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Airborne Measurements of Terrestrial Radioactivity as An Aid to Geologic Mapping

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*Prepared on behalf of the
U.S. Atomic Energy Commission*



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By JAMES A. PITKIN

G E O P H Y S I C A L F I E L D I N V E S T I G A T I O N S

G E O L O G I C A L S U R V E Y P R O F E S S I O N A L P A P E R 5 1 6 - F

*Prepared on behalf of the
U.S. Atomic Energy Commission*

*Descriptions and evaluation
of the correlation of airborne
measurements of terrestrial
radioactivity with areal geology*



UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

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GEOPHYSICAL FIELD INVESTIGATIONS

AIRBORNE MEASUREMENTS OF TERRESTRIAL RADIOACTIVITY AS AN AID TO GEOLOGIC MAPPING

By JAMES A. PITKIN

ABSTRACT

Airborne measurements of terrestrial radioactivity (aeroradioactivity) have been interpreted by correlation with areal geology. Rock-unit classification provides guidelines to the varying amounts of uranium, thorium, and potassium in the surface rock and soil which generate the measured gamma radiation. Correlations made between patterns of aeroradioactivity and geology are an aid to geologic mapping.

About 200,000 square miles in the conterminous United States and Puerto Rico was surveyed for aeroradioactivity to determine background datum levels of environmental radioactivity around nuclear facilities. The aeroradioactivity data were obtained with continuously recording scintillation detection equipment which included a multicrystal array. Corrections were made for cosmic and aircraft background and for variations from the 500-foot terrain clearance elevation.

Topography, lithology, and soil are dominant factors controlling aeroradioactivity interpretation. Topographic relief should not exceed 1,000 feet because natural radioactivity cannot be accurately measured when the airborne detector is more than 1,000 feet from ground surface.

Varying bedrock lithology with consequent radioisotope variation results in the varying patterns of aeroradioactivity that are required for successful correlation. Homogeneous distributions of radioisotopes as measured by the scintillation detector give vague and discontinuous patterns of aeroradioactivity that seldom have correlative value.

The type of soil at ground surface is generally the major factor that determines whether correlation is possible, because for successful correlation the material at ground surface must reflect bedrock composition. Residual soils are ideal for correlation, although transported soils that do reflect composition of the underlying bedrock are satisfactory. Where bedrock is covered by transported soils having a different composition, or by alluvium, loess, and under some circumstances glacial debris, correlation is usually impossible.

Examples of correlation are discussed within a general framework of physiographic provinces which include: the Piedmont and the Valley and Ridge provinces; the Coastal Plain, Columbia Plateaus, Great Plains, and Pacific Border provinces; glaciated terrain of the midwest and northeast United States; and Puerto Rico.

The Piedmont province is the ideal locale, where relief is within desired limits, rocks are lithologically varied, and soils are residual. Aeroradioactivity studies can supplement geologic mapping, which is hampered by sparse outcrops, structural complexities, and a general lack of fossils. In other areas, where circumstances are less than ideal, evaluation of correlation requires analysis within the given framework, noting the effect of topography, lithology, and soil. Aeroradioactivity surveys when combined with aeromagnetic and (or) electromagnetic surveys, in areas where the magnetic or conductive rock has a surface expression, are extremely effective facets of geophysical exploration.

The Geological Survey is calibrating and flight testing an airborne gamma-ray spectrometer system. Delineation of gamma-ray energies with this equipment will permit estimations of the relative contribution of the uranium, thorium, and potassium components of terrestrial radioactivity.

INTRODUCTION

Airborne measurements of terrestrial radioactivity have been interpreted by correlation with areal geology. The radioactivity measured consists of the gamma rays emanating from the rock and soil at the surface. This radioactivity is the gross effect of the content of uranium, thorium, and potassium in the surface rock and soil. The pattern and intensity of the surface radioactivity usually reflect the areal distribution of rock types. Thus airborne radioactivity measurements can be used as an aid to areal geologic mapping. This report discusses the correlation of aeroradioactivity measurements with areal geology. As used in this report "aeroradioactivity" refers to terrestrial gamma-ray intensity measured from an aircraft at 500 feet above ground surface.

ARMS PROGRAM

The radioactivity data used in the preparation of this report were collected during airborne surveys made by the U.S. Geological Survey on behalf of the Division of Biology and Medicine, U.S. Atomic Energy Commission, as part of the Aerial Radiological Measurement

Surveys (ARMS) program. ARMS-I, the subject of this report, was conducted by the U.S. Geological Survey, Washington, D.C.; ARMS-II, by Edgerton, Gerneshausen, and Grier, Inc., Goleta, Calif.

The purpose of the ARMS program was to establish gamma radiation datum levels (background) for areas in and adjacent to nuclear facilities. A datum level was determined as the background radioactivity at the time of flying. When the datum has been established, resurveying can disclose any significant changes that may have occurred as a result of nuclear testing, reactor or other Atomic Energy Commission operations, or radioactivity accidents.

ARMS-I surveying during July 1958–December 1961 totaled 188,000 line miles over 200,000 square miles in 23 areas in the conterminous United States and Puerto Rico (fig. 1). Published maps and reports giving results of ARMS-I are listed in table 1. An initial discussion of ARMS-I data interpretation was published in 1964 (Pitkin and others). Guillou (1964) discussed ARMS-II surveying.

TABLE 1.—*Reports and maps resulting from the ARMS-I program*

Area	Bibliography reference to CEX report ¹	Bibliography reference to GP map
Chicago.....		
Columbus.....	Bates (1966a).....	Bates (1965b).
Denver.....	Popenoe (1966a)...	Popenoe (1965).
Fort Worth-Dallas.....		
Georgia Nuclear Laboratory.....	MacKallor (1963a).....	MacKallor (1963b).....
GNOME.....	MacKallor (1965a).....	MacKallor (1964).....
Hanford.....	Schmidt (1962a)...	Schmidt (1961a).
Los Angeles.....	Books (1962a).....	Books (1962b).
Minneapolis-St. Paul.....		
Northeastern United States—north.....	Popenoe (1964b)...	Popenoe (1964a).
Northeastern United States—south.....	Popenoe (1966b)...	Popenoe (1966c).
National Reactor Testing Station.....	Bates (1965a).....	Bates (1964).
Oak Ridge National Laboratory.....	Bates (1962b).....	Bates (1962a).
Pittsburgh.....	Bates (1966b).....	Bates (1966c).
Puerto Rico.....	MacKallor (1966).....	MacKallor (1965b).
San Francisco.....	Books (1966).....	Books (1965).
Savannah River.....	Schmidt (1962b).....	Schmidt (1961b).
Washington, D.C.	Neuschel (1966)...	Neuschel (1965).

¹ Published by the Atomic Energy Commission. Available from the Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, U.S. Department of Commerce, Springfield, Va. 22151.

AERORADIOACTIVITY SURVEYING

A typical ARMS survey covers a square 100 miles on a side, centered at a nuclear facility—a total area of 10,000 square miles. Variations in area are due to either (1) more than one nuclear facility within the planned

survey which increased the area to more than 10,000 square miles or (2) topographic relief which limited the flyable area to less than 10,000 square miles. Typically, surveys are made along parallel flight lines spaced 1 or 2 miles apart and oriented normal to the strike of the rock units. Traverses along valleys and (or) ridges are made where topographic relief precludes regular surveying.

Radioactivity data are obtained with continuously recording scintillation detection equipment installed in a twin-engine aircraft. The aircraft maintains a nominal elevation of 500 feet above ground at an average air speed of 145 miles per hour. Topographic maps, county road maps, and aerial photographs are used for pilot guidance. The flight path of the aircraft is recorded by a gyro-stabilized continuous strip-film camera, and the distance of the aircraft from the ground is measured by a continuously recording radar altimeter. Fiducial markings which provide a common reference for the radioactivity and altimeter data and the camera film are made with an electromechanical edgemark device operated by a flight observer when the aircraft passes over recognizable features on the ground.

AERORADIOACTIVITY EQUIPMENT

The gamma radiation detection equipment used for the ARMS-I surveys was developed by the Health Physics Division of the Oak Ridge National Laboratory (Davis and Reinhardt, 1957). It is internally calibrated in counts per second. A diagram of the system is shown in figure 2. The detecting element consists of six thallium-activated sodium iodide crystals, each 4 inches in diameter and 2 inches thick and coupled to a photo-multiplier tube. The output of the detecting element is amplified and routed through a discriminator and pulse shaper that is set to accept only pulses originating from gamma radiation with energies greater than 50 Kev (thousand electron volts). The signal is then routed to two integrating rate meters, each of which exhibits a 1-second time constant. One rate meter feeds a circuit that records total or gross radioactivity on a graphic milliammeter. The signal from the other rate meter is recorded by a circuit from which the cosmic and aircraft background has been subtracted. The resulting net signal is then compensated for variations from the nominal 500-foot surveying altitude by using a correction potentiometer which is driven by the radar-altimeter output shaft.

At least twice daily during surveying, the aircraft ascends to 2,000 feet above ground and measures the background radioactivity. At this altitude, the ground contribution to the measured count rate is only a slight

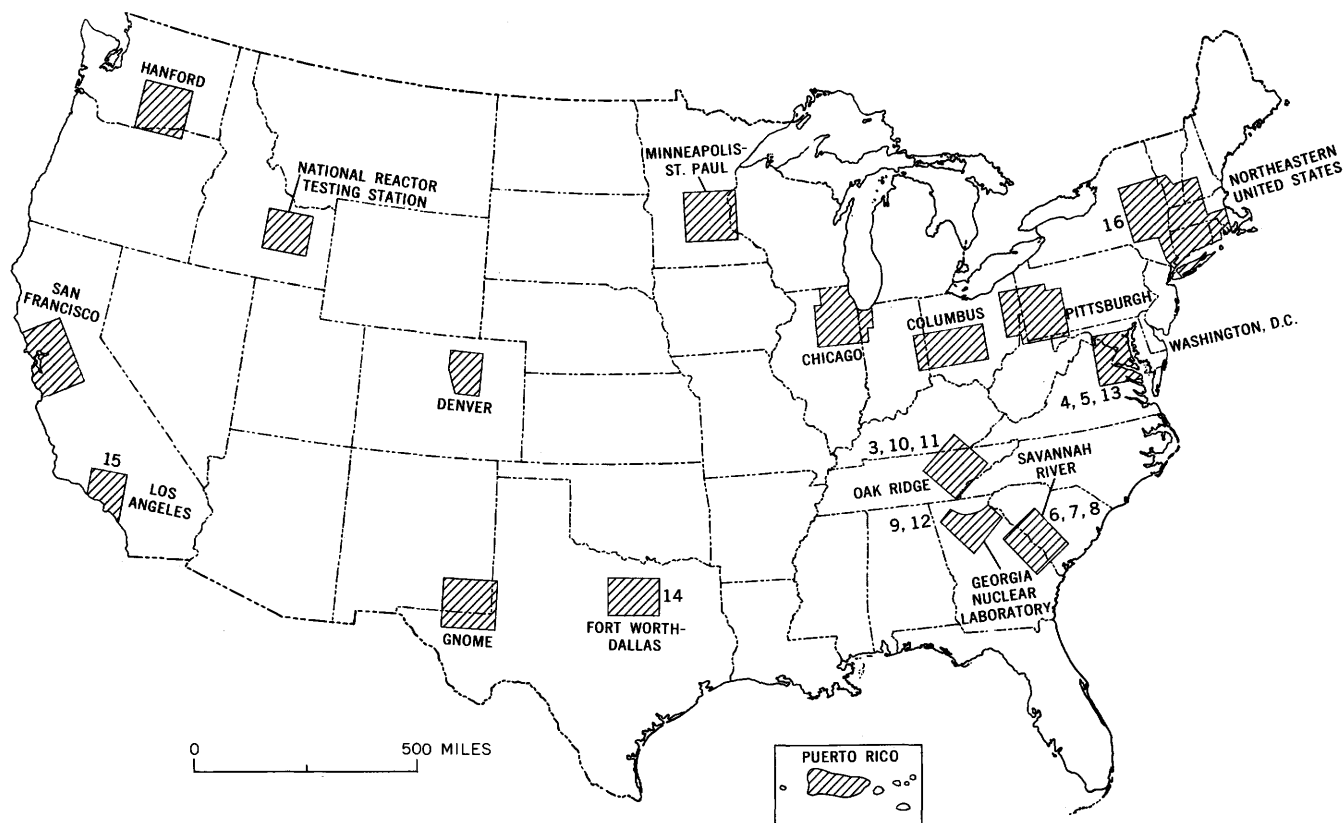


FIGURE 1.—Aeroradioactivity surveys made by the Geological Survey, 1958–61. Numbers indicate figures in the report covering all or part of areas shown.

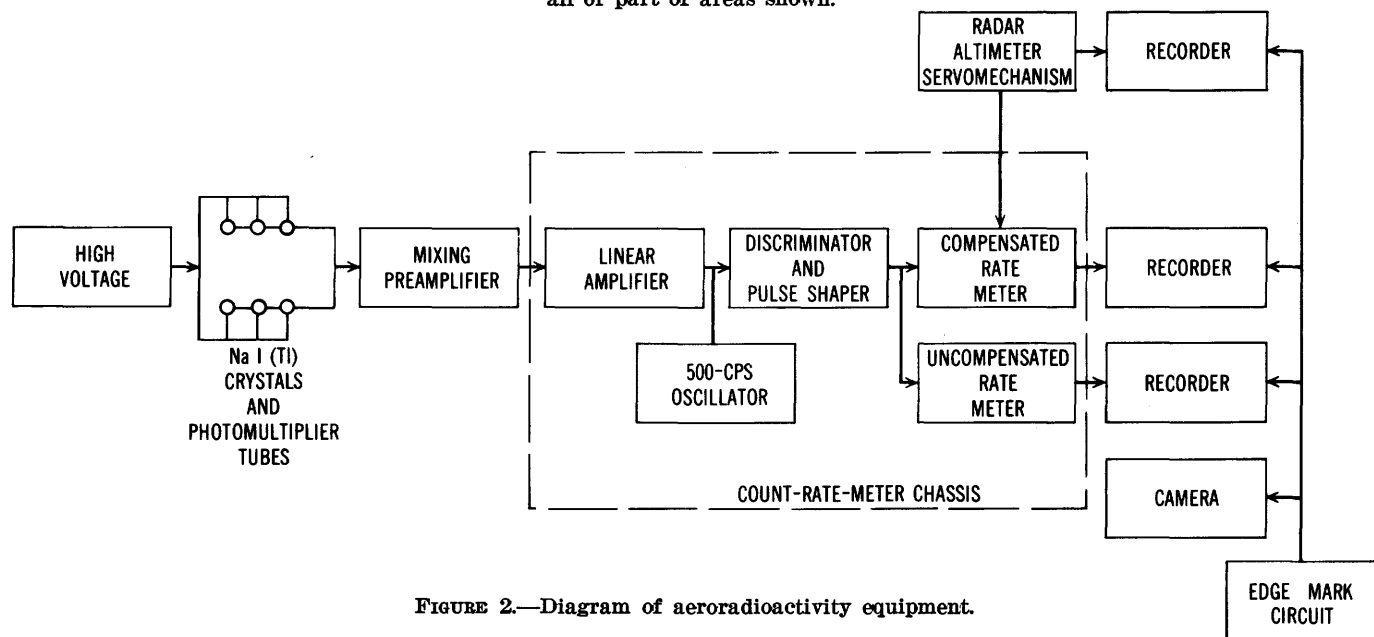


FIGURE 2.—Diagram of aeroradioactivity equipment.

fraction of that measured at 500 feet, and the 2,000-foot value is due mostly to cosmic sources. There are also contributions, usually slight, from radioisotopes in the air and from gamma-ray sources within the aircraft. All these contributions are adjusted or subtracted from

the altitude-compensated circuit. In this adjustment the cosmic component is assumed to be the main contributor to background radioactivity. A 10-percent attenuation of cosmic-ray intensity is assumed from the 1,500-foot interval between 2,000 feet and 500 feet above ground;

hence 90 percent of the total background measured at 2,000 feet is subtracted from the altitude-compensated circuit.

