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DEPARTMENT OF MINES
AND TECHNICAL SURVEYS

BULLETIN 66

GEOLOGICAL INTERPRETATION OF AERORADIOMETRIC DATA

A. F. Gregory

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By

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PREFACE

Because of the complexities in the geology of natural radioactive materials and in the attenuation of gamma radiation emitted from them through absorbing media, the interpretation of aeroradiometric data is as much a qualitative art as a quantitative science. In this report the major variables in the measured intensity of gamma radiation are discussed and a technique for interpreting the regional geology is described. This technique has been used successfully in flights over a region suitable for this type of geophysical survey to recognize several characteristic groups of rocks and certain specific rock-units.

The theory was developed by the author, in part from research for the Crown company, Eldorado Mining and Refining Limited, and was presented as his doctoral dissertation at the University of Wisconsin. His recent investigations of rock radioactivity at the Geological Survey of Canada resulted in the more complete interpretative technique described in this bulletin.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, February 1, 1960

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GEOLOGICAL INTERPRETATION OF AERORADIOMETRIC DATA

Abstract

Distinct contrasts in gamma radioactivity exist between various materials on the surface of the earth. These contrasts may be mapped with sensitive airborne detectors. Because of the many variables involved, the interpretation of radioactivity patterns so obtained has been qualitative and very general.

The present theoretical study and its application to field measurements with integrating detectors have resulted in a new quantitative technique for the interpretation of regional geology. The theory of attenuation of gamma flux suggests that for multiple scattering conditions, certain generalizations may be made which permit a simpler assessment of flux variations than is required by the established complex mathematical treatment. The major determinants of gamma flux density are: the air distance between the source and the detector, the effective radiating area of the source, and the specific surface activity of the source material. Over large air distances, the multiple-scattered radiation approximates a state of spectral equilibrium and the attenuation of this equilibrium flux may be described by a single, effective absorption coefficient.

The signal measured over a source, with both area and thickness effectively infinite in extent, is expressed as:

$$S_h = k \frac{2\pi}{\mu_E} s_o e^{-\mu_E h}$$

where S_h is the signal intensity at altitude h above the source, s_o is the theoretical signal at the surface of an elementary unit area of source material, μ_E is the effective absorption coefficient of its equilibrium flux in air, and k is a constant.

In the interpretative technique, maximum values of signal intensity and flight altitude above ground are used to plot a lithological clearance-signal curve for each rock type in the survey area. Values of s_o and μ_E which are characteristic of the rock may be determined from these curves. Accordingly, the automatic correction of data for flight altitude, based on the assumption of a single absorption coefficient, is not valid for comparative aeroradiometry.

The lithological clearance-signal data suggest that spectral analysis of gamma radiation may provide useful data for a more detailed geological interpretation than the present technique permits.

Résumé

La radioactivité gamma présente des contrastes nets selon les différentes matières qui composent la surface de la terre. On peut déterminer ces contrastes avec des détecteurs aéroportés très sensibles. Mais, à cause des nombreuses variables qui entrent en jeu, l'interprétation des courbes de radioactivité ainsi obtenues demeure qualitative et d'ordre très général.

La présente étude théorique et son application aux mesures obtenues sur le terrain à l'aide de détecteurs intégrateurs ont abouti à une nouvelle technique quantitative d'interprétation de la géologie régionale. La théorie de l'atténuation du flux de rayons gamma porte à penser que, dans des conditions de dispersion multiple, on peut arriver à certaines généralisations permettant une évaluation plus simple des variations de flux qu'avec le traitement mathématique complexe actuellement en usage. Les principaux facteurs qui déterminent la densité du flux de rayons gamma sont: l'épaisseur de la couche d'air qui sépare la source du détecteur, le champ utile de rayonnement de la

source et l'activité spécifique de surface de la matière rayonnante. Quand l'épaisseur de la couche d'air est considérable, le rayonnement à dispersion multiple est voisin d'un état d'équilibre spectral, et l'atténuation de ce flux d'équilibre peut se décrire par un seul coefficient d'absorption efficace.

Pour une source de superficie et d'épaisseur présumées infinies, le signal enregistré en vol s'exprime ainsi:

$$S_h = k \frac{2\pi}{\mu_E} s_o e^{-\mu_E h}$$

où S_h est l'intensité du signal à une altitude h au-dessus de la source; où s_o est le signal théorique à la surface d'une aire unitaire élémentaire de la matière-source, où μ_E est le coefficient d'absorption efficace de son flux d'équilibre dans l'air, et où k est une constante.

Selon la technique interprétative, les valeurs maximums de l'intensité du signal et celles de l'altitude de l'appareil au-dessus du sol servent à tracer une courbe pour chaque type de roche dans la région étudiée. De ces courbes, on peut déduire les valeurs de s_o et de μ_E qui caractérisent chaque roche. En conséquence, la correction automatique des données déterminant l'altitude de vol, données qui sont basées sur l'hypothèse d'un seul coefficient d'absorption, ne peut pas s'appliquer à l'aéroradiométrie comparative.

Les données qui ont servi à construire ces courbes permettent de penser que l'analyse spectrale de la radiation gamma peut fournir des renseignements qui aideront à une interprétation géologique plus détaillée que ne le permet la technique actuelle.

INTRODUCTION

Many thousands of miles of routine traverse have been flown with airborne radioactivity detectors on a world-wide basis. Much of this work was performed under pressure of the search for strategic radioactive minerals. Despite the broad range of experience, aeroradiometric techniques and the significance of the data collected remain highly controversial subjects.

Aeroradiometry is based on sound physical principles. A natural field of the earth is measured and variations of this field are interpreted. The terrestrial gamma radiation flux, however, is relatively weak and originates effectively only from the surface of the ground. The analytical evaluation of gamma flux densities is very complex because of the various interaction processes which may occur during transmission through absorbing media.

The general aeroradiometric survey technique is based upon carrying a sensitive scintillation counter in an aircraft. The choice of aircraft, flight pattern and flight elevation depend upon the purpose of the survey and the known or anticipated nature of the radioactive sources in the area of interest. Essential data recorded are: (1) the detector signal (generally total gamma ray flux), (2) the terrain clearance (vertical separation of aircraft and ground or water), and (3) a positioning filmstrip of the flight track. These data generally are interpreted on the basis of previous experience and semi-empirical relationships. Often the profiles are only scanned for anomalies of interest and the remaining data are neglected.

Despite the complexities of correlating aeroradiometric data with geology, the literature shows examples of correlation with stratigraphic units, acid and basic intrusions, faults, soil types, and aquifers (Stead, 1955; Bates and Gillou, 1956; Dempsey, *et al.*, 1956; Gregory, 1956; Kellog, 1956; Gillou, 1957; Bowie, *et al.*, 1958; Moxham, 1958).[1] The technique might also allow members of a consanguineous intrusive series to be differentiated on the assumption that the youngest members are the most radioactive.

In aerial mineral exploration, varying degrees of success have been experienced in locating radioactive mineral occurrences (Gregory, 1955; Lang, 1955; Boyle, 1958). Sedimentary and pegmatitic deposits having relatively large exposures were readily located; however, because of their very small natural exposures, few (if any) vein deposits were found. Beach and stream placers containing radioactive minerals have been detected (Kellog, 1956; Moxham, 1958), and also uraniferous phosphate deposits (Moxham, 1954; Espenshade, 1958). Questionable success has been reported in the aeroradiometric location of oil pools (Pringle, *et al.*, 1953; Gregory, 1956; Kellog, 1957; Laibenbahl and Skrosyreva, 1958). In addition, the technique might be useful in the exploration for potash deposits[2], bauxite[3] and bentonite[3] and for minerals associated with pegmatite dykes.

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[1] Names and dates in parentheses are those of references cited at the end of this report.

[2] Gamma-ray studies (H.C. Spicer, 1946) show that the radium equivalent of crude potassium ore (sylvite and langbeinite) is about five times greater than that of the associated sedimentary rocks.

[3] The average radioelement concentrations for bauxite and bentonite, as given by Adams, Osmond, and Rogers (1959, p. 326), suggest that these sedimentary rocks will be two to three times as radioactive as average shale.

The writer suggests that a more effective evaluation of aeroradiometric data is possible. In the succeeding paragraphs the theoretical principles are discussed and limited supporting experimental data are presented. An interpretation technique is presented which uses total gamma flux data measured with an integrating detector.

THEORY AND MEASUREMENT OF GAMMA-RAY ATTENUATION

The Transmission of Gamma Photons

Photons or discrete quanta of gamma radiation are emitted in the course of a single transition of a radioisotope. The gamma spectrum of such an isotope is defined in terms of the proportions and energies of the component photons and the spectrum is characteristic of that isotope. For naturally occurring radioisotopes, the penetrating power of a photon varies directly with its energy and inversely with the density and atomic number of the absorbing medium.

In passing through matter, gamma photons may interact with its particles and force fields with a consequent partial or complete absorption of photon energy (Fano, 1953). For the relatively low energy photons (< 3 MeV) and media of low atomic number (< 20) such as are encountered in aeroradiometric surveys, Compton scatter is the dominant interaction process; other interactions may be neglected. Under Compton scatter conditions, a photon originally directed towards the detector is deflected from its path by collision with atomic electrons of the medium with a consequent loss of energy. The magnitude of these changes depends upon the pre-collision energy of the photon.

