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AIRBORNE RADIOACTIVITY SURVEYS IN GEOLOGIC EXPLORATION

By. R. M. Moxham

Trace Elements Investigations Report 662

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

IN REPLY REFER TO:

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D. C.

February 13, 1959

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Mr. Robert D. Nininger
Assistant Director for Exploration
Division of Raw Materials
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear Bob:

Transmitted herewith are three copies of TEI-662, "Airborne radioactivity surveys in geologic exploration," by R. M. Moxham, August 1958.

We plan to submit this report for publication in Geophysics.

Sincerely yours,

John H. Eric

for W. H. Bradley
Chief Geologist

Geology and Mineralogy

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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*This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

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LETTER SYMBOLS

A = area of source

A_o = area of calibration source = 1,600 ft^2 1/

a = radius or width of source

C = instrumental constant. For U. S. Geological Survey equipment

$C_1 = 3.19 \times 10^7$ (3 crystals);

$C_2 = 6.38 \times 10^7$ (6 crystals)

H = area under curve recorded by counting-rate meter (counts)

I = intensity recorded (counts-per-second)

R = response of counting-rate meter

RC = integrating time constant of count-rate circuit

r = air distance between source and detector

S = grade of source in equivalent uranium (percent)

S_o = grade of calibration source = 0.35 percent equivalent uranium

t = time required for counting rate meter to reach half maximum response

x = altitude of detector above source plane

θ = angle between flight path and a line normal to source center line

μ = linear absorption coefficient for the most penetrating gamma-ray of the U spectrum = 1.46×10^{-3} ft^{-1} at sea level; 1.25×10^{-3} ft^{-1} at 5,000 ft. altitude

1/ Calibration source used by the U. S. Geological Survey is at Walker Airport, Grand Junction, Colorado

AIRBORNE RADIOACTIVITY SURVEYS IN GEOLOGIC EXPLORATION

By R. M. Moxham

ABSTRACT

The value of airborne radioactivity surveys in guiding uranium exploration has been well established. Recent improvements in circuitry and development of semiquantitative analytical techniques permit a more comprehensive evaluation of the geologic distribution of radioactive materials that may prove useful in exploration for other minerals and in regional geologic studies.

It is shown that placer deposits of heavy minerals can be detected from the air, and that the geometric configuration and average grade of the surficial part of the deposit can be approximated. Uranium-bearing phosphorite deposits may be similarly evaluated.

Airborne surveys over the Coastal Plain area, Texas, show that the radioactivity profiles in some instances reflect the lithologic character of the underlying rocks. The sandstones are generally low in radioactivity ($\approx$10 ppm equivalent uranium), the clays and tuffaceous rocks relatively higher. The intrinsic radioactivity of some lithologic units is sufficiently uniform and distinctive in character to permit their identification and lateral correlation on the airborne survey records. The results suggest that airborne surveys may thereby provide useful guidance in delineating lithologic continuity where the geology is poorly known or obscured.

INTRODUCTION

An airborne radioactivity surveying program was begun in 1949 by the U. S. Geological Survey to assist in uranium exploration. The immediate objective was to find new and large areas favorable for uranium deposits. Though the instrumentation was relatively crude and knowledge of gamma-ray behavior rudimentary, the techniques devised through experimentation were sufficient to meet the immediate needs. In the 1950s, many exploration surveys for uranium were made by both private and government organizations and were quite successful in finding new uranium deposits, including some of the largest in the United States. The problem involved was relatively simple and the attack straightforward, generally amounting to a search for relatively high-amplitude anomalies in geologically favorable areas. It is obvious however, that the distribution of radioelements in earth materials involves many geologic processes in addition to the emplacement of uranium ore bodies. Recent improvements in circuitry and the development of semiquantitative analytical techniques have advanced the mechanics of the surveying technique to a point where investigation of somewhat more complex geologic problems seems worthwhile.

It is shown below that by utilizing systematic surveys and semiquantitative analyses, more comprehensive results can be obtained from surveys for uranium. Moreover, the method has been successful in exploration for deposits of heavy minerals and for phosphorite deposits.

In addition to facilitating mineral exploration, the airborne radioactivity detector can provide useful data in other geologic studies. The detection system is quite sensitive to small changes ($\sim$10 ppm) in the equivalent uranium (eU) content of gross geologic features. It has been found that, in areas of sedimentary rocks, the intrinsic radioactive content of a particular geologic unit is related to its lithology. The resulting radiation intensity is in some instances distinctive in character, so that a particular lithologic unit can be identified on the radioactivity records and correlated laterally providing a guide to the geographic distribution of the unit.

This report describes the use of airborne radioactivity surveying and analytical techniques in geologic exploration by examples of the analysis or evaluation of airborne data related to specific geologic settings. The discussion below deals solely with data obtained by the U. S. Geological Survey's airborne detector, but the general analytical techniques employed and the conclusions drawn are in the main valid for any scintillation detector of comparable crystal volume and energy response.

The work described in this report was undertaken on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission. Particular acknowledgment is due to F. J. Davis and P. W. Reinhardt of the Health Physics Division, Oak Ridge National Laboratory, who were responsible for the design and construction of the Geological Survey radiation-detection equipment and who contributed materially to our present knowledge of gamma-ray scattering and absorption.

RADIATION-DETECTION EQUIPMENT

The radiation detection equipment used by the U. S. Geological Survey was designed by the Health Physics Division of the Oak Ridge National Laboratory. The circuitry is described in detail by Davis and Reinhardt (1957).

The detection element now used consists of 6 thallium-activated sodium iodide crystals 4 inches in diameter and 2 inches thick, connected in parallel. In some earlier surveys, only 3 crystals were used. The total pulse output from the crystals is fed through amplification stages and a pulse height discriminator to a count-rate recorder. Total radiation intensity is recorded by a graphic

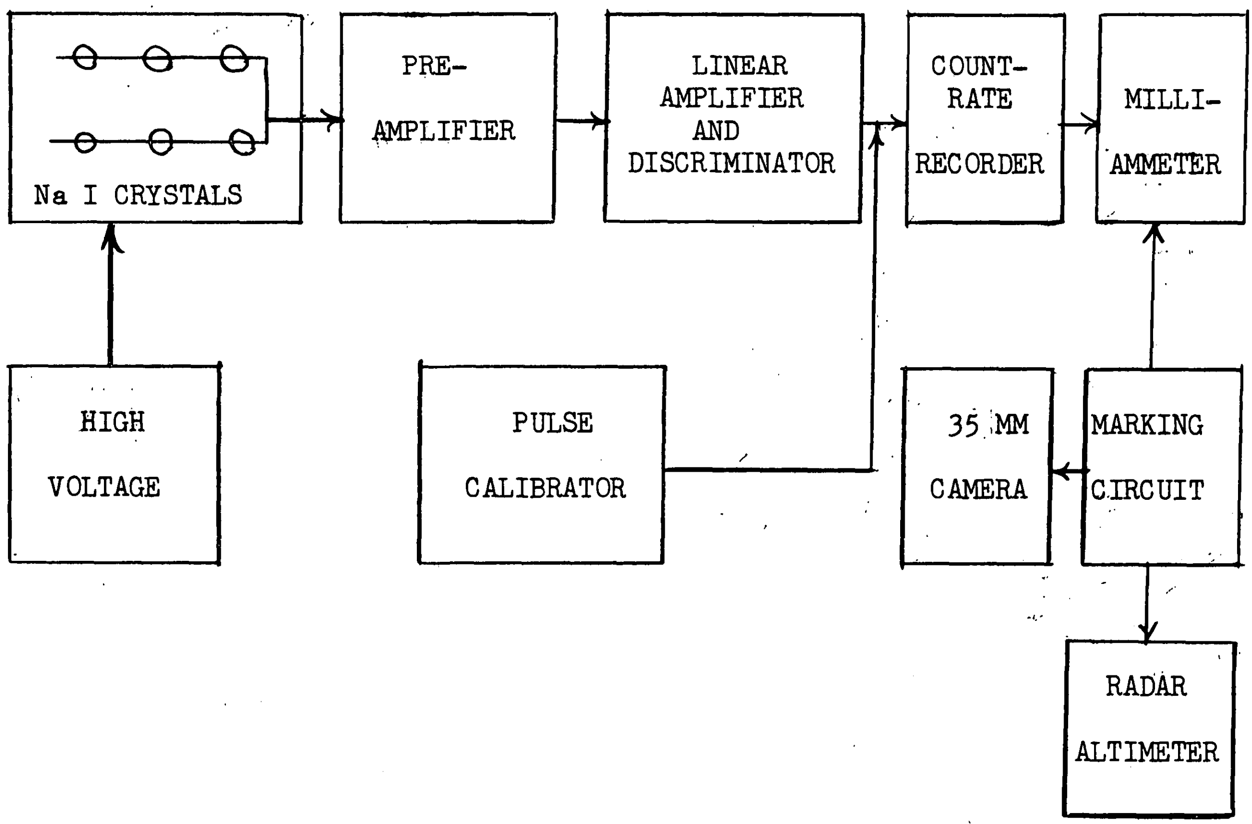


FIG. 1. BLOCK DIAGRAM OF GEOLOGICAL SURVEY AIRBORNE SCINTILLATION DETECTOR

milliammeter. The sensitivity of the equipment when 6 crystals are used is such that in a radium gamma-ray flux of one microroentgen per hour, the count-rate is 225 per second.

A simplified diagram of the equipment is shown in figure 1.

AIRCRAFT POSITIONING

The altitude of the aircraft is determined by a radar altimeter. Horizontal position is determined by an electromechanical marking system that keys the altimeter and radioactivity records to a 35 mm strip film exposed continuously along the flight path (Jensen and Balsley, 1946).

GAMMA-RAY FLUX COMPONENTS

The components of the total gamma-ray flux at a given altitude arise from the following principal sources: cosmic radiation; daughter products of the gaseous radionuclides, principally radon; and radionuclides in the upper few feet of the earth's crust. The relative contribution, percentage-wise, of the components varies widely, depending upon the energy acceptance of the detector, meteorological conditions, and the eU content of the rocks over which the measurement is made.

To illustrate, if the lower energy acceptance of the detector is about 50 kev, the measurement is made at an elevation of 500 feet, and the rocks at the earth's surface contain 0.001 percent eU, then the contribution from cosmic radiation will be about 35 percent of the total measured intensity, the radon daughter products in the atmosphere will contribute roughly 15 percent, and the rocks will furnish about 50 percent. For the purpose of this report the cosmic component is considered constant at a given survey location.

The diurnal variation in radon content in the surface layer of the atmosphere is well established. In general the radon concentration builds up during the nocturnal inversion, reaches a maximum at about 0700 to 0800, decreases to a minimum by about 1200 and remains more or less constant until about 1800 (Cotton, 1955). Concentration of radon commonly varies by a factor of 10 under such inversion (Davis and Reinhardt, 1957, p. 718). As a practical matter, unless extremely adverse atmospheric conditions exist, the changes in radon concentrations are not great enough to affect seriously the interpretation for surveys made during the late forenoon and afternoon when minimum variation is usually experienced.

GEOLOGIC DISTRIBUTION OF RADIOACTIVE MATERIALS

The geologic evaluation of airborne radioactivity data from systematic surveys is greatly enhanced by the use of the semiquantitative analytical technique devised by Sakakura (1957). Generally speaking, the equations developed by Sakakura are directly applicable only to certain simple geometric conditions so that where the geology is complex, the geometric conditions must be synthesized from an appropriate combination of fundamental forms. The following discussion, therefore, will first describe surveys where the most simple geologic and geometric conditions exist, interpret them in terms of extent and grade of the source rocks, and then treat the more complex situations by suitable synthesis. A preliminary study of all available geologic information is essential to any meaningful interpretation of flight data.

