UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

UTILIZATION OF GAMMA-RAY LOGS BY THE U. S. GEOLOGICAL SURVEY, 1949-1953

By

Kenneth G. Bell, Vasco C. Rhoden,
Ralph L. McDonald, and Carl M. Bunker

1961

This report was prepared as a guide for Geological Survey personnel engaged in gamma-ray logging, and has not been reviewed or edited for conformity with Geological Survey format and nomenclature

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INTRODUCTION

It has been known for several decades that all terrestrial materials contain radioisotopes, and that quantitative determinations of these radioisotopes can be made in the laboratory even when the quantities present are extremely minute. From the time radioactivity was discovered in 1896 to the late 1930's some quantitative data were collected on radioisotopes, particularly those of the uranium family, in different kinds of rocks, and sporadic attempts were made to utilize radioactivity in geophysical explorations. In the late 1930's it was discovered that gamma-ray logs of drill holes and wells drilled through sedimentary formations could be used as an aid to stratigraphic correlation. The first published gamma-ray well logs made by a continuous profiling process appeared in 1939 (Howell and Frosch), and within a few years the use of gamma-ray logs was firmly established in the petroleum industry.

The desirability of developing a rapid geophysical method for detecting radioactive minerals was brought about by the intensified search for uranium ore, which began about 1942. The Manhattan Project sponsored a project to develop an instrument capable of making gamma-ray logs of small-diameter holes drilled for exploring mineral deposits.

Work was started early in 1945 by private industry and an instrument was constructed and tested in the field on the Colorado Plateau during the summer of 1945. The project was discontinued in 1946 and was resumed in 1948 by the Geological Survey with the following objectives:

1. Development of a gamma-ray logging unit for obtaining gamma-ray logs of small-diameter drill holes (as small as EX size or 1½-inch diameter).
2. Calibration of gamma-ray logging equipment to interpret logs in terms of the thickness and equivalent uranium content of radioactive zones, with particular emphasis on establishing a technique capable of measuring 0.01 percent equivalent uranium with a small degree of error.
3. Evaluation of data from gamma-ray logs with particular attention to the possibility of utilizing a gamma-ray log as a tool or criterion for stratigraphic correlation of zones favorable for uranium and other radioactive ores.
4. Establishment of a systematic procedure of gamma-ray logging small diameter holes.

Gamma-ray logging investigations made by the Geological Survey have been concerned only with natural radioisotopes. The natural radioisotopes that are gamma-ray emitters are included in the daughter products of U^{238}, Th^{232}, and U^{235} which are the parent elements of the uranium, thorium, and actinium families respectively, and K^{40} and RB^{87}. Almost all the uranium contained in the earth is believed to be concentrated in the upper lithosphere. Many terrestrial materials contain uranium and its daughter products in measurable quantities, but the amounts found are often very small. Thorium also is believed to be concentrated in the upper lithosphere, but it probably is not as widely distributed as is uranium. Natural potassium consists of about 0.012 percent of the radioactive isotope K^{40}. Potassium forms a substantial part of many igneous rocks and some sedimentary rocks and, therefore, is widely distributed in the lithosphere. Rubidium is a comparatively rare element having a restricted distribution.

The radioactivity recorded during the process of making gamma-ray logs consists of contributions from all the radioisotopes listed above that happen to be present on or near the wall of the drill hole. Gamma-ray logs, therefore, always indicate some radioactivity. Conventional techniques for making gamma-ray logs do not identify the radioisotopes responsible for the radioactivity.

A gamma-ray log of a drill hole is a profile of the intensity of gamma-ray flux existing along the length of the hole. Either intermittent or continuous profiling techniques can be used to make the log. Continuous profiling makes the most economical use of time and labor for routine logging operations; this method was used for all gamma-ray logging described in this report.

A great variety of instruments and equipment is available from which to choose the components of a gamma-ray logging unit. The selection of parts depends to some extent upon the use to be made of the logs. If, for example, quantitative determinations of the grade and thickness of radioactive mineral deposits penetrated by drill holes are to be made, a more careful selection of parts is necessary than when strictly qualitative data are desired. The most important variables that should be considered in selecting components are accuracy, ruggedness, adaptability, useful life, and cost.