The probability that an interaction process will take place in a unit thickness of absorber is termed the *absorption coefficient*. When expressed as an inverse distance function (e.g., feet^{-1}) this value is called the linear absorption coefficient (μ). A more fundamental value is the mass absorption coefficient (μ_m) which relates the probability of attenuation to the quantity of matter in the absorbing medium (i.e., the thickness times the density of the medium). Thus $\mu = \rho \times \mu_m$ and accordingly, any factor that changes the density (ρ) of the medium will alter the absorption qualities and the linear coefficient.

For each gamma-ray energy, there is a specific value of the mass absorption coefficient that is determined by the atomic number of the absorbing medium. For heterogeneous media and spectra, the effective coefficient may be obtained by an averaging calculation with the specific coefficients weighted in proportion to the weight abundance of each absorbing element and to the relative abundance of photons of each energy.

For Compton scattering conditions, the mass absorption coefficient is essentially constant relative to the atomic number of the absorbing medium (i.e., for air, water, and rock), but varies with the energy of the photon (Davisson and Evans, 1952, pp. 79, 94; Glasstone, 1950, p. 170). The linear coefficient as generally used in aeroradiometric studies may thus be considered as a function of only the photon energy and the density of the medium.

For the thicknesses of absorbing medium encountered in most aerial surveys, multiple scattering conditions obtain and the scattered photons, although decreased in energy, are not necessarily lost from the original path as succeeding scattering may deflect them back in that direction.[1] Furthermore, gamma photons not originally directed towards the detector may be deflected into this path. Accordingly, the gamma flux measured in aerial surveys is a multi-energy spectrum. The proportion of degraded and more randomly directed photons increases with the distance from the source. The transmission process more nearly resembles diffusion through the medium rather than straight line penetration of it and there is a 'build-up' of flux density over that predicted by the simple exponential, single-scattering relationship.

The progressive degradation of energy results in a tendency for the gamma photons to accumulate in the low energy part of the spectrum and thus approximate a constant energy state (Fano, 1953, p. 58). Mathematical calculations show that, with increasing thickness of absorber, the energy spectrum approaches a state of equilibrium and, that beyond a certain thickness, the spectrum does not essentially change (Gorshkov and Suppe, 1957, p. 91). Limited experimental data (Gregory, 1958, pp. 145-149) suggest that the energy spectrum of radium degrades rapidly within the first hundred feet of air and approaches a constant energy distribution thereafter. Other experimental evidence (Davis and Reinhardt, 1957, p. 723; Sakakura, 1957, p. 7) shows that natural ground radiation reaches effective energy equilibrium, although the lower elevation limit at which this occurs cannot be determined because of the limitations of the experiments.

For the general aeroradiometric case, multiple Compton scattering predominates and the attenuation of flux emitted by an elemental, monoenergetic source follows the relationship:

$$I_d = \frac{I_o B e^{-\mu d}}{d^2} \tag{1}$$

where d = thickness of absorber; I_d = the total flux at distance d, corresponding to the total flux emitted by the source, I_o; μ = the absorption coefficient of the primary radiation in the absorber; B = the number 'build-up' factor for photons in the radiation flux; and e = the mathematical constant, 2.718.

The build-up factor is the ratio of total flux (unscattered + scattered photons) to the ideal primary flux (unscattered photons). The measurement of B is difficult as it is dependent upon the photon energy, the crystal efficiency, and the absorber thickness. Empirical determinations of B pertain to a given instrument and experiment.

Response of Detector to Incident Flux

The signal indicated by a detector in a constant flux is proportional to that flux if spurious counts and coincidence errors are negligible. The ratio of signal intensity to flux density is dependent upon the detector response.

Because of the large air distances and very short resolving time of the instrument, airborne detectors rarely operate at high counting rates where coincidences and spurious counts may be significant. In practice, such effects are probably negligible and signal strength directly proportional to flux density is a valid assumption when the detector response is constant.

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[1] Sakakura (1957, p. 12) pointed out the futility of any analysis of gamma-ray attenuation in which scattering is neglected.

The response of a detector to a gamma flux is a unique characteristic of the instrument. It is a complex function of the crystal efficiency and of several circuit parameters (Bell, 1955). The last are constant for specific operational conditions, as are the efficiency parameters of crystal material, size and geometry. However, the crystal efficiency also varies with the energy of the incident radiation. Accordingly, for a particular detector, the response is defined by the sensitivity[1] which is unique for the operating conditions and the energy spectrum under investigation.

Since the spectral components of a radiation may vary with the increasing penetration of that radiation into an absorbing medium, the detector sensitivity, n, in general may be expected to vary with the distance between source and detector. Thus, where spurious counts and coincidence errors are negligible, the signal for flux attenuated by passage through the absorbing medium for a distance, d, from the surface of an elementary, monoenergetic source is $s_d = n_d I_d$. The theoretical signal corresponding to the unattenuated flux emitted at the surface of this source is $s_o = n_o I_o$.

The signal at distance, d, from an elementary monoenergetic source, in terms of the parameters of the source and transmitting media, is expressed after equation (1) by the relationship:

$$s_d = \frac{n_d s_o B e^{-\mu d}}{n_o d^2} \tag{2}$$

For the conditions of aeroradiometry, variations in instrument sensitivity with change in air distance from source may be small. Thus, for crystals of thallium-activated sodium iodide, efficiencies may be considered as relatively constant (±10%) over the energy range from 1.0 to 3.0 MeV and only slightly more variable (±15%) for the range 0.5 to 3.0 MeV (Bell, 1955, pp. 151-155). The latter range includes the significant natural gamma radiations that usually are measured in aeroradiometry. Because of the approach to spectral equilibrium at large air distances and the smallness of these efficiency errors, the sensitivity may be considered effectively constant, and $n_d \approx n_o$. Thus for an elementary, monoenergetic source, the signal variation for multiple scattering conditions is:

$$s_d = \frac{s_o B e^{-\mu d}}{d^2} \tag{3}$$

Evaluation of Build-up

In practice, it is difficult to distinguish between the actual build-up of secondary radiation and the effects of certain instrument parameters on the measurements. The build-up factor can be expressed empirically in the form of a power series (Davis and Reinhardt, 1957, p. 719; Sakakura, 1957, p. 8) such as:

$$B = 1 + a\mu d + b(\mu d)^2 + \text{- - - - -}$$

where a and b are constants, μ is the absorption coefficient and d is the air distance. This empirical expression, however, includes both the actual flux build-up and the effects of instrument variables.

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[1] The change in signal intensity per specified change in the flux density under the specified conditions of measurement.

Peebles (1953, p. 1284, fig. 17) calculated that the theoretical build-up factor in a pure Compton absorber, which air approximates, is very nearly independent of the photon energy. Thus, in conjunction with the approach to spectral equilibrium at great air distances, the variation of build-up with air distance may be considered as independent of the energy. Accordingly, in aeroradiometry, the extension of build-up factors for a single energy in air to multi-energy spectra in air should occasion only minor error.

It is concluded, therefore, that for the range of energies pertinent to aeroradiometry (0.5 to 3.0 MeV), for multiple scattering in air, and for a detector with a sodium iodide crystal, the variations of sensitivity and build-up factor resulting from natural spectrum changes are minor. The indirect evidence that follows suggests that this is true, although complete evaluation is not yet possible.

The build-up factor may be interpreted from curves showing the relationship of measured signal to air distance. Such determinations of B for multiple-scattered, radium spectra in air suggest that the value $B = kd$ is a close approximation. The applicability of this value over a wide range of air distance (100 to 1,800 feet) was observed by independent investigators (Nelson, Sharp and Stead, 1952; Gregory, 1958, pp. 132-136). The power series evaluation of B approximates the value $B = kd$ for air distances greater than 500 feet (Davis and Reinhardt, 1957, p. 719), however since this is empirical in origin, the value k may represent an instrument constant. A more complete investigation of the variation of build-up of natural gamma radiations with air distance is required for a better understanding of this factor and its effect in gamma-ray transmission.

Using the evaluation of build-up, $B = kd$, the equation for multiple scattered radiation from a monoenergetic, elementary source is (from equation 3):

$$s_d = k \frac{s_o e^{-\mu d}}{d} \tag{4}$$

For multi-energy, homogeneous sources, the effective absorption coefficient μ_E may be determined by averaging the coefficients for each spectral energy weighted in proportion to the relative abundance of photon of that energy. As B is considered independent of the energy, the signal from a multi-energy, elementary source is similar to that (equation 4) for the monoenergetic source except for the introduction of the effective absorption coefficient, μ_E,

thus

$$s_d = k \frac{s_o e^{-\mu_E d}}{d} \tag{5}$$

Statistics of the Counting Rate Meter

The statistical error of integrating rate meters such as are used in most aeroradiometric surveys has been previously evaluated by Kip, Bousquet, Evans and Tuttle (1946). The absolute probable error of a single reading is shown to be $e_p = 0.477 (C/\tau)^{\frac{1}{2}}$ where τ = the time constant of the integrating circuit, C = the average counting rate and where e_p, τ and C are all expressed in the same units of time. With constant air distance and constant source characteristics any particular point on the output signal curve will show positive or negative variations from the average with the following character: e_p will be exceeded in magnitude about 25 per cent of the time; 2 e_p, 9 per cent; 3 e_p, 2.2 per cent and 4 e_p, 0.35 per cent. A graphical evaluation of the probable error of a single point on the output curve may also be made.

The probable error of the average counting rate is given by these authors as

$$e_t = \frac{(1+2t/\tau)^{\frac{1}{2}}}{1+t/\tau} \cdot e_p$$

where t is the duration of observation in the same units of time as τ and e_p.

For the time constants usually employed in aeroradiometers (one to three seconds), the percentage probable error of a single reading is about 10 per cent at low counting rates (e.g. 1,000 cpm) and less than 5 per cent at count rates greater than 5,000 cpm. Where the duration of observation is at least 50 times greater than the time constant of the integrating circuit the probable error of the average counting rate is less than one-fifth the probable error of a single reading.