Distribution with infinite dimensions

A hypothetical setting

Let us assume that a flight line is oriented normal to the contact between a large body of water and a land mass consisting of shale which contains evenly dispersed radioactive material. A radioactivity profile similar to that illustrated in figure 2 would be recorded by a detector with an instantaneous response. The radioactivity recorded over the water would exclude the gamma-ray flux component from the crust. The recorded intensity will for simplicity be termed the cosmic background (I_c). As this intensity is assumed to be constant and is recorded over material containing essentially no equivalent uranium it follows that I_c must be subtracted from the total (gross) intensity recorded over the shale to determine the (net) radiation resulting from the intrinsic radioactivity of the shale (I_s). If the surface dimensions of the water and shale masses are large compared to the area instantaneously scanned by the detector the two sources can be considered infinite in extent.

At an altitude of 500 feet above the surface the minimum dimensions for an infinite source are approximately 1,200 feet in the direction parallel to the flight path and 1,700 feet normal to flight direction. As these conditions are assumed to be met in figure 2, Sakakura's (1957, p. 10) infinite source equation will give the average eU content of the shale:

$$S = \frac{I_s S_o A_o}{2\pi C_2 \ (1 - 0.342\ \mu x) e^{-\mu x}} \qquad (1)$$

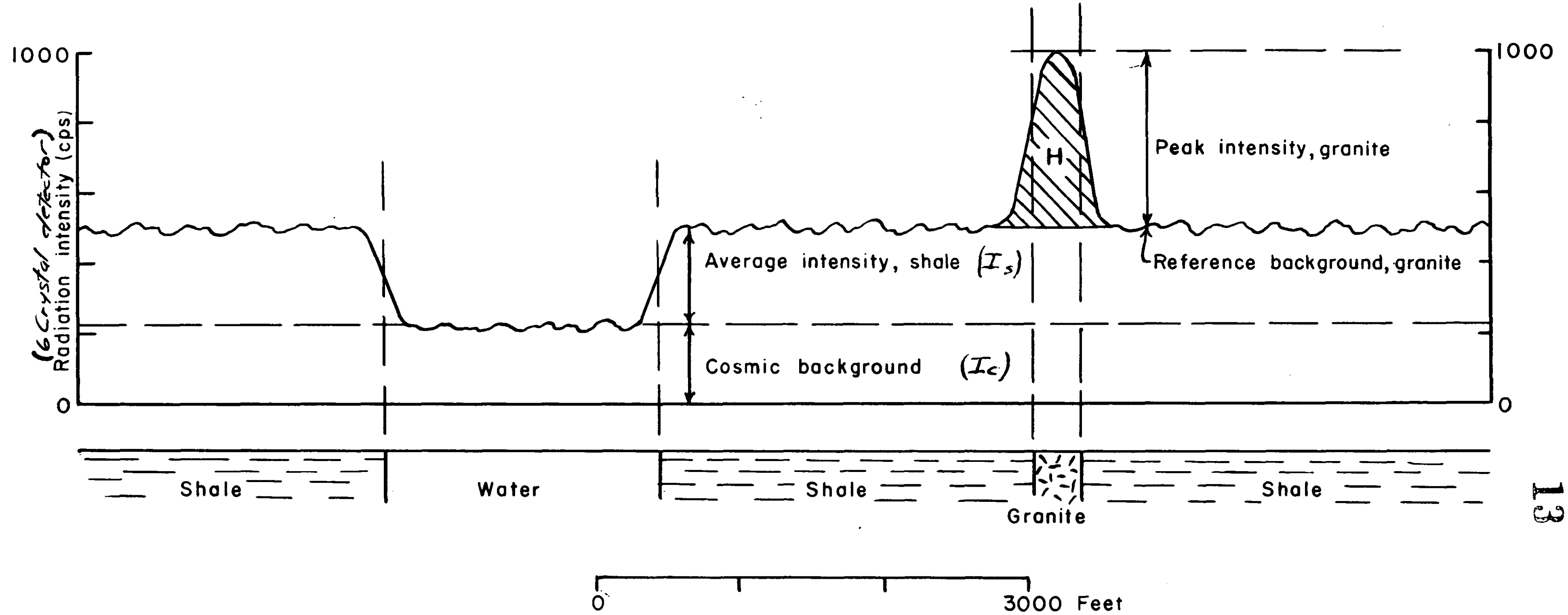


FIG 2 HYPOTHETICAL RADIOACTIVITY PROFILE AT 500 FOOT ALTITUDE OVER INFINITE (SHALE) AND FINITE (GRANITE) SOURCES

The net radiation intensity recorded over the shale indicates the eU content is 0.001 percent.

Thus, the intrinsic radioactivity of a homogeneous geologic source at any locality can be determined from the measured radiation intensity at that locality, provided the dimensions of the source meet the minimum dimension requirements set forth above.

It is also desirable to determine the geographic location of the contact between two infinite sources, as shown in figure 2. Theory dictates that the contact is at the half maximum. However, the ideal situation under discussion assumes an instrument response time of zero. In practice there will be an apparent displacement of the geographic position owing to a constant mechanical and optical lag (assuming an electromechanical and optical aircraft positioning system is employed) plus an electronic and electromechanical lag that is a function of the response (RC) time of the integrating and recording circuit, the velocity of the aircraft, and the flight direction, i.e., whether the radiation intensity is increasing or decreasing.

Sakakura (written communication) has equated the half maximum (R) in terms of the pertinent variables, where the flight line is normal to the interface and the aircraft is flying from a source of lower intensity to one of higher intensity:

$$R = 1 - 3.1\, e^{-\frac{t}{RC}} + 2.33\, e^{-1.215\frac{t}{RC}} \tag{2}$$

where the velocity of the aircraft is 220 feet per second and the altitude is 500 feet.

In the reverse direction

$$R = -2.33e^{-1.215\frac{t}{RC}} + 3.13e^{-\frac{t}{RC}} \qquad (3)$$

In equation (2), t/RC is about 0.9 at the half-maximum value so that if RC is 2 seconds, the instrument will require 1.8 seconds (t) to reach the half maximum value. Time (t) corresponds to a distance of about 400 feet at the given velocity.

The theoretical lag values given above pertain to only RC response time. Experimental flights made across a land-water interface indicate the total lag is about 450-850 feet where RC = 2 seconds. To some extent, lag is a characteristic of a particular positioning and detection system and should be determined experimentally.

From the foregoing statements it would seem that the radioactivity data from a systematic airborne survey could be used in a straightforward manner to locate contacts between geologic units having infinite dimensions if lag is removed from the data. Further consideration, however, brings out certain difficulties. The geologic contact in the subsurface may indeed be a relatively sharp interface, but more often than not, the boundary at the surface is obscured by soil development and weathering. The attendant processes result in surficial redistribution of the radioactive materials that often obscures the boundary or gives rise to a quasi-transitional boundary. Moreover, it is usually necessary that the most up-to-date base maps be utilized in flight operations and compilation of data. It seems preordained that the available geologic maps are compiled on older, and in many instances, less accurate base maps. The errors incurred in bringing the flight data and geology together on a common base are probably the major source of discrepancy between the two sets of data.

A sedimentary sequence

The conditions shown in figure 2 are highly idealized. Figure 3 illustrates more realistic results obtained on a typical survey, made in the Texas Coastal Plain area. Here the flight lines are spaced at one mile intervals and are oriented normal to the regional northeast strike. The lines extend from the Wilcox formation across the Eocene sequence to the Catahoula tuff (Miocene (?)). The stratigraphy and lithology are indicated on figure 3.

The geologic and geometric conditions shown are relatively simple, but the geology has been mapped by various workers on three different base maps, only one of which was the same as that used in compiling the radioactivity data. Errors of unknown magnitude were doubtless introduced in compiling all the data on a common base. Furthermore, we know from examination of soils maps that the mapped geologic boundaries do not everywhere represent sharp interfaces at the surface but rather that soil development and transport have obscured the boundary conditions at the surface. Despite all difficulties, the radioactivity records clearly indicate the lateral extent of most of the geologic units and the mapped geologic boundaries are for the most part in acceptable agreement with the radioactivity data.

In figure 3, the horizontal scale of the flight data has been greatly reduced, which tends to compress the curves, so that the flat response diagnostic of infinite size geologic units is not as apparent as it is at full scale. Many of the highs have been compressed into sharp peaks by the scale reduction so it is not certain that all of the emitting surfaces shown on figure 3 are infinite-size sources. However, where infinite sources are indicated by flat response,

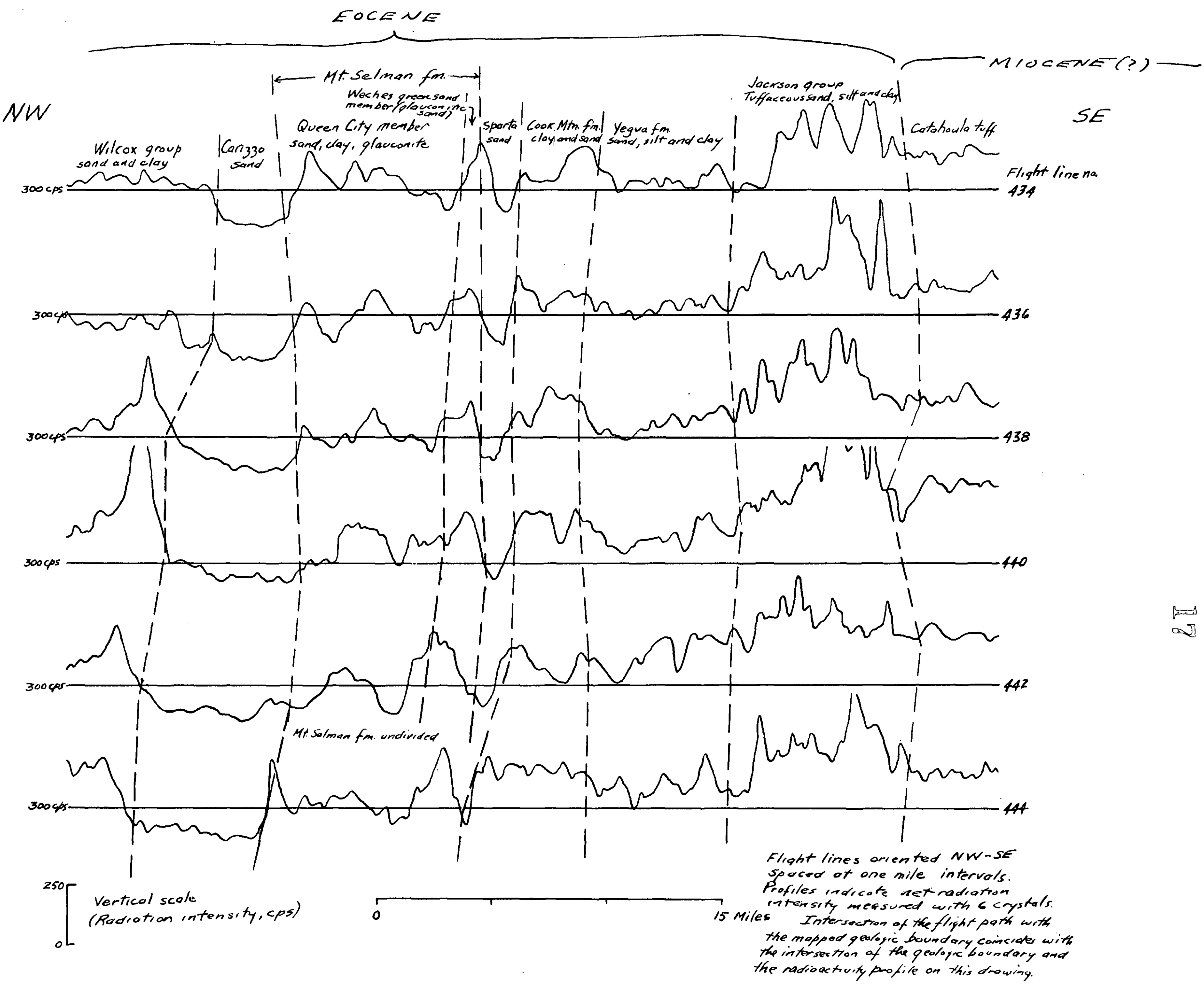


FIG. 3 RADIOACTIVITY PROFILES AT 500 FOOT ALTITUDE OVER EOCENE SECTION
WILSON AND ATASCOSA COUNTIES
TEXAS

the average intensity levels over the mapped geologic units range from 300 to 750 cps. Use of equation (1) indicates the average eU contents of most of the Eocene rocks vary through a range of only 0.002 percent. Twelve soil samples from the various geologic units from Wilcox to Jackson age were analyzed and show a range from < 0.001 to 0.003 percent eU and an average of 0.002 percent eU.

