報　文

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Aeroradiometric Survey as a Means of Measurement of Distribution of the Terrestrial Radioactivity Carried out at Tsukuba Area, Ibaraki Prefecture

by

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Abstract

An experimental aeroradiometric survey was carried out in order to measure distribution of the terrestrial radioactivity at Tsukuba area, Ibaraki prefecture. The standard intensity–altitude relation is measured above the flat ground surface of uniform radioactivity. The intensity-altitude relation is discussed by plotting data of the actual survey on semi-logarithmic graph, and topographic effect on gamma ray intensity is thus pointed out as theoretically expected. A simple method of topographic correction is presented based on the theoretical result that the effects of altitude and topographic effect can be approximately separated.

As regards the result of this survey, the biotite granite in this area is more radioactive than the adjacent Paleozoic formation. The radioactivity of the biotite granite may be medium among granitic rocks in Japan.

I. Introduction

Aeroradiometric survey is sometimes applied as an aid of geologic mapping. It is not easy to discover an outcrop of uraniferous deposit directly by aeroradiometric survey except " tree top level flying " or " rim flying." However, the favourable area for prospecting can be limited based on the distribution of radioactivity of rocks in combination with the geologic considerations. For example, Horikawa1) pointed out that uraniferous beds in sedimentary rocks in Japan were generally discovered around granitic rock masses of high radioactivity, based on the statistical study of gamma ray intensity measured by carborne survey.

For such application, the gamma ray intensity measured in the air should be corrected for the change of flight level and the altitude correction is usually made based on the empirical intensity–altitude relation measured above an uniformly radioactive and broad source. An appropriate expression of the relation is a curve drawn on semi–logarithmic graph by plotting intensity as ordinate against altitude as abscissa and the gradient, being approximately independent of altitude, is characteristic of the curve.

The gradient of intensity–altitude curve drawn by data of actual survey deviates frequently from the gradient of a standard intensity–altitude relation above an uniformly radioactive and broad source. The author2) discussed theoretically topographic effect on intensity in the air and concluded that deviation of the gradient may be mainly due to topographic effect. On the other hand, Gregory3) noticed the correlation of the gradient with rock type, which may depend on the variation of energy spectrum of gamma rays from rock. An experimental survey was carried out in the latter part of February 1962, over the area mainly

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covered by biotite granite and Paleozoic formation around Mt. Tsukuba, Ibaraki prefecture. The intensity–altitude curve made by plotting the data of this survey is, therefore, discussed on the standpoint of topographic and rock type effects in this paper.

A twin engine aircraft had been used through the aeroradiometric survey carried out by the Geological Survey of Japan. However, the use of large fixed wing aircraft is dangerous in rough mountainous areas and unsuitable for local survey. A large helicopter was therefore used in this survey. A light weight scintillation counter which is suitable for helicopter–borne survey was tested in this survey.

Before and after this aerial survey, a carborne radiometric survey was carried out in order to compare the gamma ray intensity in the air and on the ground. The measurement by a proton magnetometer installed in the helicopter was also made experimentally and the result will be published in near future.

The survey was done as a part of the project of the exploration for uranium, which had been carried out by the Geological Survey since 1954. Messrs. J. Suyama, H. Hasegawa, T. Saito, and Z. Komai who were in charge of the magnetic survey co–operated with the author in this aerial survey. Messrs. N. Obi, A. Ujiie, H. Kanaya, and S. Tanaka engaged in this carborne survey. The helicopter was chartered from the All Nippon Airways Co., Ltd. during this survey. The base of the survey flight was the Tsuchiura Aerodrome of the Eastern District Corps of the Japan Defence Army.

II. Geology

The area covered by this survey is a mountainous area forming a part of the north boundary of Kwanto Plain. The index map is shown in Fig. 1.

Mt. Tsukuba, being the highest in this area, consists of gabbroic intrusions. The small mountain range, stretching northward about 12 km long from Mt. Tsukuba, consists of mainly biotite granite contacting with Paleozoic formation at the north boundary. The highest peak is Mt. Kaba and the second is Mt. Ashio. Mt. Tsukuba and the Kaba mountain range are rather steep and these foots are thus covered by detritus. At the southern slope of Mt. Tsukuba and the adjacent hills, biotite granite and Paleozoic formation as well as two mica granites are exposed. The Paleozoic formation, which is made up of sandstone, mud stone, chert, and slate, is the base of Kwanto Plain and widely exposed at the northern and eastern mountainous areas accompanying with granitic intrusions. These granitic masses are intrusion during late Paleozoic or earlier Mesozoic age.

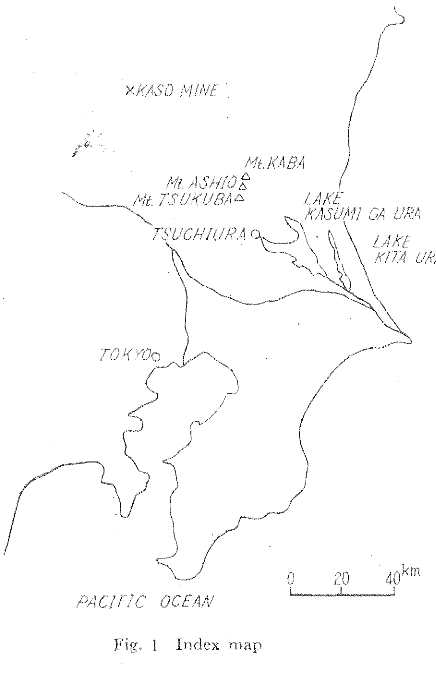


Fig. 1 Index map

Fig. 2 Geology of the surveyed area

This area has been well studied petrographically. However, the geologic sheet-mapping has never been carried out except the southern part of Mt. Tsukuba since 1900. The compiled geologic map at a scale of 1:200,000 was published by the Ibaraki prefectural Office, which is partly referred to Fig. 2.

Several occurrences of pegmatic uranium minerals are known in this area. At the Kaso mine of about 50 km north-west from Mt. Tsukuba, an uraniferous part was discovered in the cherty host rock of the manganese ore in Paleozoic formation⁴⁾.

III. Instrument

III. 1 Scintillation Counter

A Mt. Sopris's Model SC 188 DA scintillation counter was hitherto used for the aeroradiometric survey by the Geological Survey. This instrument provides sensitive detectors and stable electron tube circuit. However, light instrument in weight is desirable for helicopter–borne survey, especially, combined with a magnetometer and/or other aerial geophysical means. Transisterized circuit units have been developed for radiation measurement by the Nihon–Musen Electro–Medical Lab., Ltd. under specifications of the Geological Survey. In this survey, a combination of these units was used and satisfactorily operated.

A pre–amplifier unit is connected with a detector element consisting of a NaI(Tl) phosphor of 4 inches in diameter and 2 inches thick coupled with a 6363 photo–multiplier tube.