SOURCES OF RADIOACTIVITY

Four general classes of gamma-active sources may be encountered in survey operations:

(a) Naturally occurring radioelements in rock and soil.
(b) Secondary gamma radiation from cosmic rays.
(c) Atmospheric and terrestrial contamination.
(d) Radioelements associated with the detector.

Naturally Occurring Radioelements in Rock and Soil

Certain members of the radium and thorium series and potassium 40 are the only isotopes that are geologically significant and that have gamma photons capable of penetrating through air to the altitude at which airborne detectors are flown. Radium, thorium, and potassium occurrences vary from weak disseminations in rocks, through increasing degree of concentration, to ore deposits. The elements may occur separately or together in various proportions, depending upon the geochemical nature of the source.

It is convenient to refer to the aggregate distribution of photons from the radium series as the radium spectrum and to that from the thorium series as the thorium spectrum. These primary spectra are both heterogeneous. The primary spectrum of potassium, however, is homogeneous, as it arises from the monoenergetic gamma emission of K^{40}.

Secondary Gamma Radiation from Cosmic Rays

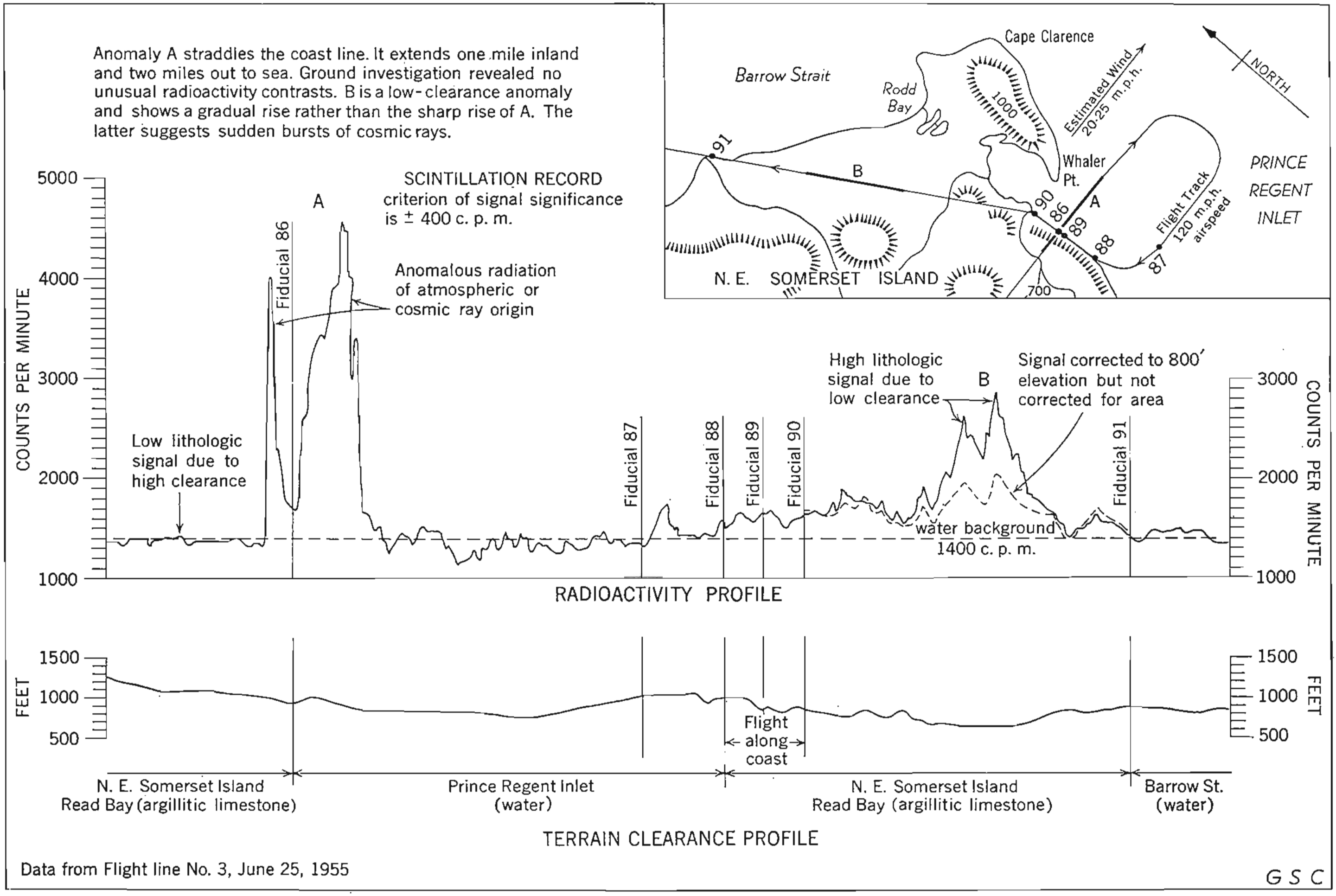
In passing through the atmosphere, high energy cosmic particles produce a radiation complex that includes gamma photons. The significance of cosmic gamma flux is incompletely evaluated, but there appears to be a relatively constant low background flux that only varies significantly at altitudes approaching 50,000 feet.

The duration and intensity of gamma flux associated with cosmic ray bursts are also incompletely evaluated but such bursts are believed to be significant. Non-reproducible, positive anomalies of short duration that were observed over the Arctic Ocean and sea-ice (*see* Fig. 1 A) may have resulted from such cosmic activity although radioactive contamination of an atmospheric air mass is another possible origin.

Secondary radiation effects resulting from cosmic ray irradiation of rocks are negligible as sources of gamma flux (Hess and Roll, 1948).

Atmospheric and Terrestrial Contamination

Gaseous radioelements existing in the atmosphere are considered to be of negligible importance as parents of anomalous gamma sources, especially in the presence of air turbulence and precipitation. However, they may contribute to the general background radiation. The gamma effect from radon daughters accumulated under



Anomaly A straddles the coast line. It extends one mile inland and two miles out to sea. Ground investigation revealed no unusual radioactivity contrasts. B is a low-clearance anomaly and shows a gradual rise rather than the sharp rise of A. The latter suggests sudden bursts of cosmic rays.

SCINTILLATION RECORD criterion of signal significance is ± 400 c. p. m.

Data from Flight line No. 3, June 25, 1955

Figure 1. *Anomalous radioactivity, northeastern Somerset Island, Arctic Archipelago. Approximate scale: 1 inch to 6 miles.*

temperature inversion conditions in the atmosphere has not been fully evaluated, but it is believed to be insignificant.

The radioactivity of natural particles in the atmosphere and in precipitation does not appear to cause appreciable changes in the natural gamma field. It is unlikely that such materials would be concentrated in soil or vegetation to form significant gamma sources.

The radioactivity of synthetic particles (e.g., fall out) in the atmosphere may cause important intensity variations. It is possible that such material could cause sharp, intense anomalies or broad, irregular anomalies depending upon the size of the contaminated air mass. Anomalous radioactivity observed over the Arctic Ocean may have resulted from such contamination (*see* Fig. 1 A). Widespread air mass contamination may make aeroradiometric surveys of terrestrial sources unreliable for the duration of such atmospheric conditions.

Sharp, intense anomalies, the cause of which is generally obvious, may result from certain industrial or mineral processing plants (e.g., facilities for storage, treatment or disposal of radioactive materials).

Radioelements Associated with the Detector

A high background may result from radioactive material in the detector and ancillary equipment. The most common sources of such interfering radiations are radioactive luminous instrument panels and wrist watches. This background may be decreased by the substitution of non-radioactive equipment and the use of shielding where necessary.

FACTORS AFFECTING SIGNAL STRENGTH

For a given detector, the significant parameters influencing the measured signal are: the specific surface activity of the source material, the effective radiating area of the source, the air attenuation factor and the time of exposure to a particular flux density. The depth of the source below the ground surface is not a significant variable as, essentially, only surface activity is measured. It is probable that, in nature, thorium and potassium contribute, on the average, a greater proportion of the gamma radiation than does radium.

The signal parameters and their determinants are summarized in Table I and are described below.

Source Characteristics

Effective radiating area and specific surface activity are the source parameters in the measured signal. Because of the complex interrelationship of these two parameters, signal variations (i.e., anomalies) do not result solely from variations of radioelement concentration. Thus a strong anomaly does not necessarily indicate highly radioactive material for anomalies of equivalent magnitude may also result from an increase in the effective radiating area of a source containing average concentrations of radioelements.

The Specific Surface Activity

The specific surface activity of a particular material is the theoretical gamma radiation flux density emitted at the surface of an elementary unit area of homogeneous source material having effectively infinite thickness. It is proportional to the specific activity of the source material but differs from it in that allowance is made for area, density and thickness of the source material. As unit area and infinite thickness are assumed, the specific surface activity is a function of the individual radioelement concentrations and the density of the source material.

The signal corresponding to the specific surface activity (i.e., flux unattenuated by air absorption) is termed the specific signal ($=s_o$).

The *source density* effects changes in the emitted gamma spectrum as a consequence of the self-absorption effect of gamma rays in the source material. The denser the material, the greater is the self-absorption. Thus the density determines the depth of material from which effective gamma flux is received at the surface of the source. Quantitative evaluation is difficult because this depth also varies with the primary energy of the flux. Effective infinity of depth is about one foot for ores (Gregory, 1958, p. 150) and probably less than this for average rock types. Similarly, because of gamma-ray absorption in the pore fluid, the specific surface activity of a porous source saturated with a fluid (e.g., water) will be 10 to 20 per cent less than that of the same material unsaturated.