The pre-Jackson sequence consists predominantly of alternating sands and clays. The sands are low in gamma emission and give rise to radiation lows whose intensity indicates < 0.001 percent eU. The clays and siltstones by contrast are generally more active (≈ 0.002 percent eU) so a typical radioactivity profile shows a series of highs and lows reflecting the lithologic and mineralogic character of the sedimentary sequence. In most places the radioactivity patterns result from the radioactivity of the residual soils and thereby reflect the bedrock geology. Locally these patterns are interrupted along the strike by drainage-oriented trends resulting from alluvial deposits that mask the underlying rocks.

It is notable that the most prolific aquifer in the Coastal Plain region, the Carrizo sand, is the geologic unit most easily identified on the radiation records, giving rise to a striking radiation low that may easily be traced for at least 70 miles across the surveyed area. It would be interesting to speculate on the value of airborne surveys in helping to delineate potential aquifers in underdeveloped, semi-arid parts of the world where the water-resources geology is poorly known.

Phosphate deposits

Natural phosphatic materials commonly contain uranium in the range 0.00X to 0.0X percent and although commercial-size deposits are presently valued mainly for the content of P_2O_5, uranium is being recovered as a byproduct from land-pebble deposits in Florida.

In 1953, extensive airborne surveys were made in geologically favorable areas in the southeastern states (Moxham, 1954; Meuschke, 1955) to locate uranium-bearing phosphate. The following discussion concerns only the surveys over phosphate terrane in Florida, but the results are applicable to exploration for uraniferous phosphorites in general.

A survey was made in Marion County, Florida (Moxham, 1954) a few miles south of Ocala, where outliers of the Hawthorn formation (Miocene) rest upon the Ocala limestone (Eocene). The Hawthorn outliers consist of clay and sand containing varying quantities of uraniferous phosphorite and phosphate pellets. The area of Ocala limestone surrounding the outliers is mantled by a thin layer of soil or sand (Espenshade, 1958).

Typical radioactivity profiles are shown in figure 4A. In some localities sharp geologic boundaries are not indicated on the profiles but instead there is a transition from lower to higher radiation sources. Nevertheless, as the abnormal radioactivity commonly extends from about one to six miles along the profiles and has lateral continuity on the same order (fig. 5), the principal anomalous areas no doubt represent infinite sources. The limits of the anomalies shown in figure 5, in the absence of clear-cut half-maximum values, were arbitrarily assumed

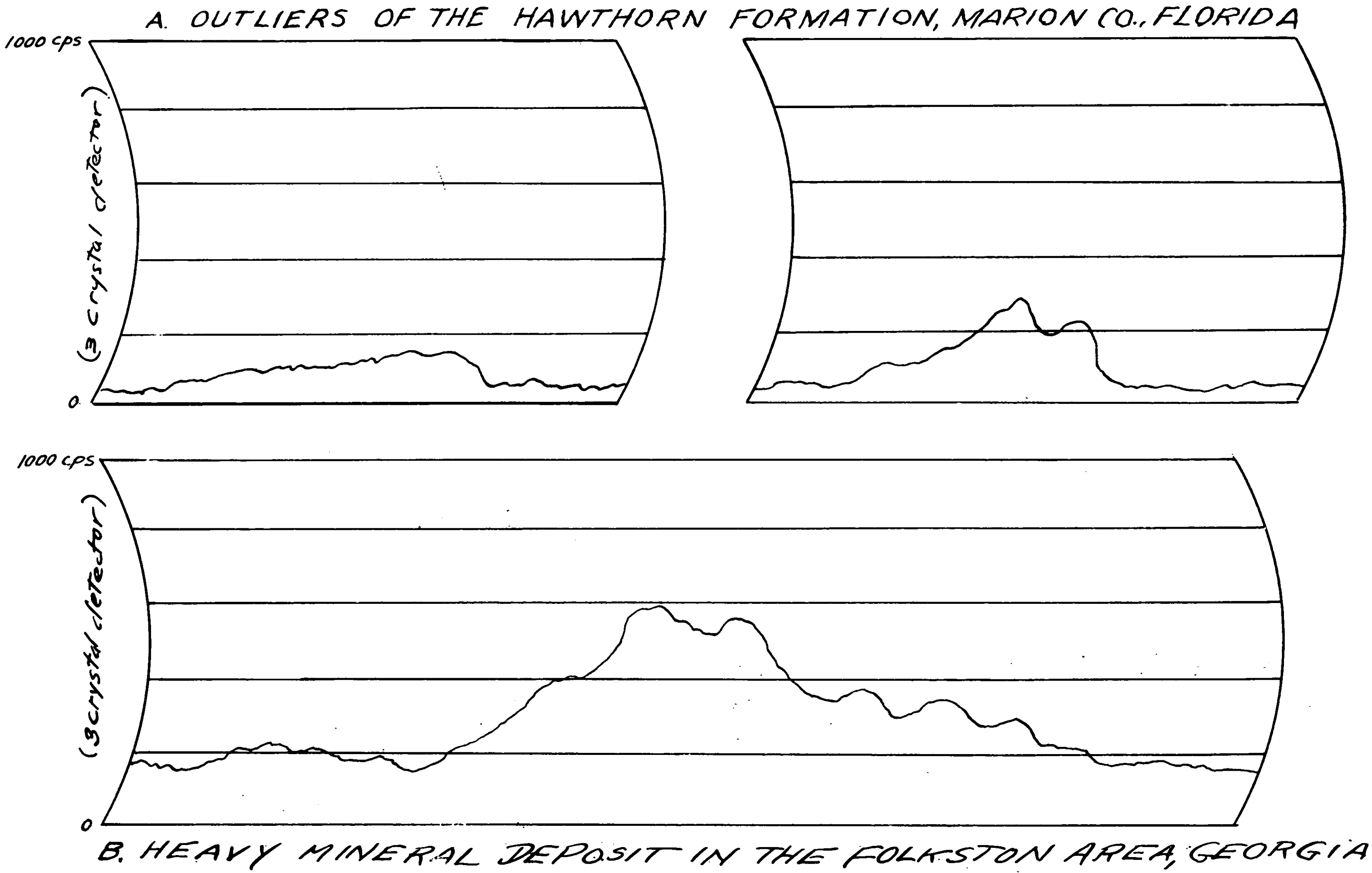
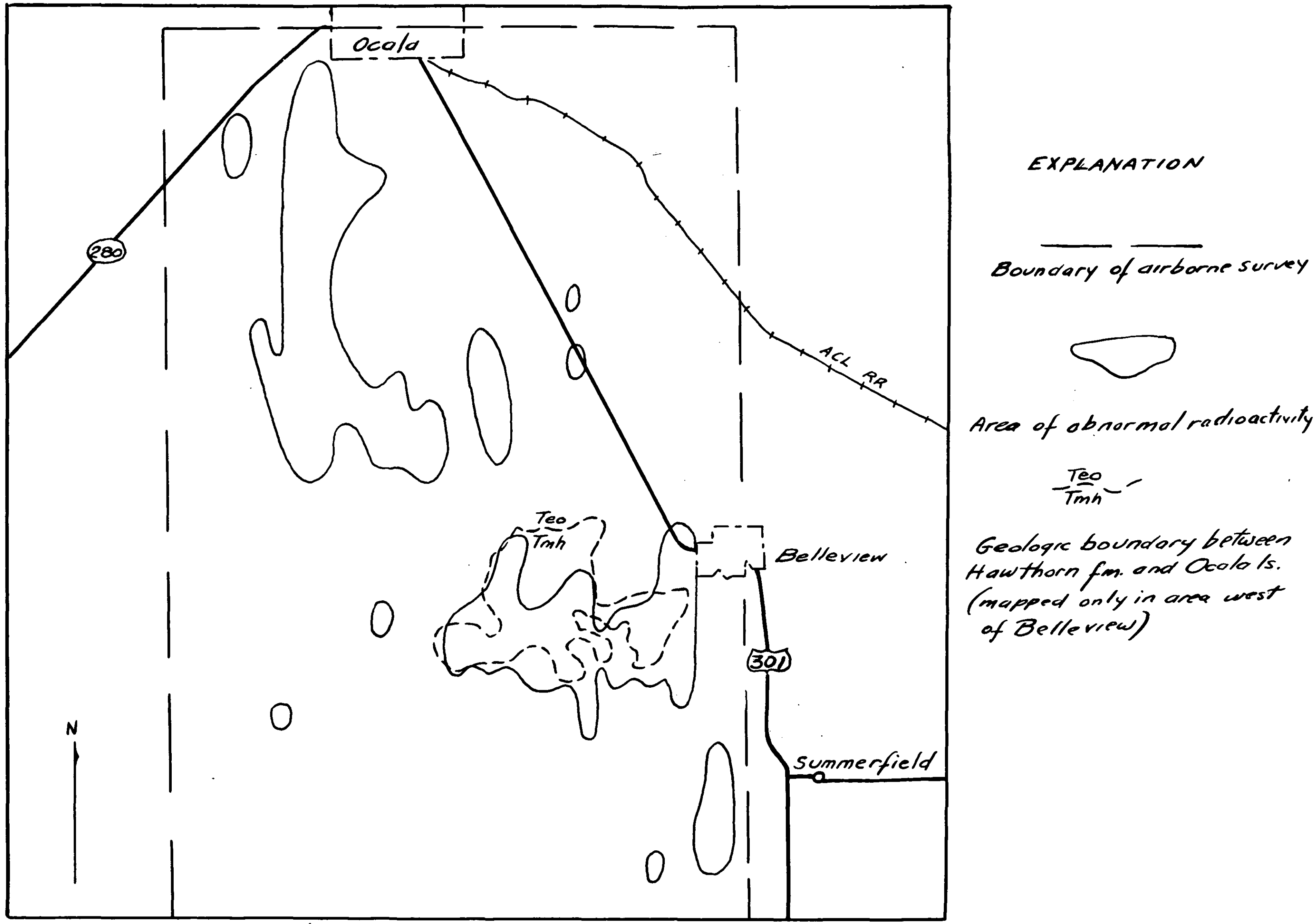


FIG. 4 EXAMPLES OF RADIOACTIVITY PROFILES AT 500 FOOT ALTITUDE OVER INFINITE SOURCES

0 — 9000 Feet

Approximate scale



Base from Florida State Highway maps

Geology by G.H. Espenshade, 1958

FIG. 5 AIRBORNE RADIOACTIVITY SURVEY OF PART OF MARION COUNTY, FLORIDA

0 4 Miles

to enclose those radiation intensities exceeding the reference background level (see fig. 2) recorded over the soil and sand surrounding the Hawthorn outliers.

