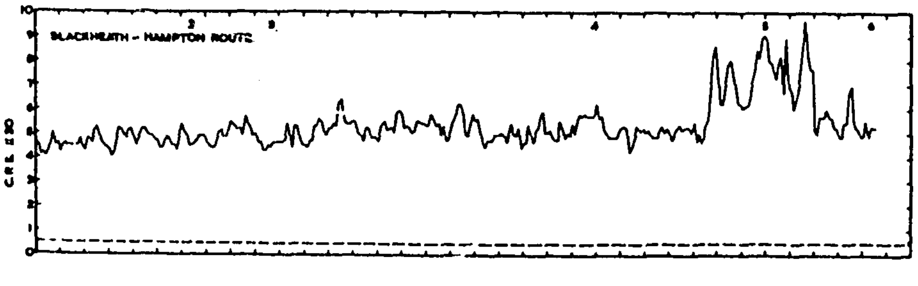


FIGURE 5. VARIATION OF SURFACE GAMMA DOSE RATE ALONG ROUTE 3