

Physical Behavior and Geologic Control of Radon in Mountain Streams

GEOLOGICAL SURVEY BULLETIN 1052-E

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United States Atomic Energy
Commission and published with
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By ALLEN S. ROGERS

EXPERIMENTAL AND THEORETICAL GEOPHYSICS

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PHYSICAL BEHAVIOR AND GEOLOGIC CONTROL OF RADON IN MOUNTAIN STREAMS

By ALLEN S. ROGERS

ABSTRACT

Radon measurements were made in several small turbulent mountain streams in the Wasatch Mountains near Salt Lake City and Ogden, Utah, to determine the relation between the distribution of radon and its geologic environment.

In this area, the distribution of radon in streams can be used to locate points where relatively large amounts of radon-bearing ground water enter a stream, even though other evidence of springs may be lacking. These points of influent ground water are marked by abrupt increases (of as much as 2 orders of magnitude within a distance of 50 feet) in the radon content of the stream waters.

This excess radon is rapidly lost to the atmosphere through stream turbulence. The rate of radon dissipation with distance of streamflow, is an exponential function, of different slopes, depending on the rate and volume of streamflow, and the gradient and nature of the stream channel.

Higher radon concentrations generally can be related to specific stratigraphic horizons in the several drainage areas studied. Thus, lithologic units that act as the primary aquifers can be identified. In one area, thrust faults were found to control the influx of ground water into the stream.

Based on radon concentrations in streams and related spring waters, estimates of major increments of ground water to streamflow can be made, where conventional methods such as stream gaging are not practical.

The radon in the waters studied was found to be almost completely unsupported by radium in solution.

INTRODUCTION

PHYSICAL PROPERTIES OF RADON

Radon (called "radium emanation" and "niton" by early investigators) belongs to the family of inert noble gases and is the only radioactive gas occurring naturally in appreciable amounts—although traces of radioactive xenon and krypton occur naturally as products of spontaneous and neutron fission. As an element, radon is comprised of three isotopes, each of which disintegrates through alpha emission: Rn^{222} (radon), with a half life of 3.825 days; Rn^{220} (thoron), with a half life of 54.5 seconds; and Rn^{218} (actinon), with a half life of 3.92 seconds. These isotopes are members of the U^{238} ,

Th²³² and U²³⁵, families, respectively. Of the three isotopes, the half life of radon (Rn²²²) is the most convenient for measurement, and this is the only isotope investigated in this report.

The interrelations of half lives of the parent radium and the immediate daughters of radon add to the convenience of radon measurements. The half life of radium (Ra²²⁶) is 1,620 years, and can be considered infinite compared to the 3.825-day half life of radon. Approximately 99 percent equilibrium is established between radon and radium within 25 days.

Radon disintegrates through a series of 4 short-lived daughter products, with which equilibrium is established in about 4 hours (Jennings and Russ, 1948, p. 42, 210-211). The next (fifth) daughter product, Pb²¹⁰ (RaD), has a half life of 22 years. Compared to 4 hours, this is sufficiently long to make the effect of Pb²¹⁰ in radon measurements negligible within the range of radon concentrations discussed in this report.

Being an inert gas, radon is quite susceptible to migration, accomplished either by gaseous diffusion or solution. The distance of migration depends on the 3.825-day half life, the rate and medium of migration, and possibly on such other factors as the adsorption of radon on carbonaceous material.

Radon is soluble in many liquids; the solubility depends upon the nature of the liquid and its temperature. The distribution ratio or solubility coefficient of radon (Rn water/Rn gas) in a gas-water system of equal volumes at various temperatures is shown and compared with selected published data in figure 44. Radon is less soluble in aqueous solutions of electrolytes than in pure water. The distribution ratio of radon in an aqueous solution of NaCl (sp gr 1.215) at 17° C. is 0.042 (Kofler, 1913). Radon is highly soluble in organic liquids. The distribution ratio may be as large as 23 in some liquids (Wahl and Bonner, 1951, p. 157).

This ability of radon to migrate allows it to be used as a tracer in uranium exploration. Perhaps more important are the potential applications to ground-water problems of studies of radon concentrations in natural waters.

RADON IN NATURAL WATERS

PREVIOUS WORK

Very little is known concerning the relation of radon in natural waters to geologic conditions. Arndt and Kuroda (1953) made a reconnaissance survey of radon in streams and lakes in parts of Garland and Hot Springs Counties, Ark. Where the same rock type crops out over a wide area, a correlation was suggested between radon

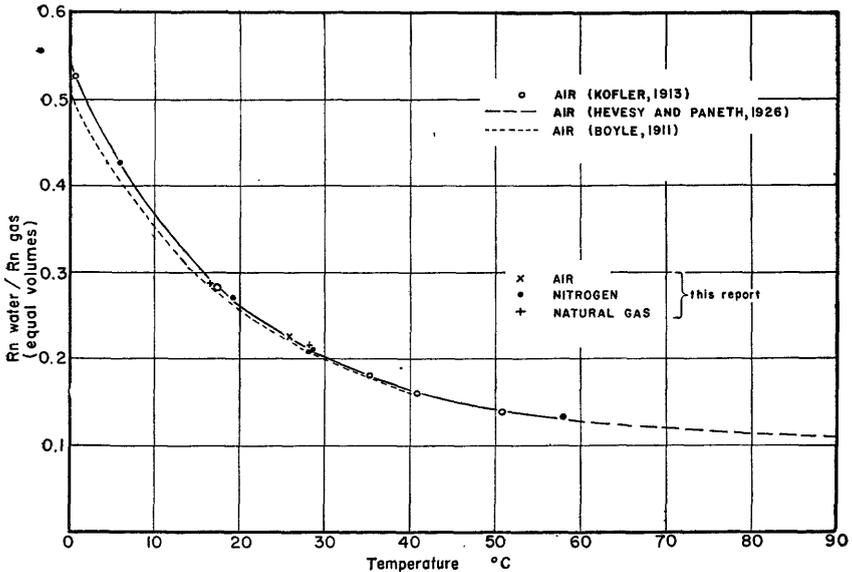


FIGURE 44.—Radon distribution ratios in a gas-water system.

in streams and the rock types over which the streams flow: the radon content of streams and springs proved higher near known uranium-bearing materials.

An abundance of literature on the radioactivity of spring waters is available. Perhaps the most intensive and complete studies in this country were those by Kuroda and his coworkers in Hot Springs National Park and vicinity in Arkansas. Here radon concentrations in both hot and cold springs and in streams are related to geologic features and to known uranium-radium minerals (Arndt and Kuroda, 1953; Kuroda, Damon, and Hyde, 1954). At Yellowstone National Park, radon determinations of gases and waters, and radium determinations of spring deposits, were made by Schlundt and Moore (1909).

Miholic (1952) analyzed water from 26 springs in Yugoslavia and found that waters from Carboniferous and Cretaceous strata contain more radon than waters from sedimentary rock of other periods.

A detailed investigation of radon and helium in the West Panhandle gas field of Texas (Faul and others, 1954), the Hugoton gas field of Kansas, and other gas fields in the Mid-Continent region was made (Pierce, Mytton and Gott, 1956). It was found that natural hydrocarbon gases may contain as much as 10^4 micromicrocuries of radon per liter (at reservoir pressure).

Kovach (1944, 1945, 1946) has described a series of measurements of radon in soil gas at Fordham University. He noted variations in

radon content that are attributable to depth and such meteorological elements as rain, snow cover, barometric pressure, and wind velocity. A similar study by Norinder, Metnieks, and Siksna (1952) was made at Uppsala, Sweden. A relation between the radon content of soil gas and the heavy mineral content of the soil was observed by Clark and Botset (1932).

PURPOSE AND SCOPE OF PRESENT INVESTIGATION

In the spring of 1953 a few preliminary radon determinations were made in several streams that drain the Wasatch Mountains near Salt Lake City, Utah. These samples showed sufficient range in radon content to warrant further investigation. This was postponed until summer, when the streams reached a stable condition and were not affected by melting snow. At that time another series of preliminary radon measurements were taken periodically over an interval of one week at several places. Since there was, in general, little variation in the radon content found at each place, it seemed reasonable to assume that significant interpretations concerning the distribution of radon in stream waters were possible.