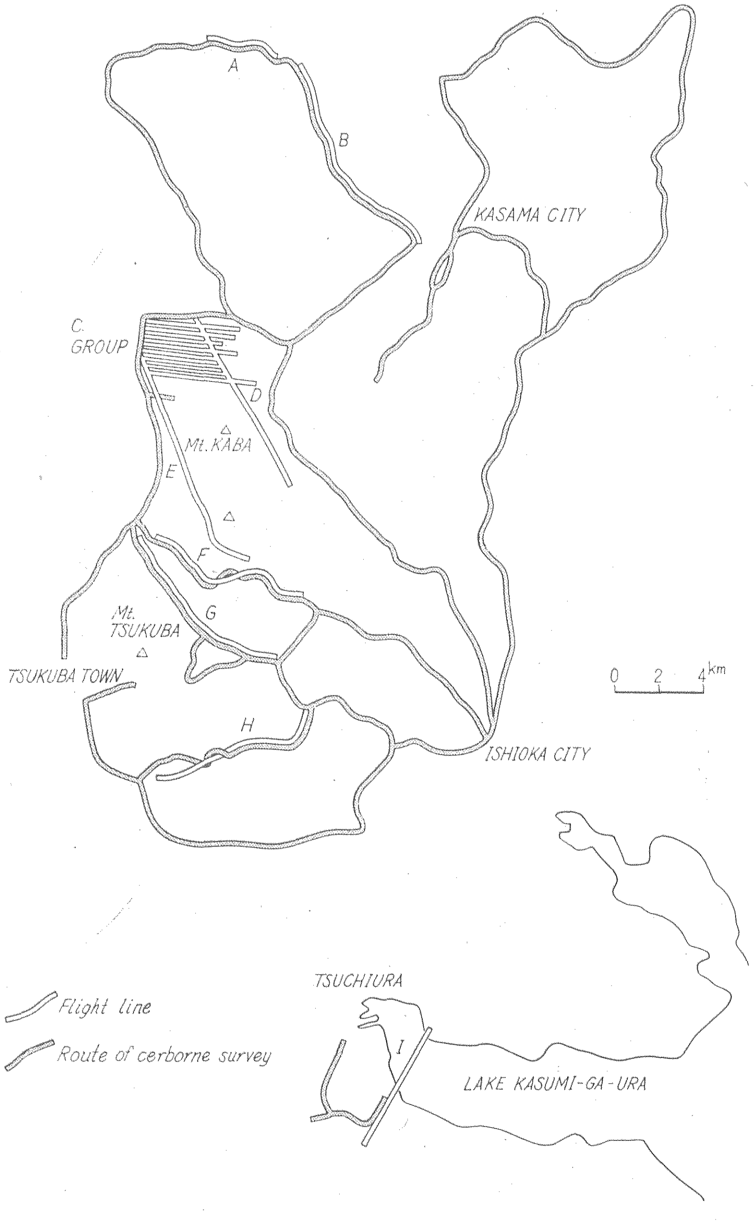


Fig. 3 Flight lines of the aeroradiometric survey and the route of the carborne survey

An amplifier–ratemeter assembly combines five units, namely, pre–amplifier, main amplifier, differential discriminator, ratemeter, and high voltage supply. The voltage gain of these amplifier units is about 10 and decreases by 3 decibels at 2 mega–cycles per second. The amplification factor can be adjusted by an attenuator at the input of the assembly. The input voltage of the discriminator unit should be from 0.5 to 10 volts for the pulse height analysis. The resolving power of the discriminator is approximately 10 micro–seconds. The baseline level and the channel width which can be spread up to a half of the range of baseline level are adjustable by five turns helical potentiometers. The range of counting–rate are as follows: 0 to 10^3, 2×10^3, 5×10^3, 10^4, 2×10^4, 5×10^4, 10^5, 2×10^5, 5×10^5, and 10^6 counts per minute and the time constants are 0.2, 0.5, 1, 2, and 5 seconds. The ratemeter unit drives an Esterline Angus's graphic recorder or a Texas Instrument's recti/riter recorder. The high voltage supply is regulated by a corona discharge tube. The necessary power is approximately 0.4 watts and supplied from mercury batteries. The weight of the assembly is about 10 kilograms containing batteries. During this survey, the discriminator unit was operated merely as an integral discriminator, of which the level corresponds to 70 kilo–electron volts in photon energy. This scintillation counter was tested in the carborne survey also.

In the carborne survey, a Mt. Sopris's Model SC 156 A scintillation counter mounted on a four–wheel driven vehicle was mainly used. The detector consists of a NaI(Tl) phosphor of 5 inches in diameter and 2 inches thick coupled with a 6364 photo–multiplier tube. This counter has been used for the routine carborne survey by the Geological Survey and the discriminating level was adjusted so as to correspond to 50 kilo–electron volts.

III. 2 Radio–altimeter and Camera

A radio–altimeter made by the Nippon Electric Co., Ltd. has been used by the Geological Survey. This is light in weight and directly drives an Esterline Angus's graphic recorder. It provides the two ranges, namely, 0 to 300, and 3,000 meters. The necessary power is approximately 15 watts and supplied from aircraft battery.

Electronic navigation system such as airborne tellrometer may be suitable for helicopterborne survey, but it could not be used. The automatic interval camera hitherto used is too heavy. In this survey, a conventional 35 millimeter camera vertically fixed to a frame was mannually operated over check points previously determined. Therefore, the use of the camera was an auxiliary means for determining flight path in this survey.

IV. Method of Survey

IV. 1 Method of the Aeroradiometric Survey

A Sikorsky S–55 helicopter, mounting a scintillation counter, a radio–altimeter, and a proton magnetometer, was used in this survey. The loading weight was decreased compared with the normal capacity, in order to increase the range of flight and the safety above mountainous area. The topographic sheet maps at a scale of 1 : 50,000 published by the Geographical Survey Institute of Japan were used for navigation and compilation of data.

As the first step of this survey, the measurement of intensity–altitude relation above the flat ground surface, being uniformly radioactive, was made along a straight line nearby the aerodrome. The gamma ray intensity measured at various altitudes along the line extending more than 1 km across the shore–line of Lake Kasumi–ga–Ura at the middle point.

Gamma ray intensity measured above a lake or the sea is contributed from various radioactive sources other than the terrestrial radioactivity and called as zero background (or water background). Zero background is therefore necessary to obtain net counting rate due to the terrestrial radiation. The measurement of zero background was made at the beginnings and the ends of every flight above the lake.

The drift of sensitivity of scintillation counter was more frequently checked by a radioactive source. The drift of response of the radio–altimeter was examined by comparing with barometric altitude above the lake at every flight. Neither variation of the zero background nor drift of the instruments was observed during this survey. The aerodrome was rather far apart from the survey area, but was favourable of these calibrations over a broad water surface.

While the usual flight pattern of aerial survey is a group of parallel traverses, several flight lines were prepared along the road so that gamma ray intensity in the air could be directly compared with intensity on the ground measured by the carborne survey and, in addition, the flight path could be easily maintained by visual navigation. Two other flight lines were set over the Kaba mountain range and a group of parallel traverses of which the spacing is about 300 m was prepared over the boundary between biotite granite and Paleozoic formation. The eight flight lines and a parallel group were thus prepared. These flight lines are called from A line to I line successively from the north. C lines are the group of parallel traverses and I line was prepared for the measurement of standard intensity–altitude relation as described before. A, B, F, G, and H lines are set along the roads traversed by the carborne survey.

The average speed at the survey flight was about 50 km per hour and the altitude was, in principle, specified at 100 m from the terrain. Visual navigation was easy at such low speed and from relatively high altitude. However, the altitude exceeded frequently over 200 m when wide range of vision was required in flying over a large ridge. Meandering parts of the road constructed along the mountain side could not be accurately followed even by helicopter.

The scale of intensity and altitude charts is approximately 1: 15,000. The time constant of ratemeter was 1 second.

Along these flight lines, such land marks as pass, cross road, shrine or school were previously selected about every 2 km as check points. The marks which indicate exposure of camera above these land marks were recorded on intensity and altitude charts as fiducials by which these records were correlated to flight paths. The determination of flight path by means of photograph is useless in mountainous area because of the lack of remarkable land marks. Therefore, the path which was determined visually was corrected by correlating minute change of altitude with topographic unduration. Intersection of flight line at ridge or riverlet was thus adjusted so as to fit the record of altitude with topographic profile. The procedure is rather troublesome and may be a temporary expedient.

IV. 2 Method of the Carborne Radiometric Survey

The route of the carborne survey was extended towards the eastern adjacent area of the aeroradiometric survey. The flat land covered by alluvium was generally excluded from the route except highways connecting large towns.

The speed of the vehicle was about 20 km per hour. The scale of the chart, being driven by odometer shaft, is constant at about 1: 5,000 and the time constant of ratemeter is set at 0.5 seconds.

The base map used for the carborne survey was the topographic sheet map published by the Geographical Survey Institute of Japan. The position of land marks was recorded about every 1.5 km on the chart of an operation recorder as the distance from a base of the route, and was also marked manually on the base map, in order to correlate intensity profile to the map. The positions of outcrop of fresh rock at cliff or road cutting, stone or concrete wall made artificially, and pavement of road were recorded on the chart, since these are necessary for the interpretation of intensity distribution.

V. Discussions on Intensity-Altitude Relation

V. 1 Standard Relation

The intensity–altitude relation above a broad source, that is the half-space uniformly filled with radioactive substances, is a standard for a specific detector and expressed, for a wide range of altitude, by a theoretical expression[2)] assuming the inverse square–exponential law with a linear build up factor as an attenuation law of gamma rays. The expression for non–directional detector is:

$$I^B=(1+k_1)\frac{K\sigma}{2\mu_a}(\mu_a h)E_2(\mu_a h)+k_a\frac{K\sigma}{2\mu_1}(\mu_a h)E_1(\mu_a h), \qquad (1)$$

where I^B = gamma ray intensity from a broad source,

μ_a = linear absorption coefficient of air,

μ_1 = linear absorption coefficient of source medium,

k_a = a constant concerning scattering by air,

k_1 = a constant concerning scattering by source medium,

K = a constant depending on the property of source substance and the sensitivity of detector,

h = altitude from the terrain,

σ = concentration (or grade) of radioactive substance in source,

and E_n = the exponential integral of n–th order.