G. H. Espenshade (oral communication) found that the anomalous areas are underlain by three types of radioactive materials: loose quartz sand containing about 0.001 percent eU; clay, locally phosphatic, containing from 0.002 to 0.006 percent eU; and leached, porous phosphatic sandstone averaging about 0.018 percent eU. It is not possible to determine the relative proportion of each type of material within a particular anomalous area but the average eU content is probably within the range 0.001-0.006 percent indicated by the recorded intensities.

The geologic boundary between the Hawthorn and Ocala formations has been mapped in the area west of Belleview. Comparison of the mapped boundary with that inferred from the airborne survey shows that the location and general dimensions of the outlier are reasonably close, but there is little agreement in detail.

Heavy-mineral deposits

Thorium-bearing heavy mineral deposits are of economic interest and can be detected from the air under proper circumstances. Deposits of this type in the southeastern Coastal Plain area are associated with shorelines developed during Pleistocene time. MacNeil (1949) has described four principal shorelines, representing maxima of marine transgression; other less distinct physiographic features are thought to reflect regressive pauses.

One of the most important heavy-mineral deposits in the United States is associated with old beaches on Trail Ridge, a remnant of a barrier island in north-central Florida. Layers range in heavy mineral content from < 1 percent to local concentrations > 6 percent and the deposits probably average about 2 percent heavy minerals. Rutile and ilmenite are the minerals of greatest economic importance. Mineral grain analyses (Thoenen and Warne, 1949, p. 35) show that the major nonopaque heavy-mineral constituents include at least two that can be expected to be radioactive -- zircon and monazite.

The potential detectability of such deposits by airborne methods depends upon the vertical distribution of the heavy minerals. At Trail Ridge and generally elsewhere in the southeast, the maximum concentration of heavy minerals is ordinarily at depths ranging from 10 to 60 feet. However, in nearly every instance, some of the layers of lower grade content of heavy minerals extend to the surface. Whether or not the deposits can be detected from the air depends on the concentration and extent of the heavy minerals exposed at the surface. At Trail Ridge there is apparently insufficient material at the surface as abnormal radioactivity was not detected on three flights crossing the deposit at different localities.

More successful results were obtained over heavy-mineral deposits in the vicinity of Folkston, Georgia (Moxham, 1955) where six areas of abnormal radioactivity were delineated. A typical radioactivity profile from the Folkston survey (fig. 4B) demonstrates that the concentration and surficial distribution of the heavy minerals are sufficient at this location to permit detection easily. The anomaly on the profile in figure 4B represents an increase of about 350 cps above the reference background which from equation (1) indicates an increase in eU content of about 0.003 percent.

No information is available on the actual distribution of the heavy minerals at Folkston. It is inferred from the airborne records that the limits of deposition are rather diffuse at the surface and sharp boundary conditions do not exist.

It is concluded on the basis of the surveys described above that the eU content of infinite sources probably can be determined within a few thousandths of a percent. The delineation of source boundaries is dependent on the nature of the contact. A sharp, well-exposed geologic boundary between strongly contrasting sources can be located within perhaps 300-600 feet but accuracy decreases to very generalized delineation as geologic conditions depart from this ideal situation.

Distribution with less-than-infinite dimensions

The term finite, which seems more appropriate to use here, has been restricted by Sakakura (1957, p. 21) to a particular configuration. To avoid confusion his terminology will be retained in this report.

The dimensions of infinite sources are sufficiently large to be easily recognized on the radiation profiles (figs. 2 and 4). The curves show some evidence of flattening at the peak, a feature that usually distinguishes them from curves arising from less-than-infinite sources. As the source dimensions decrease from infinite to less-than-infinite proportions, the source geometry becomes increasingly difficult to analyze. The most satisfactory analysis will probably require quarter-mile spaced, parallel flight lines. It is then possible to utilize the Sakakura (1957, p. 33) analytical technique, briefly summarized below (500-foot flight altitude is assumed).

If an anomaly is detected on only one flight line, a point source is indicated. If radiation from a source is detected on two lines, three source configurations are possible - slab, line, or finite. Should the peak intensity (I) and area under the curve (H) (fig. 2) on each line be approximately the same, a slab or line source is indicated. The width of the source may then be determined by the ratio H/I. If the anomalies show markedly dissimilar values of H and I on adjacent flight lines a finite source is indicated. Sakakura's work has shown that the dimensions of the fundamental geometric configurations are as follows:

Slab source:	rectangular, length > 1,700 feet.
	width < 1,200 and > 800 feet.
Line source:	rectangular, length > 1,700 feet.
	width < 800 feet.
Finite source:	circular, radius < 850 and > 275 feet.
Point source:	circular, radius < 275 feet.

Although the geometries defined above seem to set forth rather rigorous conditions, it is shown below that an erroneous analysis of geometric configuration will not lead to gross errors in computations of grade, but instead the magnitude of the error is more closely related to the estimation of the total surface area of the source. For instance, if a large slab source is mistakenly treated as an infinite source, the errors in position of the boundaries and eU content will not be excessive. If, on the other hand, an infinite source anomaly is erroneously treated as a line source, order-of-magnitude errors may be expected.

Phosphate mine (slab source)

As an example of a source that is on the borderline between less-than-finite and infinite dimensions, consider an open-pit phosphate mine in Polk County, Fla. Here, discarded aluminum phosphate zone containing a relatively small amount of uranium occurs in a well-defined rectangular configuration. The uraniferous source is surrounded by very weakly radioactive Pleistocene terrace sands.

A plan of the phosphate mine is shown in figure 6. The dimensions of the mine at the time of the survey, 2,800 by 1,150 feet are such that it constitutes a slab source, but nearly at the upper finite limit. Flights over the mine were made in an eastward direction along the lines shown, parallel to the long axis. Other flights were made at three different angles to the short (N-S) axis to determine to what extent the angle of incidence affects the grade calculations. Figure 6 shows the net peak intensity (I) to be about 1,600 cps. If an infinite source configuration is assumed, and a value of 1,600 cps for I, use of equation (1) indicates the material in the pit has an average eU content of 0.012 percent. The average eU content of twenty-five composite samples was 0.011 percent eU. From these results we conclude that for large, less-than-infinite sources, it makes little difference if the dimensions are overestimated and the grade calculation made with the infinite source equation. As a matter of fact, the infinite source solution was more accurate than the slab source solution as shown below.

The contoured radiation data were used to determine the theoretical source boundary. From considerations given above, the boundary should coincide with the half maximum (975 cps) contour midway between the

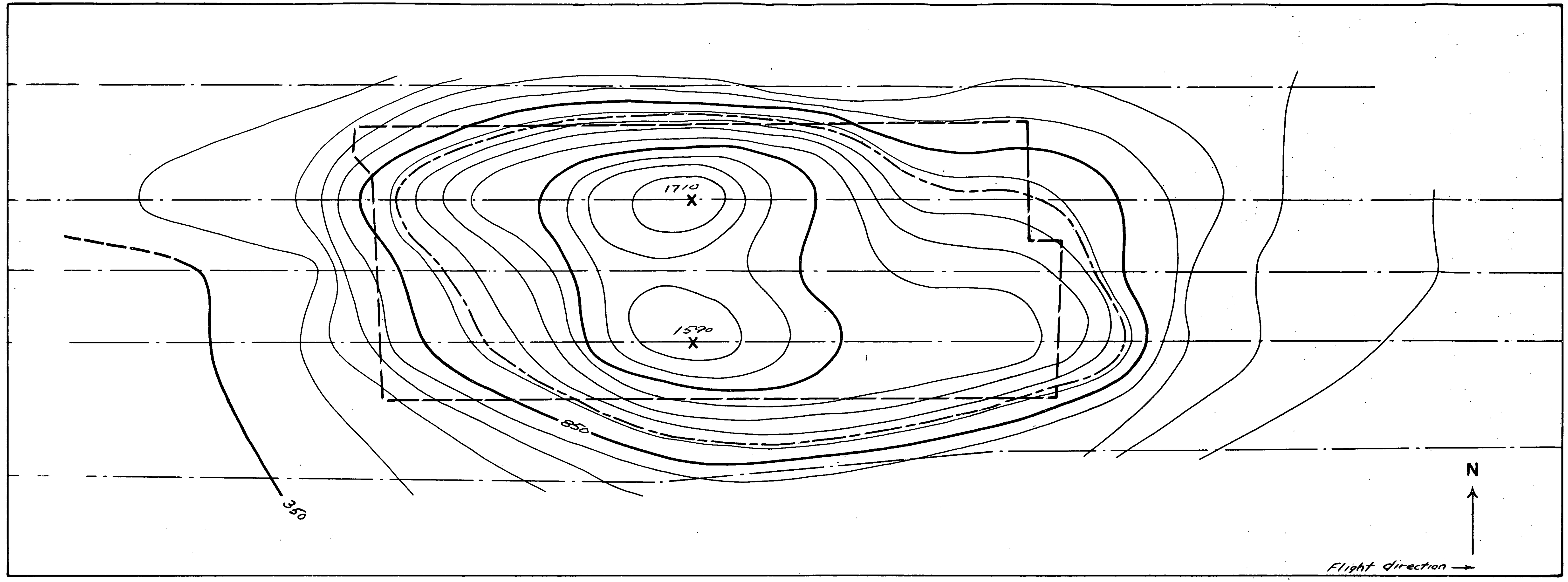


FIG. 6 MAP OF OPEN-PIT PHOSPHATE MINE SHOWING ISORADIOACTIVITY CONTOURS AT 500 FOOT ALTITUDE

400 0 400 800 FEET

ISORADIOACTIVITY CONTOUR INTERVAL 100 COUNTS PER SECOND
(3 CRYSTAL DETECTOR)

LEGEND

LIMIT OF PHOSPHATE OPEN-PIT

ISORADIOACTIVITY CONTOUR
(VALUES SHOWN INDICATE NET INTENSITY IN COUNTS PER SECOND)

FLIGHT LINE

THEORETICAL LIMIT OF SOURCE
(975 CONTOUR)

reference background (350 cps) and the average peak intensity (1,600 cps). The 975 cps contour roughly outlines the known boundary of the mine except that there is an apparent displacement of about 300 feet eastward, probably due to recording lag which was not removed in compilation of these data.

To make a slab-source analysis, five flights were made along each of three lines oriented at approximate angles of 0°, 44°, and 62°. The averaged data are given below:

θ	H	I	$H(\cos\theta)/I$
0°	11.8×10^3	2.23×10^3	5.3
44°	15.6×10^3	1.69×10^3	6.6
62°	32.9×10^3	3.11×10^3	5.0

The width of the slab is a function of the $H(\cos\theta)/I$ ratio and has been evaluated by Sakakura (1957) as shown in figure 7. Widths of 750, 1,200, and 630 feet are indicated by the flight data tabulated above. The actual width of the source is 1,150 feet.

If slab source configuration is assumed, equation (4) (Sakakura, 1957, p. 42) is applicable:

$$I = \frac{2\ CS}{S_o\ A_o}\ \mu x\ G_1 \qquad (4)$$

Numerical solution of the function G_1 which relates the instantaneous radiation intensity to the width of the slab and spatial position of the detector, has been tabulated by Sakakura (1957). Assuming the source width to be 1,150 feet and utilizing the flight data tabulated above, solution of equation (4) gives eU values of 0.010, 0.006, and 0.016 percent, respectively, for angles of 0°, 44°, and 62°. The actual eU content of the source as previously stated is 0.011 percent.