The *individual radioelement concentrations* determine the spectral composition of the radiation flux. The radioelements are assumed to be uniformly distributed in the source matter; for the relatively thin surface layer that radiates effectively, this is a reasonably valid assumption.

Table I

Factors Affecting Signal Strength

Class	Parameter	Determinants	Properties of Determinants	Effect of Determinant
Source characteristics	Specific surface activity	Individual radioelement concentrations	Determines quantity of each radioelement in the elementary source, and their ratios to each other.	Total signal = sum of partial signals for each radioelement. Each partial signal is directly proportional to the amount of that radioelement present in uniform distribution in the source. Energy spectrum varies with the proportion of radioelements. Relative specific activities are Ra $>>$ Th $>$ K. Signal variation is complexly dependent upon the radioelement ratio.
		Source density	Determines the self-absorption coefficients.	Flux attenuated and degraded in source. Complex inverse variation with source density. Water saturation of porous source will reduce specific surface intensity. Gamma radiation is a surficial characteristic of source material and has no depth potential. Complete shielding is provided by relatively thin cover. Infinity of source thickness is approximated by relatively thin sources.
	Effective radiating area	Size of exposure	Determines amount of material contributing to source flux.	Signal variation is complex in relation to area except for spot sources of elementary nature. In this instance, signal is directly proportional to area.
		Flatness	Topographic relief increases surface area of source and, depending upon the detector elevation, may vary the solid angle subtended by the source at the detector.	Complex signal variation resulting from interplay of surface area and clearance factors. Signal variation is proportional to variation of solid angle relative to planar source.

Air characteristics	Attenuation factor	Air density	Determines the absorption coefficients and thus the relative attenuation of various photons.	Complex inverse variation with density. Relative flux attenuation is Ra > Th and K. With increase in air distance, K and Th fluxes increase in prominence relative to Ra flux. Air coefficients vary with pressure, temperature, and humidity. Automatic correction for clearance variation not valid as absorption coefficient varies markedly with source type.
		Air distance	Determines the amount of matter in which scattering occurs, and thus the amount of flux attenuation. Concomitant energy degradation results in variation of effective absorption coefficient.	Complex inverse variation. At large air distances the signal may be undetectable.
Detector characteristics	Time of exposure to a particular flux density	Circuit time constant, air distance, aircraft velocity, size of source	Complex interdependency which determines the current build-up in the ratemeter, and thus the indicated signal.	If the time of exposure is less than the detector time constant (e.g., for spot sources), significant signal decrease will occur and complete erasure may attain. No effect if time of exposure is greater than time constant (e.g., for sheet and some area sources).
	Sensitivity	Crystal size and geometry, voltage and other instrument characteristics	Direct proportionality between flux density and signal.	Signal varies directly with sensitivity. Generally, sensitivity remains constant for aeroradiometric surveys, and signal thus is not affected.

The primary spectrum from an aggregate of radioelements in a source is the summation of the separate spectra for each radioelement present. The proportion of radioelements determines the relative abundance of spectral components in the total flux and thus establishes the flux density. Radium series,[1] thorium series and potassium differ greatly in their specific activities. The relative activity of each has been investigated by Russell (1944) who showed that at very short air distances, the ratios of specific gamma activity, Th: Ra: K are $2.86 \times 10^{-7}:1:1.25 \times 10^{-10}$.

Table II

Relative Activities of Selected Materials

(units of gamma radioactivity per gram, *after* Russell, 1944)

	K	Th	Ra	Total
Average acid igneous rock[1]	4.1	3.8	1.6	9.5
Average intermediate igneous rock[1]	2.9	2.9	0.9	6.7
Average basic igneous rock[1]	1.3	1.1	0.6	3.0
Average shale[1]	3.4	3.1	1.1	7.6
Average sandstone[1,6]	1.4	1.5	0.7	3.6
Average limestone[1]	0.3	0.3	0.4	1.0
Average sea water[2]	0.05	neg.	neg.	0.05
Average fresh water[3]	neg.	neg.	neg.	neg.
Granitic pegmatite[4]	15.0	12.6	6.3	33.9
Uranium ore[5]	—	—	4840.	4840.

References to concentrations of radioelements:

[1] Clarke, 1924; Daly, 1933; Evans and Goodman, 1941; Rankama and Sahama, 1952; Adams, Osmond and Rogers, 1959.

[2] Pettersson, 1954; Rankama and Sahama, 1952.

[3] Clarke, 1924; Koczy, 1954.

[4] Assumed average values from references (1) above.

[5] 0.2% U_3O_8, nil Th, nil K.

[6] According to the concentrations given by Adams, Osmond and Rogers (1959, p. 324), the activities attributed to radium and thorium in this average sandstone may be too great by factors of 5 and 3 respectively, and thus the total activity may be too great by a factor of 2.

Using Russell's approach, calculations may be made (*see* Table II) for the relative activities of representative terrestrial source materials. These data, expressed in terms of equivalent radium, are peculiar to the conditions of Russell's work. They are, nonetheless, approximately proportional to the specific surface activity of the material and indicate the relative importance of each of the radioelements in determining the flux emitted by the different types of source materials. These average values, however, have little geological significance when considering the data of a survey over a specific sequence of rocks as field experience has shown that distinct contrasts in radioactivity exist in various parts of one rock body as well as from one rock type to another.

The major significance of the data in Table II is that they illustrate the relative importance of thorium, potassium and radium in the gamma field of natural

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[1] This usage implies that all members of the series are in radioactive equilibrium.

rock sources. For such materials, it is estimated that potassium and thorium each comprise about 40 to 45 per cent of the emitted field,[1] and radium only 15 to 20 per cent.[2] The above statement applies, of course, only to fields from rocks and not to those from radioelement concentrations which may be of economic interest.

With the exception of certain rare shales and sandstones, sedimentary rocks and basic intrusive and extrusive rocks have relatively low specific surface activities. Provided that radioactive material has not been introduced, the metamorphic equivalents of such rocks will also have comparable low activities. Pegmatites and granites vary greatly from moderate to high specific surface activity with, in general, the potassium-rich varieties being the more radioactive. Intrusive and metamorphic rock complexes show a wide and varied range of specific surface activities as a consequence of the various rock types involved and the changes in radioelement concentration which may have occurred. High concentrations of radioelements resulting from sedimentary or hydrothermal accumulation have very high specific surface activities. For glacial drift, residual soils and weathered rock surfaces in general, the activity varies with the nature of the parent rock and with the amount of leaching or deposition that has occurred therein.

The important concepts concerning the specific surface activity and the related specific signal are:

(1) Although radium has a specific gamma activity much greater than that of thorium and potassium, the relative proportions of these radioelements that exist in most geological sources are such that all three radioelements are more or less equally significant in determining the specific surface activity of the source material as a whole.

(2) The specific surface activity and the energy spectrum are unique for a particular source material and the data for one cannot generally be applied to another.

The Effective Radiating Area

The effective radiating area is that surface area of radioactive material that is in an effective radiating position relative to the detector. It is a complex function of the size and flatness of the source exposure. Multiplication of this parameter by the specific surface activity or the specific signal gives the total flux density or total signal, respectively, from the source.

The *size of the source exposure* is a major signal determinant (i.e., the so-called 'mass effect'). A partial cover of non-radioactive rock, water or overburden limits the source area, as effectively complete shielding is provided by about a foot of rock, 2 feet of water and 3 to 5 feet of overburden. As a consequence, all radiometers detect radiations only from those sources at, or within a very few feet of, the surface of the

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[1] Kartashov (1957) reported comparable values for the proportion of gamma radioactivity from K in the total gamma radiation background of rocks.

[2] Since this paper went to press, the results of subsequent investigations have shown that the relative activity of the uranium-radium series given by Russell is low with respect to thorium and potassium. Thus the significance of uranium flux has been underestimated. It is probable that the K and R_a values in Table II should be reduced by about one-third. Recalculation of the radioactivities of these average rocks shows that fluxes from thorium and radium (uranium) each comprise about 30 per cent of the emitted field and that from potassium the balance. It is to be expected that measured values for specific rocks will vary greatly from these averages.

terrain. Deeply buried sources cannot be detected except by locating surface activity in some manner related to, or coincident with, the deeper source (e.g., radioactive detritus, salts or emanations that have migrated to the surface).

Integration of the elementary source relationship (equation 5) over a planar area defines the signal for various source areas (Gregory, 1958, pp. 158-180). Thus for an infinite area source:

$$S_{h,i} = k \frac{2\pi}{\mu_E} s_o e^{-\mu_E h} \tag{6}$$

where h is the terrain clearance. For a general area of circular shape and finite radius, and with the detector over the centre of the area:

$$S_{h,c} = k \frac{2\pi}{\mu_E} s_o \left(e^{-\mu_E h} - e^{-\mu_E \sqrt{h^2 + R^2}}\right) \tag{7}$$

where R is the finite radius of the circular area. For a source of small area (i.e., approximating an elementary configuration):

$$S_{h,e} = k \frac{s_o A e^{-\mu_E d}}{d} \tag{8}$$

where d is the air distance ($= \sqrt{h^2 + r^2}$), r is the range or horizontal distance from source to detector and A is the small area of the source. Signals for other more complex configurations may be similarly calculated by integration over the appropriate area.