The distribution of radon in stream waters and related springs, and the relation of this distribution to both geologic and nongeologic conditions, was then investigated in several drainage areas of the Wasatch Mountains adjacent to Salt Lake City, Utah. The results were then applied to a definite ground- and surface-water problem in a part of the lower Weber River drainage area near Ogden, Utah.

ACKNOWLEDGMENTS

The work described in this report was part of a program of investigations carried on by the U. S. Geological Survey on behalf of the Division of Research of the U. S. Atomic Energy Commission. Space and other facilities were made available by the University of Utah, where, during part of the time the writer was studying under a Shell Oil Company Research Fellowship in Geophysics. John H. Feth and Herbert A. Waite of the Geological Survey cooperated in the investigation in the lower Weber River area. Data on quality of water were supplied by J. A. Conner of the Geological Survey.

METHODS OF STUDY

INSTRUMENTS AND METHODS OF MEASUREMENT

Radon can be measured by the ionization produced by alpha emission in an ionization chamber. The degree of ionization is a measure of the radon present in the chamber and can be determined by the rate of fall of a charged gold leaf of an electroscope, or by a device capable

of counting individual pulses, or by measuring the total ionization current produced by the alpha emission.

The unit of measurement most commonly used in radon determinations is the curie, but because the curie is a very large unit, the millimicrocurie (10^{-9} curie) or micromicrocurie (10^{-12} curie) is conventionally used. The curie is defined as the amount of radon in equilibrium with one gram of radium. It has been further defined as 3.700×10^{10} radioactive disintegrations per second. A curie, in terms of volume of radon at standard temperature and pressure, is 0.66 mm^3 ; $0.66 \times 10^{-12} \text{ mm}^3$ of radon gas, therefore, is equivalent to one micromicrocurie. Thus the quantities of radon that can be accurately measured are minute. Other units that have been used are the Mache unit, which is equal to 3.6×10^{-10} curie per liter, and the Eman unit, which is equal to 1×10^{-10} curie per liter. (Hevsey and Paneth, 1926, p. 178.)

For the radon measurements given in this paper, a slow ionization chamber collecting positive ions was used, with an attached vibrating-reed electrometer to measure total ionization current. Radon was boiled out of liquid samples into an evacuated ionization chamber, while argon was simultaneously bubbled through the boiling liquid sample in order to carry the radon from the sample into the chamber. The radon was isolated in the chamber for a 4-hour period. During this time equilibrium was established with its short-lived daughter products, and the total ionization current then measured by the vibrating reed electrometer. A continuous record of the amplified current was recorded on a one-milliamperere graphic strip-chart recorder.

The currents produced by the unknown samples were compared directly with the current produced by a known amount of radon evolved from a standard radium solution. The radon content of the $10.5 \times 10^{-12} \text{ g}$ standard radium solution, obtained from the National Bureau of Standards, is measured periodically for calibration. The average of 20 such measurements is 25.7 millivolts (standard deviation, 0.6) and gives a conversion factor, in terms of micromicrocuries per millivolt.

Background measurements using nonradioactive argon were made periodically, and subtracted from all measurements. The smallest amount of radon that can be measured by this apparatus is about one micromicrocurie per liter.

Radium contents of liquids are determined in a similar fashion, except that two boilings of the liquid sample are necessary. First, all radon is driven from the sample either by making a radon determination, or by boiling it to the atmosphere. The sample is sealed in its original boiler and several days later, the radon which evolved from

the radium in the sample is driven into an ionization chamber and measured. The amount of radon evolved gives a measure of the amount of the radium in the sample.

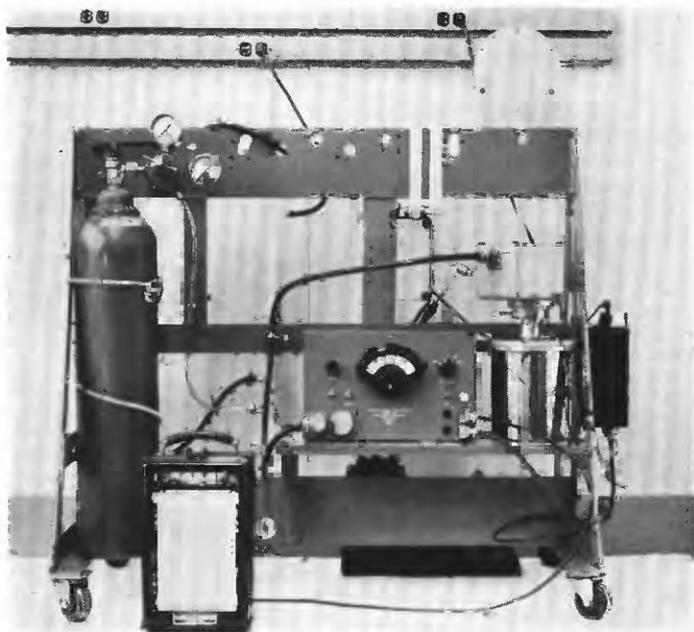
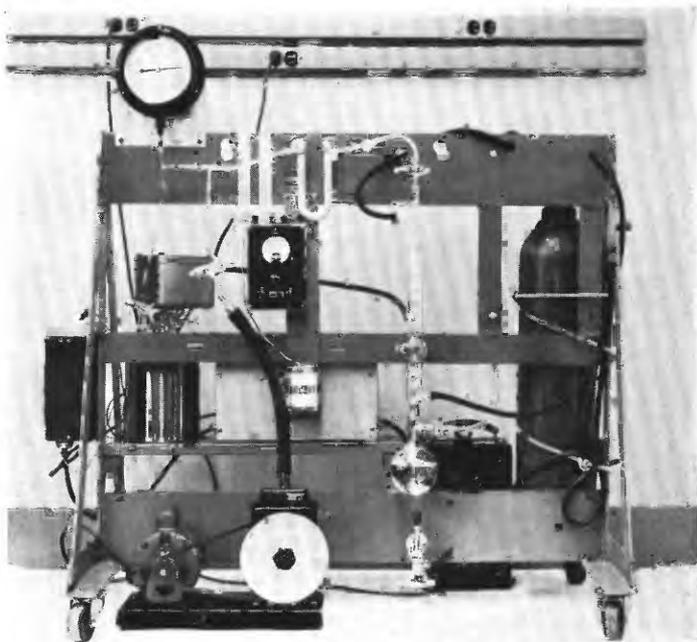
Time is an important factor in both radon and radium determinations. The amount of radon that decayed during the time between sampling and determination must be determined. Because of the 3.825-day half life, radon determinations are generally made within a day or two after sampling. In radium measurements, the time of radon evolution or buildup must be accurately known.

The equipment (pl. 6 and fig. 45) consists of a bank of three 500-milliliter reflux boilers and two 4.2-liter stainless-steel ionization chambers with a connecting gas-transfer system. The system consists of two parts: the intake line from the boilers, with attached U-tube desiccator and vacuum gage, and the exhaust line with its vacuum pump and thermocouple vacuum gage. The ionization chambers are connected to both lines. The two lines are connected by a "bridge" stopcock. When the bridge is closed, it is possible to fill one chamber while evacuating the other.

The gas-transfer system is made entirely of tygon tubing ($\frac{3}{16}$ inch inside diameter \times $\frac{1}{4}$ inch outside diameter) with glass joints and stopcocks. Tygon tubing has certain advantages over the conventional all-glass or copper tubing systems. It is cheap, and easy to construct and maintain. Changes in the system can be made easily. The cleaning of a contaminated glass or copper tubing system can be a tedious job; but if the tygon tubing becomes contaminated, it may be discarded and replaced by new tubing. Although the equipment was originally set up as a semipermanent installation in a laboratory, the tygon system was constructed with the idea that the equipment will eventually be installed as a mobile truck-mounted unit.