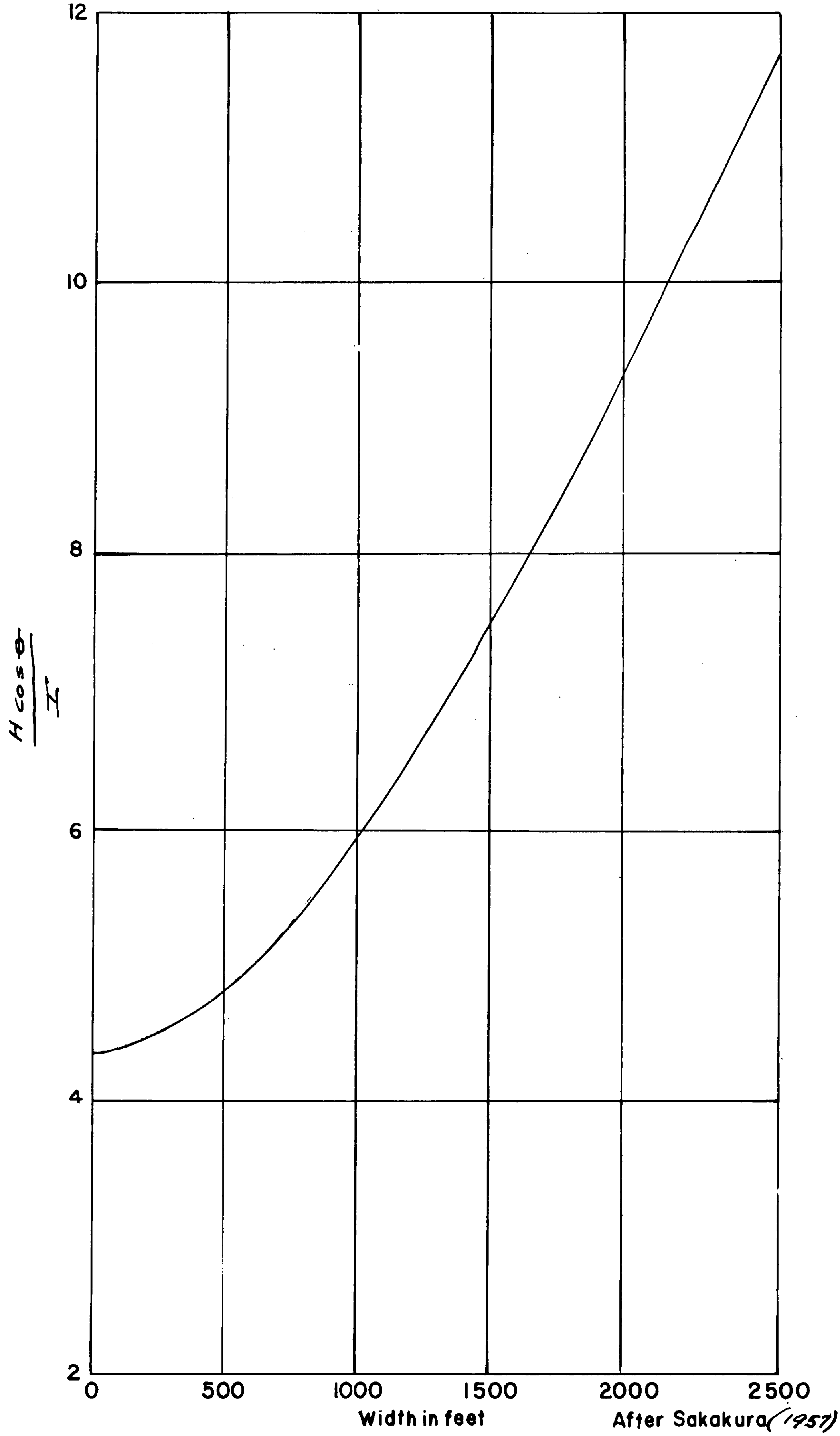


FIG. 7 RELATIONSHIP OF $\frac{H \cos \Phi}{I}$ TO WIDTH OF SLAB SOURCE

Beach-placer deposit (line source)

An airborne radioactivity survey was made in 1953 along the Atlantic coastline (Moxham and Johnson, 1953; Meuschke and others, 1953) to determine the response of the radiation detector to modern beach-placer deposits of heavy minerals. Deposits were known to occur at many localities but it was not known whether they contained sufficient radioactive minerals or were sufficiently large and well exposed to permit detection from the air.

Nineteen localities of abnormal radioactivity were detected. A cursory consideration of the geologic setting indicates that the modern beach placers would be oriented generally parallel to the coastline and that their configuration would approximate a slab or line source, depending upon the width of the mineral concentration. At one locality on Anastasia Island, Fla. (fig. 8), flight lines oriented at three different angles were made over an anomalous area. The resulting anomalies were quite asymmetrical apparently owing to the fact that the beach deposit was adjoined on the east by inert seawater and on the west by a few hundred feet (width) of slightly radioactive dune sand and still farther landward by very inactive sand. In order to eliminate these extraneous effects it was necessary to reconstruct the anomalies by using the radiation intensity over the water as the reference background and modifying the landward part of the curve so as to be symmetrical with the seaward part, as, for all practical purposes, the source lies at the land-sea boundary.

Five passes were made along each of the three flight lines. The average data obtained from the reconstructed curves are summarized as follows:

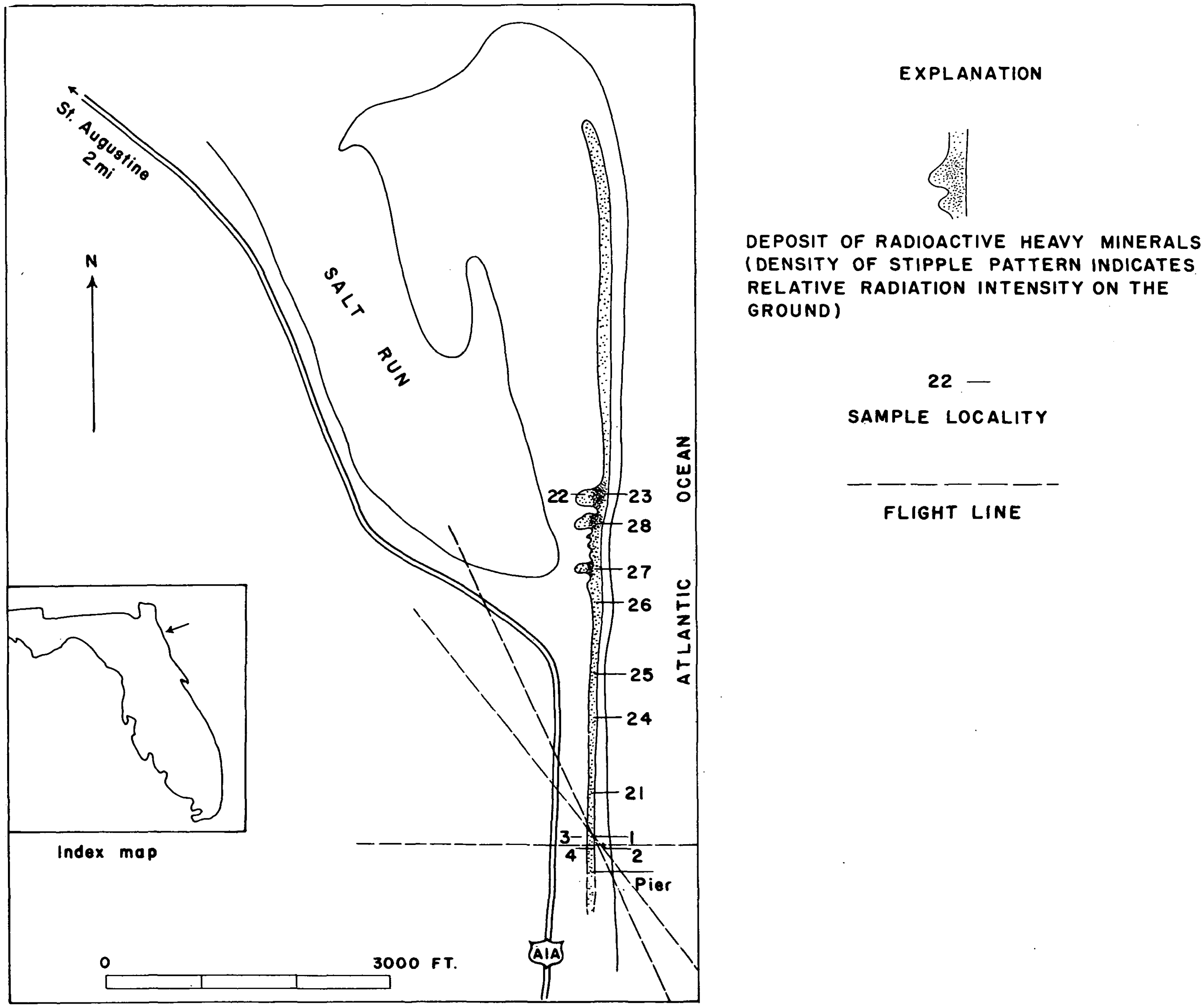


FIG. 8 SKETCH MAP SHOWING BEACH PLACER DEPOSIT, ANASTASIA ISLAND, FLORIDA

θ	H(cos θ)	I	H(cos) θ)/I
0°	2.15×10^3	4.8×10^2	4.5
53°	2.67×10^3	5.7×10^2	4.7
66°	2.27×10^3	6.0×10^2	3.8

At $\theta = 66°$, the H(cos θ)/I ratio of 3.8 is impossibly low because the smallest theoretical value is 4.3 as indicated on figure 7. The values of H(cos θ)/I for 0° and 53° indicate the width of the placer deposit to be 250 and 470 feet, respectively. However, it is important to note the manner in which the H(cos θ)/I ratio changes with source width in figure 7. The curve of this function is quite steep for widths 500 feet and greater, but flattens markedly for widths less than 500 feet. From a practical standpoint, H cos θ/I probably cannot be determined closer than ± 10 percent. Such errors mean that the width of a line source is exceedingly difficult to determine on the basis of the airborne measurements alone. This statement applies to a surveying altitude of 500 feet and may not hold true at substantially lower altitudes.

As the H cos θ /I values indicate a line source, equation (5) is required for determination of eU;

$$I = \frac{2\ CS}{S_o\ A_o}\ \mu^2\ x\ a\ \left[\frac{K_1(\mu w)}{\mu w} - .342\ K_o(\mu w)\right] \qquad (5)$$

where $w^2 = x^2 \times y^2$ and K_1 and K_o are Bessel functions of the second order kind (Watson, 1952).

The symbol y as used by Sakakura, designates the horizontal distance from the center of the source to the vertical projection of the point of observation. Here, we will use values observed where y = 0. Solution of equation (5) for the tabulated data gives an eU content of .004

percent for the flights at $\theta = 53°$ and .007 percent for the flights at $\theta = 0°$.

Twelve samples of the beach placer deposit collected in the area scanned by the flight lines average .012 percent eU, resulting chiefly from zircon and monazite. The width of the heavy-mineral deposit is 50 to 100 feet, as observed on the ground.

Uranium deposits

One of the primary uses of the airborne radioactivity detector has been, and no doubt will continue to be, to facilitate uranium exploration. Airborne surveys were chiefly responsible for finding uranium deposits that developed into several of our most productive areas. The Delta mine on the San Rafael Swell, the Jackpile mine in the Grants-Laguna area, and mines in the Washaki Basin (Maybell area, Colo.) are among the more notable. Uranium in the Coastal Plain area of Texas was also found by an airborne detector.