And

$$I^B=I-I_0, \qquad (2)$$

where I = gross intensity measured above the source, and I_0 = zero background.

The ratio $k_a/(1+k_1)$ can be estimated from experimental relation, if a value of μ_a is given. As far as the theory is phenomenological, it is convenient for further discussions to select μ_a so that $k_a=0$, although μ_a should be, theoretically, the value against the maximum energy of the gamma rays from natural radioactive elements[5)]. The values of μ_a and $k_a/(1+k_1)$ were estimated from the experimental relation from 40 to 300 m in altitude along I line by means of the least square and are shown in Table 1. The standard intensity–altitude curve along I line is shown in Fig. 4

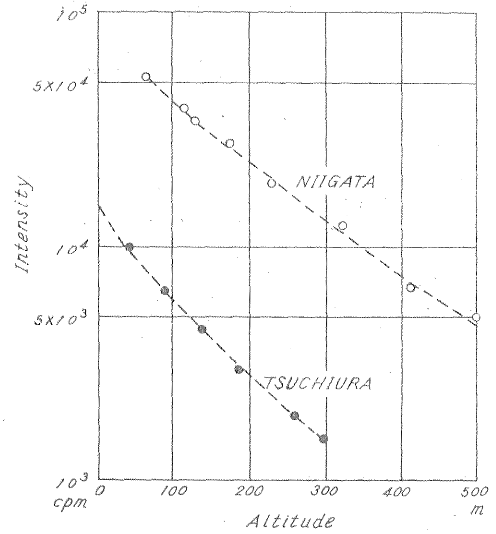


Fig. 4 Standard intensity-altitude curves

Table 1

μ_a	$k_a/(1+k_1)$
$4.5\times10^{-3}\text{m}^{-1}$	68.1
$4.3\times10^{-3}\text{m}^{-1}$	0.0
$5.9\times10^{-3}\text{m}^{-1}$	2.35

A standard relation is expressed approximately by a straight line on a semi-logarithmic graph by plotting intensity as ordinate against altitude as abscissa and therefore,

$$I^B = Ae^{-\mu_E h} \tag{3}$$

where μ_E = an effective linear absorption coefficient,
and A = a constant depending on radioactivity of the source and sensitivity of the detector.

And the gradient of the straight line, which equals to $0.4343\mu_E$, is independent of the constant A which is proportional to radioactivity of the source. The effective absorption coefficient was estimated as $7.58\times10^{-3}\pm0.08\times10^{-3}$ per meter so as to fit the data along I line.

The effective absorption coefficient may be a function of energy and directional response of detector, energy spectrum of radiation from source, and density of air, and therefore, depends on the type of detector and possibly the lithologic type of source. The estimated value of the effective absorption coefficient in this survey is compared with the results of the other measurements in Table 2. In the other experiment by the author, the different detector which connects a couple of elements consisting of NaI(T1) phosphor of 5 inches in diameter and 2 inches thick was used[2]. Therefore, the difference in the values of the effective absorption coefficient is might be due to the difference in detector element as well as discriminating level of photon energy.

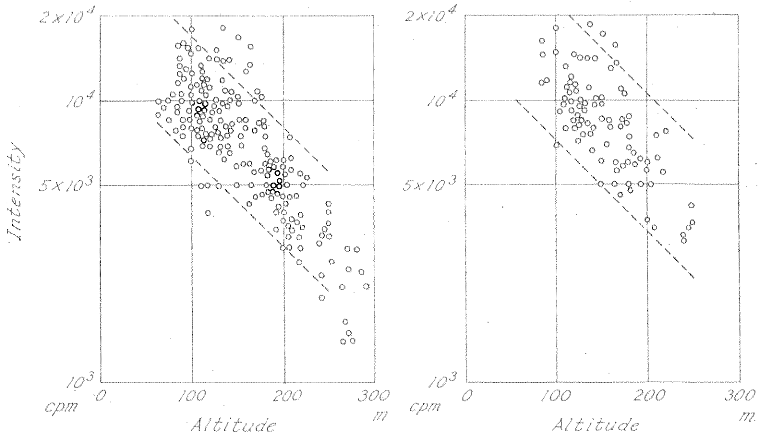
Table 2

Effective absorption coefficient	Area	Author
7.58^{-3}m^{-1}	Tsuchiura, Ibaraki Pref. (alluvium)	Sano
6.14^{-3}m^{-1}	Niigata, Niigata Pref. (alluvium, sand dune)	Sano
$*6.14^{-3}\text{m}^{-1}$	Fruita, Colorado, U.S.A.	Davis & Reinhardt
$*9.04^{-3}\text{m}^{-1}$	Ottawa, Ontario, Canada	Gregory

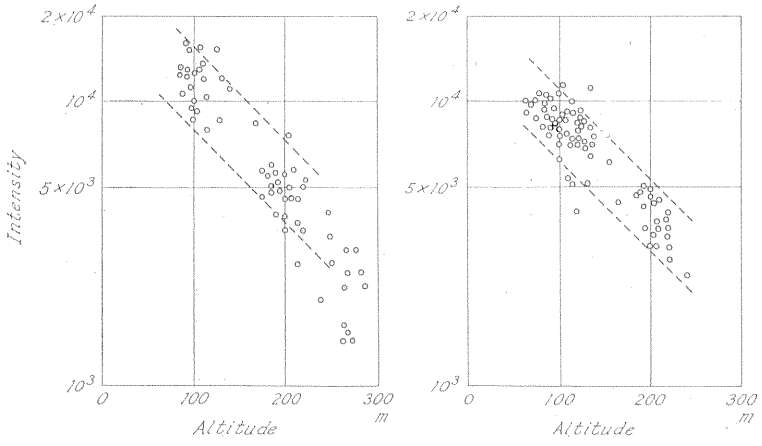
* These values are referred from the reference 3)

If intensity–altitude diagram is made by plotting, on a semi–logarithmic graph, the values read from records of actual survey, the dense distribution of plotted points may form a band parallel with the standard curve, since normal intensity may be regarded as intensity from effectively broad source. In making the diagram, time lag of the measurement should be remembered and it equals to the time constant of integrating circuit, so far as deformation of recorded curve is not remarkable. (see Appendix) Therefore, the chart of altitude in this survey correlated to the chart of intensity delayed by 1 second, since the time constant of the ratemeter was 1 second and the integrating circuit of the radio-altimeter has very short time constant.

Fig. 5(a) shows the intensity-altitude diagram plotted by the values at every 15 seconds (about 200 m) from the charts of all flight lines. The assemblage of these points may be regarded as a band parallel with the standard curve. The area under these flight lines is classified into three lithologic types, namely, biotite granite containing its detritus, Paleozoic formation, and diluvial sediment. The intensity-altitude diagrams over each lithologic type are shown in Figs. 5(b), (c), and (d). The average curves of these diagrams may be parallel with the standard curve. As for the Paleozoic formation, however, the average gradient might be steeper than the standard gradient. The distribution of the points in the diagram is not so dense that it may be affected by topographic effect and erratic distribution of radioactivity.



(a) The whole area (b) Granite and its detritus



(c) Paleozoic sediment (d) Diluvial sediment

Fig. 5 Intensity-altitude diagrams of the area

V. 2 Topographic Effect

The curve connecting successively points plotted on intensity-altitude diagram fluctuates due to error of measurement. The standard deviation of intensity is given by $\sqrt{I/2\tau}$, where I is counting-rate and τ is time constant of ratemeter. The error of altitude measured by the radio-altimeter is 5 percents of altitude with the addition of 3 meters.