The altitude compensator is designed to permit the recording of equivalent 500-foot count rate at any flight altitude between 100 and 900 feet. The compensation is within desired limits, inasmuch as experimental data show that a 1,000-foot column of air absorbs almost all terrestrial radioactivity except that from the largest or most intense natural sources (Davis and Reinhardt, 1957, p. 719). During surveying it is rarely safe for the aircraft to get within 200 feet of the ground, particularly in hilly terrain.

Figure 3 illustrates altitude compensation for an area in the Valley and Ridge province of eastern Tennessee, northeast of Knoxville. The aircraft was about 200 feet below the survey altitude of 500 feet (radar-altimeter profile) when it passed over Clinch Mountain. The top of the mountain is composed of Clinch Sandstone, which would be expected to have low to moderate aeroradioactivity. The uncompensated profile shows a peak aeroradioactivity of about 1,000 cps (counts per second) for the top of the mountain. The compensator nullifies the topographic effect, as shown in the compensated profile, where the Clinch Sandstone has a more normal and correct aeroradioactivity of 300–400 cps. Other less striking examples of compensation are also shown.

Experimental data obtained over land-water interfaces, such as a peninsula, indicate that usually 85 percent of the radioactivity measured at a flight altitude of 500 feet above the ground comes from a surface area 1,000 feet in diameter, and 95 percent from an area 2,000 feet in diameter. Thus the effective area of response of the crystal array at the average flight altitude is a circle approximately 1,000 feet in diameter.

Certain calibration procedures that are followed during surveying assure uniformity of equipment response and internal consistency of data. A test line, usually part of a regular survey line, is flown at the beginning and end of each surveying day. Comparison of test-line data enables estimation of the diurnal variation of radioisotopes (usually radon daughter products) in the air. The test-line data are also checked for any artificial change (such as would result from fallout) in the background radioactivity.

Also, a calibrative check is obtained by flying at the survey altitude over water, whose measurable aeroradioactivity is negligible. At 500 feet over water, the compensated circuit registers zero radioactivity when sufficient adjustment has been made for cosmic and extraneous sources. The body of water must be suffi-

ciently large that the crystal array does not measure the radioactivity from any exposed land surface.

The equipment is calibrated several times each surveying day with a low-energy cesium-137 source and once a week with a 10-microgram radium-226 source that gives a count rate of 2,700 cps at 90 cm (centimeters) from the crystal array. In other investigations, calibrations have been made by flying over varied radioactive sources (Davis and Reinhardt, 1962; Sakakura, 1957).

The Geological Survey crystal array loses efficiency above 200 Kev (Davis and Reinhardt, 1957, p. 717). The detector counts virtually all gamma energy below 200 Kev, but above that energy level the efficiency falls off, owing to greater penetration of the gamma rays, as more pass through the crystals without interaction. For a monoenergetic source, the count rate varies directly with the emission energy of the particular gamma ray. The more heteroenergetic the source or field, the more important the energy dependence of the efficiency function.

It is not accurate to correlate the count rate at 500 feet above ground with the gamma-ray intensity at or near a particular spot at ground surface. The radioactivity at 500 feet above ground is a mixture of energy from varied radioisotopes, of which all have been attenuated in the 500-foot column of air. Attenuation coefficients vary with the energy of the gamma ray. In the aircraft an integrated count rate is measured from the approximate 1,000-foot-diameter area of response of the detector; hence an individual ground reading has no correlative value to the airborne reading made directly above.

COMPILATION OF AERORADIOACTIVITY DATA

Flight-line locations from the camera film are plotted on transparent overlays of base maps, at a scale commonly of 1 inch to 1 mile (1:62,500 or 1:63,360). The altitude-compensated aeroradioactivity profiles are examined, three to five profiles at one time, and significant breaks or changes in level of radioactivity are correlated from flight line to flight line. These changes in level are then plotted on the overlays and connected by solid or dashed lines, depending on the degree of correlation. The solid lines denote well-defined changes in level, the dashed lines minor or subtle changes. The readings between the lines of change are then scanned, and numbers which indicate the individual range or radioactivity level are assigned to each area.

The overlays are then photographically reduced to a scale of 1 inch to about 4 miles (1:250,000). The data are plotted on the publication base map, derived from

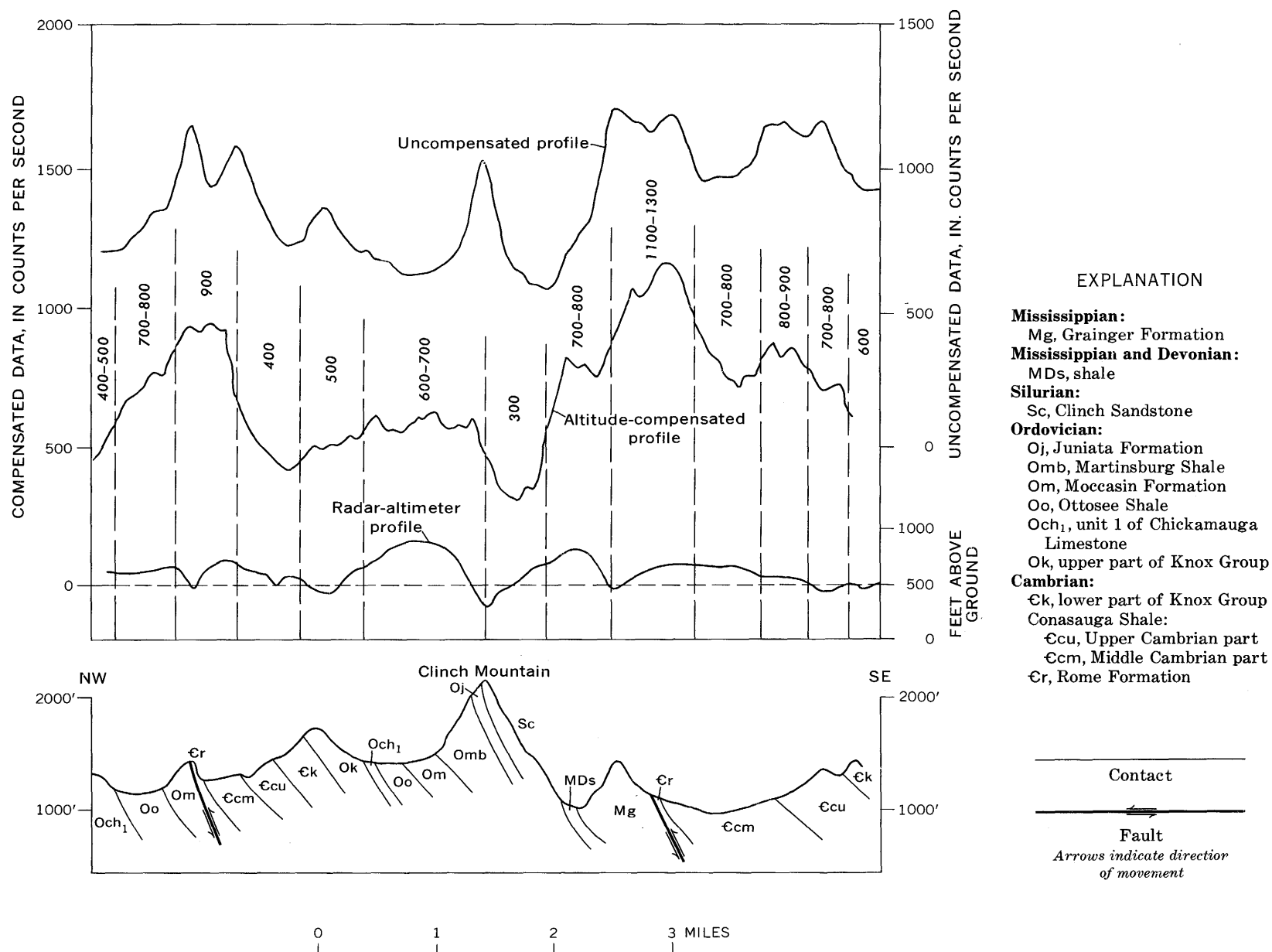


FIGURE 3.—Profiles showing aeroradioactivity, topography, and geology in the Valley and Ridge province, eastern Tennessee.
From Bates (1962b, p. 16).

Army Map Service sheets, Corps of Engineers 1:250,000-scale topographic map series. This is substantially the form in which the map will be published (table 1), with numbers and lines of change (called "boundaries") in black. Overprint patterns of green indicate generalized or approximate ranges of radioactivity level. These ranges are usually selected very arbitrarily, as their purpose is simply to facilitate interpretation and to permit broad, general correlations without close perusal of the map. The numbers and boundaries permit correlations for specific localities.

SOURCES OF AERORADIOACTIVITY

The gamma radiation detected at the surveying altitude of 500 feet above the ground results mainly from cosmic radiation, radioisotopes in the air, and radioisotopes in the surface layer of the ground, and to a lesser extent from extraneous aircraft radiation. With the present instrumentation the relative contribution of each source cannot be directly measured, but certain assumptions and calibration procedures permit reliable estimates of the components of the gross gamma radiation.

COSMIC RADIOACTIVITY

The cosmic background is measured at least twice each surveying day at 2,000 feet above the ground. Ninety percent of this value, which includes both cosmic and aircraft radiation, is subtracted from the altitude-compensated circuit of the scintillation equipment. A further check on this component is to fly at 500 feet over a sizable body of water. The measurable natural aeroradioactivity of water is so small that the cosmic-ray and aircraft backgrounds are dominant. Proper response would mean measurement of 0 cps over water, assuming that the crystal array "sees" only water and no exposed land surface and that all other background radiations are subtracted.

RADIOISOTOPES IN THE AIR

Airborne radioisotopes consist predominantly of radon isotopes and their daughter products. Their concentration in surface air is affected by many variables, such as moisture content of the soil, barometric pressure, temperature, and wind velocity. A tenfold change in the atmospheric radon concentration can occur under conditions of extreme temperature inversion. Evaluation of these variables during large-scale aeroradioactivity surveying is extremely difficult. Avoidance of survey activities during or immediately after extreme weather conditions eliminates the uncertainty as to radon contributions to the aeroradioactivity.

Presence of artificially radioactive particles in the

air will increase the airborne component. The largest source of such particles is nuclear debris. The adherence of airborne debris to the components and skin of the aircraft can so elevate the measured aeroradioactivity that further surveying is useless. Such a condition can be recognized by an excessively high, nondecreasing count rate at all altitudes. Normal operation can be resumed after the aircraft is decontaminated.

Exhaust stacks can emit contaminants in gaseous form, such as argon-41. This isotope, which is emitted at times from some reactor installations, can be detected as an anomalously high radioactive swath across the survey area at altitudes above the limit of terrestrial gamma-ray penetrations.

RADIOISOTOPES IN THE SURFACE LAYER OF THE GROUND

Ninety percent of the ground component of natural radioactivity originates in the top 8 to 12 inches of the ground (Gregory and Horwood, 1961, p. 13), whereas nuclear debris occurs as a surface layer or foliage contaminant. Ground deposits of nuclear debris particulates mask the true intensity of the natural gamma radiation and negate proper data evaluation.

NUCLEAR FALLOUT

Most of the ARMS-I data were obtained during the first nuclear moratorium, which extended from November 1958 to September 1961. Fallout was assumed to be present during all ARMS-I surveys and was definitely recognized on some occasions, but it could be considered a uniform contaminant, which would not significantly affect geologic interpretation. Most fallout products are short lived (Vennart, 1960), and experimental data indicate that in the spring of 1957 the activity due to fallout was less than one-tenth of the total gamma activity of the soil (Gustafson and others, 1958).

NATURAL RADIOISOTOPES

Natural terrestrial radioactivity consists predominantly of gamma rays from potassium-40 and from members of the thorium and uranium radioactive decay series. Potassium-40 emits a monoenergetic gamma ray; this isotope constitutes only 0.0119 percent of total potassium. Certain members of the thorium-232 and uranium-238 series decay by emission of gamma rays and are significant in geologic studies. Concentrations of these radioisotopes range from weak to strong. These radioisotopes also may occur as single series in various proportions, their occurrence depending upon the geochemical environment in which they were formed and upon events which may have disrupted decay equilibrium throughout the history of the geologic unit.

VARIATION OF RADIOISOTOPE CONTENT WITH ROCK TYPE

The distribution of uranium, thorium, and potassium in common rocks depends on several factors and can most easily be described by criteria established by general rock classification. The Geological Survey radioactivity instrumentation cannot distinguish between contributing radioisotopes, but when the interpreter knows the rock types present, he can better appraise the aeroradioactivity patterns. Table 2 gives general abundances for geologically significant radioelements in common rocks.

TABLE 2.—General amounts of uranium, thorium, and potassium in common rocks

[Adapted from Turekian and Wedepohl (1961)]

Common rocks	Uranium	Thorium	Potassium
	(parts per million)		(percent)
Ultramafic.....	0.001	0.004	0.004
Basaltic.....	1.0	4.0	.8
Granodiorite.....	3.0	8.5	2.5
Syenite.....	3.0	13.0	4.8
Granite.....	3.0	17.0	4.2
Shale.....	3.7	12.0	2.7
Sandstone.....	.5	1.7	1.1
Carbonate.....	2.2	1.7	.3

Sedimentary rocks.—Shale is usually more radioactive than sandstone or limestone, owing to potassium in the clay that composes shale. An increase of shale in the sedimentary column is often reflected in an increase in radioactivity. Sandstone is generally intermediate in radioactivity between shale (high) and limestone (low). Most sandstones owe their moderate radioactivity to radioactive heavy minerals (thorium in monazite, uranium in zircon) and (or) to interbedded shale (clay). Quartzose sandstone is an exception; being virtually homogeneous in composition it is nearly devoid of radioactivity. Limestone is usually moderately radioactive, because of interbedded (or contained) shale or clay, but the purer limestones are virtually nonradioactive. Uranium in carbonaceous shale can cause moderate to high radioactivity, but such rocks are somewhat rare in the sedimentary column.