Surveys by the Geological Survey have been made mainly in the Colorado Plateau, central Plains, and Coastal Plain areas, and have dealt principally with deposits of oxidized uranium in sedimentary rocks.

Outcrops of the uranium deposits proper are generally of less-than-infinite dimensions, although it has been shown that in regions where uranium minerals occur the reference background may be abnormally high (Moxham, 1958; Moxham and others, 1957). Examples of the data recorded in two different areas of uranium deposits in sedimentary rocks are given below.

Finite source.--Deposits of oxidized uranium minerals in the Browns Park formation of Miocene (?) age were detected during an airborne survey of the Washakie Basin, Carbon County, Wyo., and Moffat County, Colo., in 1953 (Henderson, 1954; Johnson, 1955). An analysis has been made of the flight data from sec. 5, T. 12 N., R. 92 W. in the Poison Basin area where detailed geologic data are available (Vine and Prichard, 1954). The radiation-intensity profiles of parts of lines 11 and 12 are shown in figure 9. The positions of the flight lines and peak intensities, located as accurately as possible from aerial photos, are shown in figure 10. Inspection of lines 10 and 13 showed no abnormal radioactivity in this area so we have a situation where anomalies of unequal amplitude are present on two adjacent flight lines spaced at a quarter-mile interval. A finite source situation is suggested. There are apparently three sources, denoted by peaks A, B, and C. The curve containing peaks A and B looks to represent two anomalies that have not been fully resolved. It should be noted that the easternmost anomaly (peak C) is beyond the area of the investigation, but has been shown in figure 9 as it partially overlaps B. The discussion below will deal only with A and B.

If the anomaly containing peaks A and B is assumed to be an overlap of two curves, A and B, the component curves must be resolved in order to analyze the source geometry and grade. First, curve A was reconstructed so as to be symmetrical. The curves were then subtracted to arrive at the resolved curves A' and B'.

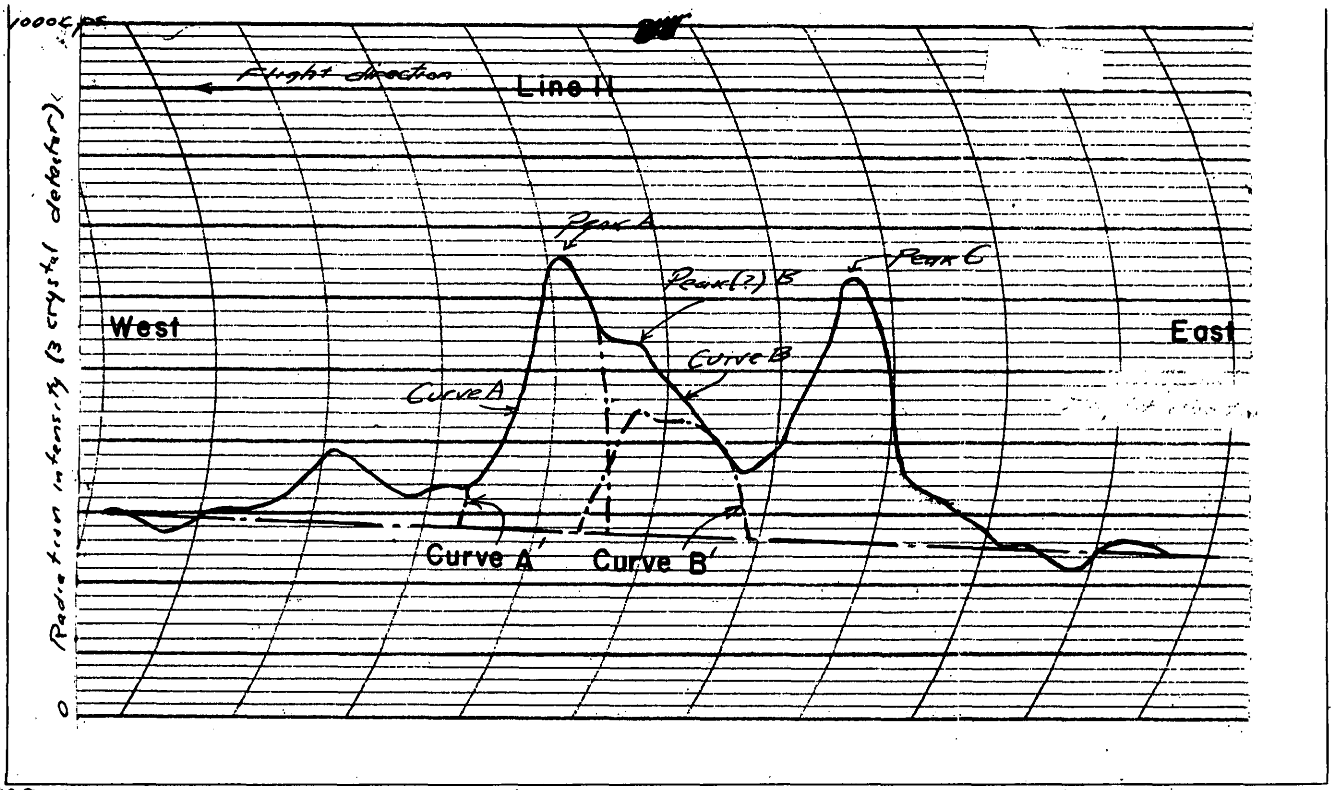
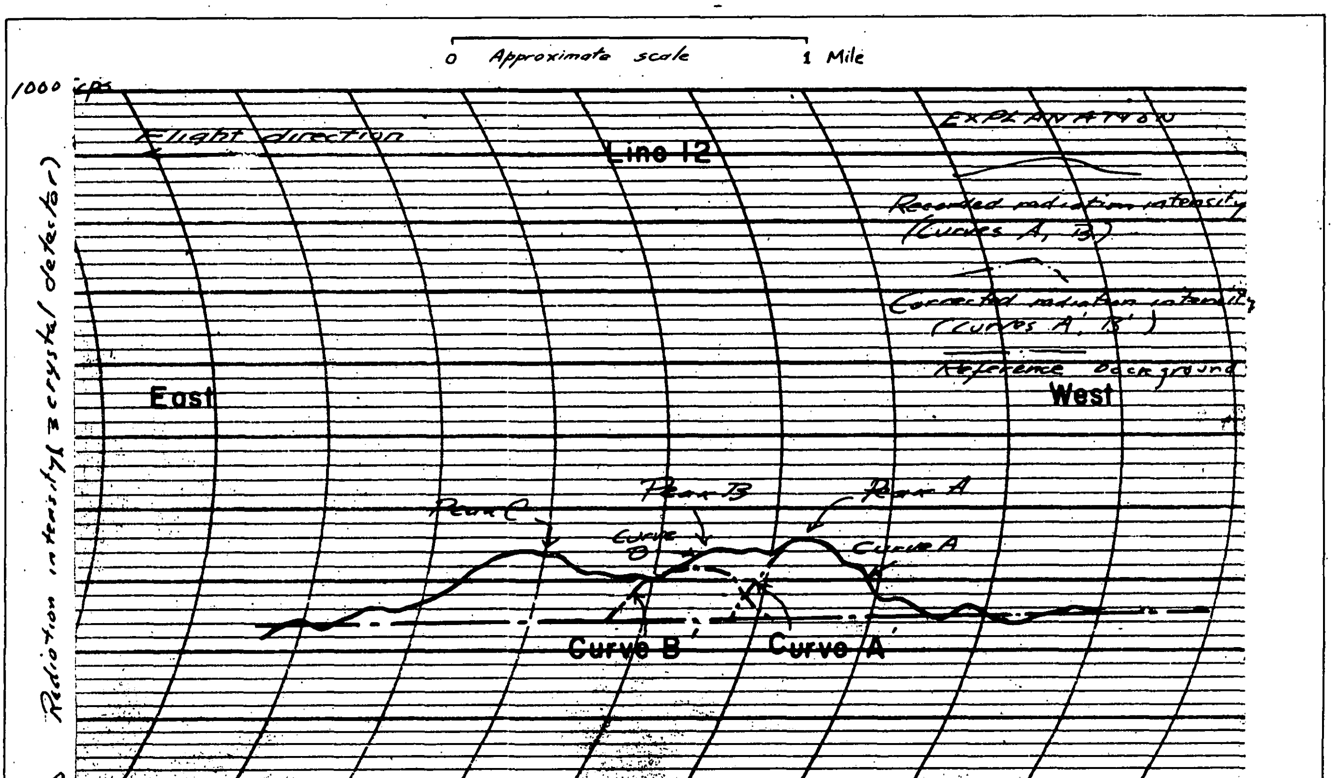
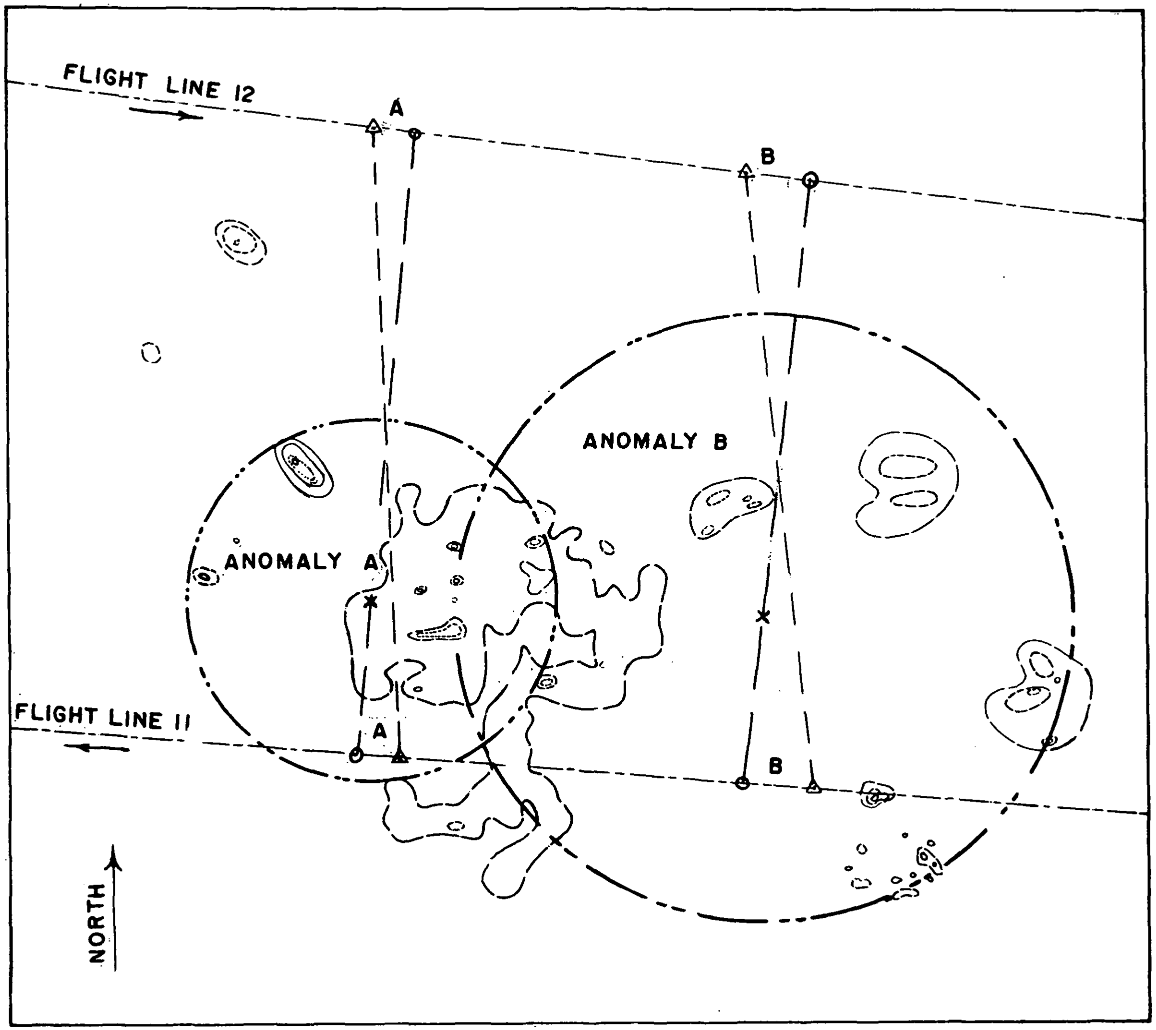


