Geology and Mineralogy

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

AN INVESTIGATION OF AIRBORNE RADIOACTIVITY ANOMALIES IN THE ROCK CORRAL AREA, SAN BERNARDINO COUNTY, CALIFORNIA

By

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August 1953

Trace Elements Investigation Report 380

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

USGS - TEI-380

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AN INVESTIGATION OF AIRBORNE RADIOACTIVITY ANOMALIES IN THE ROCK CORRAL AREA, SAN BERNARDINO COUNTY, CALIFORNIA

By R. M. Moxham, G. W. Walker and L. H. Baumgardner

ABSTRACT

The investigation in the Rock Corral area was undertaken to determine the relationship between 1) the anomalously high radioactivity recorded during an airborne survey and 2) the distribution and mineralogic mode of occurrence of radioactive material.

Thorium-bearing minerals occur in relatively small, highly radioactive biotite-rich inclusions in a porphyritic quartz monzonite. Radioactive accessory minerals are also disseminated in the porphyritic quartz monzonite and in detritus derived from the porphyritic quartz monzonite. The configuration and amplitude of the major airborne radioactivity anomalies indicate that they have resulted chiefly from the large masses of porphyritic quartz monzonite rather than the biotite-rich inclusions.

An analysis of the amplitude of the radioactivity anomalies in the Rock Corral area and the equivalent uranium content of the source rocks indicates that the lower limit of sensitivity of the airborne equipment, with regard to geologic units of extent and tenor comparable to those in the Rock Corral area, is probably 0.001 percent.

INTRODUCTION

The investigation here reported was undertaken to determine the relationship between 1) the anomalously high radioactivity detected during an airborne survey and 2) the distribution and mineralogic mode of occurrence of radioactive material in an area of about 1 3/4 square miles near Rock Corral, San Bernardino County, Calif. (fig. 1). A secondary objective was to determine whether the concentrations of radioactive minerals might constitute potential sources of thorium or uranium. A brief summary of events leading to the present investigation is given below.

In 1949, prospectors discovered in the vicinity of Rock Corral a number of small masses of rock containing thorium-bearing minerals. In early 1952, preliminary reconnaissance examinations of the known occurrences and adjacent areas by D. F. Hewett, G. W. Walker, and L. H. Baumgardner of the U. S. Geological Survey indicated that some biotite-rich inclusions in plutonic rocks exposed in the Rock Corral area contained concentrations of radioactive minerals. An airborne radioactivity survey seemed desirable to prospect for additional biotite-rich inclusions or other concentrations of the radioactive materials. In March 1952, an airborne radioactivity survey of about 80 square miles in the vicinity of Rock Corral (fig. 2) was made by the Geological Survey (Moxham, 1952). The airborne survey determined that 1) anomalous radiation intensity, which was recorded in many parts of the area, was concentrated principally in four localities lying to the east and southeast of Rock Corral, and 2) some of the anomalies were of the greatest amplitude recorded by the airborne equipment over natural sources. One of the four areas mentioned above

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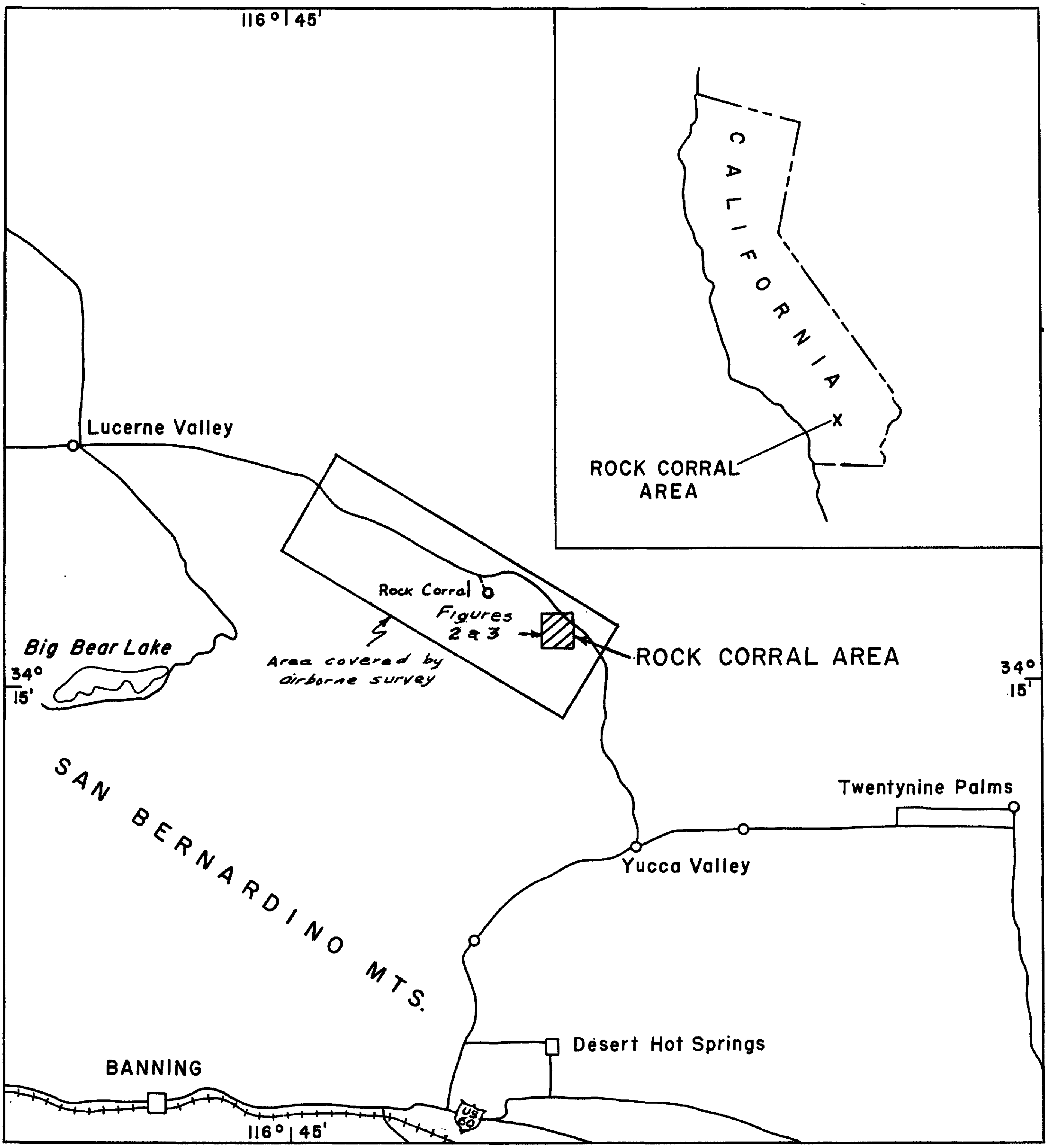