Igneous rocks.—Nearly all felsic rocks (granite, syenite) are more radioactive than mafic (gabbro, basalt) and ultramafic (peridotite) rocks, grain size seemingly making no difference. The primary reason is the greater abundance of potassium feldspar in felsic rocks. Also, two of the more common accessory minerals—monazite and zircon—are radioactive and are generally confined to felsic rocks. Rocks of intermediate composition (granodiorite, monzonite) often have to be consid-

ered individually; however, the comparative potassium feldspar abundance of an igneous rock is a very good index of its radioactivity. Increased mica (biotite, muscovite) content can increase the radioactivity of the rock; this factor seems to be less important for igneous rocks than for metamorphic rocks.

Metamorphic rocks.—Generalizations about the radioactivity of metamorphic rocks are difficult to make, because of the extreme mineralogic variations. Experience shows that the comparative abundances of potassium feldspar and the micas seem to be the best indices for their radioactivity. The composition of a metamorphic rock is determined, basically, by the composition of the original rock; however, there can be radioisotope addition or depletion during metamorphism. Whether this has occurred can be determined only by examination of individual rock units.

INTERPRETIVE TECHNIQUE

The usual interpretive technique involves the direct comparison of radioactivity map pattern with geologic map pattern. In the ideal sense, radioactivity boundaries will coincide directly with geologic contacts; radioactivity data can in some places enable more precise delineation of concealed geologic contacts, which are usually drawn on the basis of factors such as topographic expression, soil, and vegetation.

In aeroradioactivity interpretation, exact or precise correlation between boundaries and contacts is seldom possible, but association of an areal radioactivity unit with an areal geologic unit can be accomplished. In this sense, the radioactivity unit reflects the gross radioisotope content of the geologic unit. Internal variation within the radioactivity unit can reflect facies changes in the geologic unit or other subtle changes at ground surface not known to the interpreter.

CAUSATIVE FACTORS IN AERORADIOACTIVITY INTERPRETATION

The correlation of aeroradioactivity with areal geology is dependent upon evaluation of many geologic factors, which include topography, lithology, and soil. Evaluation can become difficult, especially if lithologic descriptions of detailed features are considered. Examination of gross features is often more rewarding, especially when using the 1- and 2-mile-spaced ARMS-I data. The consideration of detailed geologic information may be more rewarding when interpreting data obtained on ½- or ¼-mile spaced flight lines. High cost, however, precluded such detailed spacing during ARMS-I surveying.

TOPOGRAPHY

The optimum operating limits of the altitude compensator—100–900 feet—have already been discussed. Another factor is aircraft safety; attempting to maintain a flight altitude of 500 feet above ground precludes surveying over very hilly or mountainous terrain. Ideal terrain is mainly flat to moderately rolling, with no sudden changes in relief, and relief of less than 1,000 feet.

LITHOLOGY

Variation in lithology, and consequent variation in radioisotope content, enables successful correlation, for then changes in aeroradioactivity level (boundaries) are reflections of changes in radioisotope content (geologic contacts). Adjoining rock units that have the same radioisotope content cannot be distinguished on the basis of aeroradioactivity, even though they can readily be individually mapped by the field geologist. Radioisotope content and mappability are independent qualities. No correlation can be established where there is little or no variation in radioisotope content.

SOIL

Inasmuch as the radioactivity measured by airborne instruments comes almost entirely from the top 8 to 12 inches of the ground, the presence or absence of soil, and the type of soil, may considerably affect the correlation between aeroradioactivity map and geologic (bed-rock) map. The aeroradioactivity detected above an area will reflect the radioactivity of the bedrock only if the bedrock crops out, has a very thin cover of transported soil, or is covered by residual soil formed by weathering in place.

The aeroradioactivity of alluviated valleys is difficult to correlate with bedrock units, as the alluvial material is likely to have been derived from several rock types with subsequent mixing of radioactive minerals. A blanket of loess (wind-laid silt) over bedrock can nullify the aeroradioactivity of the bedrock. Glacial debris at ground surface has varied effects on bedrock aeroradioactivity; under some circumstances correlations can be made.

SELECTED EXAMPLES OF THE CORRELATION OF AERORADIOACTIVITY WITH AREAL GEOLOGY

ARMS-I surveys (fig. 1) were made in different areas having diverse geologic conditions. The survey boundaries usually had little relation to geology. For convenience, the survey areas are discussed according to physiographic provinces—areas of similar climate,

geologic structure, and geomorphic history. The only “artificial” category is that on “glaciated terrain,” which includes several physiographic provinces. Physiographic data are from Fenneman (1931, 1938, 1946).

PIEDMONT PHYSIOGRAPHIC PROVINCE, APPALACHIAN HIGHLANDS, EASTERN UNITED STATES

The Piedmont is a province of diverse rock types—igneous, metamorphic, and sedimentary—with consequent radioisotope variation. It extends in an approximately linear direction from eastern Pennsylvania and New Jersey southwestward into Georgia. The Piedmont is characterized by (1) infrequent outcrops in gently rolling terrain covered with thick accumulations of residual soil, (2) structural complexities, (3) variable grades of metamorphism, and (4) a general absence of diagnostic fossils (Fenneman, 1938, p. 121–148). The Piedmont is thus an excellent locale for aeroradioactivity correlation.

The Piedmont in Maryland shows “remarkably good correlation of radioactivity with geology” (Neuschel, 1966, p. 26; fig. 4 of this report). Several of the best correlations are at the contact of the Baltimore Gneiss and the Glenarm Series. The gneiss, of granitic composition, is the more radioactive rock and contains appreciable amounts of microcline, a potassium feldspar rarely present in the adjacent Glenarm rocks. The Baltimore Gneiss in the Piedmont is usually a distinct high (600–800 cps) which contrasts with the moderate range (400–650 cps) of the adjacent Glenarm rocks. Areas of the Baltimore Gneiss shown as having less than 600 cps are probably a hornblende gneiss variety of the unit, as such ferromagnesian rock is always deficient in radioactive minerals (Neuschel, 1966, p. 26–28).

The Glenarm Series is internally well defined by radioactivity throughout the Piedmont in Maryland despite fairly uniform lithology—foliated rocks with varying proportions of quartz, chlorite, muscovite, albite, and oligoclase—and a moderate range of radioactivity. The aeroradioactivity boundary shown in the northwest corner of figure 4 is correlative with the Sykesville-Wissahickon (Glenarm) contact. The Sykesville is similar to Glenarm rocks in gross composition, as it is weakly gneissic rock composed dominantly of quartz, plagioclase, and muscovite (Hopson, 1964, p. 103, 105).

Interspersed throughout Glenarm rocks are numerous mafic and ultramafic bodies of varied (gabbro, diabase, serpentine) composition. As expected by their composition, these rocks have low radioactivity and are often well defined by this characteristic. In figure 4 a north-east-trending serpentine dike is represented by a radio-

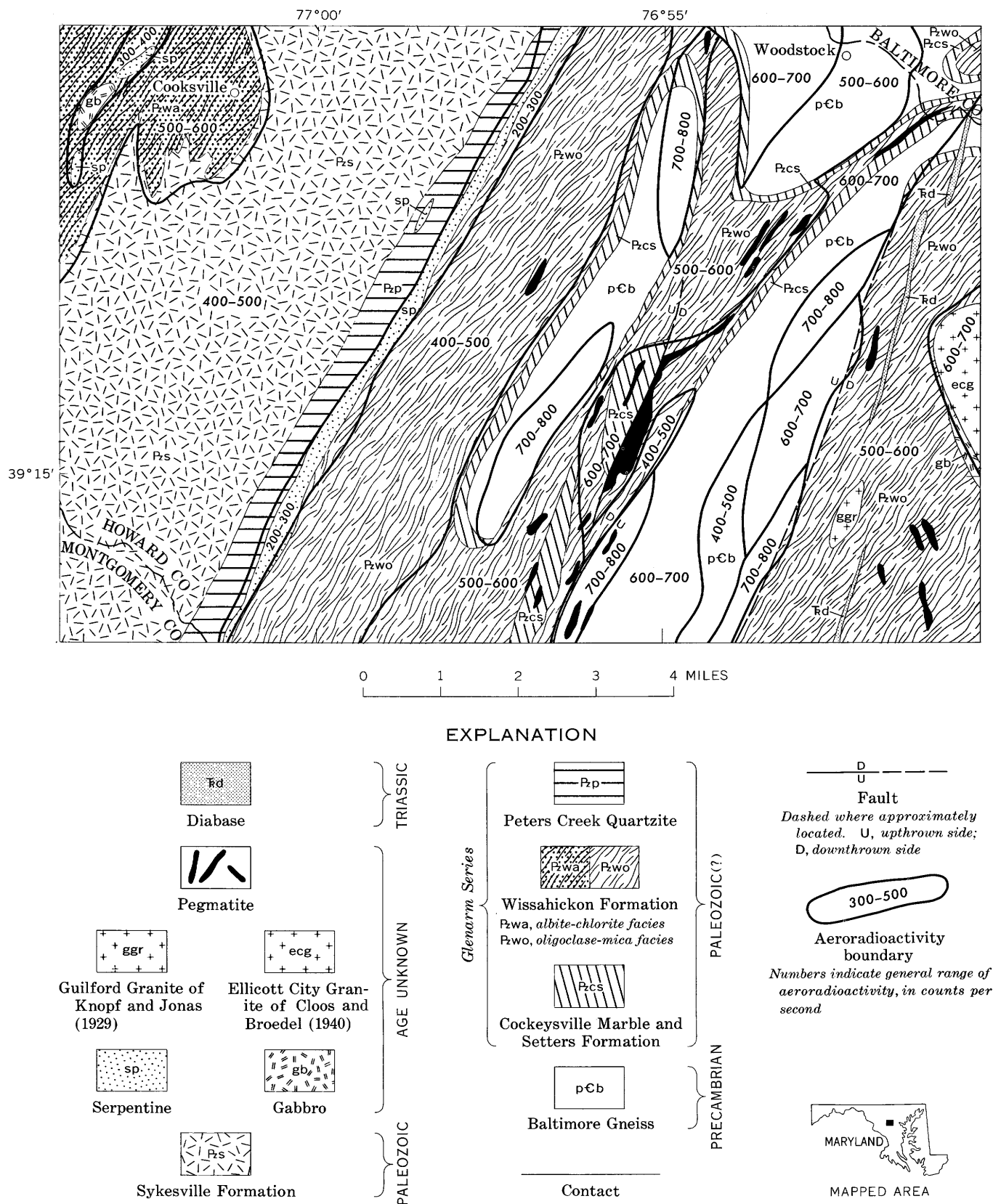


FIGURE 4.—Aeroradioactivity and geology of an area in Howard County, Md. Flight lines were flown east-west at 1-mile spacing. Modified by Neuschel (1966, p. 27) from map by Cloos and Broedel (1940).

activity low of 200–300 cps. The dike, which extends some 18 miles along strike in the Piedmont in Maryland, is only $\frac{1}{8}$ – $\frac{1}{4}$ mile wide, and yet was detected along every flight line that passed over it (Neuschel, 1966, p. 32–33).

Other intrusive bodies shown in figure 4 were evidently too small to be detected by 1-mile-spaced aeroradioactivity data. The pegmatite dikes are not individually identified in figure 4, although they probably contribute (because of their high content of potassium feldspar) to several areas of 600–800 cps.

Figure 5 shows several mafic and ultramafic bodies outlined by aeroradioactivity in the Piedmont of Maryland. Serpentine and a gabbro are lows of 200–400 cps in a higher matrix of 500–600 cps of the Wissahickon

Formation. Also delineated is a sill of Triassic diabase (Fisher, 1964, p. 14), an obvious low of 200–400 cps. An approximate halo effect of radioactivity is associated with several of these bodies. The radioactivity is low over the mafic or ultramafic rock and increases in several steps to higher radioactivity over the enclosing metasedimentary rocks. If these bodies are intrusive masses, the halos could represent the effects of alteration that occurred during intrusion and persisted during several subsequent stages of metamorphism.

Glenarm rocks in the Piedmont of northern Virginia, not mapped in detail, are associated with distinct patterns of radioactivity which include numerous lows (Neuschel, 1965). As in the Glenarm of Maryland, future mapping probably will show a correlation of

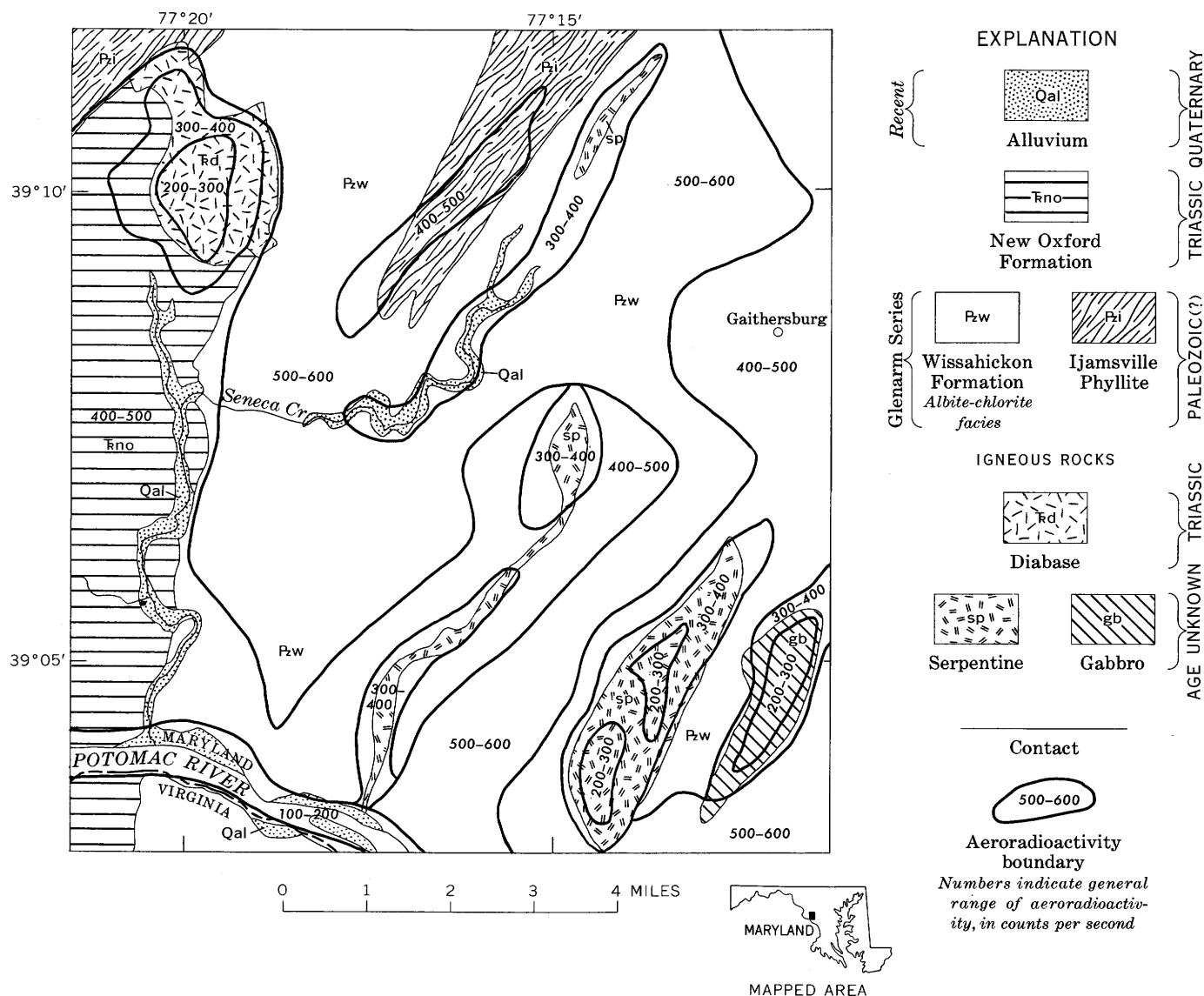


FIGURE 5.—Aeroradioactivity and geology of an area in Montgomery County, Md. Flight lines were flown east-west at 1-mile spacing. Modified by Neuschel (1966, p. 34) from maps by Cloos and Cooke (1953) and Griscom and Peterson (1961).

lows with mafic rocks. Such correlation is evident in the Fairfax quadrangle, Virginia (Bennison and Milton, 1950), where metabasalt correlates with lows of 200–400 cps and is bounded by metasedimentary rocks of 400–500 cps.