One of the most critical parts of a gamma-ray logging unit is the counter, or radiation detector, which intercepts gamma rays and initiates electrical pulses which are transmitted to the measuring element. Until recently Geiger-Mueller tubes and ionization chambers were used as counters in all gamma-ray logging equipment. Experimental work using scintillation-type detectors for gamma-ray logging has been started. The combination of scintillation detectors and pulse-discriminator circuits offers a possibility for the development of techniques for identifying radioisotopes from gamma-ray logs. All the gamma-ray logging described in this report was done with Geiger-Mueller tubes.

The first draft of this report was written in 1954 and until now (1961) it has been used as a guide by U. S. Geological Survey personnel concerned with calibrating and operating the equipment, interpreting the logs, and applying the data to geologic problems. The quantitative data contained in this report may not apply to equipment other than that described. These data include, in part, instrument response to particular grades of uranium ore, and the effect of inhole variables, such as drill-hole casing, on instrument response. These values must be determined empirically for each make and model instrument used.

During the period of time covered by this report most of the gamma-ray logging equipment used for uranium exploration was government-owned and operated. Since then, this type of equipment has become available to many logging and mining companies, and its use has increased greatly.

Many investigations pertaining to the possible uses of gamma-ray data for geologic studies--for example, using isoradioactivity contour maps as guides for exploration drilling--were relatively new ideas when the report was first written. Since then, the methods have been improved, and have been accepted as routine techniques for uranium exploration. The objectives of more recent work by the U. S. Geological Survey have been to refine some of the methods, improve the instrumentation, and make other types of studies than those described herein.

Kenneth G. Bell supervised the investigations during the period covered by this report and was responsible for initiating much of the experimental work pertaining to the calibration and interpretation techniques that are used by the U. S. Geological Survey. He was responsible for writing most of the first draft of this report.

Vasco C. Rhoden, electronics engineer, made numerous modifications on the equipment to improve instrument response and stability. He has described the design and operational characteristics of the ratemeter used with the logging equipment.

Ralph L. McDonald, geologist, used gamma-ray data as a guide for determining favorable locations for ore deposits in the Yellow Cat area, Grand County, Utah. His comparative studies of two methods of determining favorable areas, that is, on the basis of geologic criteria and on gamma-ray data, was one of the first of its kind and the results undoubtedly contributed to the increasing interest within the U. S. Geological Survey for using gamma-ray data for this purpose.

Carl M. Bunker, geophysicist, aided with the experimental work reported here, and revised the report for release to open file.

This work was undertaken by the Geological Survey on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission.

DESCRIPTION OF EQUIPMENT

A test model of a truck-mounted unit (fig. 1) designed for the Manhattan Project was assembled and used to make gamma-ray logs of several thousand feet of drill holes on the Colorado Plateau in 1945. The electronic circuits of this unit were designed by R. J. Smith (1945). Mechanical parts were designed by Henry Faul and C. H. Metzger. Because this work was part of a secret project the code work "Barnaby" was given to the logging unit. Although the secret classification has been removed, the code word is still used as a nickname for the Geological Survey's gamma-ray logging units.

The principal parts of the test model were: (1) a brass probe which contained a Geiger-Mueller tube and a pulse amplifier, (2) a coaxial cable which supported the probe in the drill hole and acted as an electrical conductor between the probe and the main electronic circuits, (3) a reel assembly which held and fed the cable, (4) the main electronic circuits which amplified and integrated the pulses received from the probe, (5) an indicating device which included a strip-chart recorder, and (6) a power supply which consisted of a bank of storage batteries and a charger. A sheave mounted on a tripod was used to guide the probe and cable vertically into the hole while logging. This model was used to log holes as deep as 200 feet.