The practical bounding limits of these sources may be evaluated (Gregory, 1958, pp. 181-186) by comparing the difference between the signals from the pertinent areas with the criterion of signal significance[1] for the operating conditions. Thus the finite area that possesses infinite radiating area characteristics is that area for which the difference between the signal from an infinite area source and a general area source (equations 6 and 7) is less than the criterion of signal significance.

These calculations are valid only in the zone of multiple scattering, which for radium gamma flux from ore concentrates is at air distances greater than about 100 feet (Gregory, 1958, pp. 132-137). For gamma radiation originating from thorium and potassium ores, and from similar multi-element sources, this limiting air distance is expected to be greater; probably about several hundred feet. However, further investigation is required to establish these spectral degradation features.

Sources of finite dimension may be conveniently classified according to their radiating character. Thus, *sheet* sources have the radiating character of an infinite area source; *spot* sources have the radiating character of an elementary source; and *area* sources are of intermediate character. In nature there are, of course, no sharp boundaries between these source classes.

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[1] The criterion of signal significance is the change in count rate that is considered to be anomalous. This change is a function of the possible error of the measurement, i.e., the probable error plus any error inherent in evaluating the gross count rates from the records. A signal variation of greater than twice the possible error is commonly accepted as significant.

The *flatness of the source exposure* may be a significant signal determinant. In areas with topographic relief, the departure from a plane surface configuration results in a variation of the effective radiating area of the source (i.e., the so-called 'solid-angle effect'). The consequent signal variations become significant where local relief is of the same order of magnitude as the flight altitude.

The amplitude of these signal variations is proportional to the change in effective radiating area resulting from source relief. For the general case (three radioelements and variable local relief), the equation of amplitude becomes complex. For the special case of a detector traversing across topography with a linear trend, a simpler assessment can be made by considering the ground traversed as a series of linear sources (Gregory, 1958, pp. 188-189). For uniform source characteristics, the maximum signal variation to be expected is from +30 to +200 per cent over narrow valleys or cliff scarps and about −25 to −50 per cent over narrow ridges (*see also* Smirnov, 1957, pp. 351-352). The observed variation, however, is greatly dependent upon the detector-source geometry and the nature of the source (including degree of exposure).

Air Characteristics

The Attenuation Factor

The attenuation factor is a complex variable that includes the scattering, build-up, and energy degradation effects of the transmitted photons. The emission spectrum and flux density are determined by the source characteristics. The determinants of the air attenuation factor are the air density and the air distance.

The *air density* is a signal determinant in that, under Compton scatter conditions, density changes alter the attenuation characteristics. The linear absorption coefficient varies directly with the density. Air density changes of up to 30 per cent from the average may occur as a consequence of variations in temperature, pressure, or humidity. Comparable changes in the linear coefficient result in signal variations as great as 25 per cent. This suggests that surveys should be performed under fairly constant meteorological conditions if detailed correlation is intended. It is probable that most diurnal variations in signal strength due to meteorological conditions are about 5 per cent and thus may be neglected during any one day, although significant variation may occur from day to day. Of course, air density variations resulting from flights at different altitudes above sea-level may also cause significant variation in the absorption coefficient.

The *air distance* is a measure of the amount of matter in which scattering and build-up occur. Variation in air distance results in a complex inverse change in signal strength resulting from simultaneous variation of flux density and energy spectrum.

Variation in terrain clearance causes a fluctuation in the signal strength with peaks that may be greater than the amount considered significant, and thus appear to be anomalous (*see* Fig. 1, B). An altimeter record allows correction for clearance variations on the basis of an assumed equation and absorption coefficient. However, automatic correction of records on the basis of one set of assumed constants is not valid as the attenuation characteristics and area parameters vary markedly with the source type.

Relatively small variations in clearance (± 25 feet) may produce significant signal changes, especially for high intensity, low energy fluxes (*see* Fig. 3). Accordingly, clearance should be very closely controlled and evaluated in aeroradiometric studies.

It is worth noting here that a source of small area and high specific-surface activity will give a very weak signal that is detectable only at low elevations. Thus, potentially economic, radioelement occurrences may be passed over and not recognized during a mineral exploration survey.

Changes in energy spectra with air distance have an important effect on the relative intensities of fluxes from each of the major radioelements (radium and thorium series and radio-potassium). A radiation with a large absorption coefficient (low energy) is attenuated more rapidly than one with a smaller coefficient (higher energy). Radium has a complex multi-energy spectrum with a few moderate energies, but dominant low energies. Thorium has a multi-energy spectrum with prominent high energies. Potassium has a homogeneous spectrum comprising moderately high energy photons. Accordingly, over large air distances, radium flux will undergo a relatively greater attenuation than will the thorium and potassium fluxes. Thus the flux intensity from thorium or potassium relative to that from radium can be expected to increase with increasing air distance[1] and at a certain distance dependent on the source characteristics, radium flux will be effectively shielded out by air absorption. Over average rocks, it is considered that the fluxes from thorium and potassium dominate over that from radium.

Detector Characteristics

The sensitivity (*see* p. 5) is a signal parameter that is unique for the specific characteristics of the detector (i.e., voltage, crystal, etc.) and is invariant throughout a survey or sequence of surveys with that detector. If these characteristics are changed or if another detector is used, the variation in signal strength resulting from this change in sensitivity must be evaluated for quantitative comparison of the resulting data. With constant sensitivity, however, the only detector parameter influencing the signal output is the velocity factor, time of exposure to a particular flux density. Inertia or friction in the recording system may occasionally be an important modifier of output signal in certain types of recorders.

Time of Exposure to a Particular Flux Density

The time of exposure of the detecting element to a particular flux density is an important signal parameter under certain conditions. In moving the detector (with otherwise constant instrument characteristics) through a flux gradient, the peak signal representing a particular flux density will be decreased by an amount dependent upon the response time of the detector, if the time interval (t) in that flux is less than the time constant (τ) in the integrating circuit of the ratemeter. If this condition exists ($t < \tau$), then the charge on the condenser of the integrating circuit will not reach its

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[1] Such a relative intensity change was observed with Ra series and Co^{60} (which is fairly close to K^{40} in energy spectrum) by the writer (Gregory, 1958).

maximum value for the particular flux density. Thus the comparable current to the ratemeter and recorder is not the maximum value, and a lesser signal is indicated. It has been shown (Pierson and Franklin, 1951; Sakakura, 1957) that for instantaneous flux (a very steep gradient), the decrease in signal strength is dependent upon the aircraft velocity, the detector time constant, and the air distance. Maximum current occurs for values of $t \geqq \tau$. Smirnov (1957, pp. 354-357) noted that in addition to the decrease in signal strength over the source, there may be a distortion of the output record that persists for a short time after the source is passed. This is attributed to sluggishness of the instrument.

For spot sources (elementary character), the flux gradient is steep and a maximum decrease in signal strength occurs. Depending upon the survey conditions, the decrease in signal strength may be so great that the source remains undetected. For area sources with the flux invariant for a finite time interval greater than the circuit time-constant, there is no loss of signal strength, as the maximum current will be attained. For certain small area sources between the above limits, the signal decrease, to a first approximation, may be considered proportional to the time spent in that particular flux (Gregory, 1958, pp. 162-167).

The modification of the signal due to the flying speed may be an important source of error in aeroradiometric surveys, especially over small sources where the clearance is low and the ground speed high. Consequently, time constants, flight clearances and aircraft velocities must be chosen to fit the nature of the sources sought.

ANALYSIS OF TOTAL FLUX AERORADIOMETRIC DATA

In 1955, aeroradiometric data were collected in a series of traverses over some of the islands in the Arctic Archipelago. Nominal flight altitude was 800 feet above ground and nominal speed was 120 mph. The terrain is barren of vegetation, with a high proportion of bedrock exposure in some areas and a prominent residual or frost-heave mantle in others. The relief varies from flat to mountainous. Rock types include Precambrian igneous and metamorphic rocks and younger sedimentary rocks.

The records (*see* Fig. 1) for a specific rock type were originally analysed by detailed plotting, on semi-logarithmic paper, the signal as ordinate against terrain clearance as abscissa. These data provided a density plot (*see* Fig. 2) limited markedly along its upper boundary by a straight line.