Interpretation is generally easier where there is a large range in radioactivity. The numerous correlations in the Piedmont of Maryland are accomplished despite the handicap of a low total range of radioactivity (200–800 cps), and an even more confined range (400–800 cps) where no ferromagnesian rocks are present. This accomplishment illustrates that the Piedmont is an ideal locale for aeroradioactivity correlation. The Piedmont of northern Virginia contains radioactivity as high as 1,600 cps, probably associated with granitic zones (migmatite) in metasedimentary rock, which are virtually lacking in the Piedmont of Maryland. The Piedmont of South Carolina and Georgia has radioactivity as high as 2,100 cps and as low as 150 cps.

Schmidt (1962b, p. 38, 40), in his study of data from South Carolina and Georgia, reported that "Field examination and comparison with geologic maps indicate that the radiation level is closely related to the type of soil or rock occurring at the surface. The association of radioactivity levels with rock types is locally so good that geologic contacts may be reasonably approximated from changes in radiation level, even though the bed-rock is mantled by thick residual soil." MacKallor (1963a, p. 34) stated that, in north-central Georgia, "The pattern of radioactivity reflects much of the geol-

ogy, and many of the local changes in the regional trend of the rocks are marked by corresponding changes in the radioactivity."

Figure 6 shows profiles of geology and associated aeroradioactivity in South Carolina and Georgia. The wide range of radioactivity is typical of the southeastern Piedmont province. There is often a twofold increase in radioactivity from low-level slate-belt rock to higher level granite or highly metamorphosed metasedimentary rock of the metamorphic complex.

Erosional windows of crystalline Piedmont rock surrounded by Coastal Plain sedimentary rock are commonly well defined by aeroradioactivity. These windows occur in headwaters of streams just southeast of the Fall Line (Piedmont-Coastal Plain contact). They were formed by headward erosion of streams cutting through the overlying Coastal Plain sedimentary rock and exposing the underlying Piedmont-type crystallines. Nearly all the Piedmont rocks are more radioactive than the Coastal Plain strata, and are obvious radioactive highs on the small-scale map of the area (Schmidt, 1961b).

Figure 7 shows a highly radioactive area in South Carolina paralleling the regional strike in what was thought to be Carolina slate-belt rock. Field investigation showed the linear area of high radioactivity to result from gneissic granitic migmatized zones in slate-belt rock. There is good but not exact agreement between radioactivity and geologic boundaries as the continuity

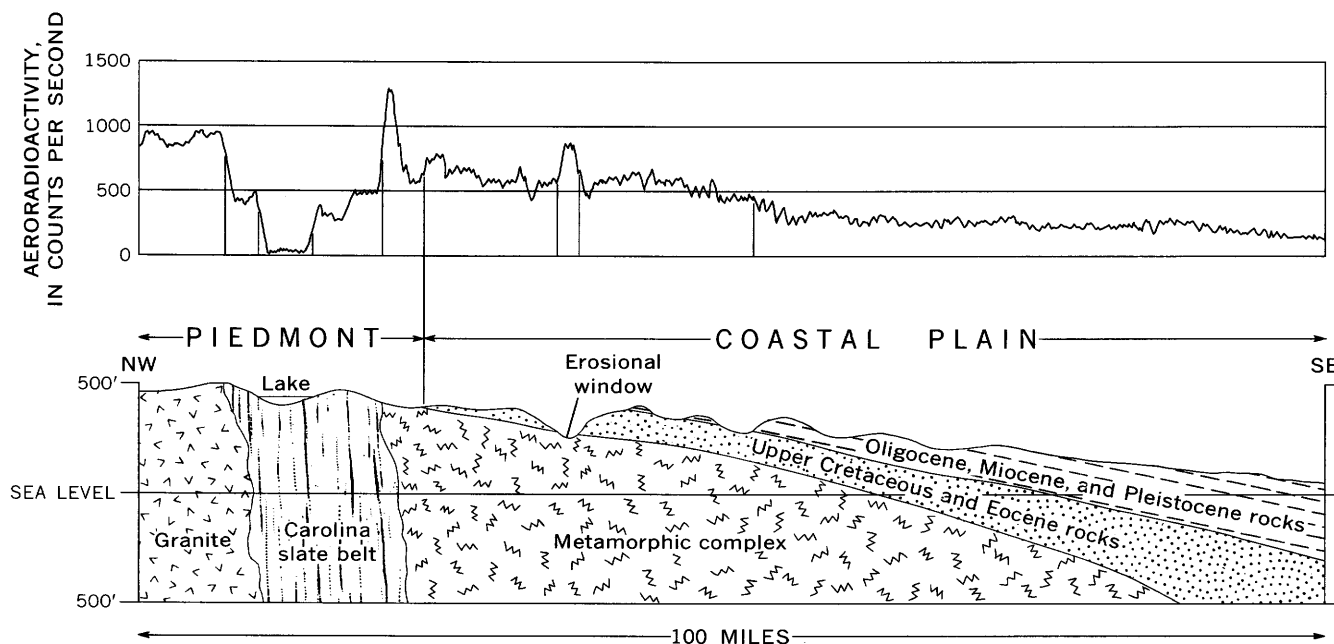


FIGURE 6.—Profiles showing characteristic aeroradioactivity and geology in parts of South Carolina and Georgia. From Schmidt (1962b, p. 22).

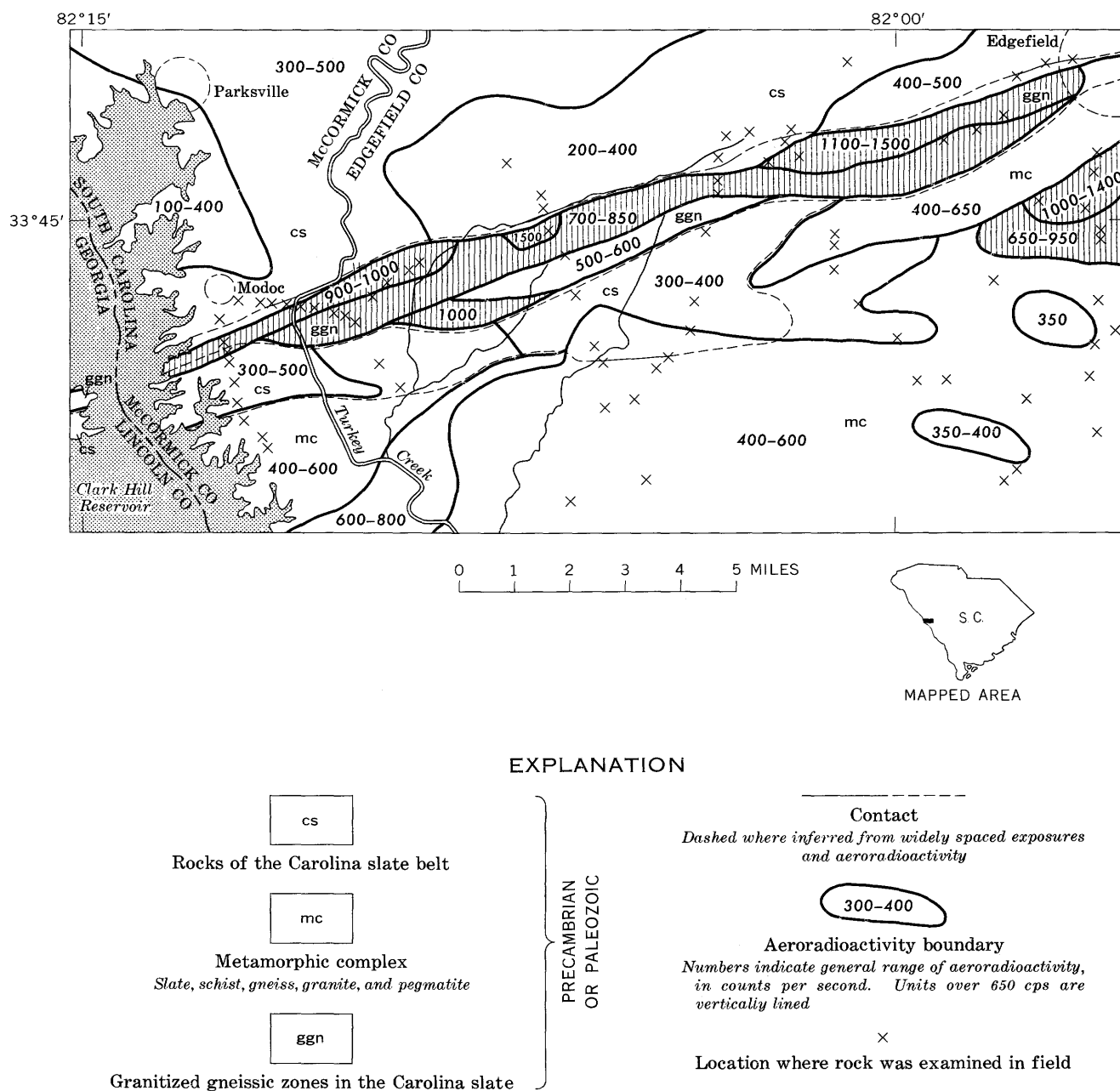


FIGURE 7.—Aeroradioactivity and geology of an area near Edgefield, S.C. Flight lines were flown northwest-southeast at 1-mile spacing. From Schmidt (1962b, p. 33).

of the altered zones is not known (Schmidt, 1962b, p. 32-33).

In the area shown in figure 8, similar circumstances enabled reconnaissance mapping of a hitherto unknown granite body. The 800- to 1,400-cps high was a striking feature in a regional background of 350-850 cps. Field examination disclosed biotite granite exposures within the radioactivity high along two roads 5 miles apart. On the basis of the aeroradioactivity data, radioactivity

boundaries were assumed to coincide with boundaries of the granite. Further fieldwork might disclose that granite or a similar radioactive rock underlies the 850- to 1,100-cps unit extending northeast to the Coastal Plain overlap from the 800- to 1,400-cps unit (Schmidt, 1962b, p. 32, 34).

Another distinct feature shown in figure 8 is the contact of the Piedmont and the Coastal Plain, along which nearly every flight line indicates a marked change in

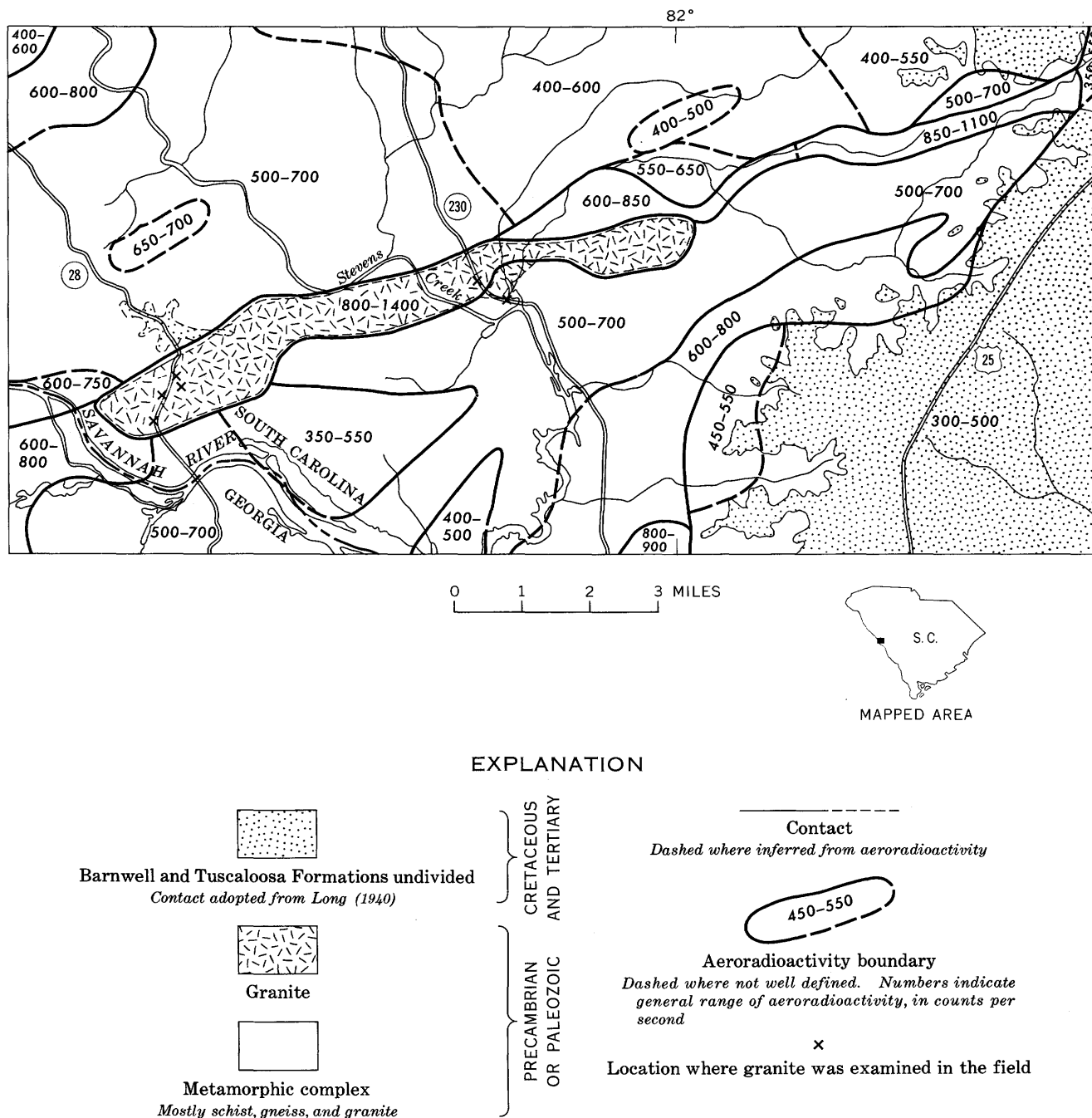


FIGURE 8.—Aeroradioactivity and geology of an area in the Clarks Hill-Warrenville quadrangles, South Carolina and Georgia. Flight lines were flown northwest-southeast at 1-mile spacing. From Schmidt (1962b, p. 34).

aeroradioactivity from the more radioactive Piedmont to the less radioactive Coastal Plain. The 1-mile-spaced flight lines have delimited this contact, even though numerous erosional outliers of Coastal Plain material are not detected. More closely spaced lines would more accurately define the contact.