Since

$$\mu_E = \log A - \log(I - I_0)/h, \tag{4}$$

$$\Delta\mu_E/\mu_E/ = |\Delta h/h| + |\Delta I + \Delta I_0| \,/\mu_E h(I-I_0) \tag{5}$$

where $\Delta\mu_E$, Δh, ΔI, and ΔI_0 are respectively the errors of μ_E, h, I, and I_0. In this equation, one may put $\Delta h/h = 0.05$, $\Delta I = \sqrt{I/2\tau}$, and $\Delta I_0 = 0$ in the present case. When $h = 150$ meters, $I - I_0 = 2\times10^4$ counts per minute, and $I_0 = 4\times10^3$ counts per minute, from Eq. (5)

$$\Delta\mu_E/\mu_E/ = 0.103$$

Therefore, the error of the effective absorption coefficient is about 10 percents at average values of intensity and altitude. In the case of the measurement of standard curve, the errors may be small since mean values of 1 km long were used.

The altitude measured by radio-altimeter is treated as the really vertical height, even in the case that the ground surface is not horizontal. If the measured altitude is length of the perpendicular from aircraft to the ground surface, the vertical height h is expressed by the measured altitude h' as follows:

$$h = h'\sec\theta, \tag{6}$$

where θ is the angle between the horizontal plane and the inclined ground surface. Therefore,

$$\Delta\mu_E/\mu_E = \sec\theta - 1, \tag{7}$$

and when $\theta = 30$ degrees, that is extremely large value for ordinary topography,

$$\Delta\mu_E/\mu_E = 0.12$$

This value is not greater than the other error of measurement. The error of this type may be also caused by tilting of aircraft.

The intensity-altitude diagram is discussed based on the assumption that the ground as a source is uniformly radioactive. The intensity-altitude relations above small source, heterogeneous source, or boundary of homogeneous sources are different with the standard relation and they are thus regarded as clearly exceptional cases. However, the effect of surface unduration of homogeneous source, that is topographic effect, is worth to be noticed.

The author[2)] calculated the intensity-altitude relation above typical topography, namely, two dimensional ridge and valley, and independent peak of cone type. The expression of intensity are as follows:

(i) above the top of two dimensional and symmetric ridge,

$$I^R = (1+k_1)\frac{K\sigma}{\mu_a \pi}\int_0^{\pi/2} \mu_a h \cos\theta \, E_2(\mu_a h \cos\theta\sqrt{1+\sec^2\phi\,\tan^2\theta})\,d\phi \tag{8}$$

(ii) above the bottom of two dimensional and symmetrical valley,

$$I^V = (1+k_1)\frac{K\sigma}{\mu_a}\Big[(\mu_a h \cos\theta \, E_2(\mu_a h \cos\theta) - \int_0^{\pi/2}\{\mu_a h \cos\theta \, E_2(\mu_a h \cos\theta\sqrt{1+\sec^2\phi\,\tan^2\theta})\}\,d\phi\Big] \tag{9}$$

(iii) above the top of independent peak of cone type,

$$I^P=(1+k_1)\frac{K\sigma}{2\mu_a}\int_0^{\pi/2-\theta}\exp.\left(-\frac{\mu_a h}{\cos\phi-\sin\phi\tan\theta}\right)\sin\phi\,d\phi \tag{10}$$

In numerical calculation of these formulae, the value of μ_a should be 4.3×10^{-3} per meter for the detector used in this survey since k_a is neglected.

The calculated curves as shown in Fig. 6 are nearly parallel with the standard curve

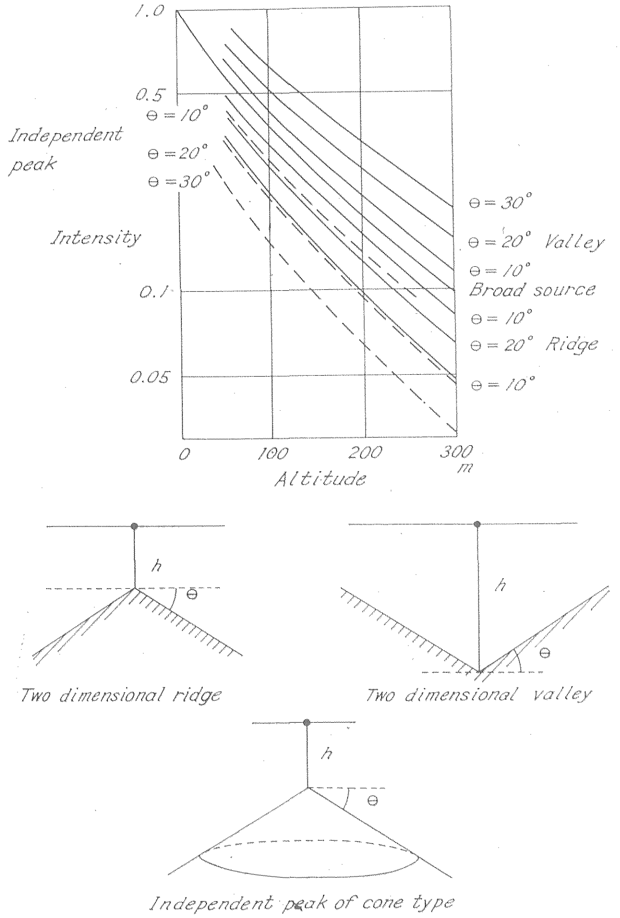


Fig. 6 Topographic effect on intensity-altitude curve

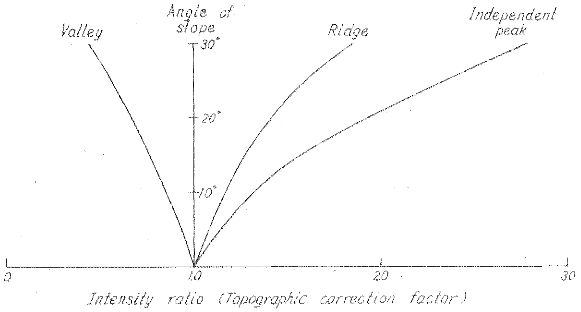


Fig. 7 Average ratio of intensity above typical topography to broad source intensity (Topographic correction factor)

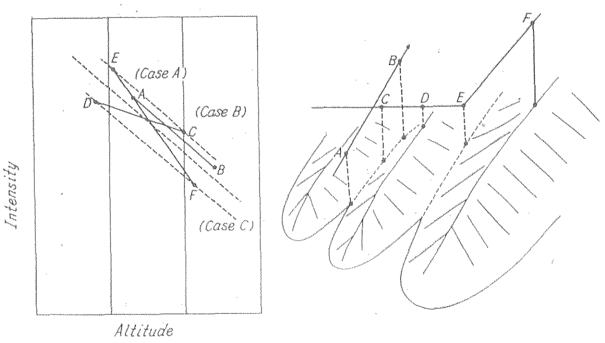
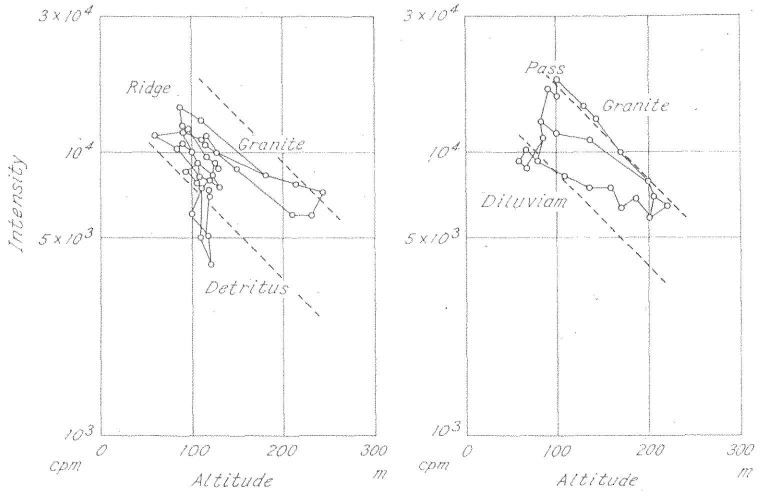
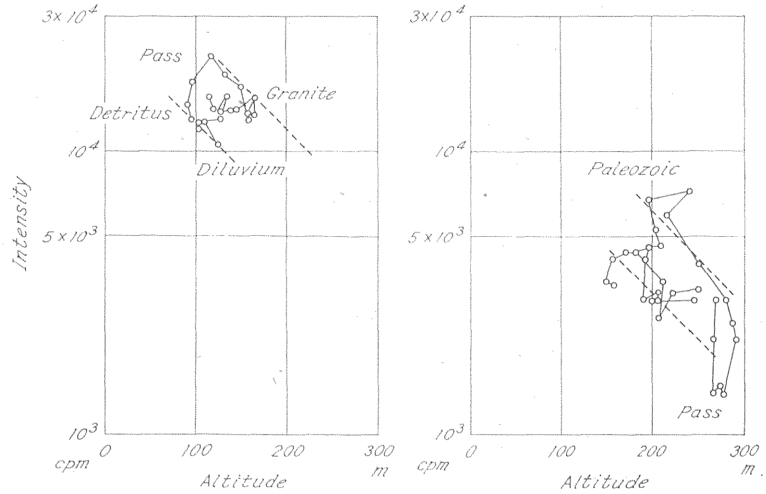


Fig. 8 Schematic explanation of variation in gradient of intensity-altitude curve



(a) Line E

(b) Line F



(c) Line G

(d) Line H

Fig. 9 Intensity-altitude curves obtained from the records of actual survey and, therefore, the ratio of intensity above typical topography to the broad source intensity is nearly independent of altitude, while the ratio depends on the type of topography and the angle of slope as shown in Fig. 7.