Figure 1. Index map of the Rock Corral area, San Bernardino County, California

5 0 5 10 15 MILES

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includes the anomaly of greatest peak intensity recorded in the Mojave Desert region, as well as several lesser anomalies, and for that reason was selected for the detailed study on the ground.

The investigation, made in June 1952, consisted of detailed geologic mapping of an area of approximately 1 3/4 square miles, hereafter referred to as the Rock Corral area. A radioactivity survey on a 300-foot grid was made in a selected portion of the area (fig. 3), and the various rock types exposed in the area were sampled for petrographic study and for analyses of their equivalent uranium content. This work was done on behalf of the Division of Raw Materials of the Atomic Energy Commission.

Location of the area

The Rock Corral area described in this report is in San Bernardino County, Calif., 50 miles east-northeast of San Bernardino. The mapped area is at the southeast end of the San Bernardino Mountains, on the southern edge of the Mojave Desert. Most of the area is in secs. 4 and 9, T. 2 N., R. 5 E., San Bernardino meridian, though a part extends into sec. 5 and part may extend into sec. 8. Rock Corral, which is located at one of the few permanent springs in the area, lies 5 miles to the northwest of the center of the area mapped.

STRATIGRAPHY

No previous geologic mapping has been done in the area described in this report, although reconnaissance mapping by Vaughn (1922) in an extensive area a few miles to the west and southwest has established a background adequate for a discussion of the geologic environment of the radioactive minerals. The Rock Corral area is geologically similar to the area mapped by Vaughn and to other areas in the western Mojave Desert. In these adjacent areas the plutonic rocks, which intrude pre-Cambrian metamorphic rocks, are divided by Vaughn into "heterogeneous plutonic rocks" of undetermined age and a younger intrusive called the Cactus granite of Upper Jurassic age. 1/

1/ According to D. F. Hewett, U. S. Geological Survey, recent studies indicate the intrusive rocks named Cactus granite by Vaughn are probably Cretaceous rather than Upper Jurassic in age. Oral communication, December 1951.

Pre-Cambrian rocks

Metamorphic rocks of pre-Cambrian age are exposed predominantly in the northeast and east part of the mapped area (figs. 2 and 3) and consist of biotite gneiss, siliceous metasediments, and dark colored, intercalated recrystallized metavolcanics (?). The metamorphic rocks are contorted and intricately intruded by porphyritic quartz monzonite of pre-Cretaceous age and are commonly recrystallized adjacent to contacts with the quartz monzonite. Numerous apophyses and small separate masses of contaminated quartz monzonite occur in these recrystallized zones. Some of the recrystallized metamorphic rocks and the contaminated quartz monzonite are similar megascopically, and in many localities the various petrographic types are so intricately related as to preclude mapping as individual units. They have been grouped, therefore, into a single unit labelled igneous and metamorphic complex (figs. 2 and 3).

Pre-Cretaceous rocks

The pre-Cambrian rocks have been intruded by pre-Cretaceous quartz monzonite, buff to gray in color, which in detail varies considerably in texture and composition; in most places the rock is porphyritic, containing alined, but erratically distributed, orthoclase phenocrysts in a medium-grained groundmass. An average sample of the quartz monzonite contains orthoclase (about 40 percent), plagioclase that ranges in composition from oligoclase to calcic andesine (about 30 percent), quartz (about 20 percent), biotite (3 to 5 percent), small amounts of magnetite, allanite, apatite, zircon, muscovite, fluorite, and minor amounts of many other accessory minerals. Chlorite, derived from biotite, is present in small amounts, and most of the feldspar has either been sericitized or saussuritized. Locally, as in the southwest part of the area, the orthoclase phenocrysts predominate over the groundmass, and the quartz monzonite contains only sparse mafic and accessory minerals. In other outcrops, the mafic and accessory minerals are unusually abundant.

Near contacts with the pre-Cambrian metamorphic rocks, the quartz monzonite contains numerous, metasomatically altered biotite-rich inclusions of wall rock. These inclusions vary in shape and size from nearly equidimensional masses as much as 20 feet in diameter to 50-foot tabular plates, which may represent reconstituted sections of sedimentary beds. Some inclusions, or small roof pendants, are gray mica schist and others are non-foliated black masses composed of 80 to 90 percent biotite, minor amounts of andesine, magnetite, allanite, sphene, apatite, and zircon. The term contaminated quartz monzonite is used below to designate those occurrences of quartz monzonite containing substantial quantities of wall rock.

Parts of the Rock Corral area are underlain by a fine-grained, intrusive (?) crystalline rock with a texture and composition like the groundmass of the porphyritic quartz monzonite. The fine-grained rock contains no orthoclase phenocrysts, sparse accessory minerals except for biotite, and is commonly more strongly foliated than the quartz monzonite. Locally, contacts between the quartz monzonite and the fine-grained rock are sharp, whereas in other areas, contacts appear to be gradational; probably the fine-grained rock represents an early phase of quartz monzonite intrusion, perhaps correlative with the porphyritic quartz monzonite. Small intrusive bodies of quartz-feldspar pegmatite, which are probably genetically related to the quartz monzonite, occur in areas underlain by the igneous and metamorphic complex and the pre-Cambrian metamorphic rocks.