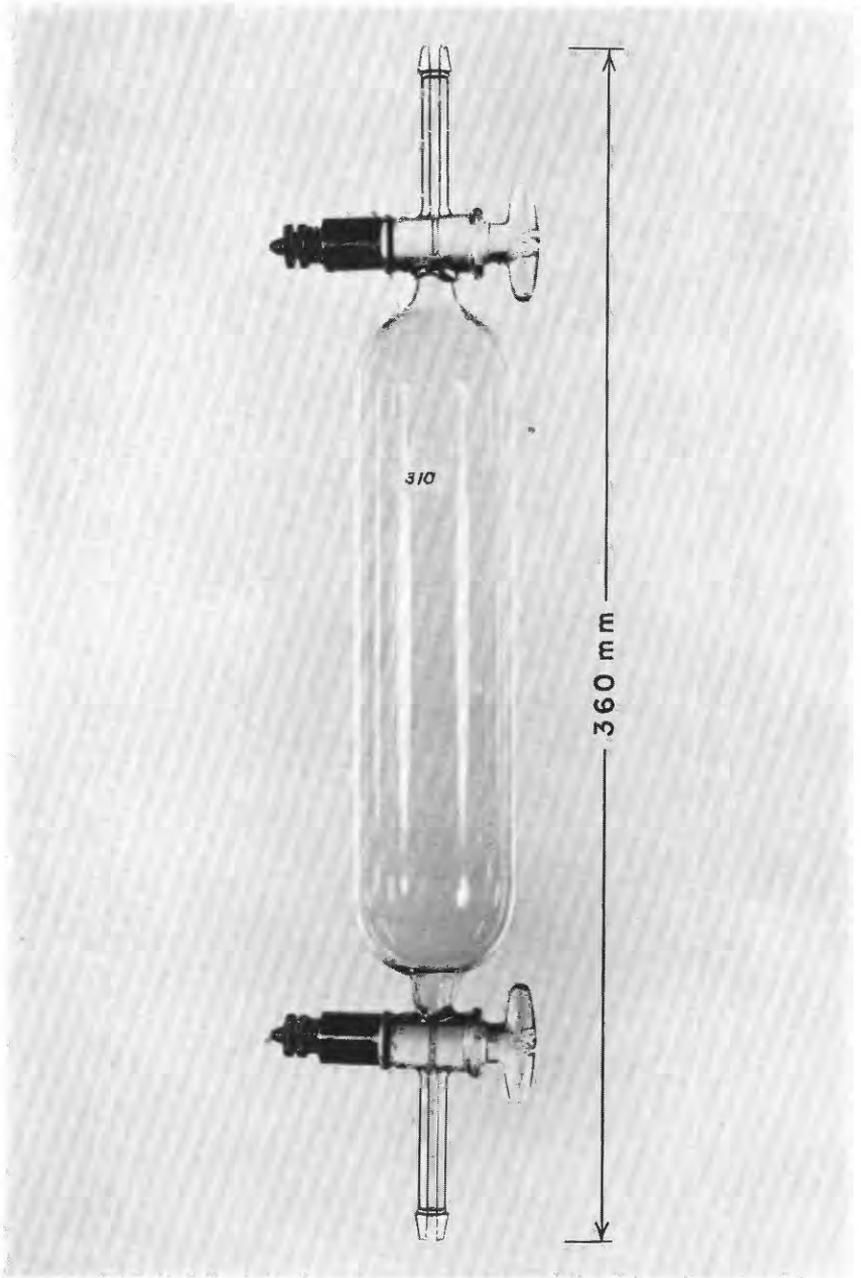
No leaks formed in the tygon tubing-glass connections during 1 year of almost daily use. A low-vapor-pressure silicone grease is used as a seal and lubricant in the connections. No organic greases or black rubber should be used because they tend to adsorb radon.

A few limited experiments showed that no appreciable radon is lost in the tygon system by adsorption or diffusion. Radon was allowed to expand freely from a full ionization chamber through about 20 feet of tygon tubing into an evacuated chamber. The radon was then measured in each chamber and generally there was less than 1 percent difference. R. D. Evans (personal communication) has investigated radon losses in black rubber, gum rubber, and tygon tubing. His results indicate that the loss of radon to gum rubber or tygon tubing in a breath-collecting system is negligible if the volume of the

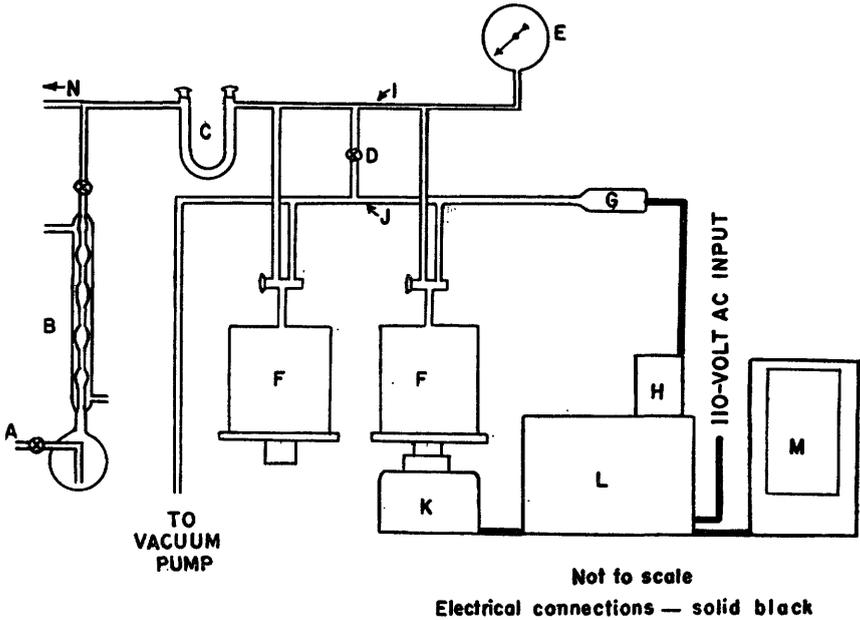


RADON-MEASUREMENT APPARATUS

Only one reflux boiler and ionization chamber are shown on this plate. See figure 45 for layout of apparatus actually used.



SAMPLING TUBE



- A - ARGON AND SAMPLE INTAKE
- B - 500-MILLILITER REFLUX BOILER
- C - U-TUBE DESICCATOR
- D - "BRIDGE" STOPCOCK
- E - VACUUM GAGE
- F - IONIZATION CHAMBERS
- G - THERMOCOUPLE VACUUM GAGE
- H - THERMOCOUPLE GAGE CONTROL UNIT
- I - INTAKE LINE
- J - EXHAUST LINE
- K - VIBRATING-REED ELECTROMETER
- L - VIBRATING-REED ELECTROMETER AMPLIFIER
- M - ONE-MILLIAMPERE STRIP-CHART RECORDER
- N - TO TWO ADDITIONAL REFLUX BOILERS

FIGURE 45.—Diagrammatic sketch of radon-measuring apparatus.

radon-air (radon-argon in this report) enclosed by the tubing at any time is small compared to the total volume collected.

SAMPLING TECHNIQUES

Samples of waters were collected in glass tubes of approximately 300 ml volume, with pressure-adapted stopcocks at each end (pl. 7).

The tubes were first flushed with argon in the laboratory and then filled by gently applying suction with the mouth to one end of the tube, with the other end immersed in the stream or spring. The radon content of water from sample tubes thus filled by suction, and that of comparable water collected in tubes evacuated in the laboratory differed by only 1 or 2 percent, which was considered negligible in this work. The water samples, after collection, were never again exposed to the air, as radon is rapidly flushed from any water sample that is allowed to mix with the atmosphere. It has been found that about 45 percent of the radon is dissipated to the atmosphere when a water sample is collected in a bottle, a volume measured out into a graduate, and the measured volume then poured into a reflux boiler. Kuroda, Damon, and Hyde (1954) report the same phenomenon.

FIELD PROCEDURES

At the start of the first radon survey, stream samples were taken at widely spaced intervals, chiefly near prominent outcrops and changes in lithology. When a large amount of radon was found in the stream, samples were taken both upstream and downstream from that point.

It soon became evident that the source of the radon could be established accurately if the sample intervals were short.

All samples were usually taken from the center of the stream at a depth of about 1 inch, and primarily in fast-flowing parts of the streams. All stagnant pools and beaver ponds were avoided. The samples were returned to the laboratory for radon determination, usually within 3 days.

RADON DISTRIBUTION IN SURFACE WATERS DRAINING PARTS OF THE WASATCH MOUNTAINS

GEOLOGIC SETTING

The Wasatch Mountains extend from Nephi, in central Utah, northward into Idaho. Their western face forms part of the eastern limit of the Basin and Range province. Salt Lake City is in the northeast part of Jordan Valley near the steep front of the central Wasatch Mountains.

The area adjacent to Salt Lake City (fig. 46), which includes Red Butte Canyon, City Creek, and Mill Creek, has a relief of 2,500 to 5,000 feet above the floor of the valley.