FIG. 9 RADIOACTIVITY PROFILES AT 500 FOOT ALTITUDE ALONG LINES 11 AND 12, POISON BASIN AREA, WYOMING





Modified from an unpublished map by Pritchard and Chisholm

EXPLANATION

FLIGHT LINE

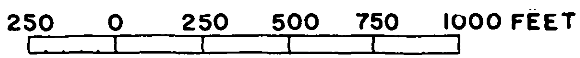
o *Theoretical* △ *Observed*
LOCATION OF ANOMALY PEAK

COMPUTED SOURCE BOUNDARY

0.03
0.06
0.12
0.24

GROUND ISORADIOACTIVITY CONTOURS
(milliroentgens per hour)

FIG. 10 GROUND RADIOACTIVITY SURVEY OF PART OF THE POISON BASIN AREA, WYOMING



We have assumed then, that there are two sources: source A, represented by the A' curves, and source B, represented by the B' curves. These sources lie somewhere between lines 11 and 12, and we can further assume that the centers of the two anomalies lie on the lines connecting the theoretical peak locations (fig. 10). Owing to the relative amplitudes the centers are closer to line 11 than line 12.

The data from the reconstructed curves are summarized below:

Line no.	Curve	H	I	H/I
11	A'	2,150	390	5.5
11	B'	1,390	180	7.7
12	A'	710	115	6.2
12	B'	450	75	6.0

The radius of a finite source and the distance from the center of the source to the nearer of the two flight lines is a function of the relationship between H/I ratios as shown in figure 11. The H/I ratios indicated above yield a radius of 530 feet for source A. The ratio for source B does not fall within the graph which immediately indicates that all is not well. We are forced to assume that the radius is large and will accept the nearest point on the graph, i.e., 900 feet. The distance from the centers of sources A and B to the nearest flight line (11) are about 460 and 500 feet respectively.

The grade-area product (SA) of the two sources may be calculated from the point source equation (6) and by means of an appropriate factor (table 1) can be converted to finite form:

$$SA = \frac{S_0 A_0 \, 500\pi}{2C\mu} \left[\frac{H}{4.36 \, I^{.788}} \right]^{4.72} \qquad (6)$$

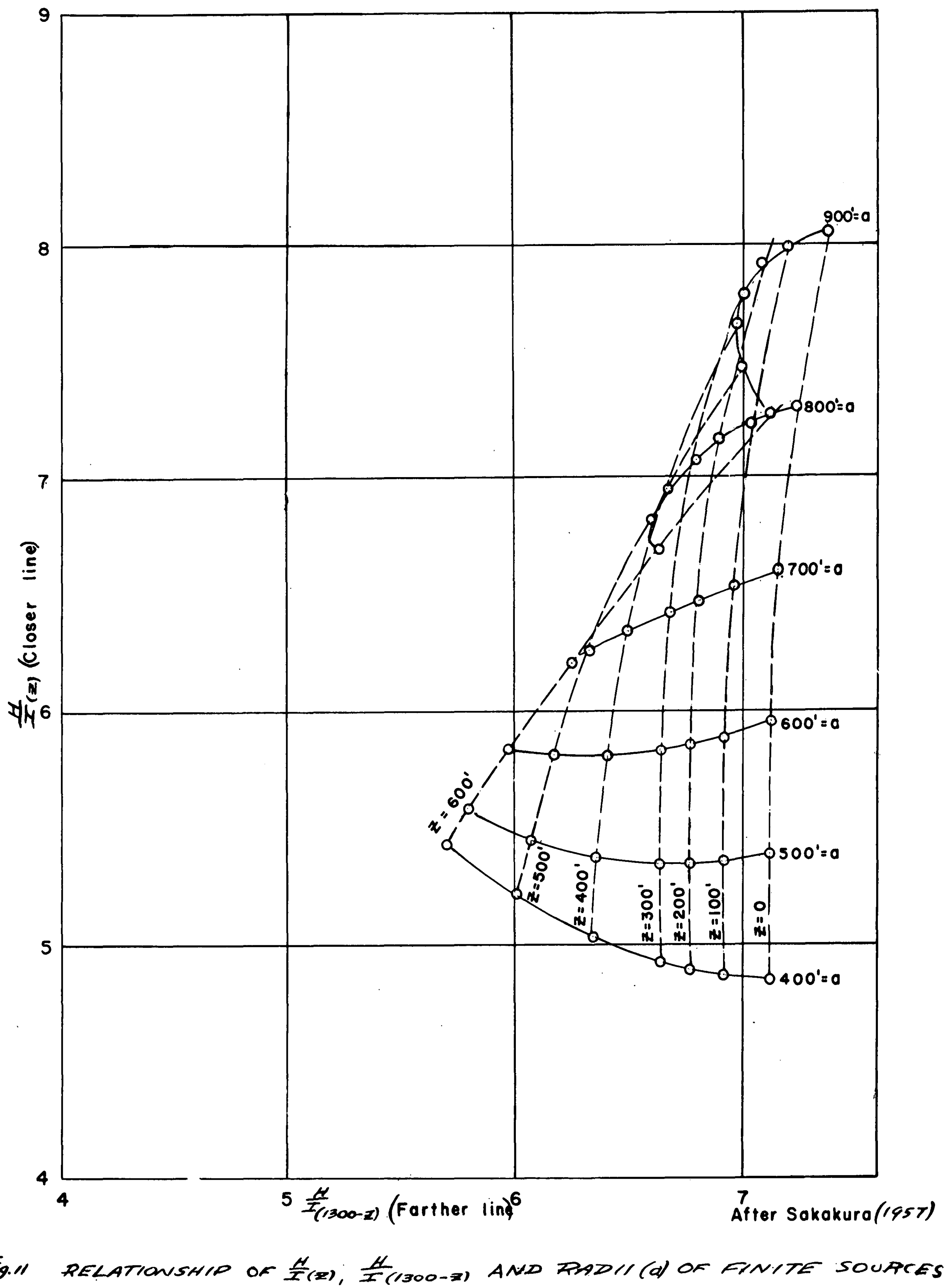


Fig. 11 RELATIONSHIP OF $\frac{H}{I(z)}$, $\frac{H}{I(1300-z)}$ AND RADII (a) OF FINITE SOURCES

Table 1.--Conversion factors to correct point source grade-area to finite source grade-area

Radius (a) (feet)	Minimum	Average	Maximum
0	1.000	1.000	1.000
400	.714	.765	.813
500	.568	.613	.684
600	.426	.477	.540
700	.324	.368	.425
800	.244	.276	.319
900	.185	.207	.233
1,000	.139	.151	.167

Solution of equation (6) using the data from the reconstructed curves and application of the appropriate conversion factors indicate that the eU content of sources A and B is .006 and .001 percent, respectively.

The computed source boundaries have been plotted on figure 10. Instead of two sources as the flight records would indicate, there are in reality several local concentrations of radioactive material. In anomaly A, the local concentrations are scattered over an area that on the whole is abnormally radioactive. The computed center of anomaly A is offset perhaps 200 feet to the west, which is probably a combination of lag and errors in transferring the airborne data from photos to the base map. However, the computed size of anomaly A is reasonable. Anomaly B partly overlaps anomaly A, as the unresolved radiation profile curves would suggest. In area B, the concentrations of radioactive material are more widely scattered. The computed radius embraces an area that is obviously too large.

In regard to the grade of the anomalies, the ground radioactivity survey (fig. 10) indicates the average radiation intensity in area A is about 0.03 mr/hr which in turn indicates the rocks contain about 0.006 percent eU. In area B, the radioactivity is so dispersed that we can only estimate that the eU content is considerably less than that in area A.

The computed value (0.006) for A is the same as the observed value. Considering all the uncertainties involved, no particular significance may be attached to the remarkable agreement. While the observed value for area B is lower than that for A, the computed value, .001 percent, is obviously too low, probably by a factor of two or three. The average reference background in area B from the airborne data is about 270 cps which indicates that hostrrocks contain about .001 percent eU. The recorded anomaly represents an increase above the background, which the computed value does not reflect.

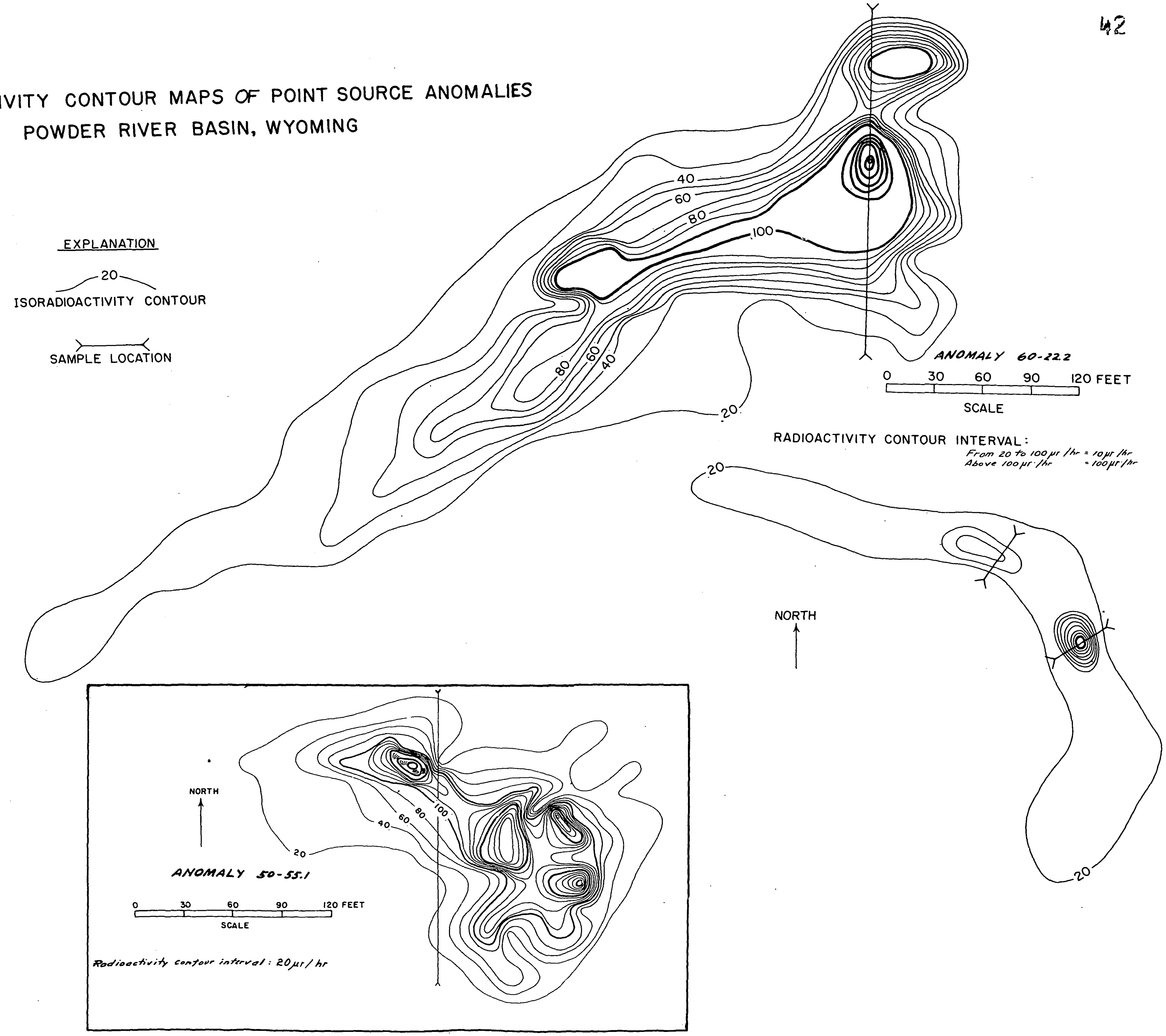
Point source.--A review of the Geological Survey flight records to obtain typical examples of point-source anomalies showed that such sources were indeed rare. Even in areas where the uranium minerals are highly localized for the most part, such as in the Pumpkin Buttes area of the Powder River Basin, northeastern Wyoming, an anomaly is seldom confined to a single flight line, as would be dictated if true point-source conditions prevailed. The two examples given below that did meet point-source specifications were exceptions rather than the rule.