Cretaceous rocks

Cactus granite

The Cactus granite, which is younger than the porphyritic quartz monzonite, intrudes both the pre-Cretaceous quartz monzonite and the pre-Cambrian metamorphic rocks. On the west edge of the area, in a typical exposure, the granite is uniformly coarse-grained, light-gray, and composed of orthoclase, andesine, quartz and minor amounts of biotite, magnetite, chlorite, muscovite, zircon, apatite, sphene, and allanite. The plagioclase and orthoclase may be present in equal amounts, though commonly the plagioclase predominates; according to some rock classifications the rock would be named a quartz monzonite rather than a granite.

Numerous fine-grained felsic sills and dikes extend from the main granite body into the older rocks. The texture and composition of the sills and dikes near the main intrusive mass are identical with the Cactus granite, but at localities more remote from the main mass these apophyses are commonly very fine-grained, locally porphyritic and resemble dacite. A few of the fine-grained dikes, which cannot definitely be correlated with the Cactus granite, may possibly be Tertiary volcanic intrusive rocks, but in this report all of them are grouped with the Cactus granite.

Tertiary and Quaternary rocks

Small remnants of a Tertiary olivine basalt flow are exposed in the southwest part of the area.

Parts of the area adjacent to the dry washes are covered by Quaternary bench gravels or slope wash. The washes and valleys of the area are floored with Recent alluvium.

STRUCTURE

The dominant faults trend northwest and dip at steep angles both east and west. Although the regional structure is poorly known, it is believed that some of the northwest-trending faults in the Rock Corral area are extensions of normal faults which other workers have mapped along the northeast edge of the San Bernardino Mountains; the movement on these faults has dropped the valley, or northeast block, down in relation to the mountain, or southwest block. Some of the northwest-trending faults may have existed before the intrusion of the porphyritic quartz monzonite, though recurring movement along these, or later parallel faults, has displaced masses of Cactus granite and possibly also displaces the Tertiary olivine basalt. A second set of faults, which trends northeast, locally offsets the northwest faults; some of the northeast faults are, in turn, displaced by northwest faults. Many of the zones of rupture are filled with intrusive Cactus granite or by a fine-grained, dacite-like rock comparable to the Cactus granite.

OCCURRENCE OF RADIOACTIVE MINERALS

Petrographic studies of 18 samples of the various rock types in the area indicate that a variety of radioactive accessory minerals is present. Significant concentrations of these accessory minerals occur in metasomatically altered, biotite-rich inclusions in the quartz monzonite, in porphyritic quartz monzonite, and in detritus deposited in washes that drain outcrop areas of the porphyritic quartz monzonite. Not all outcrops of the rock types mentioned above, however, contain significant concentrations of the radioactive accessory minerals.

The minerals responsible for the radioactivity of the various rock types were for the most part identified either by means of radioactivity measurements of relatively pure fractions of a particular mineral, or the presence of pleochroic halos around a particular mineral species. Some accessory minerals such as monazite (?) and xenotime (?) were present in such small quantities that it was not possible to separate a pure fraction for radioactivity tests nor were they found in association with biotite. There is little doubt, however, that such minerals do contain radioactive elements and have contributed to the total radioactivity in the Rock Corral area.

The radioactive minerals that have been identified include allanite, zircon, apatite, sphene, monazite (?), and xenotime (?). Allanite is the principal source of the anomalous radioactivity in the Rock Corral area.

Eight samples representative of each of the four major lithologic types in the area were collected for determination of equivalent uranium content. Each bedrock sample consisted of fresh chips collected at approximate 3-foot intervals along lines indicated on figures 2 and 3; the samples of alluvium represent surficial material collected at about 3-foot intervals along the lines indicated on the same figures. The equivalent uranium content of each sample, determined by beta-gamma radioactivity measurements, is:

Sample no.	Description	Equivalent uranium (precent)
1	biotite-rich inclusion	0.032
2	porphyritic quartz monzonite	.007
5	do.	.008
6	do.	.008
7	do.	.007
9	alluvium	.0023
10	metasediments	.0026
11	alluvium	.0026

Analyst: B. A. McCall, U. S. Geological Survey

The heavy minerals (>3.3 sp. gr.) were separated from sample 6 and further separated into magnetic susceptibility fractions by means of an alnico magnetic and a Frantz isodynamic separator. Each magnetic fraction was analyzed for equivalent uranium content.

Heavy-mineral fraction of sample no. 6

Magnetic susceptibility fraction	Equivalent uranium (percent)
Alnico magnetic (few grains)	-----
Frantz .3 amp.	0.09
Do. .6 amp.	0.17
Do. .9	1.00
non-magnetic	0.24

Analyst: B. A. McCall, U. S. Geological Survey

Porphyritic quartz monzonite

Samples of various phases of porphyritic quartz monzonite collected from a number of different localities in the area contain an unusual number of accessory minerals, and the relative abundance of the accessory minerals is different in each phase of the monzonite. The porphyritic quartz monzonite, in which the groundmass predominates over the orthoclase phenocrysts, invariably contains a greater abundance and probably a greater variety of accessory minerals than does the quartz monzonite in which the phenocrysts predominate. The most abundant accessory mineral identified is biotite, but the rocks also contain magnetite, ilmenite, fluorite, apatite, allanite, many varieties of zircon, two varieties of sphene, and lesser amounts of zoisite, rutile, xenotime (?), corroded hornblende, tourmaline, garnet, monazite (?), and topaz (?). Some outcrops of quartz monzonite in which the groundmass predominates contain appreciably more biotite and fluorite than elsewhere. An increase in the biotite and fluorite content generally indicates an increase in the content of allanite, zircon, and apatite and may indicate an increase in the monazite (?) and xenotime (?). A point-count, petrographic analysis was made of a thin section of porphyritic quartz monzonite which contains fluorite, moderate amounts of biotite, and other accessory minerals. The analysis shows that locally this rock contains as much as 4.5 percent allanite and nearly 1.5 percent zircon.