The apparent variations in gradient of intensity–altitude curve are deduced from the result of the calculation. When aircraft flies parallel with the direction of ridge or valley, the curve would be the same gradient as the standard.(Case A) When aircraft flies horizontally across a ridge, the curve would be less oblique than the standard curve since the altitude above the valley is higher than that above the ridge and the intensity above the valley is higher than the broad source intensity at the same altitude.(Case B) If aircraft rises up rapidly before crossing over a large ridge in order to get wide range of vision, the curve would be more high–pitched than the standard curve.(Case C) The graphic interpretation of these cases are illustrated in Fig. 8.

The intensity–altitude curves along the flight lines of E, F, G, and H are drawn by the values at every 15 seconds or 3.75 seconds, if necessary, and are shown respectively in Figs. 9a, b, c, and d. The topographic maps around these flight lines are reproduced in Figs. 12e, f, g, and h. Some parts of the curves deviate from the standard curve than the errors of measurement.

The south part of E line crossing the Kaba mountain range may be a typical example of the case B of topographic effect and an example of the case C may be the curve at the middle part of H line, crossing the main ridge consisting of Paleozoic formation. As for the curves shown in Figs. 9a, and c, the topographic effect is not clear, although F and G lines cross over the mountain range. In this case, the effects of ridge and valley are cancelled out each other since the flight lines were set along valleys cutting the mountain range.

It is not clearly recognized on the diagrams that the gradient of curve is different with lithologic type. Along the other flight lines, the range of altitude is so small that intensity-altitude curve could not be drawn.

V. 3 Altitude Correction

The measured gamma ray intensity in the air should be corrected to intensity at a constant altitude for the purpose of comparing radioactivity of rocks. The altitude correction is usually made by the assumptions that the intensity is measured always above broad source and standard relation is thus applicable. The correction may be carried out by a simple analog computer and the automatic correction on aircraft has been brought into practice by the United States Geological Survey and in U.S.S.R..

The author had once a plan of constructing a computer, however the idea was stopped since variation of intensity-altitude relation was noticed. The discussion of the preceding section suggests that the variation can be explained by topographic effect and standard relation

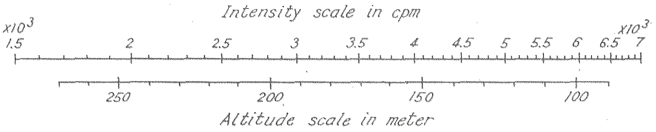


Fig. 10 Slide rule for altitude correction

is applied to altitude correction since topographic effect is approximately independent of altitude. The altitude correction was made at every 3.75 seconds (about 50 m) or by shorter interval, if necessary. The slide rule which consists of a logarithmic intensity scale and a linear altitude scale as shown in Fig. 10 is useful as far as Eq. (3) is valid and easily altered from an ordinary slide rule.

The error of ΔI_C of corrected intensity I_C is obtained from Eq. (3):

$$\Delta I_C/I_C \leq \Delta I|/(I-I_0)+|\Delta I_0|/(I-I_0)+\mu_E|\Delta h|+|h_0-h|\cdot|\Delta\mu_E| \tag{11}$$

where h_0 is standard altitude for which intensity is corrected. One may put that $\Delta I=\sqrt{I/2\tau}$, $\Delta I_0=0$, and $\Delta h=0.05h$. In this survey, $I_0=4\times10^3$ counts per minute, $\mu_E=7.58\times10^{-3}$ per meter, and $h_0=100$ meters, and $\Delta\mu_E=0.75\times10^{-3}$ per meter. The distribution of the error thus calculated is shown in Fig. 11. The error is about 10 percents at high intensity and standard altitude but more than 50 percents at low intensity and high altitude.

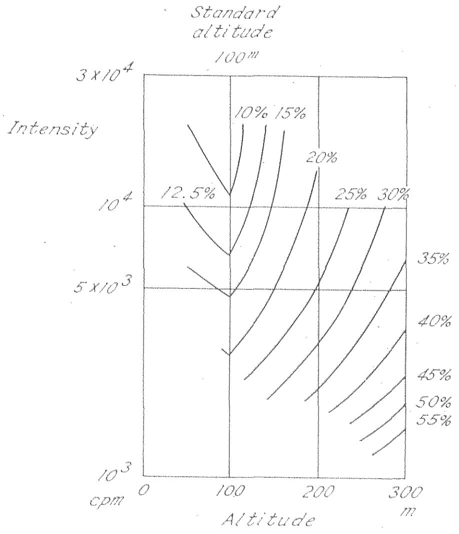


Fig. 11 Error in altitude correction

VI. Results of Survey

VI. 1 Topographic Correction and Distribution of the Terrestrial Radioactivity

The intensity measured in the air is corrected to an altitude of 100 m. The profiles of the corrected intensity are shown in Figs. 12a to h with the profiles of altitude and the corresponding intensity profiles measured by carborne survey. At a glance of the figures, the correlation between fluctuation of the corrected intensity and change of the altitude is still notable. It may suggest topographic effect, however some increases of intensity might be due to the exposure of pegmatite or of fresh granite at quarry.

The topographic correction is troublesome, if it is strictly made for actual and complicated topography. However, a rough estimation is easily carried out by applying the factor illustrated in Fig. 7 to the intensity corrected for an altitude.

The factor is calculated only in the case of detector which is located above the top of two-dimensional ridge or independent peak, and the bottom of two-dimensional valley.

In addition, topographic effect would be vanished at about the middle point of a slope forming a ridge at one end and a valley at another end. Topographic correction is estimated at such positions of flight line.

If the two-dimensional topography is unsymmetrical, the arithmetic mean of two factors for different angles of slope may be applicable. For the combination of ridge and valley in two direction perpendicular to each other, an approximate correction may be done as the product of the corrected intensities obtained by regarding the topography in each direction as two-dimensional one. For example, a pass is usually treated as the top of ridge in a direction and as the bottom of valley in another direction.

If minute change in intensity can be neglected, topographic effect may be eliminated by removing fluctuation of intensity, for instance, by successive mean. As for this survey, the corrected intensity is smoothed by the successive mean of every 1 km along flight line, considering the wave lengths of minute change in topography. The profiles of the smoothed intensity are also shown in Figs. 12a to h. In estimating topographic effect from the smoothed