Near Salt Lake City, the major structural element of the Wasatch Mountains is a broad eastward-trending syncline, which is modified by smaller folds along its trough. The syncline is flanked on the south by the Cottonwood uplift and on the north by the northern Utah

uplift. The sedimentary rocks range in age from Precambrian to early Tertiary.

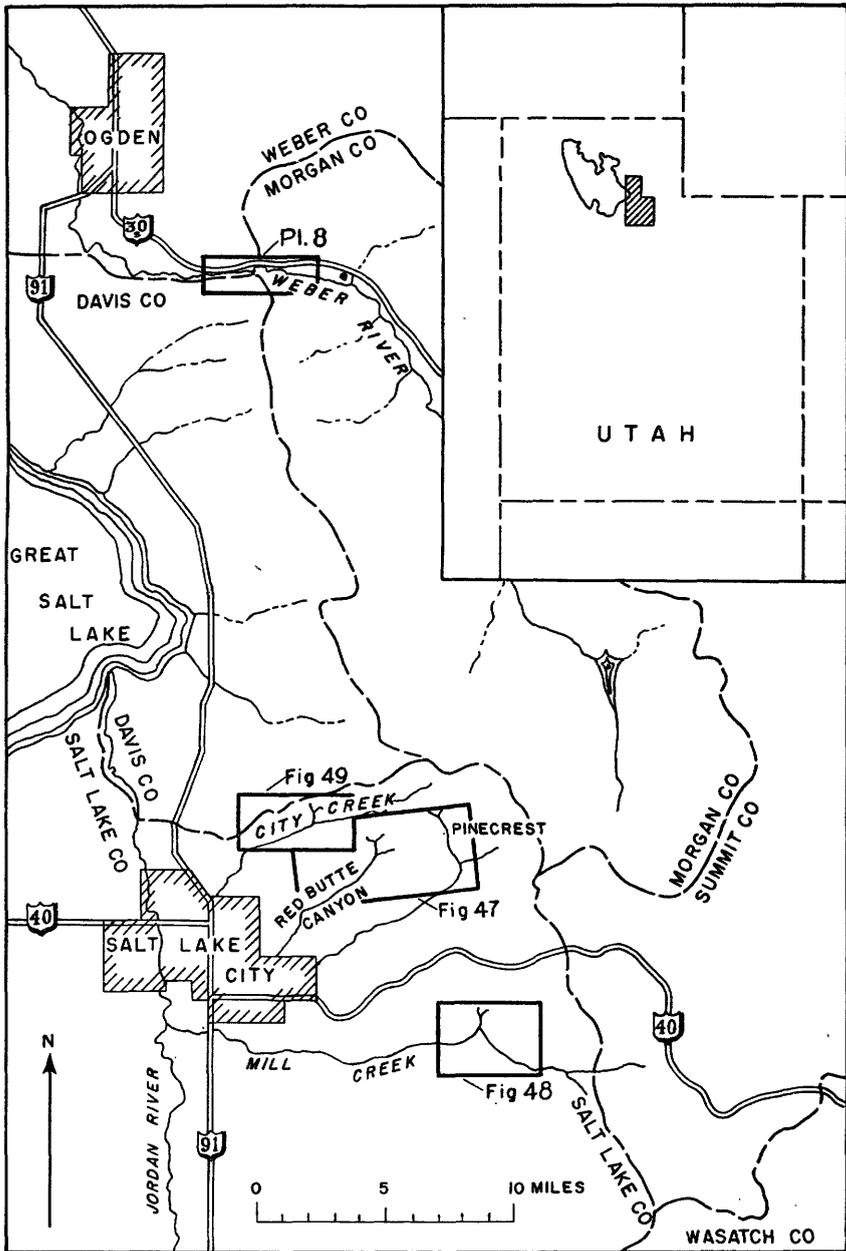


FIGURE 46.—Index map of area near Salt Lake City, showing location of radon surveys.

The sedimentary rocks in the Red Butte Canyon and Pinecrest area range in age from Pennsylvanian to Tertiary (fig. 47). The oldest formation is the Weber quartzite of Pennsylvanian age with an estimated thickness of 1,200 feet. Apparently conformably overlying the Weber quartzite is the Park City formation, of Permian age. Granger (1953) measured a thickness of 974 feet of Park City formation at the head of Red Butte Canyon. For the most part, the Park City formation is made up of limestone with a thick, somewhat phosphatic, shale member in the middle of the formation.

Approximately 3,600 feet of Triassic sedimentary rocks overlie the Park City formation, and include red shale of the Woodside shale, marine limestone and shale of the Thaynes formation, and red shale, siltstone, and sandstone of the Ankareh shale. The Thaynes formation, which is of particular interest in the present investigation, has a thickness of 1,931 feet (Granger, 1953) and consists primarily of shale, sandy and shaly limestone, and one or more beds of gray limestone, which form prominent ridges.

The Triassic sedimentary rocks are overlain by approximately 4,700 feet of Jurassic sandstone, argillaceous limestone, and red siltstone beds.

The conglomerate and red siltstone of the Kelvin formation of Cretaceous age overlie the Jurassic strata with apparent conformity and total about 1,500 feet thick.

Unconformably overlapping the older rocks in the northern part of the area is the Almy (?) conglomerate, of Tertiary age.

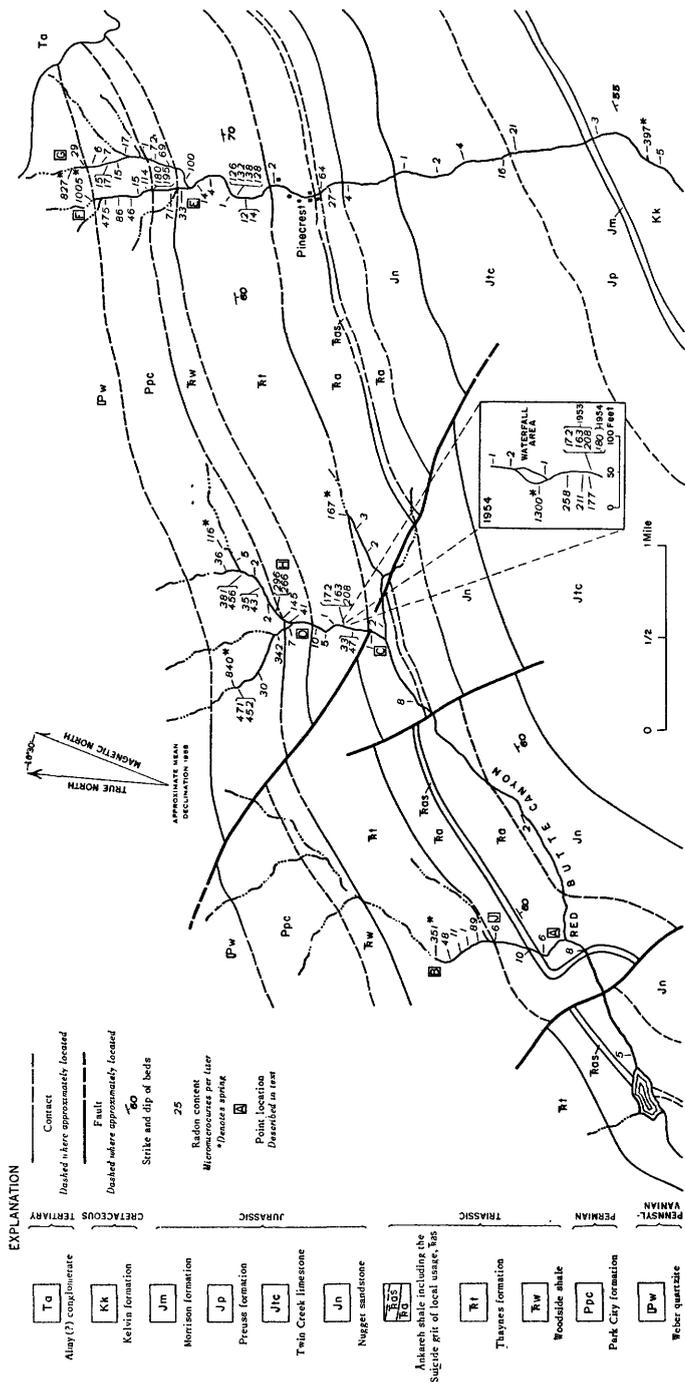
The lithology in the Mill Creek area (fig. 48) is similar to that of the Red Butte Canyon and Pinecrest area. The lower half of the Thaynes formation includes 3 rather thick limestone ridge-forming strata.