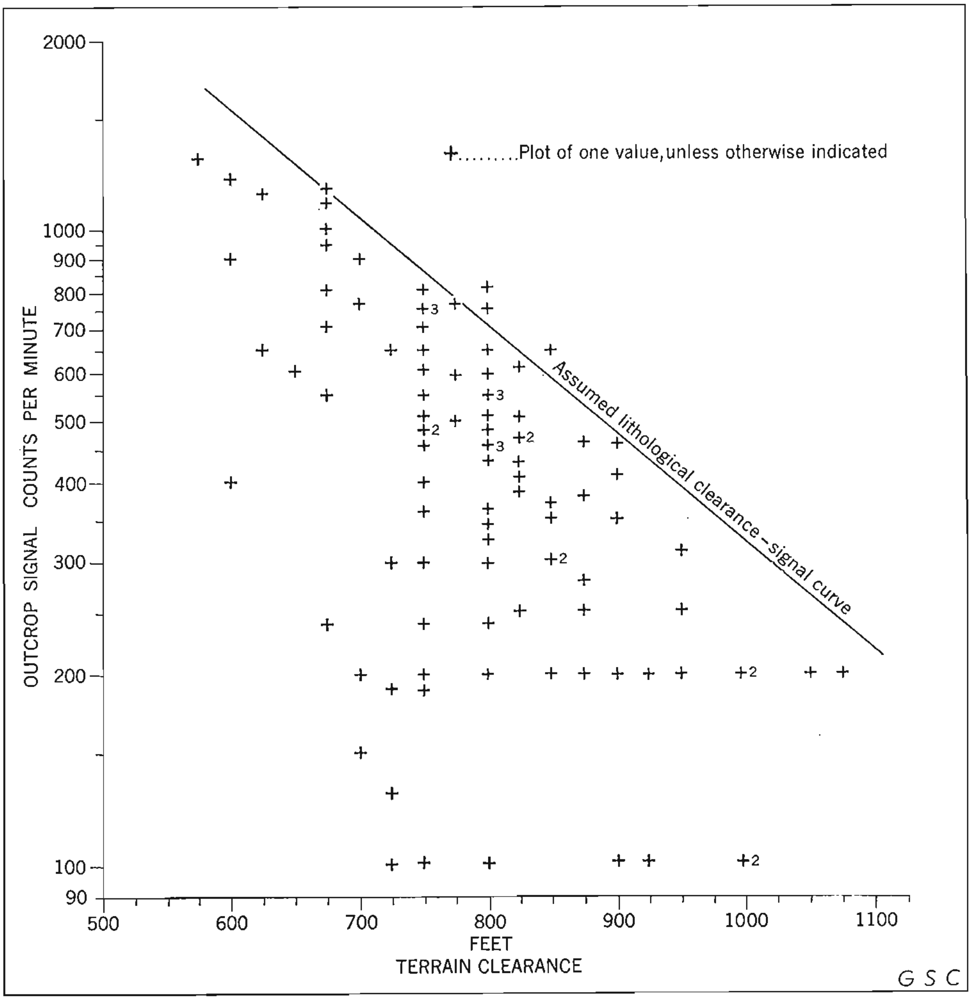

Figure 2. Typical outcrop clearance-signal plot, Read Bay argillaceous limestone.

On the assumption that, for constant source material, the maximum signal for any one clearance is produced by the maximum area, this limiting line[1] was considered to represent the signal-clearance relationship for sheet (effective infinite area) sources. For the same clearance, all lower signal values represent lesser areas. The signal from a sheet source of a particular rock may be called the *lithological signal,* and that from an area source *the outcrop signal.* The corresponding curves showing the variation of signal strength with clearance are termed the *lithological clearance-signal curve* and the *outcrop clearance-signal curve* respectively.

It was subsequently determined that this curve of lithological signal variation could be obtained, if a sufficient range of data were available, by scanning the records and plotting only the clearance-signal data for peak signals and peak clearances.

On assuming infinite source area for the lithological signal, the equation expressing the relationship is:

(from equation 6)

$$L_h = k \frac{2\pi}{\mu_E} s_0 e^{-\mu_E h} \tag{9}$$

The slope of the curve is equal to $-0.4343\ \mu_E$, and conversely, the effective absorption coefficient,

$$\mu_E = -\frac{\text{slope}}{0.4343}$$

$$= \frac{\log L_{h_1} - \log L_{h_2}}{0.4343(h_2 - h_1)}$$

The specific signal, s_o, may also be derived from equation 9. In theory, the radiation is never completely absorbed according to the equations used here, but in practice the flux density may be so low that it is not measurable. No correction can be made for photons not effectively represented numerically in the measured spectrum, i.e., for photons which are absorbed to a degree that their presence is not indicated by the detector. Accordingly, the calculated value of specific signal, s_c, is not necessarily equal to the source parameter, s_o, although it may be. The actual significance of s_c relative to source parameters remains to be evaluated. However, for aeroradiometric measurements obtained in the zone of multiple scattering, the calculated values of s_c and μ_E will define the source radiating characteristics and they are specific for a particular, uniform source.[2] Probable error resulting from statistical error in the counting rate will be less than 5 per cent for μ_E and less than 10 per cent for s_c.

The lithological clearance-signal curves for a number of rock types encountered in the survey of the Arctic Archipelago, together with other comparative data, are shown in Figure 3. Inspection of these curves reveals the character of the radioactivity variations, both between rock types and within a single rock type. Three general source groupings may be recognized on the basis of the specific signal (s_c) and the effective absorption coefficient (μ_E). Carbonate and siliceous sedimentary rocks

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[1] A few values are expected to occur above (and below) the limiting line as a consequence of statistical fluctuations and minor variations in the radioelement content of the source.

[2] The calculated value, s_o, of the specific signal here contains the constant k. This does not alter the significance of the interpretation, however such values of s_o are dependent upon the detector used.

	ROCK TYPE	μ_E per foot $\times 10^3$	S_c c. p. m. / sq. ft.
1.	Peel Sd. sandstone	4.70	144
2.	Proterozoic qtzite. and dolomite	4.44	138
3.	Peel Sd. conglomerate	4.48	160
4.	Allen Bay limestone and dolomite	4.39	160
5.	Read Bay argillaceous limestone	3.93	103
6.	Cornwallis argillaceous limestone	3.93	103
7.	Somerset I. granite	6.20	181
8.	Devon I. granitic gneiss	7.60	118
9.	Bird Fiord fm. (shaly and slightly carbonaceous ss. and ls.)	7.11	404
10.	Okse Bay carbonaceous sandstone	4.38	250
11.	Bathurst I. shale and arg. limestone	5.02	477

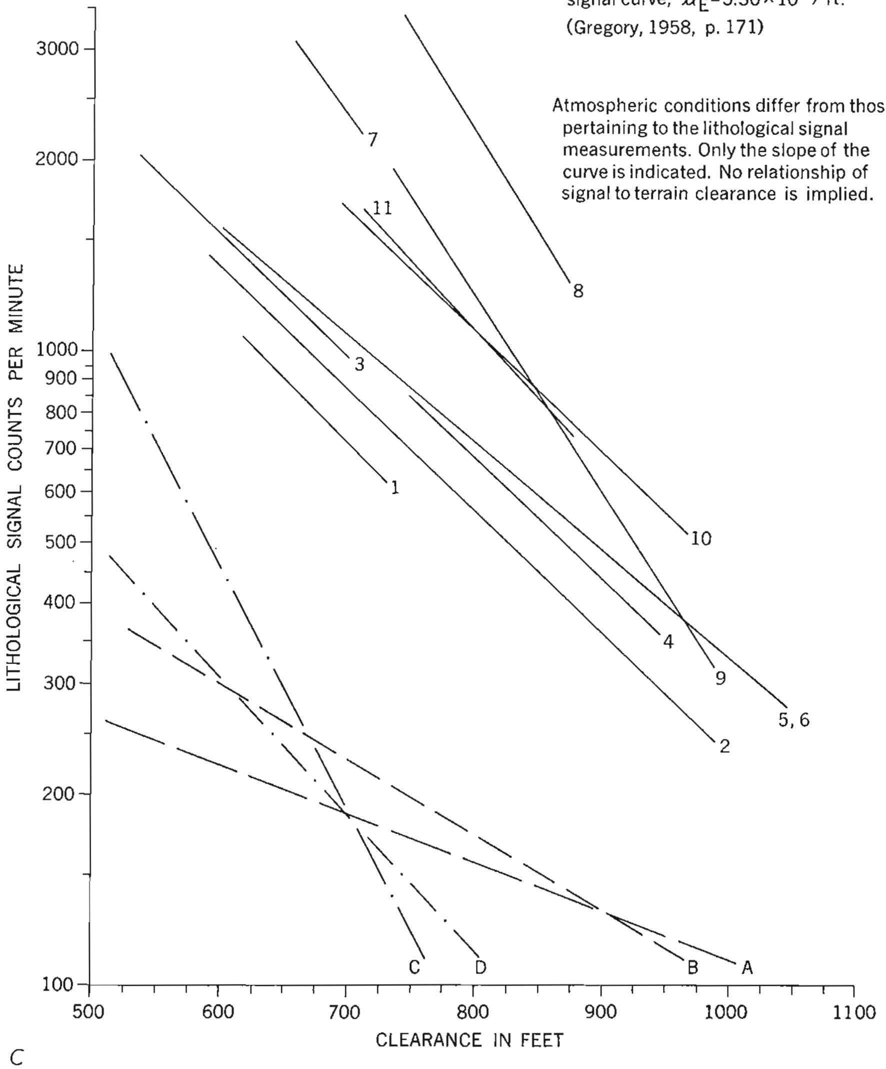
COMPARATIVE DATA

A. Slope of natural ground radiation signal curve, Fruita, Colo. $\mu_E = 1.87 \times 10^{-3}$/ft. (Davis and Reinhardt, 1957, figure 8)

B. Slope of natural ground radiation signal curve, Ottawa, Ont. $\mu_E = 2.76 \times 10^{-3}$/ft. (Gregory, 1958, fig. 4)

C. Slope of radium radiation signal curve, $\mu_E = 8.91 \times 10^{-3}$/ft. (Gregory, 1958, p. 135)

D. Calculated slope for potassium radiation signal curve, $\mu_E = 5.30 \times 10^{-3}$/ft. (Gregory, 1958, p. 171)



Atmospheric conditions differ from those pertaining to the lithological signal measurements. Only the slope of the curve is indicated. No relationship of signal to terrain clearance is implied.

G S C

Figure 3. Lithological clearance-signal curves, Arctic Archipelago.

have low to moderate values of μ_E and low to moderate values of s_c; shales and argillaceous varieties of the rocks in the previous group have moderate values of μ_E and moderate values of s_c; granites and granitic gneisses have moderate to high values of μ_E and low to moderate values of s_c. Three exceptions to these generalizations occur, all on Bathurst Island, where the strata of the Bird Fiord, Okse Bay and Bathurst Island formations are more strongly radioactive[1] than similar and correlative rock types elsewhere in the archipelago.