The Pumpkin Buttes area is underlain by sandstone, shale, and coal of the Fort Union (Paleocene) and Wasatch (Eocene) formations. Deposits of secondary uranium minerals are found in "rolls" and disseminated in several sandstone layers in the Wasatch formation. The grade and area of the materials involved range from slightly abnormal "soil highs," extending for several hundreds of square feet, at which no uranium minerals are apparent at the surface, to small highly mineralized pods usually amounting to a few tons or less of ore containing uranium in the 0X.0 percent range. The surface area of such deposits seldom exceeds a few tens of square feet.

The airborne survey of the Pumpkin Buttes area, which resulted in the discovery of radioactive deposits in this region, covered approximately 830 square miles in Johnson and Campbell Counties. Flight lines were oriented east-west, spaced at quarter-mile intervals, and flown at a nominal 500-foot altitude. The locations of anomalous radioactivity detected from the air are shown in a report by Stead and others (1952). Near a given deposit the flight records generally indicate very marked abnormal radioactivity on one flight line with the shape (steep slope and sharp peak) and amplitude of the curve suggesting a point source. However, on most records some evidence of abnormality exists on one or both adjacent lines, indicating that the surface area of the source is much greater than the area of visible ore outcrop and probably is finite size, according to the definitions given above. This thesis was further supported by calculations of the grade-area of the sources, based upon the flight data. At several deposits the calculated values were much greater than the grade-area values based upon field observations, as the observed values are ordinarily contingent upon the extent of the deposit as determined by visible uranium minerals or by obviously abnormal radioactivity.

The reason for the discrepancy between computed and observed values was found by means of isorad surveys at two localities (fig. 12) that showed an aura of slightly abnormal radioactivity extending for several

FIG.12 ISORADIOACTIVITY CONTOUR MAPS OF POINT SOURCE ANOMALIES
POWDER RIVER BASIN, WYOMING



tens to more than a hundred feet from the loci of visible mineralization. The radioactivity is not sufficiently intense to be detected easily unless systematic surveys are made. It is not known whether the aura represents a weakly mineralized zone surrounding the locus of maximum concentration or whether it is a weathering and erosion phenomenon whereby fragments of the higher grade material are carried laterally by these processes. The aura definitely contributes to the radiation intensity recorded in the air and must therefore enter into calculation of the grade-area product. Moreover, it is indeed doubtful that many sandstone-type uranium deposits would have been found were it not for the extensive radioactive aura.

Two radiation profiles that typify point-source behavior are shown in figure 13.

As the anomaly resulting from a point-source is recorded on only one flight line, it is possible to determine from equation (6) the minimum grade-area product of the source, but little can be learned of the source position. The geographic location of the peak intensity fixes the position of the source in the direction of flight, that is, the center of the source lies along a line normal to the flight path through the peak-intensity position. The location of the center normal to flight direction may be at any distance from 0 to 750 feet from the flight line.

Radioactivity profiles recorded at 500-foot altitude over the two uranium deposits mentioned above are shown in figure 13. Two flights were made over anomaly 50-55.1 and three were made over 60-22.2. Equation (6) was used to determine the grade of the anomalous areas.

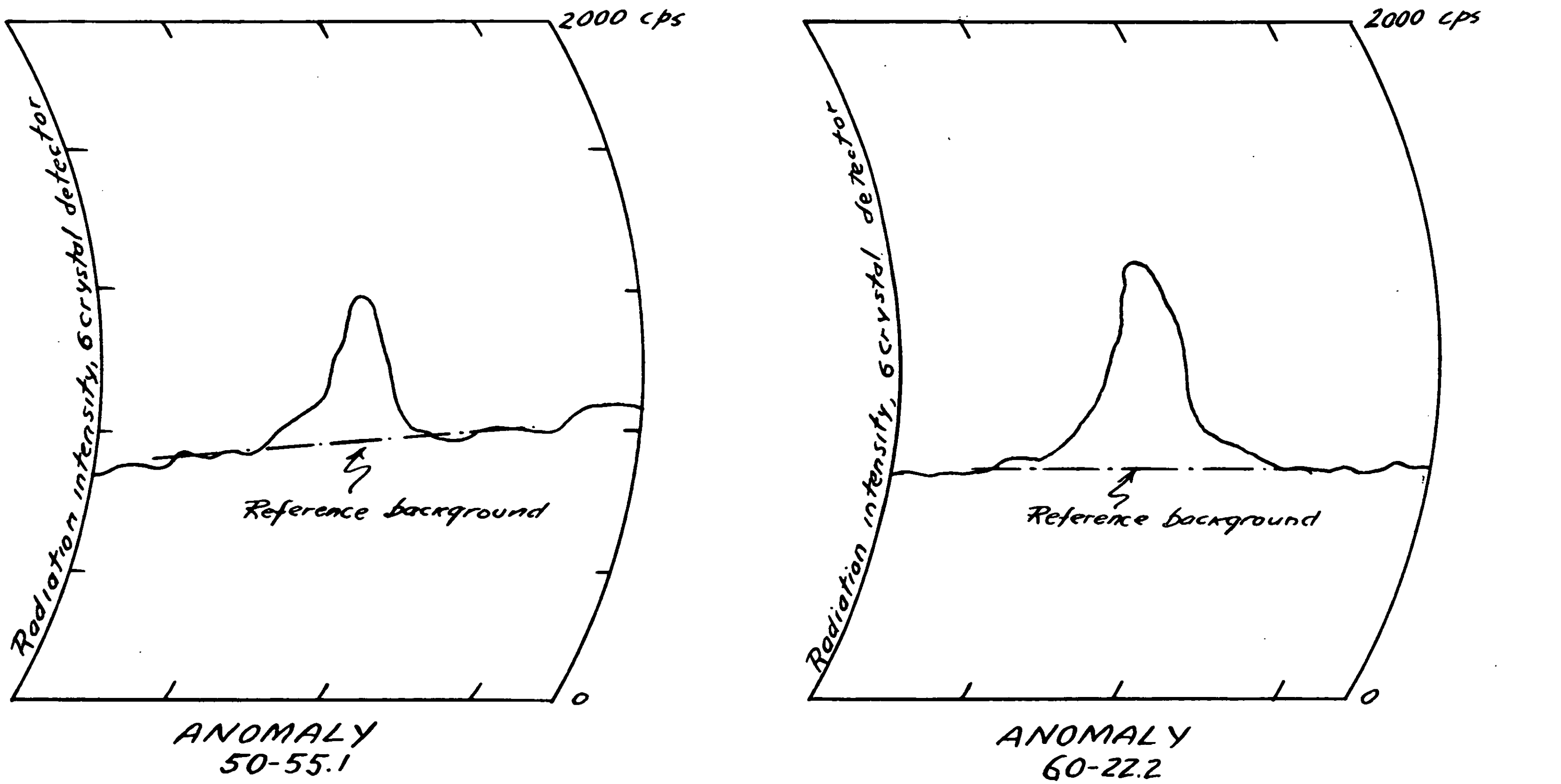


FIG.13 RADIOACTIVITY PROFILES AT 500 FOOT ALTITUDE OVER POINT SOURCES, POWDER RIVER BASIN WYOMING

The deposits were visible on the ground and the flight path was observed to be nearly directly over the deposits, so that r = x.

The flight data, results of computation, and the observed data are tabulated below:

Anomaly	I	H	Grade-area (equation 6)	Average grade-area (equation 6)	Grade-area observed
50-55.1				5.99×10^3	1.4×10^3
pass 1	660	3,520	9.50×10^3		
pass 2	430	1,890	2.48		
60-22.2				8.10×10^3	3.0×10^3
pass 1	580	3,260	9.95		
pass 2	440	2,270	5.50		
pass 3	630	3,350	8.85		

The spread in the airborne data probably is typical of what one may expect from point sources. Comparison of the calculated data with the observed values show the calculated values to be consistently high. At the maximum deviation from the observed figure, the airborne data are high by a factor of about seven.

SURVEYS FOR PETROLEUM

A report on airborne radioactivity surveys in geologic exploration could not omit reference to the relation of radioactivity to oil and gas fields that has been the subject of many papers in the last few years.

Nearly all of the airborne radioactivity surveys made by the U. S. Geological Survey have been undertaken on behalf of the Atomic Energy Commission and the primary objective of the surveys was the exploration for radioactive minerals. Flights over petroliferous areas were made only incidental to the stated objective and the flight data were not compiled in such a manner that intensive study with respect to the petroleum problem could be made. Examination of the relatively few data that were obtained did not show obvious characteristics that were diagnostic of, or could be related to, the occurrence of petroleum. However, our experience in this aspect of airborne surveys is quite limited and we certainly are not in a position to take a dogmatic view at this time.

SUMMARY AND CONCLUSIONS

The results of the present study indicate that, in general, the adequacy of an analysis of airborne radioactivity survey data will depend upon the geometric and geologic complexity of the source and the areal extent of the source.

It is obvious that, as the source geometry departs from one of the simple configurations described above, the difficulty in interpretation becomes greater. The same applies to the distribution of radioactive materials within the source. Homogeneous material of simple geometry will yield a generally distinctive curve while complex geometries and a heterogeneous distribution of radioactive materials within the source tend to obscure and override the diagnostic characteristics.

The airborne radioactivity data can provide the field geologist a useful guide in determining the continuity of lithologic units where outcrops are scarce or concealed by residual soils. In a sedimentary terrane the relative levels of radiation intensity, in many places, indicate the general composition of the parent rock, for low radioactivity generally is associated with sands, higher radioactivity with clays. In addition to their obvious value in exploration for uranium, aerial surveys can provide useful information in exploration for beach placers, both modern and ancient, and for marine phosphate deposits.

The results further indicate that the eU content of homogeneous infinite sources can be determined perhaps to within a few thousandths of a percent and the source boundary can be placed within a few hundred feet, given adequate flight-line spacing. At the other extreme, the grade-area of a point source under ideal conditions can be determined within a factor of about five but little can be learned of either specific parameter. The results of analyses of simple finite and slab sources will probably fall somewhere between the two extremes of infinite and point sources.

In dealing with what are obviously complex source conditions it is essential that all available geologic information be utilized in order to choose the most logical mode of analysis.

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