In all types of porphyritic quartz monzonite, the allanite and some types of zircon are definitely radioactive; both are invariably surrounded by pleochroic halos where found in contact with biotite. Nearly pure fractions of the allanite and the zircon are appreciably radioactive. Monazite(?) and xenotime (?) occur only in minute quantities and are not found in association with biotite; they have been classed therefore, as probably radioactive.

Apatite, which is locally abundant and is commonly associated with biotite, is essentially non-radioactive; however, a few apatite grains, containing minute unidentified inclusions are surrounded by faint pleochroic halos in the enclosing biotite. Sphene, like apatite, is considered essentially non-radioactive, though one grain of sphene observed in a thin section is apparently surrounded by a faint pleochroic halo. Tests of the other accessory minerals indicate that they are not radioactive.

Porphyritic quartz monzonite which contains concentrations of both biotite and fluorite and appreciable amounts of radioactive minerals crops out extensively along the ridge northwest of check point 76, flight line 4A (figs. 2 and 3) and north to the fault contact between the quartz monzonite and the igneous and metamorphic complex. South of the ridge, to midway between flight lines 4A and 5, the quartz monzonite contains appreciably less fluorite; the biotite, zircon, and allanite content south of the ridge varies locally, but is commonly less than in the quartz monzonite along the crest and north of the ridge. Allanite, zircon, and probably other radioactive minerals are present in the masses of porphyritic quartz monzonite exposed in the north and northeast part of the area. No attempt has been made, however, to determine the quantity or distribution of the radioactive minerals in these masses.

One sample of the porphyritic quartz monzonite (no. 6) was analyzed spectrographically, with the following results:

Over 10%	1.0-10.0%	0.1-1.0%	0.01-0.1%	0.001-0.01%	0.001-0.001%
Al, Si,	Ca, K, Na, Fe	Mg, Ba	Ce, Sr, Ti, Nd, B, Cr, La, Mn, Fr, Co	Pb, Ga, V Y, Cu, Sc	Yb, Be

Analyst: H. W. Worthing, U. S. Geological Survey

Biotite-rich inclusions

The mineralogic composition of the biotite-rich inclusions varies slightly from one inclusion to another but is alike in that the inclusions invariably contain 60 percent or more of olive-green to brown biotite. A thin section of one inclusion about 15 feet in diameter was petrographically analyzed by the point-count method. The analysis shows about 74 percent biotite, about 8 percent feldspar, slightly more than 7 percent allanite, 5 to 6 percent magnetite, about 3 percent apatite, and 1 percent of each sphene and zircon. The inclusion is appreciably radioactive largely due to the high content of allanite; distinct pleochroic halos surround crystals of both allanite and zircon. Other biotite-rich inclusions exposed in the area are also appreciably radioactive, probably due to allanite.

In the Rock Corral area biotite-rich inclusions in the porphyritic quartz monzonite are exposed at only a few localities. All of the appreciably radioactive inclusions occur in the south-central part of the area. The total outcrop area of all the biotite-rich inclusions is not more than a few hundred square feet in an area of nearly 1 3/4 square miles.

Alluvium

Some of the alluvium, which fills the washes that drain areas underlain by the contaminated porphyritic quartz monzonite, is nearly identical in mineralogic composition to the contaminated quartz monzonite. The alluvium in these washes is composed of abundant quartz and feldspar, and lesser amounts of biotite and accessory minerals. Some placer concentrations of dark-colored minerals occur as thin discontinuous layers in the alluvium and, locally, on the surface of the alluvium. The principal constituents of the dark layers are quartz, feldspar, biotite, and magnetite; the content of radioactive minerals is only slightly greater than that found in typical specimens of porphyritic quartz monzonite.

RADIOACTIVITY SURVEYS

Airborne surveys

The airborne radioactivity surveys in the Rock Corral area were made with gamma radiation detection equipment mounted in a Douglas DC-3 aircraft. A nominal 500-foot flight level was maintained during all traverses, and the distance of the aircraft from the ground was measured with a radar altimeter and continuously recorded by a graphic milliammeter. Aerial photographs were used for pilot guidance, and the flight path of the aircraft was recorded by a 35 mm. gyrostabilized continuous strip-film camera (Jensen and Balsley, 1946).

The flight records are integrated by means of a synchronous marking circuit, operated by the observer, which simultaneously marks the radiation and altimeter records and the strip film.

All measurements of gamma radiation intensity were made with scintillation detection equipment developed by the Oak Ridge National Laboratory, Division of Health Physics, in cooperation with the Geological Survey. The components of the equipment are shown in figure 4. The equipment comprises two independent detecting and recording units operated from a common power supply. The detectors of each unit consist of three 2-inch thick by 4-inch diameter thallium-activated sodium iodide crystals. A photomultiplier tube, mounted in direct contact with each crystal, collects the scintillations and feeds the resultant pulses into the amplification stages.