The slopes of the curves for granitic rocks and Bird Fiord formation approximate the slope of the curves for the radium family (μ_E for Ra *after* Gregory, 1958, p. 135) whereas the slopes of the curves for other rocks are flatter (the values of μ_E for Th and K have not been determined, but they should be appreciably less than μ_E for Ra and thus the curves for them should also be flatter). Slopes of the family of lines for two different ground radiations are also given for comparison in Figure 3. The relationship of μ_E and s_c to radioelement content of source is unevaluated, as representative sampling of the rocks was not possible.

These lithological clearance-signal curves illustrate very effectively the variation of signal with terrain clearance for each petrological unit and thus indicate the fundamental differences in the source and attenuation characteristics of these units. Variation of these values may be measured where suitable contrast in lithology exists.

The variation of signal with effective source radiating area may be illustrated by plotting against source size the ratio of outcrop signal to lithological signal (equations 7 and 6 respectively), calculated for representative values of μ_E (Fig. 4). The ratio of outcrop signal to lithological signal is:

$$\frac{e^{-\mu_E h} - e^{-\mu_E \sqrt{h^2 + R^2}}}{e^{-\mu_E h}} = 1 - \frac{e^{-\mu_E \sqrt{h^2 + R^2}}}{e^{-\mu_E h}}$$

where $R^2 = A/\pi$

The importance of evaluating the effective radiating area of the source is apparent. The limits of effective source infinity are also indicated.

The clearance-signal analysis cannot be applied to data measured at low elevations ($h < 200$ ft. ?) as multiple scattering conditions do not prevail. Because of this, the semi-logarithmic plots of signal strength against clearance will curve up rapidly at low clearances where single scattering conditions attain and the inverse square law of attenuation is approximated. Furthermore, if the value of μ_E is determined at air distances beyond that of effective Ra photon penetration, a semi-logarithmic plot may curve upwards at lesser air distances, if and when Ra photons become significant in the total flux because of the higher value of μ_E for such a flux. It is possible that all clearance-signal plots should curve upwards at lower elevations because of this effect, but further evaluation is required.

The clearance-signal analysis of aeroradiometric data has been used to extrapolate known geology into unmapped areas in the Arctic Archipelago and to

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[1] The radiometric analyses of a few hand specimens of these rocks suggest that this radioactive contrast is real.

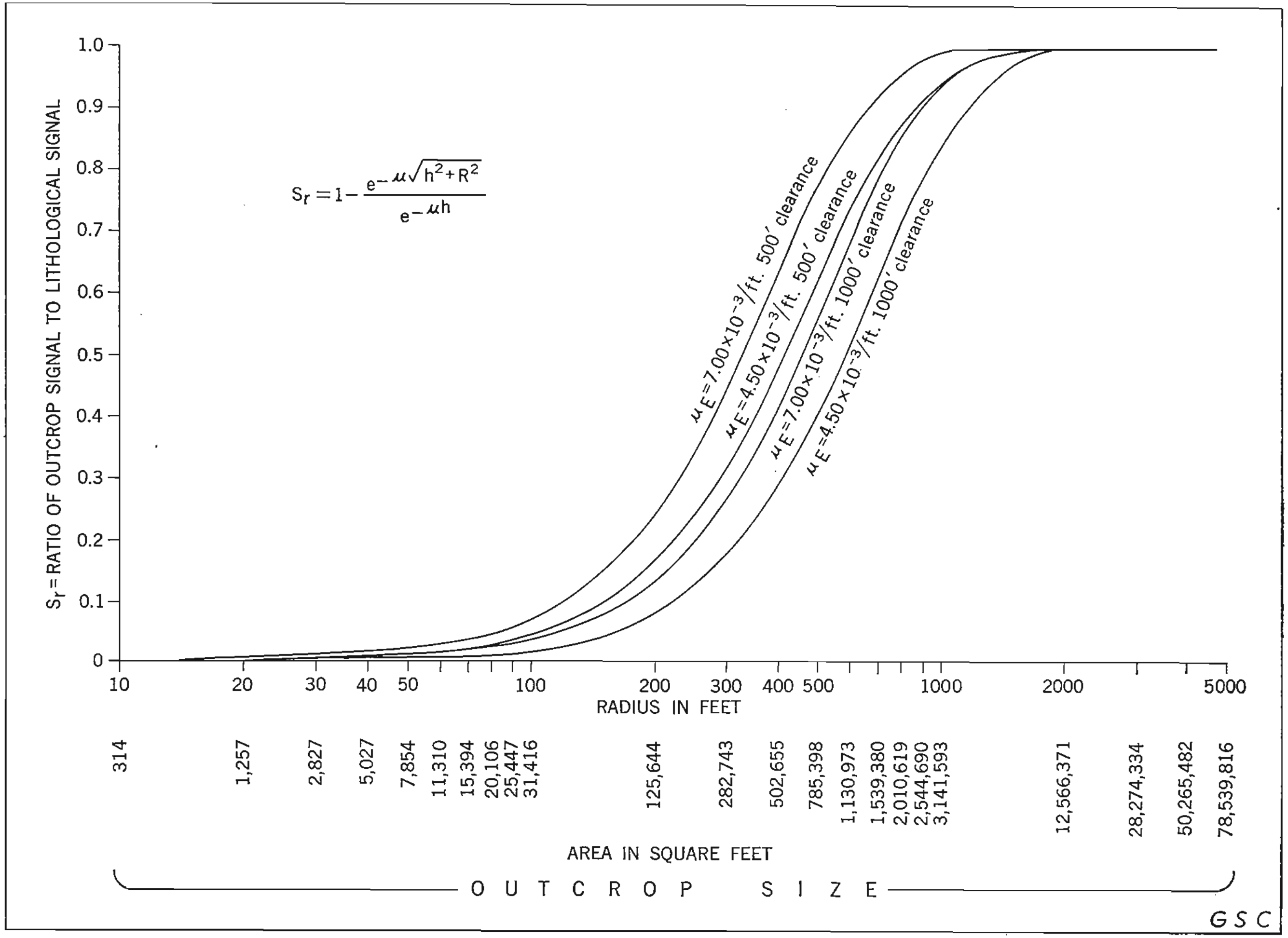

Figure 4. Variation of signal with source size (normalized to lithological signal = 1).

recognize rocks of unusually high radioactivity relative to the activity of similar or correlative rock types. The interpretation[1] was made by constructing lithological clearance-signal curves for the known rock types and grouping these into the three general groups previously noted: carbonate and siliceous sedimentary rocks, shales and argillaceous rocks, granites and granite-gneisses. Aeroradiometric data from adjacent areas which were not geologically mapped were then compared with these curves on the assumption that the known radioactivity contrasts in the rocks were of regional extent. Significant variations in radioactivity within a rock type may cause that rock to fall into a different radioactivity grouping than it normally does, and this anomaly is readily detected. Generally this technique cannot be applied to small area sources as, in most cases, there is insufficient data to define the clearance-signal curve and the actual surface area of the source is unknown.

This slope analysis of the lithological clearance-signal curve reveals variations in the energy spectrum of natural sources. The differences in these curves (*see* Fig. 3) suggest contrasting energy spectra and it is probable that a gamma-ray spectrometer would provide greater detail in these degraded spectra.

For prospecting, an automatic correction based on the sheet-source equation might be useful as it would emphasize the signal from localized sources of possible economic interest. The correction applied to the measured intensity would be less than that required by the equation pertinent to the actual nature and area of the localized source. The attenuation coefficient to be applied would depend on the geological nature of the source environment. However, no technique can allow for sources that do not produce a measurable signal at the altitude at which the detector is flown.

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[1] The interpretation of aeroradiometric data was made in conjunction with an interpretation of aeromagnetic data obtained simultaneously, the whole to be published at a later date.

SUMMARY AND CONCLUSIONS

Naturally occurring radioelements (Ra, Th, and K) in an infinite number of distribution patterns are the targets of aeroradiometric surveys for geological purposes. The gamma radiation effectively originates from the terrain surface and is of relatively low flux density, but distinct contrasts in specific intensity may exist within and between various rock types. These contrasts are measurable with sensitive airborne detectors and aeromapping of gamma radioactivity patterns has been achieved.

Fluxes from thorium and potassium are believed to contribute more to the natural gamma field at large air distances than does radium flux, except for concentrations of radium in uranium occurrences that approach ore grade. A decrease in source intensity will result from loss of energy by absorption in porous sources that are saturated with water or other fluid.

Radiations that interfere with the natural terrestrial flux exist, but can be recognized. Their effects must be minimized if useful measurements are to be made of low gamma flux densities. Effective discrimination against 'anomalous' variations in cosmic or atmospheric gamma flux might be achieved by a monitoring detector shielded from terrestrial sources.

The interpretation of gamma radiation patterns is complicated by many variables. The gamma flux comprises a complex energy spectrum which degrades differentially with increasing multiple scattering. The major parameters in the recorded signal are: the specific surface activity of the source, the effective radiating area of the source, and the air attenuation factor. The determinants of these parameters and their effects on the signal are detailed in the test and summarized in Table I. Close control of terrain clearance is a prerequisite for effective geological correlation of the data. Variations in air density may result in signal changes as great as 25 per cent, and comparative radiometry will require thorough meteorological control.

Activity and attenuation parameters are specific for each source material and they cannot generally be extrapolated from one type of source to another. The automatic correction of the records on the basis of one set of parameters cannot therefore be made in comparative radiometry.

Aeroradiometric data show a close correlation with the exposed bedrock formations, and the soil or water cover when interpreted under the foregoing conditions. Because of the different attenuation characteristics for the Ra, Th and K spectra and the variation, with the depth of air penetrated, in the relative importance of these separate spectra in the total flux, the aeroradiometric data may or may not correlate with surface radiometric data or surface distribution of equivalent uranium analyses.