In north-central Georgia the contact of the Piedmont (crystallines) and Valley and Ridge (folded sedimentary rocks) physiographic provinces is the Cartersville fault, whose surface trace is marked by a major radioactivity boundary. The sedimentary rocks on the northwest (Valley and Ridge) range from 450 to 800

cps, whereas the crystallines on the southeast (Piedmont) range from 550 to 1,300 cps. Every flight crossing the fault detected a change in aeroradioactivity correlative with the fault trace, the general magnitude being 100–200 cps (MacKallor, 1963a, p. 23). Even though the same contrasting rocks are not present all along the fault, the fault has apparently at all locales juxtaposed rocks having different levels of radioactivity; in addition, ground-water or hydrothermal solutions may have deposited radioactive minerals along the fault plane, although there is no evidence for this.

The complex geology of the Piedmont is exemplified in the map of Hart County, Ga. (fig. 9), where the complicated results of multistage metamorphism are well illustrated. In such terrain, the detector will often measure gamma energy from several geologic units simultaneously. Nevertheless, some correlations are seen, such as the eastern contacts of both outcrops of biotite-plagioclase gneiss; adjacent sillimanite-mica and sillimanite-graphite schist is more radioactive, locally twice as much or more. Throughout this area are numerous individual boundary correlations of aeroradioactivity and geology. In such complex terrain, $\frac{1}{2}$ - or even $\frac{1}{4}$ -mile spacing of flight lines is desirable for detailed interpretation.

VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCE APPALACHIAN HIGHLANDS, EASTERN UNITED STATES

The Valley and Ridge province is composed of many thousands of feet of Paleozoic sedimentary rocks. These strata have been folded, faulted, and eroded into long, linear, slightly arcuate valleys and ridges. In places the ridges are widely spaced or isolated; in others, so numerous and closely spaced that the valleys are discontinuous or even absent. Owing to differential erosion, the stronger sandstones and conglomerates are the ridge formers, whereas the weaker shales and limestones underlie the valleys (Fenneman, 1938, p. 195–196). The province extends in a long narrow belt from southern New York on the north to the Coastal Plain overlap in Alabama in the south. It is bordered on the east by the Piedmont and Blue Ridge provinces and on the west by the Appalachian Plateaus province. Relief in those parts of the Valley and Ridge province included in several ARMS-I surveys is not usually so extreme as to impede low-level aeroradioactivity surveying.

The linear trend of the geologic units enables many correlations with aeroradioactivity. The correlations are often made on the basis of gross lithologies, because the scintillation detector cannot distinguish between the thinner stratigraphic units. The larger stratigraphic

units which have distinctive contents of radioactive minerals are separable on the basis of their radioactivity.

The Valley and Ridge province in eastern Tennessee has numerous excellent correlations.

* * * Some radioactivity units are continuous along strike * * * [for] a distance of 100 miles. Many can be traced for 50 miles or more (Bates, 1962b, p. 41). This is particularly noteworthy considering the relatively low levels of radioactivity involved and considering that although some adjacent radioactivity units differ by only 100 cps, this difference is geologically significant. The area is also geologically complex; repeated thrust faulting has resulted in repetition and omission of beds, and units are laterally gradational within the area (Bates, 1962b, p. 33).

Figure 10 shows an area in the Valley and Ridge province around Clinton, Tenn., where there is excellent definition by aeroradioactivity of gross lithologies. Southeast to northwest across figure 10, the radioactivity units are labeled A through G. The units may constitute as many as three formations. Units A, B, D, and G are dominantly shales, and units C, E, and F are mostly carbonates. The shales have an overall range of 600 to 1,100 cps and the carbonates, 500 to 800 cps.

The traces of several thrust faults are clearly indicated by radioactivity boundaries (fig. 10). In several places, thrust faults in eastern Tennessee are traceable for tens of miles by radioactivity. Where there are different radioactive rocks on opposite sides of the fault the resulting radioactivity boundary is as distinctive as one resulting from a stratigraphic change. Faulting in uniformly radioactive rock is not detectable by aeroradioactivity.

Figure 11 shows a similar area around Athens, Tenn., where many geologic contacts are accurately defined by aeroradioactivity boundaries. However, near Clinton the change at the aeroradioactivity boundary was generally about 200 cps. Near Athens (fig. 11), the change at the boundary was only 100 cps; nevertheless, numerous boundaries are distinct linear features for many miles. In the southeast corner of figure 11, several geologic units of small areal extent are defined by radioactivity boundaries, in spite of limitations of the area of response (1,000-ft diameter) of the scintillation detector. Conspicuous within figure 11 is the close definition of several thrust faults, notably the Copper Creek, Beaver Creek, and Chestuee. The Knoxville fault, west and southwest of Athens, is in uniformly radioactive rock, mostly carbonates, and is hence not defined by radioactivity.

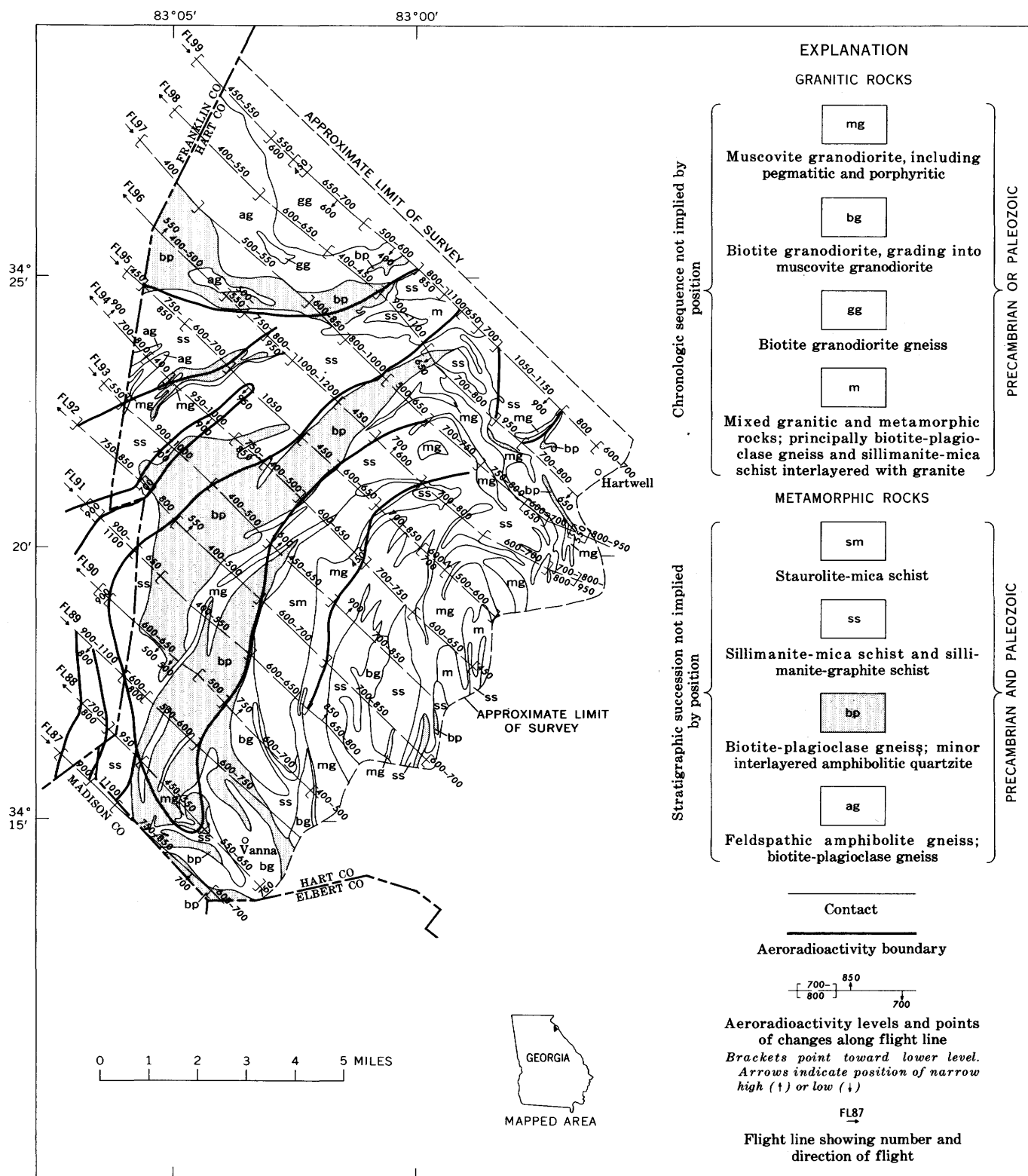


FIGURE 9.—Aeroradioactivity and geology of part of Hart County, Ga. Flight lines were flown northwest-southeast at 1-mile spacing. Modified by MacKallor (1963a, p. 25) from map by Grant (1953).

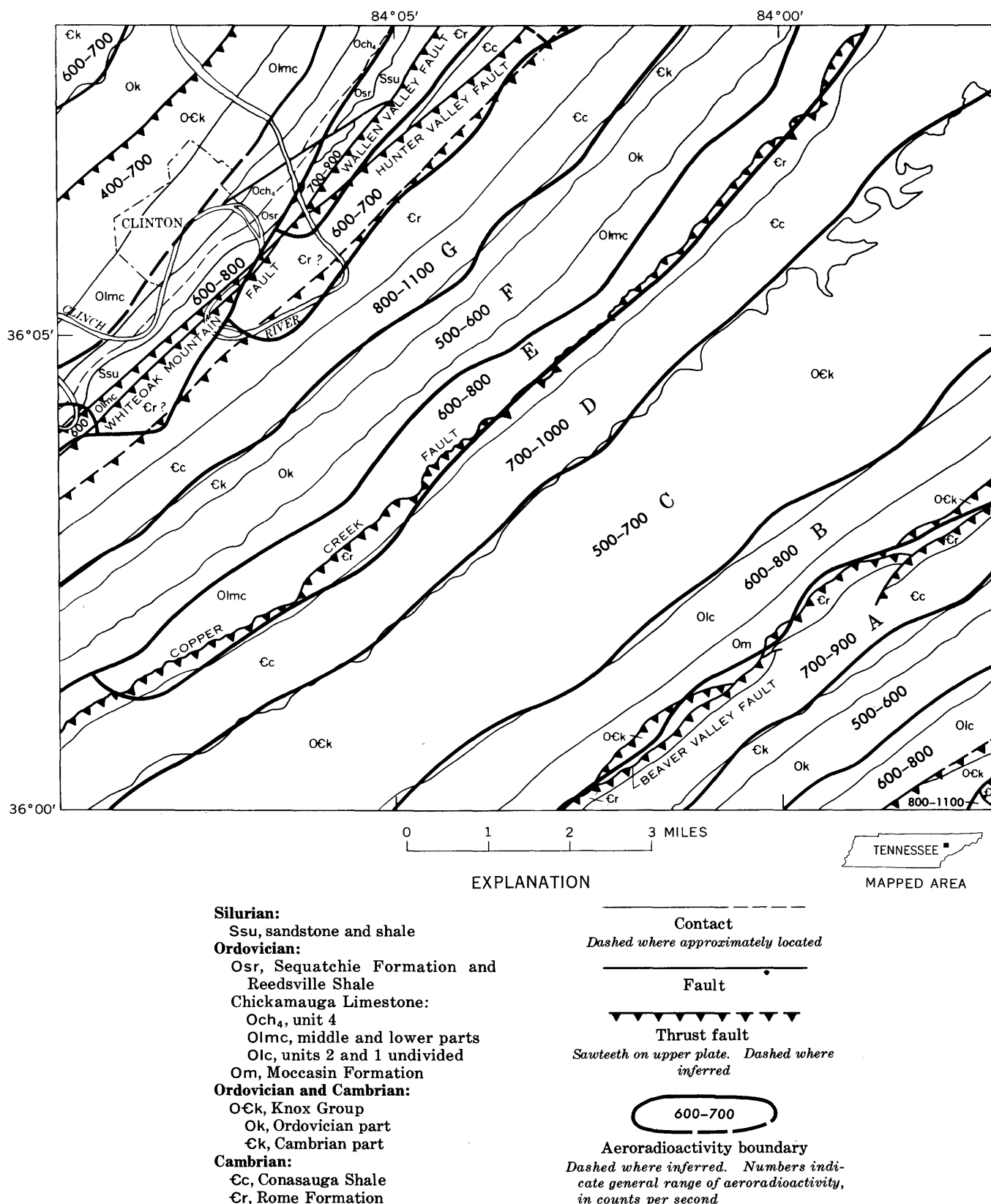


FIGURE 10.—Aeroradioactivity and geology of an area near Clinton, Tenn. Flight lines were flown northwest-southeast at 1-mile spacing. A-G, radioactivity units referred to in text. Modified by Bates (1962b, p. 36) from map by Rodgers (1953).

Figure 3 also shows an area in the Valley and Ridge province of eastern Tennessee wherein the aeroradioactivity pattern closely follows the pattern of geologic units.

In north-central Georgia (fig. 12), Valley and Ridge province, the structural setting is more complex. Several stratigraphic units, notably the Rome and Conasauga Formations (shales) and the Knox Group (carbonates), occur both here and in eastern Tennessee. Where shale and carbonate adjoin, their contact is marked by a distinct radioactivity boundary. Where shale units adjoin one another (northeast part, fig. 12), they comprise one radioactivity unit owing to their general lithologic homogeneity.