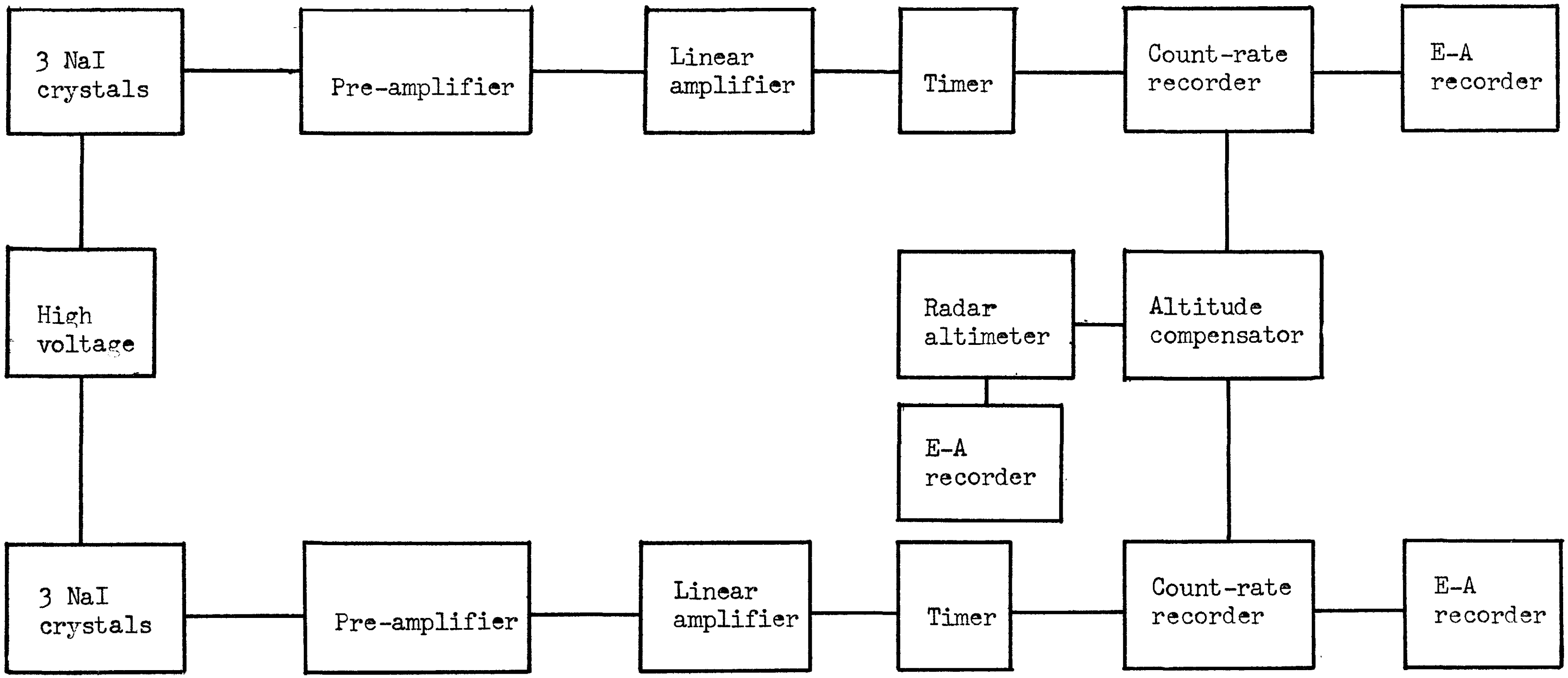

Figure 4.--Block diagram of the scintillation detection equipment

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The amplified pulses are fed into a count-rate recorder which is essentially similar to a scaling circuit. The incoming signal is measured over a one-second period and is recorded in the following one-second interval. A continuous record is provided through the incorporation of two identical channels in each recorder which alternately measure and record the radiation intensity. A mechanical timer driven by a synchronous motor provides the necessary switching. The development of this recording technique has been discussed by Stead (1951).

To compensate for variation in radiation intensity with variation in distance from the ground, the output of the radar altimeter is fed to the recording circuit in such a manner as to modify the sensitivity of the count-rate recorder proportional to $e^{-\mu h}$ (where μ = linear absorption coefficient of air and h = height of the aircraft above the ground).

The airborne equipment was calibrated in terms of mr/hr by the Oak Ridge National Laboratory.

The flight lines of the airborne survey (fig. 1) were oriented in a general northwestward direction and, in the greater part of the area, were spaced at 1/4-mile intervals. In the eastern part of the area, intermediate flight lines were spaced at 1/8-mile intervals to provide greater detail where occurrences of radioactive materials were known to exist. Seven flight lines (nos. 2A, 3, 3A, 4, 4A, 5 and 5A), spaced at approximate 1/8-mile intervals, cross the area discussed in this report (figs. 2 and 3).

The width of the zone on the ground from which anomalous radioactivity is measured at the nominal 500-foot flight altitude varies with the areal extent and radiation intensity of the source rocks. However, at

1/4-mile flight line spacing the radiation from smaller areas of considerable intensity located midway between the flight lines probably would not be resolved. By employing a 1/8-mile flight line interval at a nominal 500-foot flight altitude, smaller variations of the source distribution are better delineated.

To determine the relationship between the measurements of radiation intensity at the 500-foot flight level and the surface distribution of source materials, the data of the airborne radioactivity survey were compiled as an isoradioactivity contour map (fig. 2).

The maximum radiation intensity recorded at the 500-foot flight level over the central portion of the mapped area is related to the main mass of quartz monzonite. On flight line 4A the radiation intensity exceeded the limit of the graphic recorder on the particular sensitivity scale at which it was being operated so that the configuration of the peak of the anomaly is not fully known. The shape of the radiation intensity profile along this line suggests that at least one, and possibly two, additional contours would be needed to delineate the true magnitude of the radiation. One additional contour has been sketched on figure 2, but its location may be considerably in error. The areal extent of the principal anomaly in the central part of the area conforms in most places to the principal outcrop area of quartz monzonite. A northeastward extension of the principal anomaly conforms in general to the alluvium-filled wash which drains the northern part of the main mass of quartz monzonite, and another extension in the east-central part of the area is situated over outcrops of the igneous and metamorphic complex which contains a considerable amount of quartz monzonite. In most localities a rather sharp decrease in the radiation intensity was recorded over the fine-grained intrusive (?) rock which borders the porphyritic quartz monzonite on the north and east.

The pre-Cambrian gneiss, metasediments and metavolcanics are generally low in radioactivity, as is the Cactus granite which occupies the western part of the area. The areas of Tertiary basalt in the southwest and south-central part of the area are rather limited in extent and appear to have had little influence on the configuration of the radiation flux.

The typical relationship, along flight line 5, between the radiation intensity profile at the 500-foot flight level and the various geologic units in the mapped area is shown in figure 5.

Ground surveys

The ground radioactivity survey was undertaken to determine the surface distribution of radioactive materials in the Rock Corral area and to relate the surface distribution to the data obtained by airborne measurements at the 500-foot flight level.