Several modifications and improvements in the design of the original logging unit have been made since 1945, although the same basic components are still used. The pulse amplifier in the probe has been eliminated,

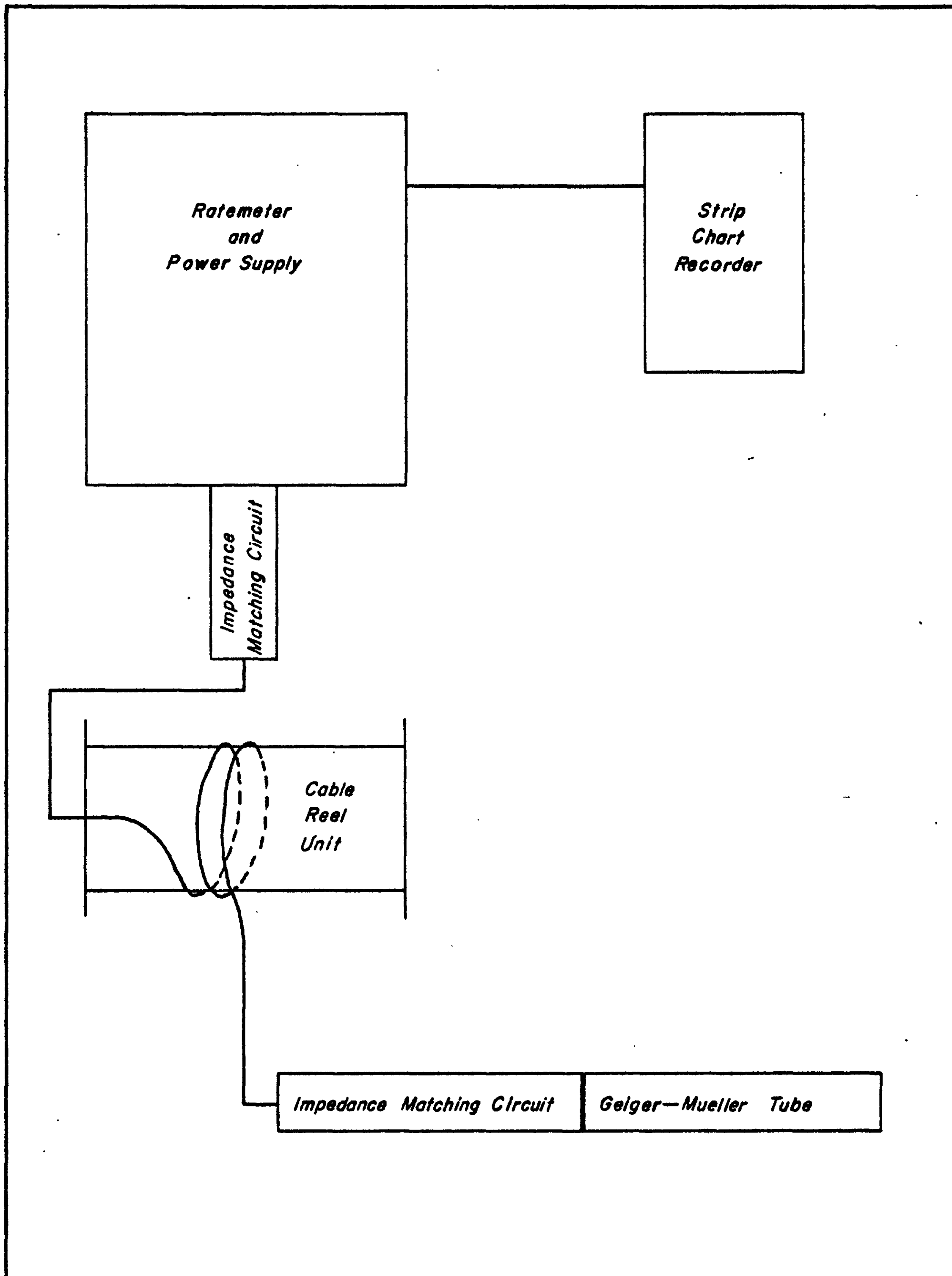

FIGURE I. DIAGRAMMATIC SKETCH OF LOGGING EQUIPMENT.

the reel assembly has been enlarged to accommodate more cable, the electronic ratemeter has been redesigned, and a gasoline-engine driven motor-generator unit has been substituted for the bank of storage batteries.