In the City Creek area there is sequence of vertically dipping Paleozoic sedimentary rocks (fig. 49) that is an entirely different section than that in the Red Butte Canyon and Mill Creek areas. Here the Paleozoic strata are unconformably overlain by Tertiary conglomerate and volcanic rocks.

DRAINAGE

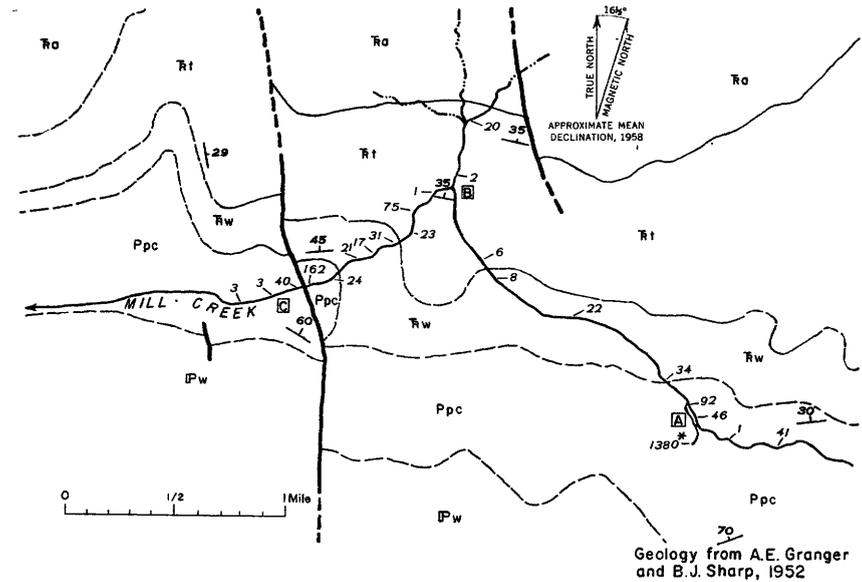
The streams in the Red Butte Canyon and Pinecrest area are small, with steep gradients. The flow at points *A*, *C*, and *E* (fig. 47) is probably about 1 cubic foot per second. The average stream gradients, which were approximated from topographic maps, are: *B* to *A*, about 300 feet per mile; *D* to *C*, including headwaters, about 850 feet per mile; and from either *F* or *G* to Pinecrest, about 800 feet per mile.

The average stream gradient of Mill Creek (fig. 48) between *A* and *C* is about 300 feet per mile. About 3 miles downstream from point *C*,



Geology from A. E. Granger and B. J. Sharp, 1932

FIGURE 47.—Geologic map of Red Butte Canyon and Pinecrest areas, showing radon distribution in streams and springs.



EXPLANATION

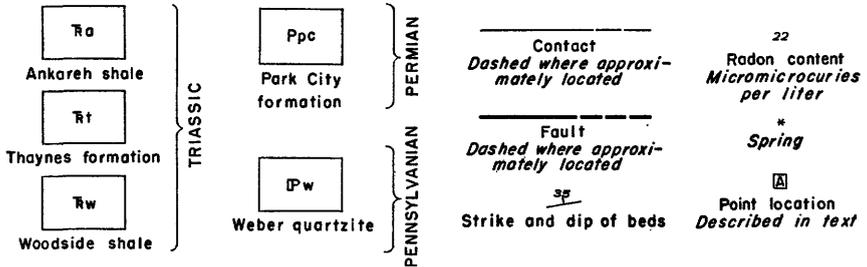


FIGURE 48.—Geologic map of part of Mill Creek area, showing radon distribution in streams and springs.

the streamflow was approximately 12 cubic feet per second. Because of water diversion, the streamflow between *A* and *B*, perhaps 8 or 10 cubic feet per second, is probably twice the flow between *B* and *C*.

The average stream gradient of City Creek (fig. 49) between *D* and *B* is about 800 feet per mile. At point *A* the streamflow, based on 1950 measurements, is probably about 2 cubic feet per second in each fork.

OBSERVATIONS IN RED BUTTE CANYON AND PINECREST AREAS

The radon contents of stream waters and springs in these areas are shown in figure 47 in micromicrocuries per liter. All repeat samples at the same localities are shown in brackets.

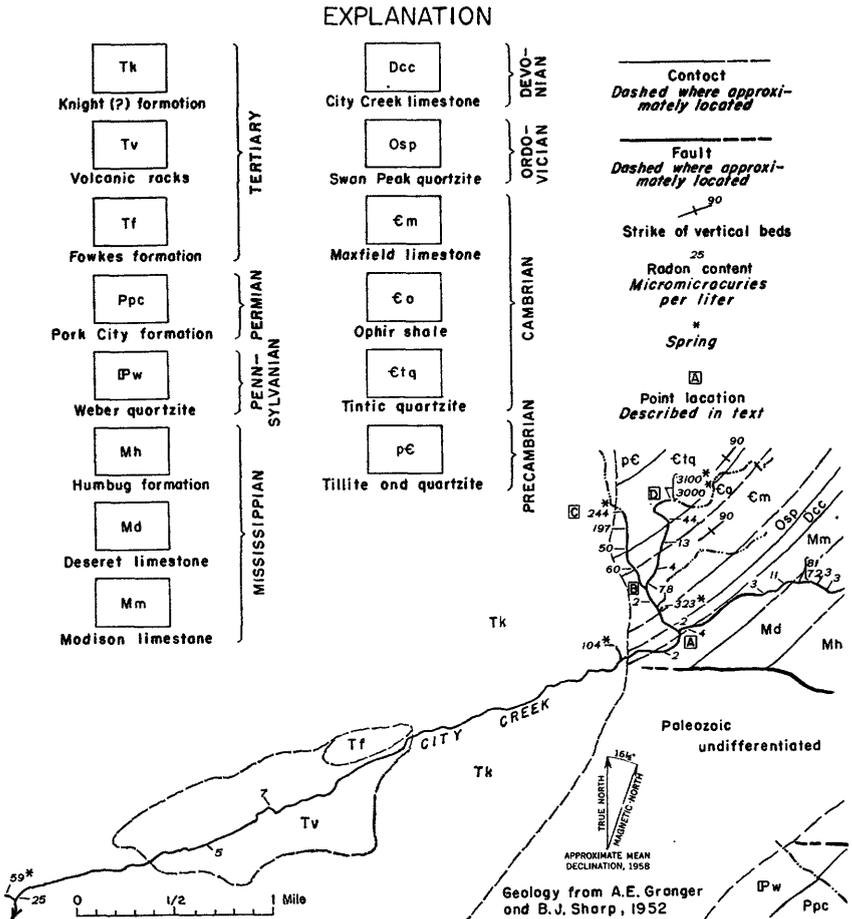


FIGURE 49.—Geologic map of part of City Creek area, showing radon distribution in streams and springs.

The distribution of radon in the stream waters was found to follow a definite pattern. In each case relatively high radon contents are found in springs at the sources of the various streams. As the water moves downstream, the radon content decreases rapidly, in some places almost to zero within 500 feet. Further downstream other zones of high radon concentrations are noted in the stream waters. These concentrations also decrease rapidly as the water moves downstream.

This pattern of radon distribution in stream waters apparently depends upon the influx of radon-bearing ground water into the stream, and, in turn, upon the loss of radon from the stream water to the atmosphere. As air usually contains less than one micromicrocurie per liter, any radon exceeding one micromicrocurie per

liter in the stream water is out of equilibrium with that in the atmosphere and will therefore decrease and approach equilibrium (fig. 44). After a large amount of radon has been introduced into the stream by ground water, it is quickly released to the atmosphere at a rate governed by the volume and gradient of the stream, and the nature of the stream channel. Radon content plotted against distance of streamflow shows the loss of radon to the atmosphere to be an exponential function with somewhat different slopes in different drainage areas (fig. 50).

The anomalously high radon concentrations indicate areas where ground water, in large amounts relative to the stream volume, is being added to the stream, even though, in most places, no evidence of springs is apparent.