The survey was made by occupying stations on a 300-foot grid with one coordinate of the grid laid out to coincide with the vertical projections of the flight lines. The data obtained were compiled as an isoradioactivity contour map (fig. 3).

All radioactivity measurements were made with a portable survey meter, equipped with a 2-inch diameter by 24-inch long brass-walled Geiger counter. The net radioactivity (total count minus the cosmic component), was determined at each station and the results were contoured at an interval of 6 μr/hr. The resulting isoradioactivity map presents only the gross configuration of the radioactivity field, owing to the rather wide spacing of the survey grid necessitated by the relatively large area to be covered.

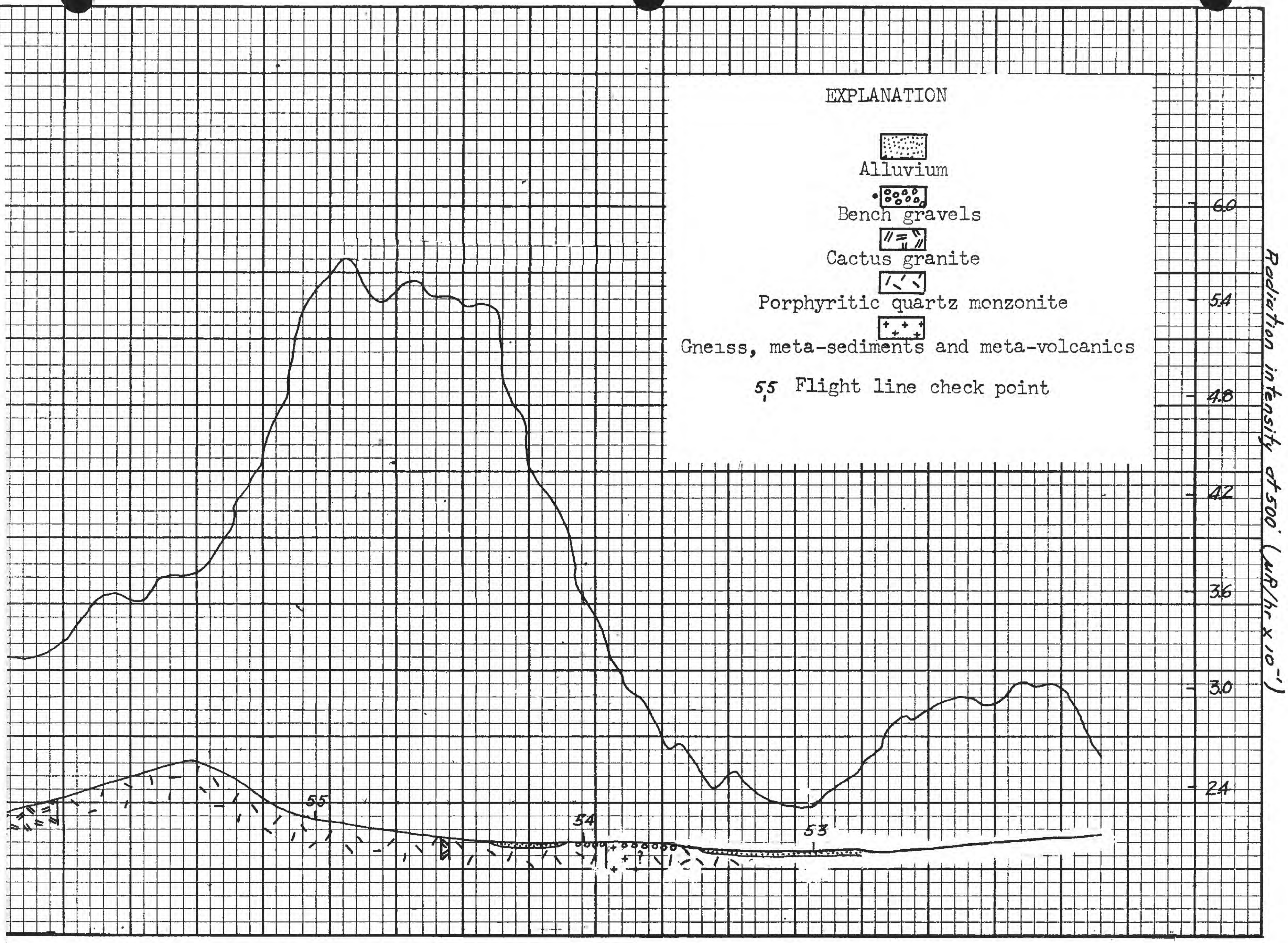

Figure 5. Geologic section and airborne radiation intensity profile along flight line 5.

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For instance, the felsic dikes, related to the Cactus granite, and biotite-rich inclusions are relatively small geologic features which are quite anomalous insofar as their radioactivity is concerned, but few of these small features could be resolved on the 300-foot grid.

The occurrences of radioactive materials are confined chiefly to the biotite-rich inclusions and the quartz monzonite host rock. The minerals responsible for the radioactivity have been described above.

The biotite-rich inclusions in the quartz monzonite contain the most significant concentrations of radioactive minerals in the Rock Corral area. A chip sample collected across the biotite-rich mass at sample location no. 1, contains 0.032 percent equivalent uranium, which is the maximum radioactivity found in the area. None of the biotite-rich masses were so situated geographically or were of sufficient size or tenor to influence the isoradioactivity data.

The average equivalent uranium content of the principal mass of quartz monzonite in the central part of the area is about 0.006 percent. The radioactive content is highest in the northeastern part of the outcrop area where the quartz monzonite is in fault contact with the igneous and metamorphic complex. In the localities of maximum radiation intensity the quartz monzonite, which here is coarsely porphyritic, probably contains as much as 0.009 percent equivalent uranium; to the southwest, the rock becomes increasingly fine-grained and the equivalent uranium content decreases to an average of 0.003 percent.

In most localities there is a sharp decrease in radioactivity from the porphyritic quartz monzonite to the foliated, fine-grained intrusive rock which bounds the quartz monzonite on the northeast (geologic contact shown by dashed line in figures 2 and 3).