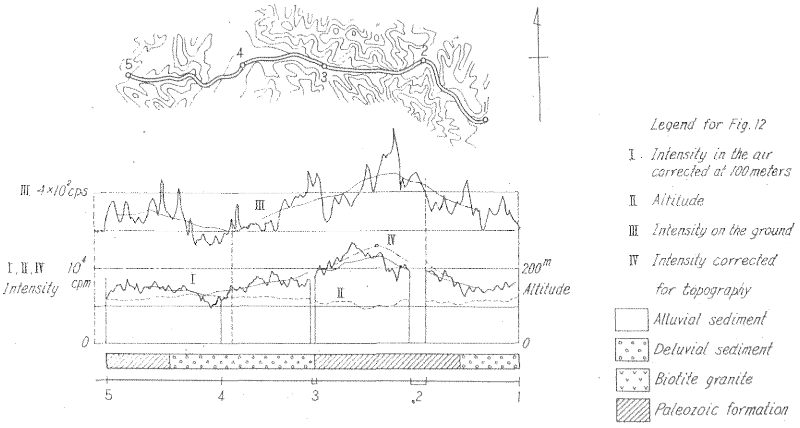


Fig. 12a Results of the survey along A line

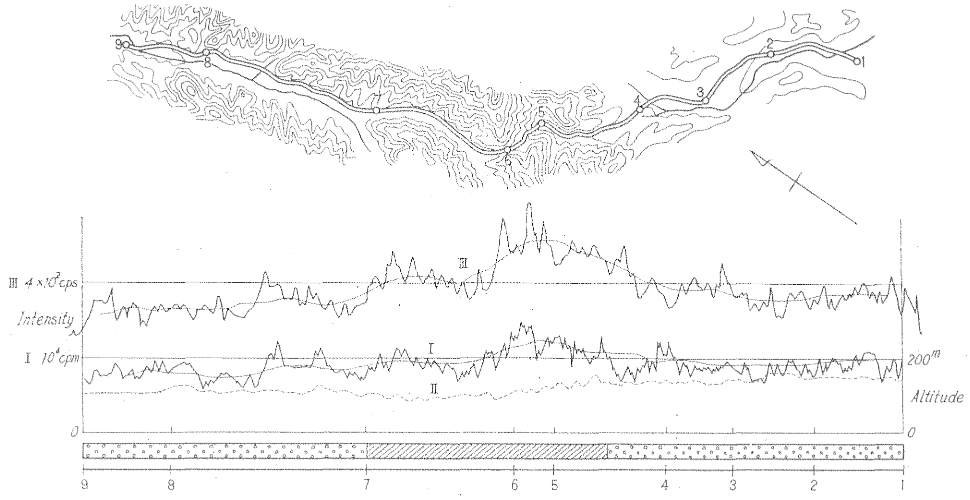


Fig. 12b Results of the survey along B line

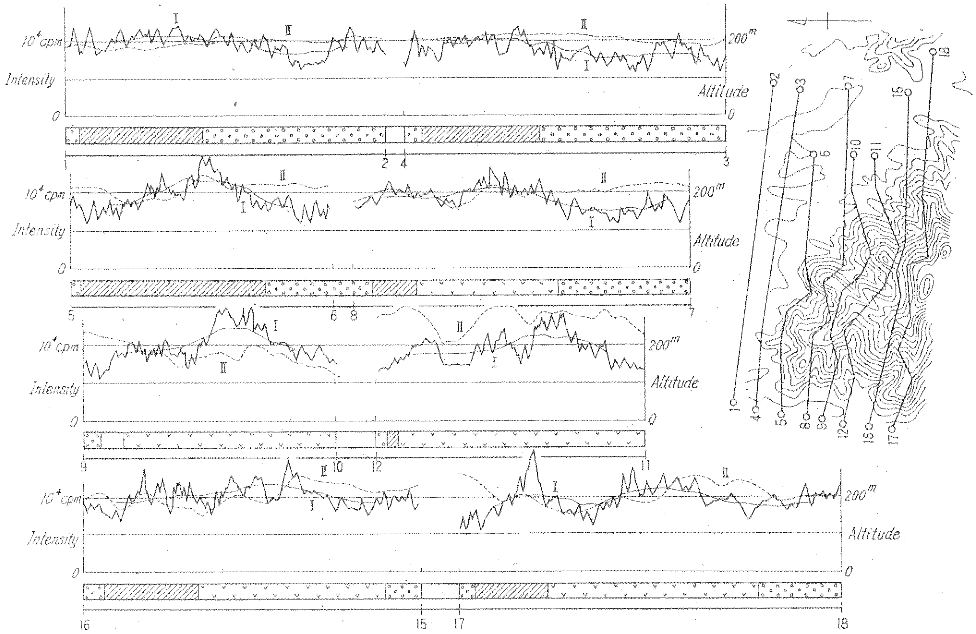


Fig. 12c Results of the survey along C line

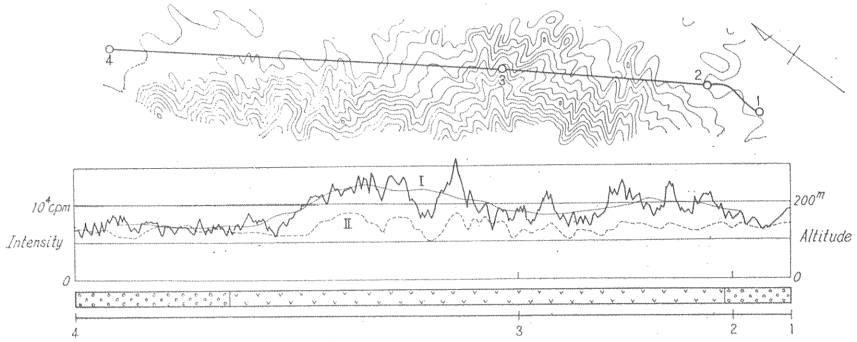


Fig. 12d Results of the survey along D line

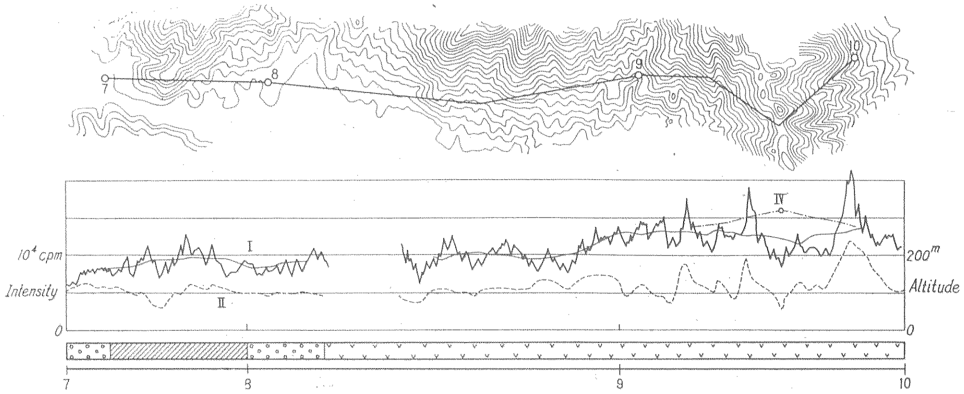


Fig. 12e Results of the survey along E line

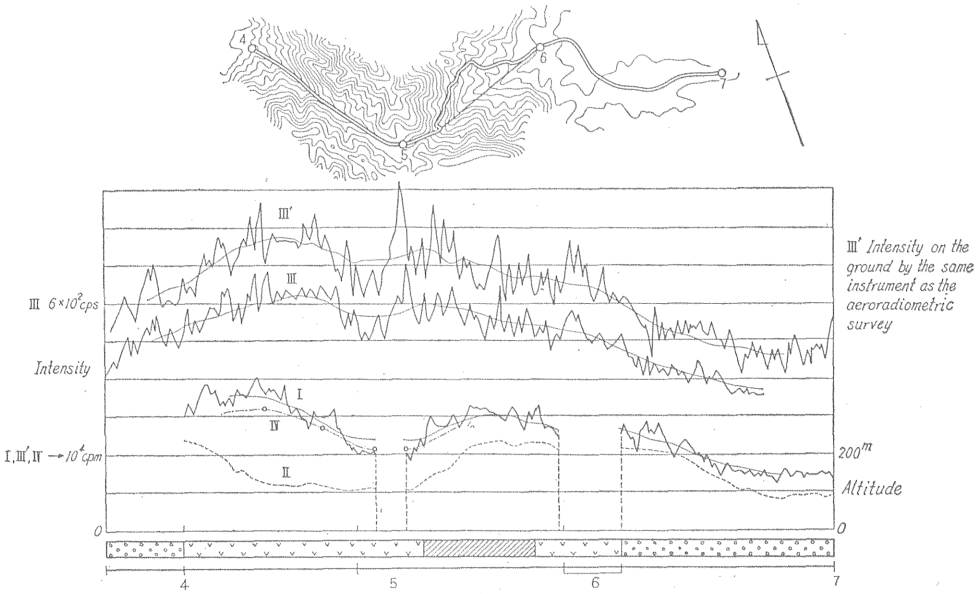


Fig. 12f Results of the survey along F line

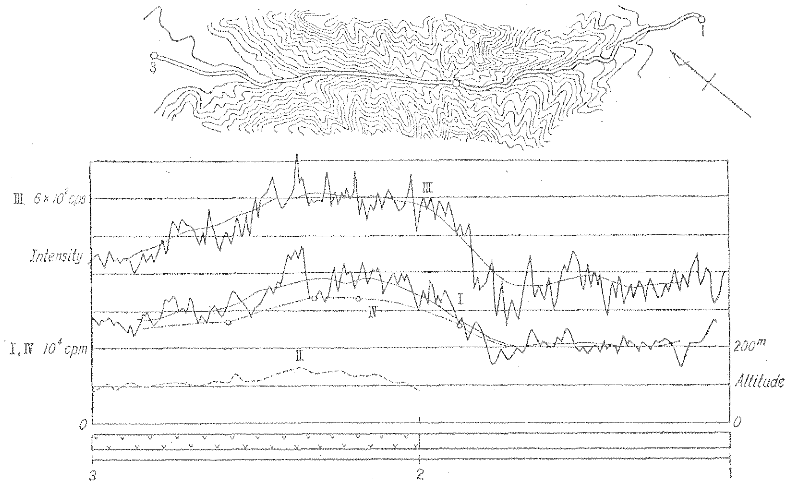


Fig. 12g Results of the survey along G line

intensity, topography also should be smoothed in the direction of flight line. However, estimation of topographic effect from unsmoothed intensity according to unsmoothed topography may be preferable since the effective range of detector is less than 1 km. The knowledge for range of detector is necessary, although the discussion is neglected in this paper.*

The iso-intensity contour map was made from the results of the correction along C to G lines as shown in Fig. 13. The iso-intensity contour of 10^4 counts per minute coincides nearly with the contact of Paleozoic formation to biotite granite at the north part of the area. The radioactivity of biotite granite, constructing the Kaba mountain range, increases

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* refer to the discussion for a broad source in IV. 2 of the reference 2)

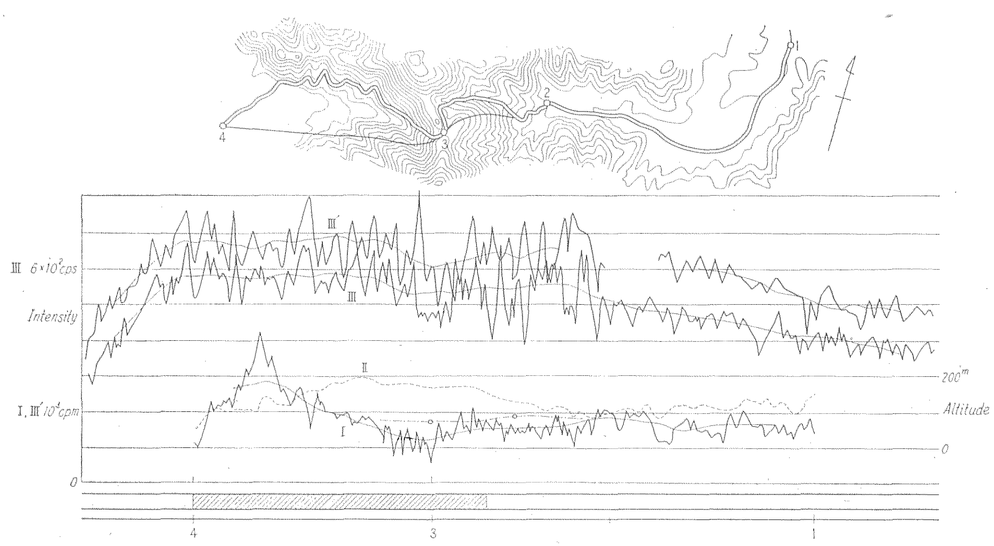

Fig. 12h Results of the survey along H line

from north to south. However, it is not clear whether the variation is due to the difference in radioactivity of granite itself or the difference in weathring of the surface. The radioactivity of Paleozoic formation exposed along A and B lines seems to be a little higher, however it also might be due to the effect of weathering. The range of radioactivity may be 1.6 to 1.0×10^4 counts per minute for biotite granite containing its detritus and 1.3 to 0.8×10^4 counts per minute for Paleozoic formation.

VI. 2 Gamma Ray Intensity on the Ground and Comparison with Intensity in the Air