The 900- to 1,000-cps unit over parts of the usually moderately radioactive Weisner Formation and Shady Dolomite is probably anomalous (eastern part of fig. 12). Most likely the higher radioactivity results from rubble of graphite schist which bounds these sedimentary units on the other side of the nearby Cartersville fault. Despite their differing lithologies, the Weisner and Shady are not separable by differences in radioactivity, probably because rubble of the more resistant Weisner covers the adjacent Shady and gives the two formations a uniform aeroradioactivity and because they are not extensive (MacKallor, 1963a, p. 19).

The Shenandoah Valley of northern Virginia shows the same correspondence of geology and aeroradioactivity. Neuschel (1966, p. 36) stated that

Excellent defined linear radioactivity units parallel the strike of the rocks throughout the Appalachian [Shenandoah] Valley. Some of the best correlations of aeroradioactivity to geology in the area surveyed [Washington, D.C.] are found in this region. In general, low radioactivity is found over the relatively pure limestones and dolomites, and higher values over the shales and less pure limestones.

Facies changes within a stratigraphic unit are denoted by a wide range of radioactivity numbers for the unit, whereas the more homogeneous units have a smaller or narrower range of radioactivity numbers.

The numerous excellent correlations in the Valley and Ridge are where sedimentary rocks are considerably tilted. Where sedimentary rocks are virtually horizontal (such as in the Coastal Plain and the Appalachian Plateaus), correlations are few and often nebulous, as the scintillation detector has only large-scale areal features to measure. Aeroradioactivity patterns in the Appalachian Plateaus are weak and indistinct, and correlations are consequently lacking (Bates, 1962b, p. 28, 32; 1966b, p. 12-13).

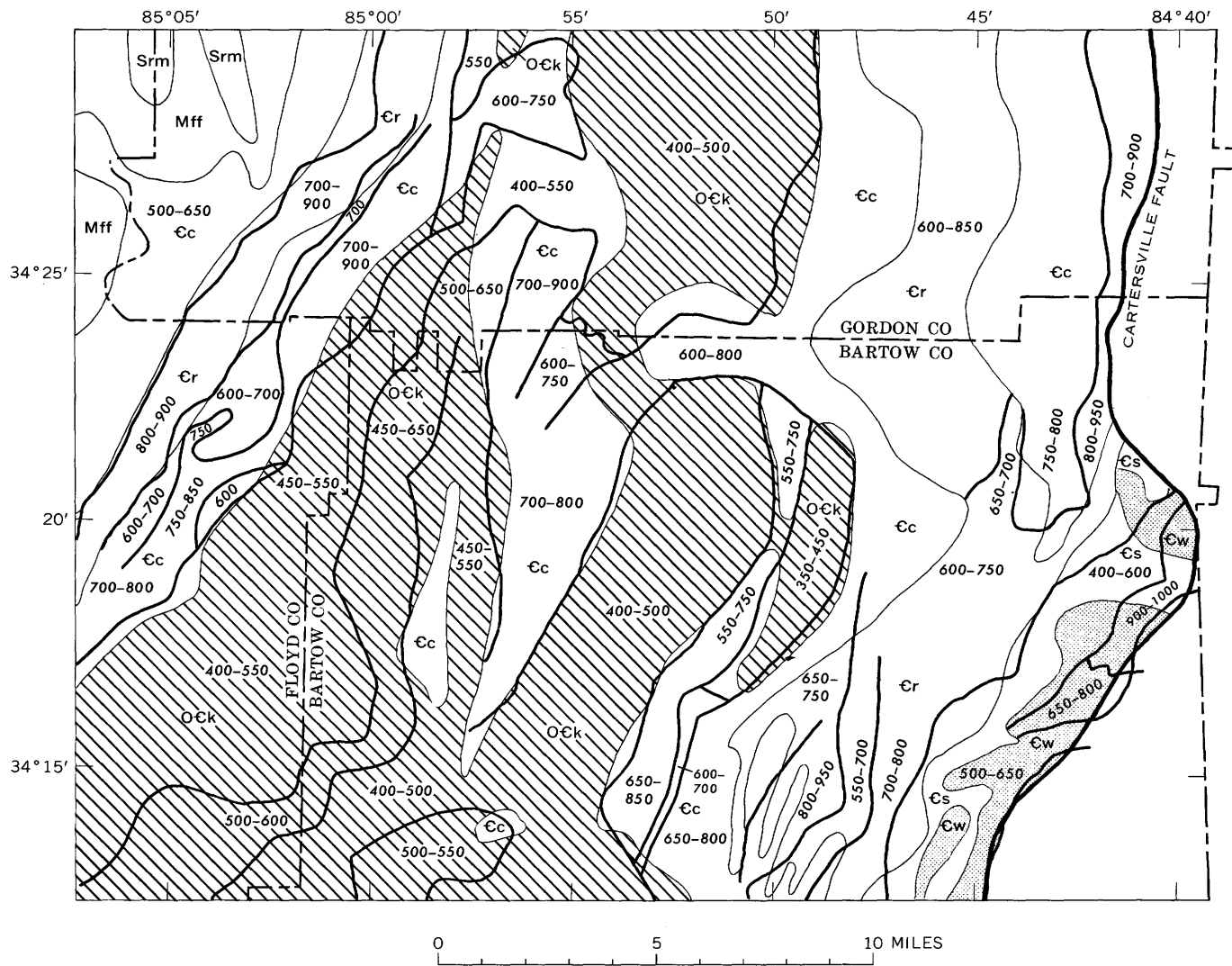
COASTAL PLAIN PHYSIOGRAPHIC PROVINCE, EASTERN, SOUTHEASTERN, AND SOUTH-CENTRAL UNITED STATES

In the Coastal Plain province the strata are horizontal or nearly so, virtually undeformed, and often only semiconsolidated, and transported soils bearing no resemblance to underlying bedrock are the common surface component. Aeroradioactivity patterns are usually discontinuous and seldom correlative to the bedrock geology. Also, the low total range of aeroradioactivity hinders interpretation. The low radioactivity is often, especially along the coasts, due to abundant marshy or swampy terrain with much included water, which absorbs most terrestrial radioactivity present. In certain conditions aeroradioactivity correlation is possible.

One such circumstance is when anomalous radioactivity in the Coastal Plain is due to concentration of radioactive minerals derived from nearby crystalline rocks. An example is seen along the Rappahannock River in Virginia, from Fredericksburg, Va., southeast toward Chesapeake Bay. A strip along the river is approximately twice as radioactive as the adjacent Coastal Plain. According to Neuschel (1966, p. 25), "It is probable that the area of higher radioactivity along the Rappahannock River is over stream valley alluvium which contains radioactive detrital material derived from the granitic areas upstream [Piedmont]." The flood plains of several rivers in South Carolina and Georgia are higher in radioactivity than the adjacent Coastal Plain, despite the swampiness and the general abundance of water. Schmidt (1962b, p. 38) made the similar hypothesis that the anomalies probably indicate transport and deposition of radioactive minerals from headwaters (in the Piedmont) to flood plains.

In the Coastal Plain of Maryland (fig. 13), correlation is possible owing to presence of the radioactive sedimentary mineral glauconite, a complex silicate of marine origin, which contains potassium. The Monmouth and Aquia Formations are glauconite sands; the other formations are mainly nonglauconitic. The Monmouth probably contains more glauconite than the Aquia, as its outcrop is slightly more radioactive than that of the Aquia (Neuschel, 1966, p. 23).

The Hawthorn Formation (Miocene) occurs in the Coastal Plain of South Carolina and Georgia. The Hawthorn is known in the subsurface for its content of uraniferous phosphatic material; hence, one might conclude that it would be readily detected by aeroradioactivity. However, at the surface, the Hawthorn did not



EXPLANATION

Mississippian:

Mff, Floyd Shale and Fort Payne Chert (includes limestone and sandstone)

Silurian:

Srm, Red Mountain Formation (ferruginous shale and sandstone)

Ordovician and Cambrian:

Ock, Knox Group (includes limestone and chert)

Cambrian:

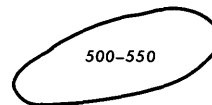
Cc, Conasauga Formation (mostly shale; some limestone)

Cr, Rome Formation (shale and sandstone)

Cs, Shady Dolomite

Cw, Weisner Formation (shale and sandstone)

Contact



Aeroradioactivity boundary

Numbers indicate general range of aeroradioactivity, in counts per second



MAPPED AREA

FIGURE 12.—Aeroradioactivity and geology in part of the Valley and Ridge province, north-central Georgia. Flight lines were flown northwest-southeast at 1-mile spacing. Modified by MacKallor (1963a, p. 20) from map by Butts (1946).

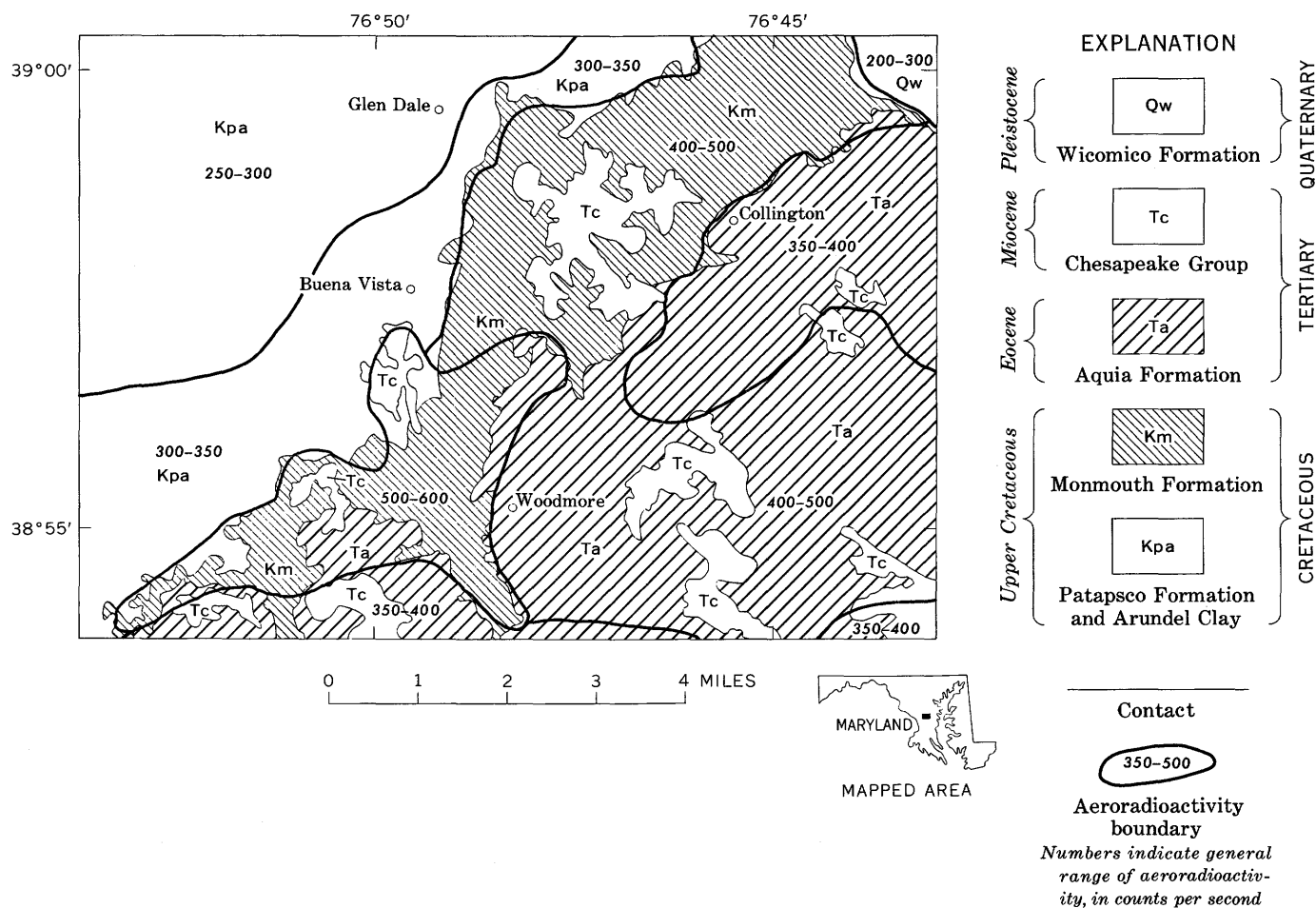


FIGURE 13.—Aeroradioactivity and geology of an area in Prince Georges County, Md. Flight lines were flown east-west at 1-mile spacing. Modified by Neuschel (1966, p. 24) from map by Cooke and Cloos (1951).

show appreciable aeroradioactivity. "It can be speculated that the surface exposures of the Hawthorn formation in the Savannah River Plant area are only weakly radioactive because the uranium has been leached from the surficial layers" (Schmidt, 1962b, p. 38).

The previous examples of Coastal Plain aeroradioactivity are concerned with the unusual rather than the usual circumstances. The basic difficulty in aeroradioactivity interpretation there is that the individual surface units as seen by the scintillation detector had no essential sameness, no integral lithologic homogeneity. The result is aeroradioactivity patterns of discontinuous nature which are nearly impossible to interpret.

In the Coastal Plain of north-central Texas, Upper Cretaceous strata in the vicinity of Dallas are not thick, yet have a broad areal expression because of their shallow dip. These units—Taylor Marl, Austin Chalk, Eagle Ford Shale, and Woodbine Sand—do have an individual

gross lithologic homogeneity which permits association of aeroradioactivity patterns with the particular units. Shale is the most radioactive, chalk the least, and sand and marl intermediate. Yet some good boundary correlations are possible in this area, especially away from the major drainage, where alluvium disrupts the correlative patterns.

To the west near Fort Worth, Lower Cretaceous strata crop out. There is lithologic variation and consequent radioactive mineral variation, but most stratigraphic units have too small an areal extent to permit separation by the scintillation detector. Figure 14 shows an area west of Fort Worth, where strata are so nearly horizontal that geologic contacts approximate topographic contours. For interpretive purposes, varying lithologic types were combined into a calcareous unit and a quartz-sand unit. This enabled some correlation with the aeroradioactivity pattern, but generally in this terrain few correlations are possible.