The radioactivity of the igneous and metamorphic complex varies directly with the amount of quartz monzonite included but is generally considerably lower than the main mass of the quartz monzonite.

The pre-Cambrian rocks are generally low in radioactivity. One sample (no. 10) collected from an outcrop of metasediments in the southeastern part of the area contains 0.0026 percent equivalent uranium. Likewise, the felsic dikes found locally in the area, and which are related to the Cretaceous Cactus granite, are relatively low in radioactivity, probably containing less than 0.002 percent equivalent uranium. The composition of the slope wash is essentially the same as the quartz monzonite from which it was derived and in general is comparable in radioactivity to the parent material. Two samples of alluvium, nos. 9 and 11, contain 0.0023 and 0.0026 percent equivalent uranium respectively. The main outcrop areas of the Tertiary olivine basalt flows were a short distance beyond the limits of the ground radioactivity survey. On the basis of the radiation intensity measured in the airborne survey, the basalt contains negligible quantities of radioactive material.

The relationship of the surface radiation intensity of the various rock types in the surveyed area to the equivalent uranium content of the rocks is shown in figure 6.

RELATIONSHIP BETWEEN THE RADIOACTIVITY OF THE SOURCE ROCKS AND THE AIRBORNE MEASUREMENTS

The basic problem involved in this study was to determine the relationship between the distribution of radioactive materials in the area mapped and the airborne radioactivity measurements. More specifically it was desired to know whether or not the anomalies resulted from the biotite-rich thorium-bearing inclusions or from some other source materials.

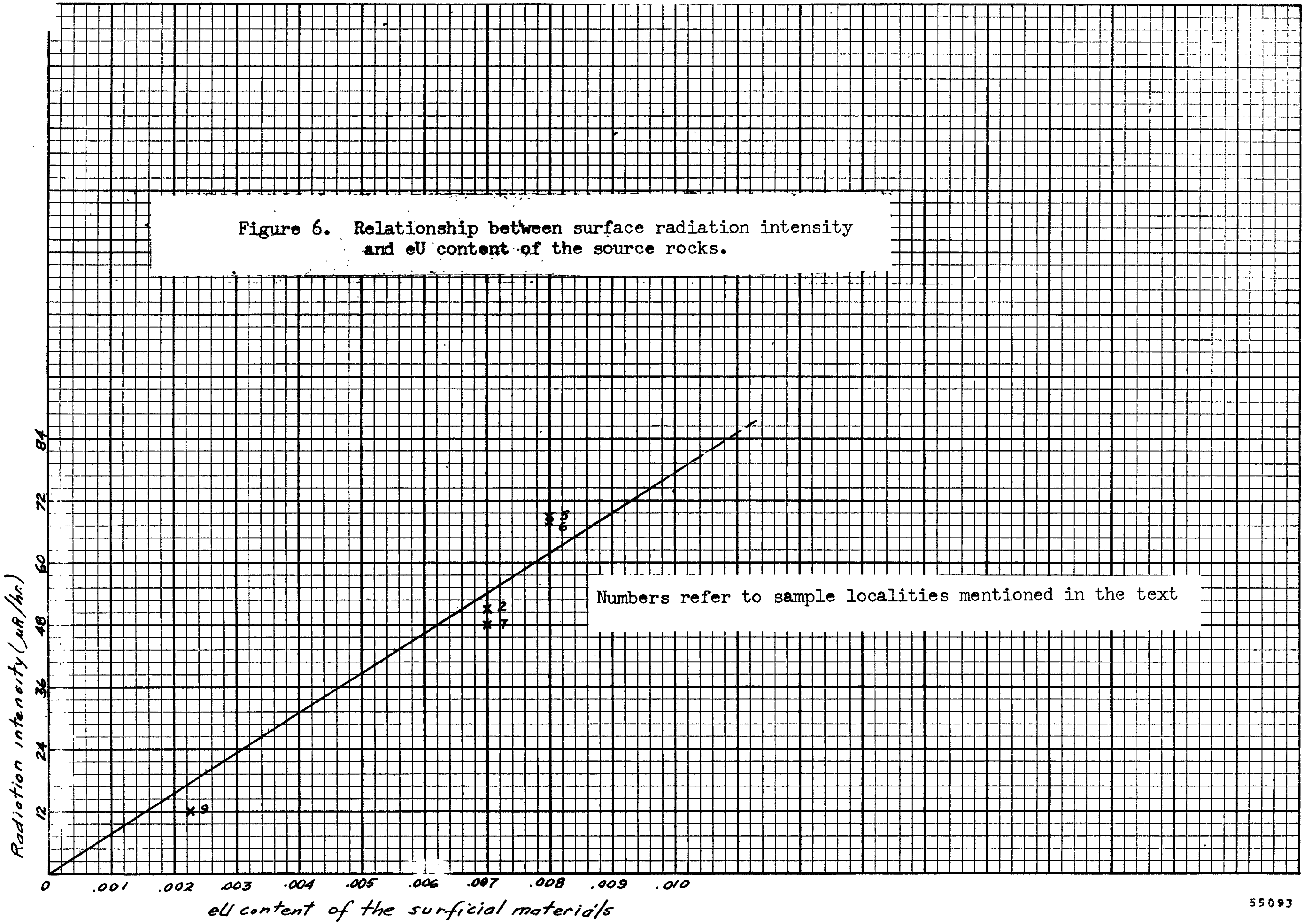

Figure 6. Relationship between surface radiation intensity and eU content of the source rocks.

The principal anomalies in the mapped area, as shown on the iso-radioactivity contour map at the 500-foot level, are symmetrically disposed (approximately) in relation to the outcrop areas of the Cretaceous quartz monzonite, the igneous and metamorphic complex containing quartz monzonite, and alluvium containing a high percentage of quartz monzonite detritus.