Gamma ray intensity measured by carborne survey changes with various factors and these factors change so minutely and complexly along road that no corrections are usually made. The general principles of interpretation for intensity distribution are as follows: (1) Intensity increases at the place of good geometry and (2) intensity decreases with the progress of weathering from fresh rock to soil. For instance, the intensity beside the outcrop of fresh granitic rock at precipitous cliff is as high as the intensity due to the spot exposure of uraniferous deposit. Sometimes, the effect by such artificial structure as stone or concrete wall and pavement should be noticed. Besides, zero background is not subtracted since it is not easy to estimate in the case of car-mounted instrument.

Therefore, the result of carborne survey is represented as a route map showing uncorrected intensity distribution or a map indicating the location of anomalous intensity. Fig. 13 is the intensity route map in which values of uncorrected intensity are devided into three ranges of more than 600, from 600 to 400, and less than 400 counts per second. Locations of the highest intensity range are distributed at the granitic area close to Mt. Tsukuba.

The profiles of uncorrected intensity measured by the carborne survey are illustrated in Figs. 12a, b, f, g, and h together with the corrected intensity by the aeroradiometric survey. The intensity on the ground was smoothed by the successive mean of every 1 km and by this procedure the geometric effect may be vanished since geometric factor is usually of short

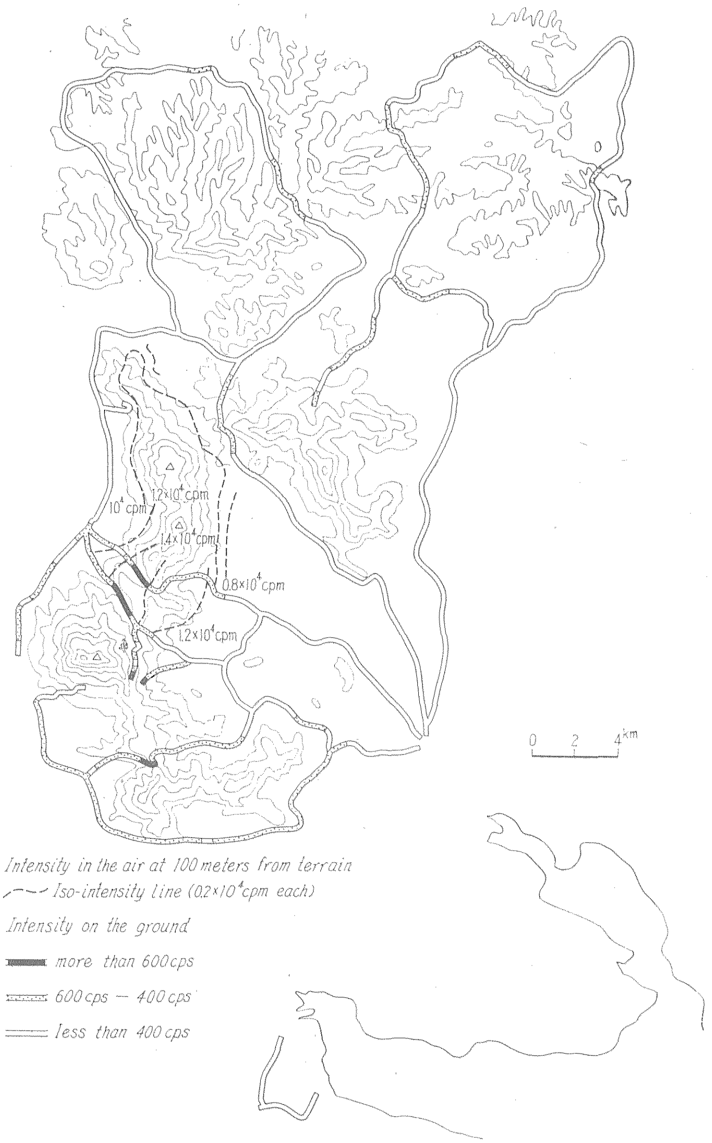

Fig. 13 Distribution of the intensity

wave lengths.

The carborne survey by using the instrument mounted on the helicopter was carried out along F and H lines. The profiles of the intensity are parallel with those measured by the other instrument as shown in Figs. 12f and g. The relation between counting rates by the two counters is shown in Fig. 14 by plotting the values of the smoothed intensities at every 500 m along road and these counting rates are approximately equal to each other.