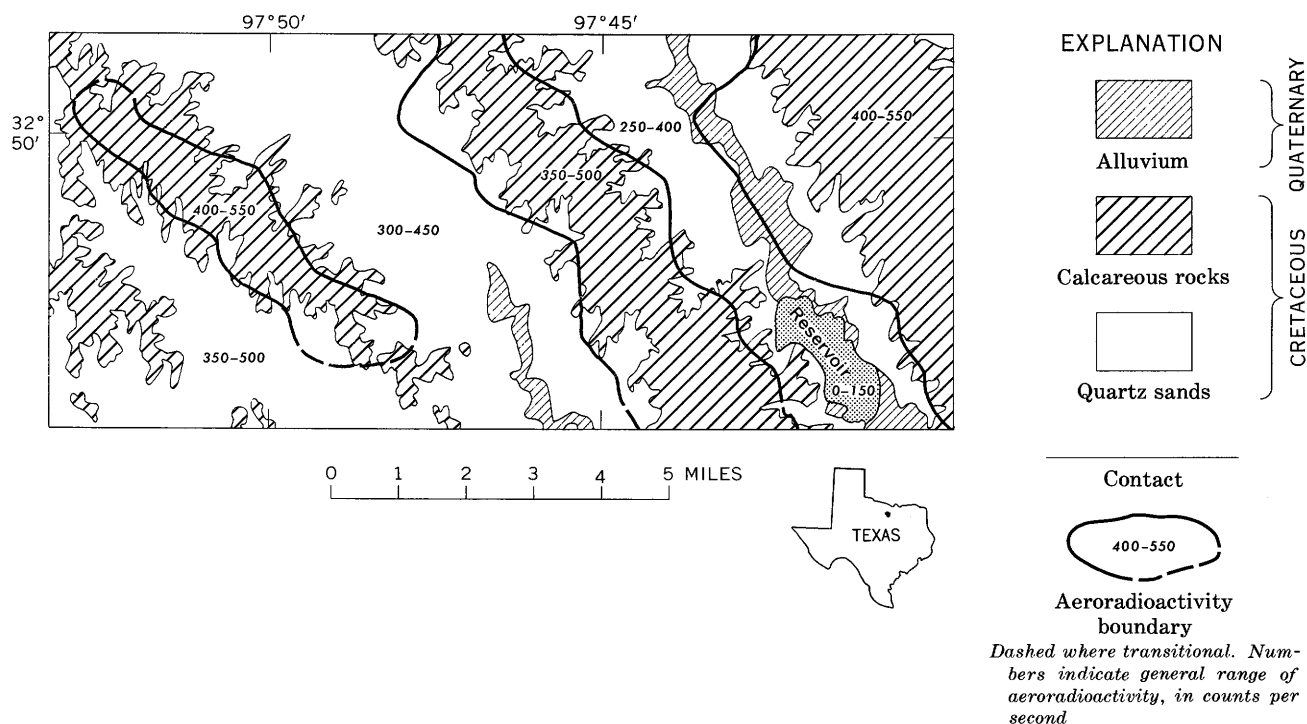


FIGURE 14.—Aeroradioactivity and geology of an area in Parker County, Tex. Flight lines were flown east-west at 1-mile spacing. Modified from map by Hendricks (1957).

COLUMBIA PLATEAUS PHYSIOGRAPHIC PROVINCE, NORTHWESTERN UNITED STATES

The Columbia Plateaus province consists of thick almost horizontal lava flows, mainly basalt. The lava at ground surface is usually bare and virtually unaltered or covered by only a very thin veneer of soil or loess. Any aeroradioactivity measurements should then reflect the true radioactivity of the rock, unaffected by surface cover. However, in part of the Columbia Plateaus the surface cover does not reflect bedrock composition, and consequently correlation is impossible.

In southern Idaho, the Snake River Plain section of the Columbia Plateaus, where the loess cover is thin or absent, exhibits excellent correlations between aeroradioactivity and geology. The basalts of the Snake River Plain show radioactivity ranging from 300 to 1,300 cps. The higher radioactivity is probably due to an increased content of potassium feldspar. The wide variation in radioactivity permits distinguishing between several flows. Common sources for some basalt flows were suggested by either their uniform or varying aeroradioactivity. The scattered rhyolites present were more radioactive (maximum 2,100 cps) and thus were easily recognized (Bates, 1964).

In southern Washington, correlative aeroradioactivity diminishes, as conditions are quite different from those in southern Idaho. Loess in thick quantities (as

much as 75 ft) masks the volcanic and sedimentary bedrock, and little of its aeroradioactivity character is determinable. Some few exposures of basalt are low to moderate in radioactivity (300–600 cps), whereas the loess itself has moderate radioactivity (500–750 cps) (Schmidt, 1962b, p. 18, 21).

GREAT PLAINS PHYSIOGRAPHIC PROVINCE, WEST-CENTRAL UNITED STATES

DENVER AREA

The Denver ARMS-I area lies in the drainage system of the South Platte River, which is within the Colorado Piedmont physiographic section of the Great Plains. The Piedmont is the dissected remnant of a great fluvial plain that once extended from the Rocky Mountains eastward to the Central Lowlands. The original mantle was unconsolidated silt with lesser amounts of sand, gravel, and locally abundant lime cement. The mantle has been destroyed to the extent that the underlying Mesozoic strata are locally deeply eroded. There is still, however, a widespread cover of eolian sand, silt, and alluvium (Fenneman, 1931, p. 11–13, 30–31).

Most of the surface material and most of the underlying Mesozoic sedimentary rocks were derived from the crystalline rocks of the Front Range of the Rocky Mountains, which are a complex assemblage of metamorphic and igneous rocks. They are comparatively

rich in potassium feldspar, as well as accessory minerals containing thorium and (or) uranium. The Denver area has the highest average aeroradioactivity of all the ARMS-I survey areas. The average is 800–900 cps; the total range is 300 to 1,400 cps. These factors have resulted in several interesting relationships between aeroradioactivity and geology (Popenoe, 1966a, p. 14–15).

The Mesozoic strata, dipping steeply to the east off the Front Range, have been differentially eroded into topographic ridges called hogbacks. Where these can be surveyed at a 500-foot terrain clearance, these hogbacks show linear patterns of radioactivity similar to those of the Valley and Ridge province. Strata underlying most of the Denver area east of the hogbacks are largely of arkosic composition (feldspar detritus), and where the eolian and (or) alluvial cover is thin enough, a good expression of their radioactive character has been obtained (Popenoe, 1966a, p. 15–25).

Most definitive in the Denver area is the outlining of the drainage pattern by aeroradioactivity. Granitic debris from the Front Range constitutes the bulk of the alluvium, and provides such a high radioactive count that the Quaternary drainage is accurately outlined by aeroradioactivity boundaries. The highest radioactivity is along and adjacent to the immediate stream course and the radioactivity diminishes toward the upland surface or interstream area. The radioactivity of the older materials (chiefly gravels) capping interstream divides is significantly lower than that of the more recent alluviums. "This lower level is probably due to the leaching and weathering, and accumulation of calcium carbonate accompanying soil development" (Popenoe, 1966a, p. 25).

Loess and dune sand are extensive on interstream areas east of the South Platte River, away from the Front Range. Where present they preclude determination of bedrock aeroradioactivity. The sand is generally moderately radioactive and some of the loess is highly radioactive; these above-average levels probably reflect derivation at long range from radioactive Front Range rocks.

GNOME AREA

In the GNOME ARMS-I area around Carlsbad, N. Mex. (Mackallor, 1965a), physiography is similar and correlative aeroradioactivity is dissimilar. There is no source area of radioactive rock within or adjoining the GNOME survey area, and this lack is reflected by low to moderate (100–600 cps) radioactivity. Few boundary correlations were possible, although some correlation of radioactivity level with type of surface material was made. The area is characterized by alluviated plains

which represent mixtures of minerals from various sedimentary rocks of generally low to moderate radioactivity. The mixing of radioactive minerals means that the radioactivity measured is rarely representative of a single rock type, and thus correlation is seldom possible.

Two playas (dry lakes) in the GNOME area were distinguishable by aeroradioactivity because they were 100–200 cps higher than the adjacent area. The anomalies probably represent concentration through evaporation of radioactive minerals, most likely potassium salts (MacKallor, 1965a, p. 27). Detection of two of the many playas in the GNOME area was probably fortuitous, as all are small and the area was surveyed on a combination of 1- and 2-mile-spaced flight lines.

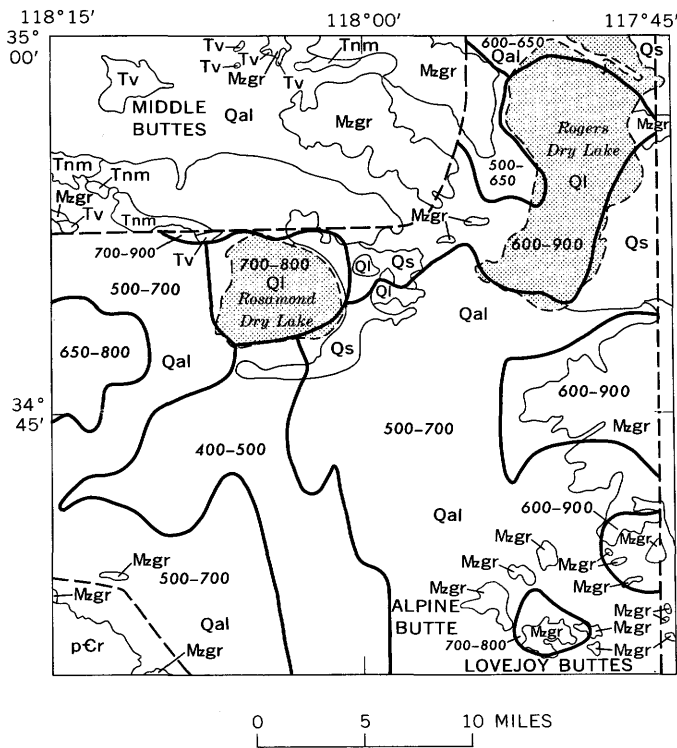
An aeroradioactivity survey at 1/8-mile spacing around the immediate GNOME test site indicated that detailed data would provide correlative information in desert terrain despite generally low radioactivity. Distinction was made between several Quaternary units and between the Quaternary and red beds of Permian and Triassic age (W. J. Dempsey, written commun., 1963).

PACIFIC BORDER PHYSIOGRAPHIC PROVINCE, WESTERN UNITED STATES

The Pacific Border province consists of a series of coastal mountains on the west and an eastern series of valleys. Topographic relief in the mountains usually precludes aeroradioactivity surveying, and thus most of the San Francisco and Los Angeles ARMS-I surveys were restricted to valley and (or) lowland areas. Where data were obtained in the Coast Ranges, mostly north and east of San Francisco Bay, correlation is lacking because of (1) discontinuity of geologic outcrops and (2) relief greater than 1,000 feet. There is variation in radioactivity due to variation in type of rock, but still correlation is lacking (Books, 1962a, 1966).

The valleys and lowlands are mantled by detritus (clay, sand, gravel) from varied rock types. Definite correlation is possible only where bedrock is exposed, at valley margins, or where bedrock controls soil types, residual or transported. In marshy areas or near bays, the abundant water effectively masks most of the radioactivity. With several exceptions of gross correlations with igneous rock-derived soil, correlative data are nearly totally lacking (Books, 1966, p. 14–22).

Figure 15 shows the western end of the Mojave Desert of southern California, where radioactivity delineated Rosamond and Rogers dry lakes. These are probably similar in sedimentologic origin to the playas of New Mexico (see Great Plains discussion), although the Mojave playas are slightly higher in contrasting radio-



EXPLANATION

Quaternary:

- Qal, alluvium
- Ql, lake deposits
- Qs, eolian sand

Tertiary:

- Tnm, nonmarine rocks
- Tv, volcanic rocks

Mesozoic:

- Mzgr, granitic rocks (mostly of Mesozoic age)

Precambrian(?):

- pCr, gneiss and schist

Contact

Limit of aeroradioactivity survey

700-800

Aeroradioactivity boundary

Numbers indicate general range of aeroradioactivity, in counts per second



MAPPED AREA

activity. Most likely the waters that were caught and then evaporated in the playa carried radioisotopes, either in solution or as detritus. The mode and character of the radioisotopes being unknown, potassium salts are the most likely assumption (Books, 1962a, p. 21). The higher radioactivity in the western Mojave is mostly related to granitic rock exposures, but correlations are vague and discontinuous.

GLACIATED TERRAIN, MIDWESTERN AND NORTHEASTERN UNITED STATES

Parts of five ARMS-I surveys lie within the limits of Pleistocene glaciation. These are (fig. 1, table 1) Minneapolis-St. Paul (all), Chicago (all), Columbus (part), Pittsburgh (part), and northeast United States (all). The correlative value of the ARMS-I data varies from slight or even nil for the first-named four areas, all within the so-called midwestern United States, to appreciable for the northeastern United States (New England plus southeastern New York).

Bedrock in glaciated terrain is nearly everywhere obscured by debris called glacial drift. Drift has a great variation in grain size, from clay to boulders, and in lithology, provenance, and thickness. Even though most drift has not been carried far from the rock from which it was derived, a matter of several tens of miles or less, in the Midwest any lithologic or other resemblance of drift to underlying bedrock is fortuitous. In west-central Ohio, for example, " * * * the glacial deposits are mixtures of material derived almost wholly from local bedrock sources which * * * [mostly] have similar radioactivity levels" (Bates, 1966a, p. 18). The result is heterogeneous surface material with a generally homogeneous aeroradioactivity.

In addition, the upper Midwest is blanketed by varied thicknesses of loess, which is interbedded with or overlies drift. Drift and associated loess are so extensive and thick as to negate determination of bedrock aeroradioactivity. The aeroradioactivity measured in the Midwest was that of the drift and loess whose lithology is characteristically so heterogeneous that any correlation of these geologic units with aeroradioactivity is seldom accomplished.

FIGURE 15.—Aeroradioactivity and geology of part of the western Mojave Desert, southern California. Flight lines were flown north-south at 1-mile spacing. Modified by Books (1962a, p. 18) from map by Kundert (1955) and information provided by T. W. Dibblee, Jr. (U.S. Geol. Survey, written commun., 1961), and California Division of Mines (unpub. data, San Bernardino 2° sheet).

Correlation can be accomplished when the glacial feature is of homogeneous character, such as a large area of sand dunes or sand plains, which resulted from winnowing of debris by proglacial streams in an outwash plain. One is the Anoka sand plain, north of Minneapolis-St. Paul, Minn. (U.S. Geol. Survey, 1962, p. A25). Another is the area of glacial Lakes Waubesa and Watseka south and southwest of Chicago, Ill. (U.S. Geol. Survey, 1962, p. A25). These areas are principally quartzose sand at the surface, and their extent and boundaries are well defined by characteristic low radioactivity (100–200 cps). In the general Minneapolis-St. Paul area (exclusive of the sand plain), elongate areas having low radioactivity suggest the location of former drainage courses and the past existence of many more lakes (U.S. Geol. Survey, 1965, p. A82).

As previously mentioned, correlation is effective in the northeastern United States, all of which was glaciated during the Pleistocene. Bedrock in the northeast is mostly of metamorphic and igneous origin. A thinner cover of glacial drift, because of the less readily eroded rocks, and a greater variation in radioactivity combine to make aeroradioactivity measurement more useful.

Loess—the major factor in the lack of correlation in the Midwest—is virtually absent in the northeast, where relief is somewhat greater, sand is more abundant than clay and silt (which constitute loess), and the climate is moist-continental rather than steppe (Flint, 1957, p. 189). “The greater moisture, forest cover, and lower wind velocities of the moist-continental climate operate to reduce surficial drying of the outwash in preparation for deflation” (Flint, 1957, p. 189).