Effective radiating areas are relative and specific for a particular elevation, source character, and detector. A source may be an area source at one elevation, but a point source at a higher elevation. Furthermore, for each source type and for each specific source area, there is a critical elevation above which no significant signal will be obtained. For a constant source material, the larger the area, the greater is the optimum air distance at which that material may be detected. Small area sources of economic interest will cause signals that probably will not be recognized in surveys with high terrain clearance. On the other hand, with low terrain clearance the signal from such sources will be decreased due to the short time that the detector is exposed to the peak flux density and the source may pass unrecognized. Exact values for the clearance and velocity at which these effects take place are not significant as they must be determined for the particular detector and survey procedure used.

The geological use of aeroradiometric mapping techniques is limited by the variable areas of exposure. Overburden is no problem if radioactive contrasts in the soils are of interest, however, if the interest is in mapping bedrock contrasts then the limitation of exposure by cover may be a great disadvantage. For the latter usage, the method has its greatest value in regions where either the bedrock is widely exposed or the associated cover is a residual soil.

The clearance-signal analysis used here suggests that significant spectral contrasts exist in the natural gamma fields and that a procedure of spectral analysis may provide more useful detailed aeroradiometric data.

REFERENCES

Adams, J. A. S., Osmond, J. K., and Rogers, J. J. W.

1959: The Geochemistry of Thorium and Uranium *in* Physics and Chemistry of the Earth; vol. 3, Pergamon Press, pp. 298-348.

Bates, R., and Gillou, R.

1956: Correlation of Airborne Radioactivity Data and Areal Geology *in* Geologic Investigations of Radioactive Deposits; U.S. Geol. Surv.—U.S.A.E.C. rept. TEI-640, pp. 245-48.

Bell, P.R.

1955: The Scintillation Method *in* Beta- and Gamma-Ray Spectroscopy; K. Siegbahn, editor, New York Interscience Publishers, esp. pp. 151-55.

Bowie, S. H. V., Miller, J. M., Pickup, J., and Williams, D.

1958: Airborne Radiometric Survey of Cornwall; a paper (A/conf. 15/P/43 U.K.) at the Second U.N. Internat. Conference on Peaceful Uses of Atomic Energy.

Boyle, T. L.

1958: Low-level Aerial Radiometric Surveying in the U.S.A.; a paper (A/conf. 15/P/775 U.S.A.) at the Second U.N. Internat. Conference on Peaceful Uses of Atomic Energy.

Clarke, F. W.

1924: Data of Geochemistry; *U.S. Geol. Surv.*, Bull. 770.

Daly, R. A.

1933: Igneous Rocks and the Depths of the Earth; McGraw Hill Pub. Co.

Davis, F. J., and Reinhardt, P. W.

1957: Instrumentation in Aircraft for Radiation Measurements; *Nuclear Sci. and Eng.*, vol. 2, No. 6, pp. 713-27.

Davisson, C. M., and Evans, R. D.

1952: Gamma-Ray Absorption Coefficients; *Reviews Modern Phys.*, vol. 24, No. 2, pp. 79-107.

Dempsey, W. J., Gillou, R., Moxham, R. M., and Bates, R.

1956: Correlation of Airborne Radioactivity Data and Areal Geology *in* Geologic Investigations of Radioactive Deposits; U.S. Geol. Surv.—U.S.A.E.C. rept. TEI-620, pp. 282-86.

Espenshade, G. H.

1958: Geological Features of Areas of Abnormal Radioactivity, Marion Co., Florida; *U.S. Geol. Surv.*, Bull. 1046-J.

Evans, R. D., and Goodman, C.

1941: Radioactivity Measurements of Rocks; *Bull. Geol. Soc. Amer.*, vol. 52, pp. 459-90.

Fano, U.

1953: Gamma-Ray Attenuation; *Nucleonics*, vol. 11, No. 8, pp. 8-12, and No. 9, pp. 55-61.

Gillou, R.

1957: Correlation of Airborne Radioactivity Data and Areal Geology *in* Geologic Investigations of Radioactive Deposits; U.S. Geol. Surv.—U.S.A.E.C. rept. TEI-700, p. 201.

Glasstone, S.

1950: Sourcebook on Atomic Energy; New York, D. van Nostrand Co., Inc., p. 546.

Gorshkov, G. V., and Suppe, S. A.

1957: Radioactive Radiations and their Interaction with Substances *in* Radiometric Methods in the Prospecting and Exploration of Uranium Ores; edited by V. V. Alekseev, A. G. Grammakov, A. I. Nikonov and G. P. Tafeev, Moscow: in English translation AEC-tr-3738, Book I and Book II, U.S.A.E.C., 1959.

Gregory, A. F.

1955: Aerial Detection of Radioactive Mineral Deposits; *Trans. Can. Inst. Mining Met.*, vol. 58, pp. 261-67.

1956: Analysis of Radioactive Sources in Aeroradiometric Surveys over Oil Fields; *Bull. Am. Assoc. Petrol. Geol.*, vol. 40, No. 10, pp. 2457-74.

1958: Analysis and Interpretation of Gamma Radiation Patterns Obtained through Low Elevation Aeroradiometry; Univ. of Wisconsin, unpub. Ph.D. thesis.

Hess, V. F., and Roll, J. D.
1948: New Experiments Concerning the Surplus Gamma Radiation of Rocks; *Phys. Review*, vol. 73, pp. 592-95.

Kartashov, N. P.
1957: Uranium Equivalents of Potassium Gamma and Beta Radiation; *Izvest. Vostoch. Filialov. Akad. Nauk S.S.S.R.*, #4-5, pp. 62-70.

Kellog, W. C.
1956: The Development and Interpretation of Aerial Radioactivity Surveys; *Mines Magazine*, vol. 46, No. 7, pp. 31-34.
1957: Observations and Interpretations of Radioactive Patterns over Some California Oil Fields; *Mines Magazine*, vol. 47, No. 7, pp. 26-28.

Kip, A., Bousquet, A., Evans, R., and Tuttle, W.
1946: Design and Operation of an Improved Counting Rate Meter; *Rev. Sci. Instr.*, vol. 17, #9, pp. 323-33.

Koczy, F. F.
1954: Radioactive Elements in Ocean Waters and Sediments: Geochemical Balance in the Hydrosphere *in* Nuclear Geology; edited by H. Faul, John Wiley & Sons, pp. 120-7.

Laibenbahl, A. I., and Skrosyreva, L. N.
1958: The Use of Aerial Radiometric Survey for the Study of Oil and Gas Deposits; *Petroleum Geology*, vol. 2, No. 2A, pp. 142-51, translated by *The Review of Russian Geology.*

Lang, A. H.
1955: Uranium Prospecting in Canada, Ground and Aerial Surveys; a paper (A/conf. 8/P/1, Canada) at the First U.N. Internat. Conference on Peaceful Uses of Atomic Energy.

Moxham, R. M.
1954: Airborne Radioactivity Surveys for Phosphate in Florida; *U.S. Geol. Surv.*, Circular 230.
1958: Geologic Evaluation of Airborne Radioactivity Survey Data; a paper (A/conf. 15/P/1907, U.S.A.) at the Second U.N. Internat. Conference on Peaceful Uses of Atomic Energy.

Nelson, R. A., Sharp, W. N., and Stead, F. W.
1952: Airborne Radioactivity Survey of the Red Desert Region, Sweetwater County, Wyoming; U.S. Geol. Surv.—U.S.A.E.C. rept. TEM-147.

Peebles, G. H.
1953: Attenuation of Gamma-Rays.I.Transmission Values for Finite Slabs of Lead, Iron and the Compton Scatterer; *J. Applied Phys.*, vol. 24, #10, pp. 1272-87.

Pettersson, H.
1954: Radioactive Elements in Ocean Waters and Sediments: Historical Review and Experimental Results; *in* Nuclear Geology; edited by H. Faul, John Wiley & Sons, pp. 115-20.

Pierson, D. H., and Franklin, E.
1951: Aerial Prospecting for Radioactive Minerals; *J. Applied Phys.*, vol. 2, pp. 281-91.

Pringle, R. W., Roulston, K. I., Brownell, G. W., and Lundberg, H. T. F.
1953: The Scintillation Counter in the Search for Oil; *Mining Eng.*, (December), pp. 1255-61.

Rankama, K., and Sahama, T. G.
1952: Geochemistry; Univ. of Chicago Press, 2nd ed.

Russell, W. L.
1944: The Total Gamma Ray Activity of Rocks as Indicated by Geiger Counter Determinations; *Geophysics*, vol. 9, pp. 180-216.

Sakakura, A.
1957: Scattered Gamma Rays from Thick Uranium Sources; *U.S. Geol. Surv.*, Bull. 1052-A.

Smirnov, G. S.
1957: Aerial Gamma-Search for Uranium Deposits *in* Radiometric Methods in the Prospecting and Exploration of Uranium Ores; edited by V. V. Alekseev, A. G. Grammakov, A. I. Nikonov and G. P. Tafeev, Moscow: in English translation, AEC-tr-3738, Book I and Book II, U.S.A.E.C., 1959.

Spicer, H. C.
1946: Gamma-ray studies of Potassium Salts and Associated Geologic Formations; *U.S. Geol. Surv.*, Bull. 950, pp. 143-159.

Stead, F. W.
1955: Airborne Investigation Techniques; *U.S. Geol. Surv.*, Prof. Paper 300, pp. 710-13.