The probe assembly consists of a brass housing, a Geiger-Mueller tube that has an effective length of 7¼ inches, and an impedance matching circuit. The basic design (fig. 2) is used to make probe housing with external diameters ranging from 7/8 inch up to 2¼ inches. The housing consists of a seamless tube threaded internally at the ends, and a detachable point and head. The probe head is drilled out longitudinally so that the coaxial cable can extend into the interior of the housing. The top of the probe head is made in the form of a slotted cone over which an internally tapered binding cap is tightened to grip the coaxial cable. At the bottom of the probe head there is a recess, the lower part of which is threaded, and into which a rubber washer is inserted. A threaded brass bushing is tightly screwed into the recess over the rubber washer to form a water-tight seal about the coaxial cable. The probe head and point are threaded (40 threads/inch) to fit into the tube so that the external joints are flush. These seals are easily assembled in the field. Only one special tool is required, a spanner wrench (fig. 3), to insert the bushing into the recess in the probe head. These probes have been used without leakage under heads of 1,600 feet of water and 1,200 feet of saturated brine. The probe housings are made to hold the Geiger-Mueller tube and impedance matching circuit without excessive play. The sequence of operations for assembling the probe are outlined in figure 3.

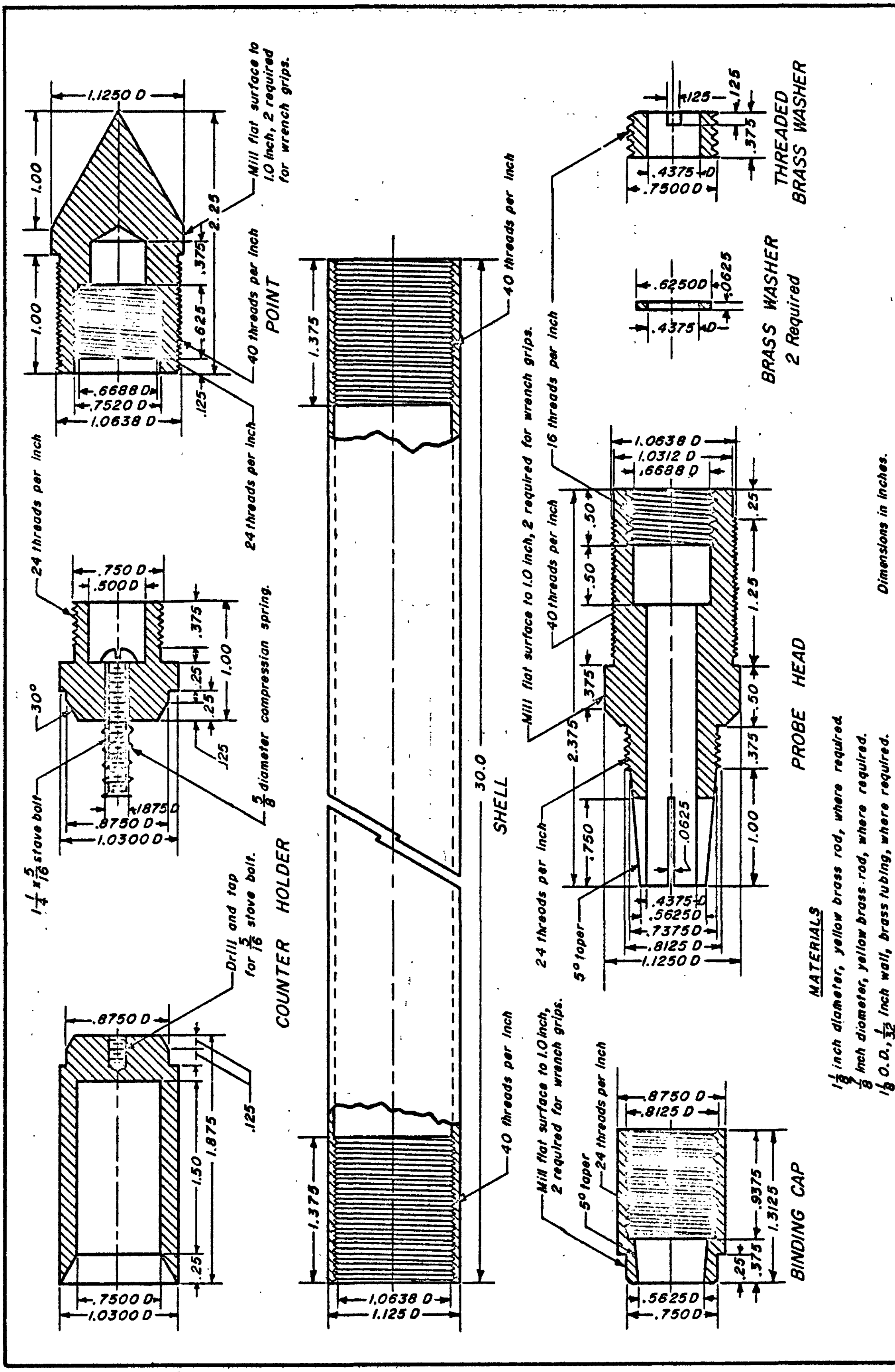

FIGURE 2. PROBE HOUSING.