This ground-water source for the anomalous radon concentrations in stream waters is postulated for the following reasons:

1. The springs in the area generally contain more radon than the stream waters and seem to be the logical source. A water-saturated sedimentary rock with a density of 2.5, a 10-percent porosity, uranium content of 1 ppm (3.3×10^{-13} grams of radium per gram of rock), and an emanating power of 10 percent can theoretically contribute 825 micromicrocuries of radon per liter to the enclosed ground water under static conditions. If ground water, under dynamic conditions, containing about 800 micromicrocuries of radon per liter enters and contributes 10 percent to the total volume of streamflow, the radon concentration in the stream water will increase by about 80 micromicrocuries per liter at the point of ground-water entrance.

2. The decay constant for radon is 0.007551 per hour or 0.000126 per minute. This shows the fraction of radon per unit of time that will form from a radium source. Hence, it seems unlikely that the radium content of the rocks and detritus exposed in the stream channel itself will contribute much radon to the stream's waters, because the radon will be continuously and swiftly swept downstream and dissipated to the atmosphere.

3. Surveys with a scintillation counter showed no abnormally high radioactivity in the rocks along the stream channels. On the contrary, the limestone beds in the area, with which most radon anomalies in the stream waters are related, show a normal, lower background than that of the adjacent shale.

4. A definite relation has been found between some high radon content in stream waters and adjacent radon-bearing springs.

The areas of relatively large amounts of ground-water influx thus marked by radon anomalies can be related to rather definite stratigraphic horizons. The anomaly of 126 micromicrocuries per liter

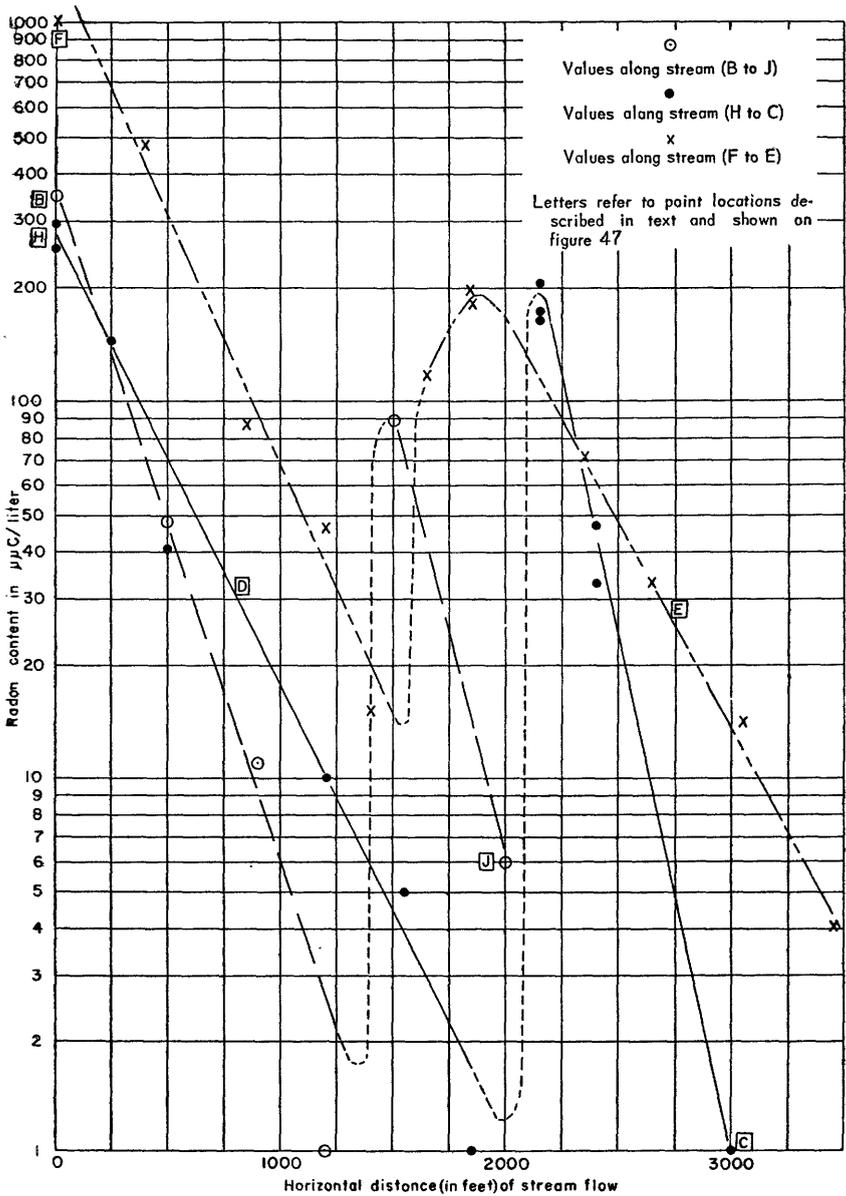


FIGURE 50.—Radon loss from streams and springs in Red Butte and Pinecrest areas.

about ½ mile north of Pinecrest at a point where repeat samples were taken over a period of 3 months, is related to a thin (10 or 20 feet) prominent limestone ridge in the Thaynes formation that causes an abrupt change in stream gradient. The anomaly in the Thaynes in drainage DC is similarly related to a thin limestone ridge. Although

no prominent limestone ridge was noted in the Thaynes formation in drainage *BA*, there is an anomaly of 89 micromicrocuries per liter at a point of abrupt change in stream gradient, which suggests that the limestone is also present at the point of the anomaly in drainage *BA*. Another limestone ridge occurs near the base of the Thaynes formation north of Pinecrest, where an anomaly of 100 micromicrocuries per liter is found.

The upper limestone member of the Park City formation also acts as an aquifer, particularly near its contact with the Woodside shale. Radon anomalies that are generally small are associated with the middle part of the Ankareh shale. This part of the Ankareh is the Suicide grit of local usage and may be equivalent to the Shinarump member of the Chinle formation.

A somewhat perplexing difference in radon distribution exists between drainage *FE* and *GE*, which are parallel and only about 1,500 feet apart. Drainage *FE* contains a higher level of radon concentration than drainage *GE*, and there is a large radon anomaly near the Park City-Woodside contact in drainage *FE*; yet no anomaly was found in drainage *GE*. This marked difference may be due to the differences in the two stream channels. The channel of drainage *FE* is partly bedrock, and partly soil derived from bedrock, and has considerable vegetation. Whether the vegetation is supported by water from the stream or by spring water is not known, although there is presumably some influx of ground water into the stream to maintain the relatively high radon content.

Channel *GE* is choked with cobbles and boulders of Weber quartzite and Almy (?) conglomerate at least 15 feet thick near the Park City-Woodside contact. Increased turbulence probably contributes to the low radon concentrations. It is also possible that any ground water that enters the channel does so at depth, and then emerges to mix with the stream water in the area of the Woodside shale, where the layer of cobbles and boulders is thinner or absent.

In the summer of 1954 a more detailed study was made of the anomaly associated with a small limestone ridge in the Thaynes formation in drainage *DC* (see inset on fig. 47). By sampling at very close intervals, the radon anomaly was pinpointed to within 50 feet of its source. The source was traced to a small spring containing 1,300 micromicrocuries of radon per liter issuing from a small limestone cavern under a small waterfall. This spring had not been noticed during the 1953 survey. A spring flowing about 50 gallons per minute from the bottom of the stream channel and containing 550 micromicrocuries of radon per liter was found about 50 feet upstream from the radon anomaly in the Thaynes formation $\frac{1}{2}$ mile

north of Pinecrest. The entire streamflow had been diverted for domestic purposes and the stream channel upstream from the spring was completely dry.

OBSERVATIONS IN THE MILL CREEK AREA

Large increases in radon content were found in the stream waters near limestone beds in the Park City and Thaynes formations. These limestone beds apparently act as aquifers in a manner similar to that found in the Red Butte Canyon and Pinecrest area. The spring at point *A* (fig. 48) also acts as a source of radon in the stream water.

A plot of radon content versus distance of streamflow between *A* and *C* is shown in figure 51. This plot also shows that the rate of radon loss is an exponential function with respect to distance of stream-flow. The slope of the curve between *A* and *B* is much flatter than those for drainages in the Red Butte Canyon and Pinecrest area (note the difference in the distance scale), probably owing to the greater stream volume and lower gradient in the Mill Creek area. The exponential function has a flatter slope between *A* and *B* than near point *C*. This is probably due to the smaller stream volume near point *C*. The slope of the function near point *C* is almost identical to those in the Red Butte Canyon and Pinecrest area.