At a glance of Fig. 12, it may be notable that the variation of the intensity measured in the air corresponds to the intensity on the ground on the whole. The flight path of H line deviates from the route of the carborne survey especially at the western part and the eastern part of F line also deviates from the road. Excluding the data of these deviated courses, the

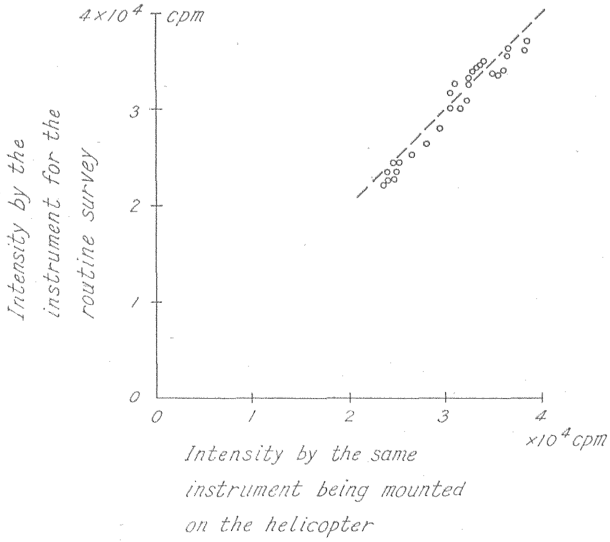

Fig. 14 Relation between the counting rates by two counters

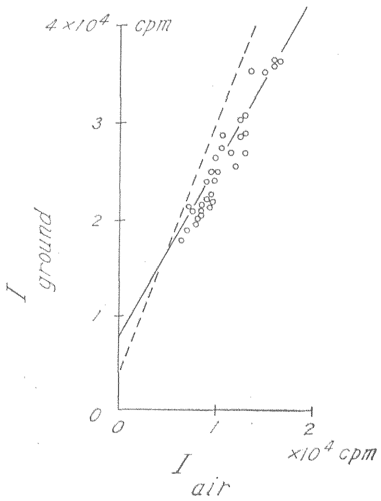

Fig. 15 Relation between the intensity at 100 meters from the ground and the intensity on the ground

relation of the intensities is shown in Fig. 15 by plotting the smoothed intensity on the ground as ordinate against the corrected intensity for both altitude and topography as abscissa.

If Eq. (1) is valid when $k_a = 0$ and zero background measured in the helicopter is applicable to the measurement in the vehicle, the relation between the intensities is represented by:

$$I_{\mathrm{air}} = 0.37\ (I_{\mathrm{ground}} - 4{,}000), \qquad (12)$$

where I_{air} and I_{ground} are respectively the intensity at 100 m from the terrain and the intensity on the ground, expressed in counts per minute. However, the empirical relation obtained by means of the least square:

$$I_{\mathrm{air}} = 0.59\ (I_{\mathrm{ground}} - 7{,}900), \tag{13}$$

is different from the theoretical formula. If the empirical intensity-altitude curve is combined with the intensity on the ground surface measured by the instrument mounted on the vehicle, the curve is nearly a straight line. However the theoretical curve is concave at low altitude.

The absorption of gamma rays by wall of body of helicopter or vehicle is not negligible and if the decrease of intensity by the absorption is different, the theoretical relation (12) is not clearly applicable. The difference may be explained by other causes. The theoretical intensity-altitude curve approaches to a straight line as μ_a increases if the assumption that $k_a = 0$ is removed or as the sensitivity of detector increases in the vertical direction when the detector is directional.2) However, the fact that the intensity in the air is proportional to the intensity on the ground may be satisfactory for estimating the terrestrial radioactivity by aeroradiometric survey.

The gamma ray intensity measured by carborne survey beside the outcrops of biotite granite nearby Mt. Tsukuba is about 700 counts per second and this is medium value among granitic rocks in Japan, according to the statistical study on the intensity measured by carborne radiometric survey.1)

VII. Summary and Conclusions

An experimental aeroradiometric survey was carried out in order to measure the distribution of the terrestrial radioactivity at Tsukuba area, Ibaraki prefecture. A large helicopter equipped with a transisterized scintillation counter and a radio-altimeter was used. Several flight lines were selected along the road in order to compare the radiation intensity with the intensity on the ground measured by carborne survey, besides flight lines acrossing a small mountain range.

The flight level was specified to 100 m from the terrain, however it exceeds over 200 m in flying over large ridge or valley. The average speed of survey flight was 50 km per hour. The flight path was determined visually and corrected by comparing the record of radio-altimeter with minute change of topography. The photograph by a conventional camera exposed above remarkable land marks was used as a auxiliary means. Calibration of the instruments was frequently made and zero background was measured at every flights.

The standard intensity-altitude relation was measured along a flight line over the flat and uniformly radioactive ground. The intensity-altitude diagram was made from the records of the actual survey and average relation may agree with the standard relation. However, the curve connecting successively points plotted on the diagram deviates from the standard relation over the limit of errors of measurement. The difference may be explained by topographic effect.

The altitude correction was made based on the standard relation. The elimination of topographic effect was tried by means of successive arithmetic mean of every 1 km. However, the smoothed intensity is still affected by the topography of long wavelengths. The topographic correction was roughly made, at the top of ridge and the bottom of valley, by applying the factor which was theoretically calculated by using a linear absorption coefficient derived from the standard relation.

The intensity thus corrected is proportional to the intensity measured on the ground, which was also eliminated topographic effect by successive mean. However, the ratio is different from the theoretical value and the several interpretations of the difference may be possible.

The biotite granite intruding on the north of Mt. Tsukuba is more radioactive than the adjacent Paleozoic formation. The radioactivity of the biotite granite decreases from south to north, however it might be due to the difference in weathering of the surface. The radioactivity of the south part of biotite granite may be medium among granitic rocks in Japan.

In this paper, intensity–altitude relation in aeroradiometric survey is discussed based on the experimental data and the theoretical study previously carried out by the author. Topographic effect on the intensity in the air, thus revealed, is not always negligible in mountainous area and therefore, it should be corrected in the aeroradiometric survey for the purpose of measuring distribution of the terrestrial radioactivity.

Simple and rough correction can be made according to the theoretical result that the effects of altitude and topography are approximately separated. The author proposed a method, in which the estimation of the effect, is done at specific position above typical topography being a substitute for actual undulation of the terrain.

More precise and accurate method might be unnecessary since aerial survey is usually a means for reconnaissance. Topographic map is indispensable for the correction. However, the sufficient knowledge of topography may be obtained from aerial photograph, if the map could not be available. And the interpretation of aeroradiometric survey combined with photo–geologic study may be advantageous.

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Appendix

Delay of Isolated Peak of Counting Rate Curve Recorded by Ratemeter

The dynamic character of ratemeter is:

$$n(t) = n'(t) + \tau \frac{dn'(t)}{dt} \quad , \tag{14}$$

where $n =$ true variation of counting rate,

n' = variation of counting rate recorded by ratemeter,

τ = time constant of ratemeter,

and t = time.

By Tailor's expansion,

$$n'(t+\varDelta t) = n'(t) + \varDelta t \frac{dn'(t)}{dt} + \sum_{n=2}^{\infty} \frac{(\varDelta t)^n}{n\,!} \frac{d^n n'(t)}{dt^n} \tag{15}$$

If the deformation of recorded curve is not remarkable,

$$n(t) = n'(t+\varDelta t)$$

and the third term of the right side of Eq. (15) is negligible in the case of isolated peak. Then, comparing Eqs. (14) with (15), we have:

$$\varDelta t = \tau,$$

that is, the delay is equal to the time constant.

茨城県筑波地区で実施した天然放射能分布の測定のための空中放射能探査

佐 野 浚 一

要 旨

空中放射能探査によってウラン鉱床を直接発見することは困難であるとしても，地表の放射能の分布と地質学的な考察との組合せによって，探査する地域を限定することができる。空中放射能探査によって地表の放射能分布をなるべく正確に求めるために，高度とガンマ線強度との関係を検討する目的で，茨城県筑波地域において実験的な探査を行なった。その結果，理論的に予期していたように，地形補正が必要であることが認められた。高度補正と地形補正とは近似的に分離できるという理論的結果に基づいて，ごく簡単な地形補正の方法を提案した。筑波地域の黒雲母花崗岩は日本の花崗岩質岩中で中程度の放射能を示す。