Also greatly aiding correlation in the northeast is the fact that about 90 percent of the glacial debris was locally derived; the detritus is identical with the underlying bedrock or with the bedrock a short distance to the north. This local origin is reflected in the aeroradioactivity data: the smaller geologic units are not identifiable on the basis of aeroradioactivity, but the larger geologic units are distinguished for many miles along strike by their characteristic aeroradioactivity. Sharp boundary correlations are rare, because the material overlying geologic contacts is intermingled detritus from adjacent units, which precludes any abrupt changes in aeroradioactivity. The resistant bedrock has generally resulted in thinner drift cover on ridgetops or highland areas, which permits correlations that are not possible over the more thickly filled valleys or lowland areas.

The northeastern United States ARMS-I survey encompassed 28,000 square miles. Some of the numerous correlations (Popenoe, 1964b; 1966b) are exemplified

in figure 16, which shows an area in the eastern New England Highlands where distinctive low radioactivity (generally 150–400 cps) is associated with rocks of the Oliverian Plutonic Series. Higher radioactivity is associated with the Kinsman Quartz Monzonite and the surrounding volcanic rocks. Though only a few boundary correlations are shown, the association of areal radioactivity units with areal geologic units is well demonstrated. Such association is very noteworthy on the small-scale aeroradioactivity maps of the northeastern United States (Popenoe, 1964a; 1966c). In addition, the radioactivity lows due to swamps and lakes in glaciated terrain must be ignored while attempting any correlation with bedrock geology. The published maps show all sizable bodies of water as 0 cps (Popenoe, 1964b; 1966b).

PUERTO RICO

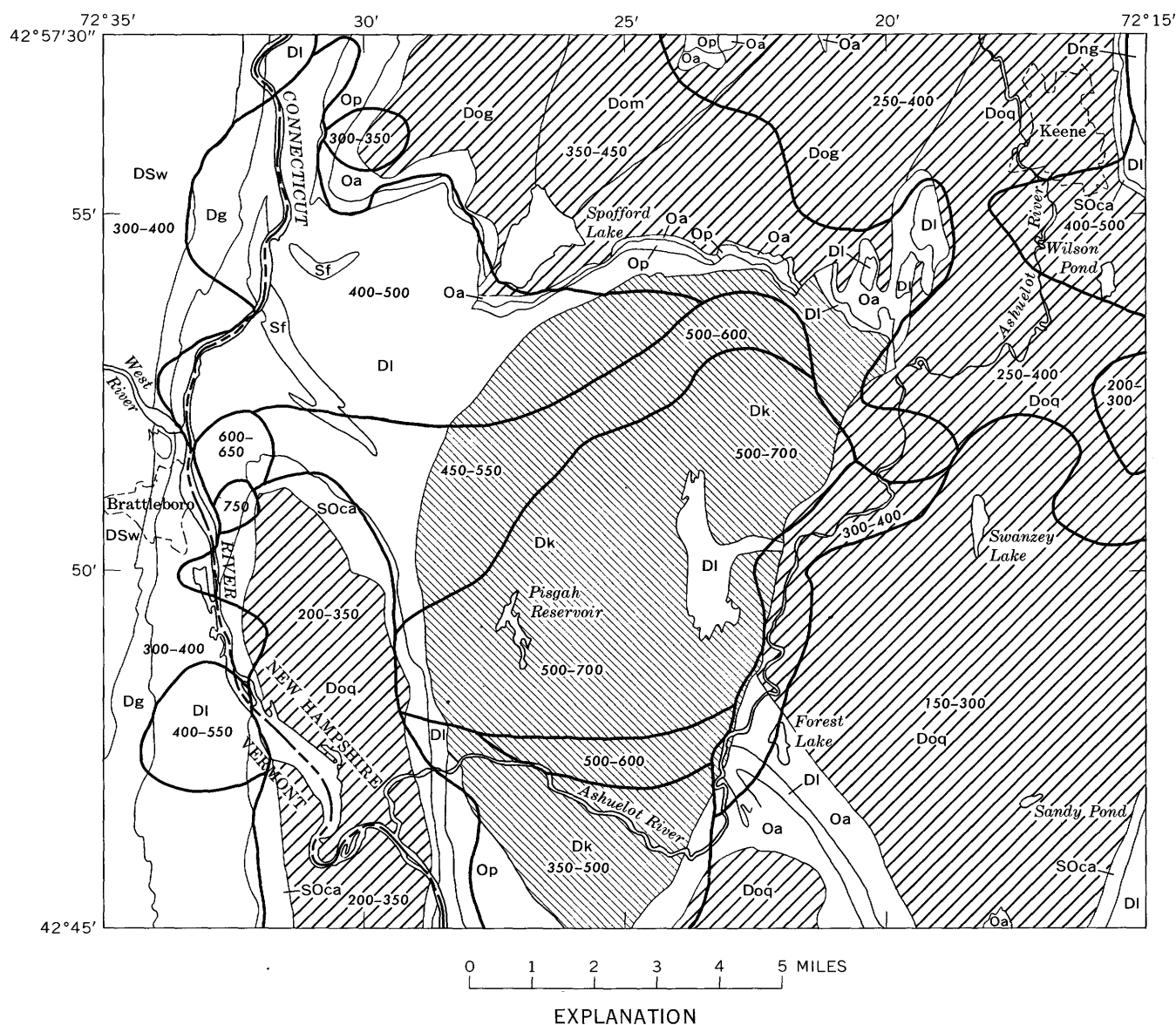
Puerto Rico is composed of a central east-trending backbone of clastic sedimentary rocks composed chiefly of andesitic detritus and several granodiorite plutons and bodies of serpentinite. This backbone is flanked by north- and south-dipping carbonate strata, chiefly limestones. These dominantly nonradioactive rocks provide a moderate range of aeroradioactivity, 50 to 800 cps; the range is only 50 to 300 cps for more than 75 percent of the island. The andesitic backbone is slightly more radioactive than the calcareous flanks (MacKallor, 1966, p. 13).

The extreme relief of the mountainous central backbone required that the flight lines be oriented east-west, paralleling the dominant topography and the strike of most rock units. The relief is mostly more than 1,000 feet, which negates effective detection of terrestrial radioactivity. These factors are responsible for the general lack of boundary correlations.

USE OF AERORADIOACTIVITY MEASUREMENTS IN CONJUNCTION WITH OTHER GEOPHYSICAL METHODS

Of the common geophysical methods, only those that can measure ground-surface phenomena can be used in complementary interpretation with aeroradioactivity. Seismology and gravimetry deal almost exclusively with thick sections of rock that rarely have surface expression. Electromagnetic measurements and total field magnetic measurements can, on occasion, be related to the ground surface and then be interpreted in conjunction with aeroradioactivity.

Electromagnetic methods are fundamentally different from radioactivity, magnetic, and gravity methods in that an artificial source of energy is employed. The source of energy is an alternating magnetic field which induces eddy currents in conductive earth materials. The eddy currents, in turn, set up secondary fields

**Devonian(?):**

- Dk, Kinsman Quartz Monzonite
- Dng, binary granite of New Hampshire Plutonic Series
- Oliverian Plutonic Series:
- Doq, quartz diorite
- Dog, granodiorite
- Dom, quartz monzonite

Devonian:

- DI, Littleton Formation
- Dg, Gile Mountain Formation

Devonian and Silurian:

- DSw, Waits River Formation

Silurian:

- Sf, Fitch Formation
- Sc, Clough Formation

Silurian and Ordovician:

- SOca, Clough Formation and Ammonoosuc Volcanics undivided

Ordovician:

- Op, Partridge Formation
- Oa, Ammonoosuc Volcanics

Contact

250-400

Aeroradioactivity boundary

Numbers indicate general range of aeroradioactivity, in counts per second

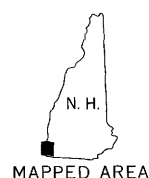


FIGURE 16.—Aeroradioactivity and geology of part of the Keene and Brattleboro quadrangles, New Hampshire and Vermont. Flight lines were flown east-west at 1-mile spacing. Modified by Popenoe (1964b, p. 20) from Billings (1956), Doll, Cady, Thompson, and Billings (1961), and Moore (1949).

which can be measured on the ground or from an aircraft. The intensity and direction of these secondary fields depend on the conductivity and distribution of conductive material within the earth. Airborne electromagnetic measurements are responsive to conductive material at depths as great as about 300 feet and are most commonly used in exploration for sulfide ore bodies. Airborne electromagnetic data can be expected to correlate with aeroradioactivity data when the material at the surface is representative of the materials within tens or hundreds of feet of the surface.

The Geological Survey aircraft is equipped with a fluxgate magnetometer, and aeromagnetic data are nearly always obtained concurrently with any surveying at 500 feet for aeroradioactivity. The magnetometer measures variations in the total intensity of the earth's field, which are related to rocks that may or may not be at ground surface. Where sedimentary rocks are at the surface and the magnetic rocks are buried, magnetic data are generally uncorrelatable with surface geology; where metamorphic or igneous rocks are at the surface, magnetic measurements can be used in conjunction with aeroradioactivity data.

Two combined aeroradioactivity-aeromagnetic interpretations have been made in the Piedmont of the eastern United States, where the magnetic rock is usually at ground surface. One area is in Montgomery County, Md., within the ARMS-I survey area but flown prior to that survey. Airborne data were obtained on 1/4-mile-spaced lines, and gravity coverage was obtained. Serpentinities are accurately indicated by radioactivity lows and magnetic highs, whereas gabbros are radioactivity lows and magnetic lows, bordered by highs. The country rock is micaceous quartzofeldspathic schists of the Wissahickon Formation, within which radioactivity and magnetic trends often correspond and prove very useful to the mapping geologist (Griscom and Peterson, 1961).

Another area is the Concord quadrangle of North Carolina, where mapping of characteristic Piedmont geology is well aided by geophysical methods. The most striking feature in the quadrangle is a ring structure composed of two arcuate masses of syenite which partly surround a large gabbro body. The ring structure has distinct radioactivity and magnetic characteristics which helped to define field relationships. The geophysical data also permitted more accurate delineation of some small granite bodies, by indicating lithologic differences and by giving better knowledge of surface extent (radioactivity) and subsurface configuration (magnetics) in this area of sparse outcrops and thick, abundant residual soils. Several granites were discov-

ered by means of geophysical data (Bates and Bell, 1965).

Aeromagnetic measurements can also be made at elevations greater than 500 feet above ground. The usual technique, particularly in rugged areas, is to fly at some given barometric elevation above sea level that permits easy and safe clearance of ground obstacles. The greater altitude attenuates the intensity of magnetism measured because of the increased distance between the aircraft and the magnetic rock. Aeroradioactivity measurements attempted at more than 1,000 feet above ground effectively measure only cosmic radiation; effective aeroradioactivity surveying is limited to areas that can be surveyed at 100-900 feet above ground. Aeromagnetic surveying is, then, much more versatile as it can be accomplished in any topographic region.

EVALUATION OF THE METHOD—CORRELATION OF AERORADIOACTIVITY MEASUREMENTS WITH AREAL GEOLOGY

Numerous examples of the correlations of aeroradioactivity measurements with areal geology have been presented. The ideal conditions are low to moderate topography, material at ground surface that reflects bedrock composition, and bedrock lithologies that vary in gross radioisotope content. Such ideal conditions are comparatively rare, and the use of aeroradioactivity in less than ideal conditions must be considered.

Topography is a constant, not a variable, factor. The aircraft must be able to safely average 500 feet above ground surface; if this is not feasible, aeroradioactivity surveying cannot be accomplished.

The material at ground surface as seen by the scintillometer, for any determination of bedrock aeroradioactivity, must in some way reflect bedrock composition. Also, there must be gross radioisotope variation at ground surface that results in aeroradioactivity variation. Distinct patterns of aeroradioactivity, though not absolutely necessary, simplify interpretation. A relative blandness or uniformity of gross radioisotope content greatly complicates effective correlation. Correlation also requires some reasonable geologic explanation for radioisotope variation. If the interpreter cannot explain radioisotope variation, awareness of such variation will not aid geologic mapping.

No attempt has been made to assign actual values in counts per second to general rock types, as has been accomplished with laboratory-derived parts-per-million and percent numbers in table 2, because the counts per second for a given rock type differ too much for reasonable usage. This report has emphasized (1) the relative change in count-per-second numbers from unit to unit, and (2) the pattern of aeroradioactivity as related to the pattern of areal geology. Specific count-

per-second numbers are important in many circumstances, but the magnitude of the change and the pattern thereof are more definitive parameters.

Aeroradioactivity surveying can be both an aid to geologic mapping and a combined tool in geophysical exploration. The relative usefulness has a wide variance, being dependent on many geologic factors. Once the possibility of flying over an area at low elevations has been established, the area should be assessed by varied geologic criteria to establish the feasibility of surveying. Prior assessment is essential, because airborne geophysical surveying is rather expensive and should be carefully planned. To provide greater scientific return for money expended, an aeroradioactivity survey can be done concurrently with aeromagnetic or electromagnetic surveys.

AIRBORNE GAMMA-RAY SPECTROMETRY

A recent development in geophysical exploration has been the adaptation of gamma-ray spectrometer systems for airborne use. Such equipment enables the determination of the relative contributions of uranium and thorium daughters and potassium to the total field of terrestrial radioactivity.

Gamma-ray spectrometers have been in use for some time in the laboratory (Hurley, 1956; Crouthamel, 1960; Mero, 1960; Adams, 1964). Spectrometers have recently been used in the field, where they were hand carried (Adams and Fryer, 1964; Wollenberg and Smith, 1964) or mounted in a truck (Moxham and others, 1965). The fact that these systems utilize the scintillation method in conjunction with pulse-height analyzers permits delineation of gamma-ray energies. Advances in the manufacture of large crystals and in solid-state electronics have permitted their use in airborne geophysical exploration.

The Geological Survey is at present calibrating and flight testing an airborne gamma-ray spectrometer system. The detector for the system will consist of two 11½- by 4-inch thallium-activated sodium iodide crystals. Gamma energy measured by the detector will be processed into both digital and analog form. The digital system will include a 400-channel pulse-height analyzer and a magnetic tape recorder. The analog system will consist of four single-channel analyzers and associated circuitry. Three of the single-channel analyzers will be gated for two high-energy daughter products of uranium and thorium and for potassium-40. The fourth analyzer will be gated to record total radioactivity, counting essentially the same spectrum as, and being analogous to, the compensated circuit of the ARMS-I instrumentation. It will then be possible to

relate ARMS-I data to those obtained by the new instrumentation.

The effectiveness of total count aeroradioactivity as a viable aid to geologic mapping has been demonstrated; the determination of the relative amounts of natural radioisotopes will be an even more valuable contribution of exploration geophysics.

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Geophysical Field Investigations, 1964-67

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