As Mill Creek is a fairly wide stream, a series of samples were taken near point *A* at various positions in the stream to determine whether sampling position is a critical factor. The stream at this point is about 7 feet wide. The radon content, on the basis of this one experiment, varies only about 5 percent with respect to stream position. The results shown in figure 52 indicate that the maximum radon content is in the center of the stream, and is apparently constant with depth.

OBSERVATIONS IN THE CITY CREEK AREA

The results of the radon survey in the City Creek area (fig. 49) are similar to those in the other two areas, although City Creek flows over an entirely different sequence of rocks than those exposed in the Red Butte and Mill Creek areas. Many small springs maintain a higher level of radon concentration along the fork *CB* than in fork *DB*.

RADIUM IN STREAMS AND SPRINGS

Several radium determinations of stream- and spring-water samples show that the radon is almost completely unsupported by its parent radium in solution. The radium content in each sample is of the order of 1 micromicrocurie per liter. As this small amount ap-

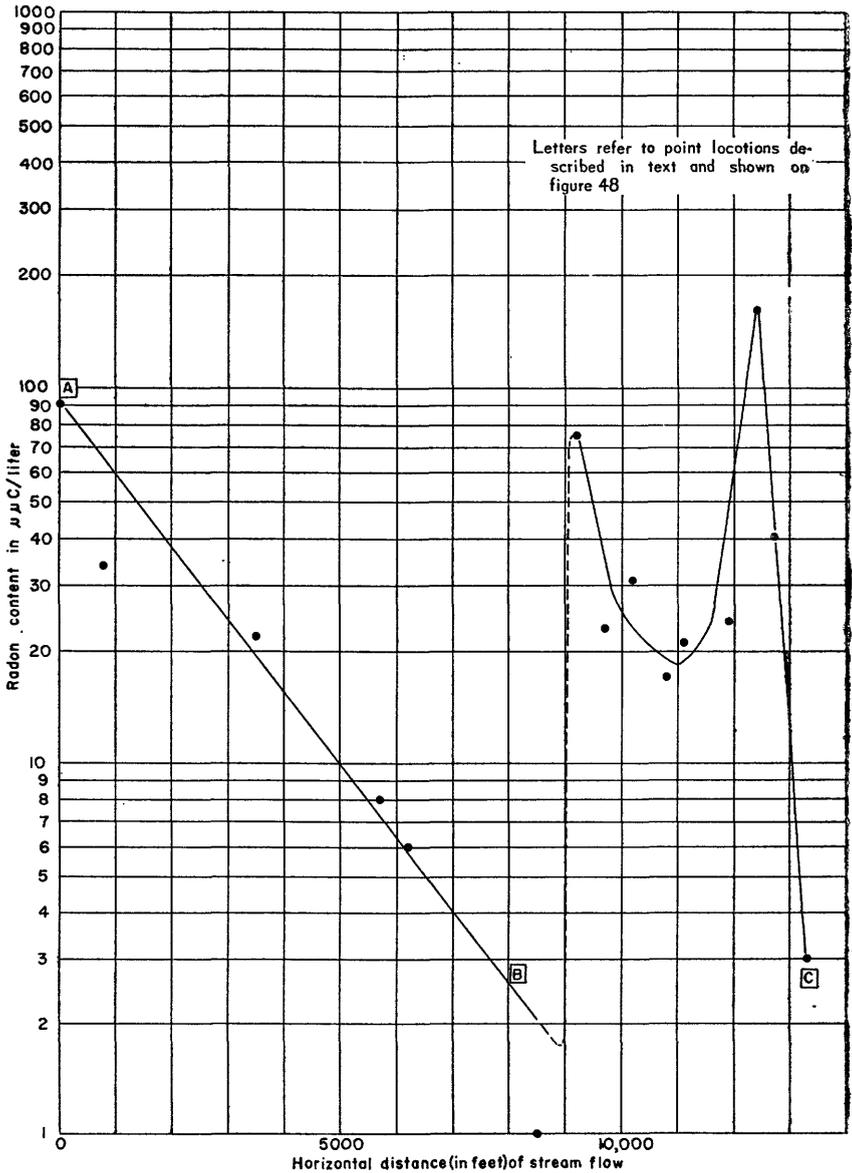


FIGURE 51.—Radon loss from part of Mill Creek.

proaches the limit of the sensitivity of the instrument, the radium content may be less. No uranium analyses of the samples were made.

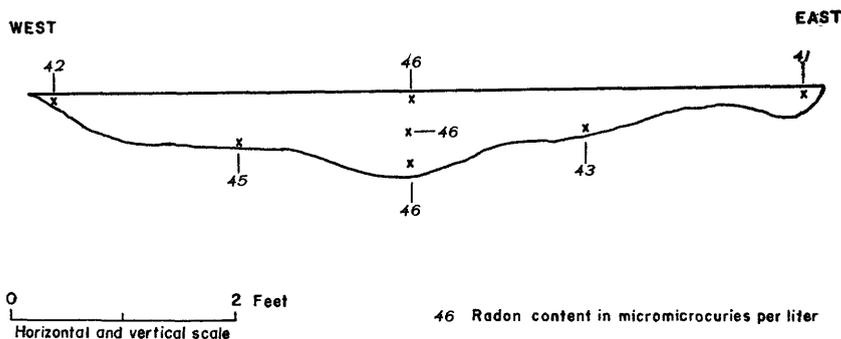


FIGURE 52.—Cross section of Mill Creek showing radon distribution.

APPLICATION TO A SURFACE-WATER PROBLEM IN THE WEBER RIVER DRAINAGE AREA

Radon determinations in stream waters and related springs were applied to a ground-water problem in a part of the lower Weber River drainage area, near Ogden, Utah (pl. 8).

The Weber River in this area flows due west through a steep-walled canyon in the northern Farmington Mountains. The Farmington Mountains, a division of the Wasatch Range, are characterized by a well-exposed Precambrian metamorphic terrain. Ten thrust plates, represented by diaphthorite zones of retrograde metamorphism, are exposed near the Weber River canyon (Bell, 1952).

Measurements by John Feth of the Geological Survey show that the flow of the Weber River increases from 2.82 cubic feet per second at point *A* to 7.50 cubic feet per second at point *D*, a distance of 1½ miles (pl. 8). The only visible additions to the streamflow, from springs at points *E*, *F*, and *G*, amounted to about 20 gallons per minute (about ½₂₀ cubic foot per second). The stream gradient is about 100 feet per mile.

The problem was to determine whether the increase in stream volume was due to a continual influx of ground water along the stream course between *A* and *D* or whether it was mostly confined to the limited area of visible seeps, at points *E*, *F*, and *G*. An attempt was also made to determine if the increase in stream volume was due to the influx of bedrock or bank storage ground water. It was impractical to gage the stream flow between *A* and *D* because of the abundance of large boulders in the stream channel.

The radon contents of stream waters and springs were determined in the Weber canyon area (pl. 8). Radon contents of the major springs in the Gateway Tunnel, U. S. Bureau of Reclamation Project, were also determined. The radon determinations in the tunnel,

which are underlined on the map, were collected from galvanized troughs or drips from the back, and are considered to have been lowered at least 50 percent, and possibly more, by loss of radon to the air.

No abnormal radioactivity was detected by a scintillation counter traverse through the tunnel except in a small area 1,000 feet from the east portal. A sample was collected by John Powers, U. S. Geological Survey, Salt Lake City, Utah, who made the scintillation-counter traverse. The sample, which was taken from a podlike mass of pegmatitic material, contained 0.003 percent equivalent uranium.

Quality-of-water measurements were made on 3 spring and 4 stream samples, at points *A* through *G*, by J. G. Connor, U. S. Geological Survey, Salt Lake City, Utah. These measurements were made partly to aid in ground- and surface-water studies in the Ogden, Utah, area, and partly to determine if any relation can be established between quality-of-water and radon measurements. The results of the quality tests are listed in the following table. There is no apparent direct relation between quality of water and radon content.