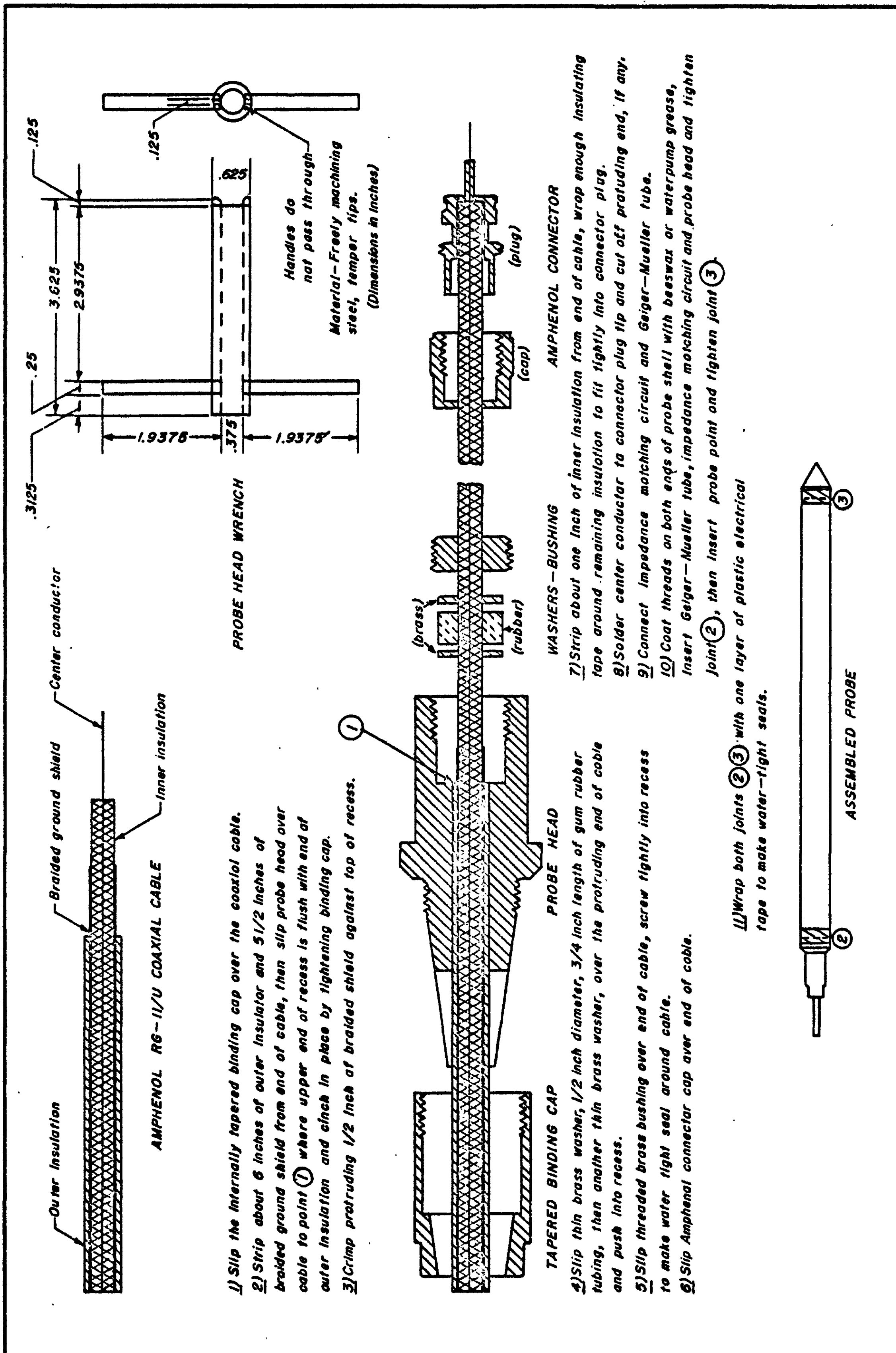

FIGURE 3. DIRECTIONS FOR ASSEMBLING PROBE HOUSING.

Any coaxial cable having satisfactory electrical characteristics and the strength to support its own weight plus that of the probe can be used. Water-tight seals can be made more easily about rubber- or synthetic rubber-covered cables than about wire- or wire mesh-covered cables.

Cable reels are made to hold a minimum of 2,000 feet of RG 11/U or RG 59/U cable. Reels are equipped with level-winding cable-laying devices and measuring wheels that are driven from the drum axle by a chain and sprocket arrangement. Electrical connections from the coaxial cable through the revolving reel drum to the electronic ratemeter are made by a slip-ring and brush assembly mounted on the drum shaft. Power for driving the reel is furnished by an electric motor and is transmitted through a speed reducer and variable speed pulleys.

The main electronic circuits consist of a ratemeter, the metering circuit of which is connected in series with the measuring element of a strip-chart recorder, and an electronic power supply. The ratemeter now being used is a modification of the model designed by R. J. Smith (1945). Geological Survey personnel who have participated in the redesigning and modification are Henry Faul, Kenneth A. Kiesel, Vasco C. Rhoden, and William W. Vaughn.

The strip-chart recorder is equipped with a one milliampere movement and phantom chart drive. The movement is series connected with the metering circuit of the electronic ratemeter. The chart-drive mechanism is powered from the axle of the cable-measuring wheel on the reel through a flexible shaft and gear box. A choice of gear ratios permits the vertical scale of the chart to be changed.