In regard to the major anomaly recorded over the outcrop area of the biotite-rich inclusions and the quartz monzonite host rock, it is of interest to ascertain the radiation intensity which would have been recorded solely as a result of the quartz monzonite, in the absence of any biotite-rich inclusions. The radiation intensity recorded at the aircraft above source rocks of broad distribution with respect to the solid angle subtended at the plane is given by the following equation (Oak Ridge National Laboratory, 1950):

$$R = \frac{K\ Se^{-\mu h}}{2\mu_2}$$

where R is measured in units of deflection of the recorder and

K = constant of proportionality

S = radium content of the source rocks in curies per gram

μ = linear absorption coefficient of air

h = height of the aircraft in feet

μ_2 = mass absorption coefficient of the source rocks.

The mass absorption coefficient for granite and ultramafic rocks has been determined by Urry (1948, p. 600) as .045 $cm^2\ g^{-1}$ and .043 $cm^2 g^{-1}$, respectively, so that the variation in chemical composition of the rocks in the mapped area would have little effect upon the radiation intensity insofar as the mass absorption within the source is concerned. The height of the aircraft and linear absorption coefficient of air are assumed to remain constant, so that a direct proportion exists between the units of detection as recorded and the radioactive content of the source rocks in curies per gram (or percent equivalent uranium content).

Let us consider the relationship along flight line 4 (fig. 3) between 1) the surface and airborne radioactivity measurements and 2) the radiation intensity of the source rocks in terms of equivalent uranium content. In the extreme eastern part of the area, flight line 4 crosses a belt of alluvium between check points 34 and 35. At sample locality 11, this alluvium contains 0.0026 percent equivalent uranium. The surface radiation intensity along line 4 increases, in general, northwestward from 20 μr/hr at sample locality 11 to a maximum of about 54 μr/hr at outcrops of the igneous and metamorphic complex between check points 31 and 32. The intensity measured at these outcrops indicates (fig. 6) an equivalent uranium content of about 0.007 percent. Thus, the equivalent uranium content of the source rocks between location 11 and the location of peak intensity increases by a factor of 2.7.

The radiation intensity recorded by the airborne equipment over sample locality 11 (between check points 34 and 35) was about 2.1 μr/hr, increasing to 6 μr/hr at the location of peak intensity, or a factor of 2.9, so that little increase in radiation intensity can be ascribed to the biotite-rich inclusions or to topographic effects. This is further borne out by a calculation of the response of the airborne equipment which might be expected from a typical biotite-rich body. If it is assumed that

(1) the emitting surface is 50 feet long by 15 feet wide = 750 sq. ft.,

(2) the effective thickness of the emitting layer is 6 inches,

(3) specific gravity of the material = 3,

(4) the material averages 0.05 percent equivalent uranium,

then the deposit in question is equivalent to a point source of 4.55 mg of radium.

The attenuation of radiation with distance from a point source is given very roughly by

$$I = \frac{I_o e^{-\mu h}}{h}$$

where I_o = radiation intensity at the source

I = radiation intensity at distance h

μ = linear absorption coefficient of air

so that the intensity of a point source of 4.55 mg of radium at 500 feet would be about 2.3 μr/hr. This value is approximately the level of background radiation, so that it is doubtful that the biotite-rich bodies are detectable, in this particular geologic environment.

Some speculation on the lower limit of sensitivity of the airborne equipment may be warranted from the flight data obtained during the Rock Corral survey. The sensitivity scale on which the equipment was operated had a full scale deflection of about 6 μr/hr. Full scale deflection was obtained over relatively broad source rocks containing about 0.007 percent equivalent uranium so that a change of 0.001 percent in the equivalent uranium content of the source rocks would result in a change of about 14 percent in the recorded radiation intensity, if a linear relationship may be assumed. The range of statistical deviation of the measurements during the Rock Corral survey was about 5 percent, so that changes on the order of 0.001 percent in the equivalent uranium content of broad source materials should be within the detectable limit of the airborne equipment, assuming conditions of geometry and energy spectrum comparable to those existing in the Rock Corral area.

For example, consider the anomalous area, outlined by the ground isoradioactivity contours (fig. 3), which extends northeastward from flight line 3A across lines 3 and 2A. The peak intensity along the crest of the anomaly (fig. 2) is somewhat in excess of 30 μr/hr, and the average equivalent uranium content of the source rocks (as determined from figure 6) is approximately 0.004 percent. In a northwestward direction from the crest, the radiation intensity at ground level decreases to about 12 μr/hr, indicating that the equivalent uranium content has decreased to between 0.001 and 0.002 percent. The airborne radioactivity anomaly, outlined by the airborne isoradioactivity contours (fig. 2), has therefore resulted from an overall difference in equivalent uranium content of about 0.003 percent in source rocks occupying about 10,000 square feet. The airborne anomaly in question is well defined, and it seems likely that a lower sensitivity limit of 0.001 percent equivalent uranium is possible for geologic units of similar extent.

CONCLUSIONS

Radioactive materials in the Rock Corral area are confined chiefly to:

1) Quartz monzonite intrusive masses, containing as much as 0.009 percent equivalent uranium; the radioactivity is attributed to disseminated thorium-bearing accessory minerals, chiefly allanite and zircon.
2) Biotite-rich inclusions in the quartz monzonite, usually less than a hundred square feet in extent, containing as much as 0.03 percent equivalent. The radioactivity is due chiefly to allanite.
3) Alluvium composed largely of quartz monzonite detritus.

The airborne radioactivity anomalies resulted from the outcrops of quartz monzonite, rather than from the small biotite-rich inclusions.

As the inclusions are associated, at least in the area mapped, with the most radioactive geologic unit in the area, it might be possible to determine other areas of the Mojave region most favorable for the occurrence of biotite-rich inclusions by delineating the outcrops of the abnormally radioactive host rock.

Well defined anomalies were recorded over source rocks of about 10,000 square feet in areal extent, which are anomalous only to the extent of 0.003 percent equivalent uranium, with respect to contiguous rocks. It is concluded that a lower sensitivity limit of the airborne equipment is at least 0.001 percent equivalent uranium for geologic units of comparable extent.

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