Data on quality of water, Weber River, Feb. 15, 1954

[Data from J. G. Connor, Quality of Water Branch, U. S. Geological Survey, Salt Lake City, Utah]

Sample location	Temp. (° F.)	pH	HCO ₃ (ppm)	SO ₄ (ppm)	Cl (ppm)	Hardness (CaCO ₃ -ppm)	Noncarbonate hardness (ppm)	Specific conductance (micromhos)	Radon content/l
Stream samples									
A.....	39	8.1	280	32	26	257	27	554	15
B.....	35	8.3	277	32	26	256	29	549	5
C.....	42	8.0	256	32	22	234	24	512	156
D.....	42	8.2	218	28	20	200	21	446	78
Spring samples									
E.....	47	7.6	243	32	19	220	21	482	532
F.....	46	7.8	248	32	18	222	19	487	516
G.....	45	7.7	228	28	19	210	23	465	755

A clear relation was found between the distribution of high radon concentrations in the Weber River and the radon-bearing springs at *E*, *F*, and *G*. The distribution pattern is similar to that found in the streams in the Wasatch Mountains near Salt Lake City, Utah. When radon is plotted against distance of streamflow (fig. 53), the loss of radon again is an exponential function of distance.

Because other high radon concentrations in the stream waters are related to springs, it is believed that ground water contributes a small amount to the streamflow below the railroad bridge in the S-shaped part of the stream, and a larger amount in a zone between *D* and *K*. The large addition of ground water in the zone between *D* and *K* is

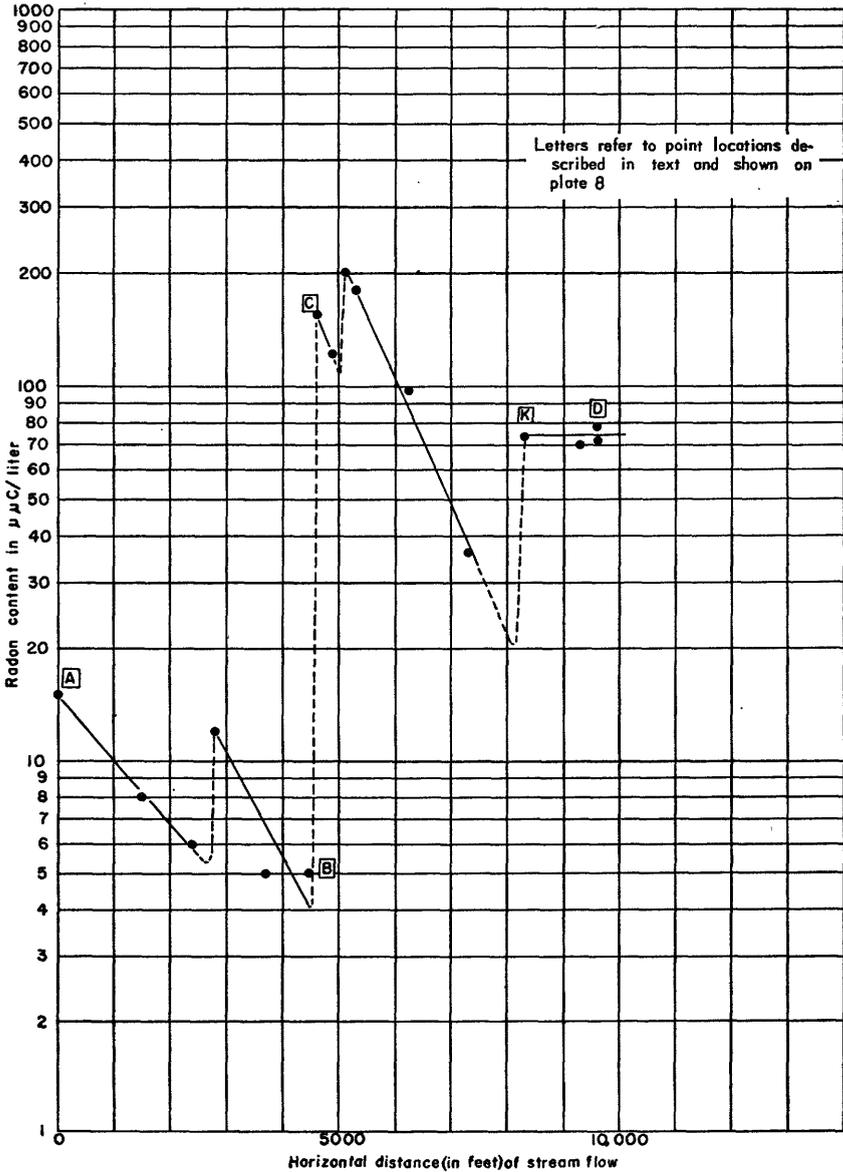


FIGURE 53.—Radon loss from part of Weber River.

supported further by the quality-of-water analyses as shown in the above table. The measurements of total hardness and specific conductance show that the solids content of the stream at point *D* is less than the solids content upstream at points *A*, *B*, and *C*, and also less than the solids content of the springs at *E*, *F*, and *G*. If it is assumed

that the stream is not precipitating part of its solid content, then an addition of better quality water occurs between *G* and *D*.

The area of visible springs at *E*, *F*, and *G*, as well as at *D* and *K*, which are the other areas of large ground-water influx, show a marked relation to the surface expression of thrust plates in the canyon. If bank storage is the controlling factor in the movement of ground water in this area, the entrance of ground water into the stream, and the resultant radon anomalies in the stream, would probably be in the areas where a large amount of alluvial material is present.

An attempt was made to use the radon measurements of stream and spring waters to calculate the increments of stream volume between points *A* and *D*, where intermediary stream gaging was impractical because of the many large boulders in the channel.

The following assumptions were made in the calculations:

1. The stream does not lose or gain in volume between the points of radon anomalies; that is, the streamflow at *B* is $2.82 + 0.04$ cubic feet per second. Similarly, the streamflow at point *K* is assumed to be $2.82 + 0.4 + 1.2 + 0.75$ cubic feet per second.

2. Radon contents of the springs are representative of all ground water entering the stream at the particular point.

3. Complete mixing of radon occurs in the stream waters.

4. The rate of radon loss in the stream is constant. For instance, at a point just upstream from *K*, the stream is assumed to contain about 20 micromicrocuries per liter, based on the exponential rate of radon dissipation between *G* and *K* (fig. 53).

5. In the area *DK*, the radon content of the ground water entering the stream is assumed to be 600 micromicrocuries per liter, based on the average radon content of known springs at *E*, *F*, and *G*.

The results of the calculations, which are believed to be reasonable estimates, are shown on plate 8 at points *F*, *G*, the zone between *D* and *K*, and the small radon anomaly in the S-shaped part of the stream. At point *F*, for instance, the amount of influx of ground water, containing approximately 500 micromicrocuries per liter, was determined to be 1.2 cubic feet per second, since it raised the radon concentration in the stream from 5 (at point *B*) to 156 (at point *C*) micromicrocuries per liter. The calculations thus account for about 65 percent of the streamflow increase between *A* and *D*.

In summary, the bulk of the ground water that enters and increases the flow of the Weber River can be considered bedrock rather than bank storage ground water. The movement of ground water in the area is apparently controlled by the diaphthorite thrust plates. On the basis of radon concentrations in the stream waters and related springs, calculations were made which accounted for about 65 percent of the total increase in streamflow between points *A* and *D*.

SUMMARY OF CONCLUSIONS

Radon concentrations in stream waters can be used to determine areas where relatively large amounts of radon-bearing water enter small turbulent streams. These areas of influent ground water are marked by abrupt increases in the radon content of the stream waters and can be determined accurately, provided short intervals of sample spacing are used. The high radon concentration in the stream water is then rapidly dissipated to the atmosphere as an exponential function, of various slopes, with respect to distance of streamflow. The rate of radon dissipation is dependent upon the radon distribution ratio, the rate and volume of streamflow, the gradient of the stream, and the nature of the stream channel.

In the Wasatch Mountains adjacent to Salt Lake City, Utah, the high radon concentration in stream waters can generally be related to definite stratigraphic horizons in several drainage areas. Thus, lithologic units which act as the primary aquifers can be determined.

The technique of locating areas of ground-water influx into streams by radon determinations was applied to a definite ground-and surface-water problem in a part of the lower Weber River area. The problem was to determine the points of streamflow increase and whether this was due to the addition of bedrock or bank-storage ground water. Conventional methods, such as stream gaging, were not practical in this instance. The increase in stream flow was found primarily in three areas apparently associated with thrust faults. Calculations, based on radon concentrations in stream waters and adjoining springs, were made to determine the amount of ground water entering the Weber River at each zone of increase.

The radon content of both stream and spring waters was found to be almost completely out of equilibrium with its parent radium.

The results of the present investigation on the distribution of radon in streams and related springs should have applications to ground-water studies.

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