Early models of the logging units were powered by storage batteries and chargers. Storage batteries were unsatisfactory because of (1) voltage drop across cables connecting batteries to the ratemeters, (2) the necessity of using a vibrator in the electronic power supply and the frequent injection into the ratemeter of spurious pulses originating in the vibrator, and (3) maintenance required to keep storage batteries in operating condition. Units now being used are powered by two-cylinder gasoline-engine driven motor-generator plants having a 1,500-watt, 110-volt output. These plants furnish power for the ratemeter and the reel motor. A constant-voltage transformer is placed in the line between the generator and the ratemeter.

The logging unit is constructed to permit easy removal and replacement of the major components such as the probe, cable reel-assembly, ratemeter, strip-chart recorder, and motor-generator plant. All these components can be replaced while the logging unit is in the field thereby eliminating lengthy shut-downs for repairs.

FUNCTIONAL DESIGN AND OPERATIONAL CHARACTERISTICS OF THE RATEMETER

The ratemeter electrically receives, amplifies, shapes, integrates, and records the average number of pulses per unit time on a strip-chart recorder. The pulses originate in a Geiger-Mueller tube enclosed in a probe which is suspended on the end of a coaxial cable in the drill hole. To achieve an efficient coupling of the small electrical pulse through the relatively long length of cable (up to 2,000 feet), an electrical coupling circuit in the probe unit matches the high impedance of the Geiger-Mueller tube to the low impedance of the coaxial cable, and it inverts the pulse as the ratemeter is designed to accept only positive pulses.

At the input of the ratemeter another coupling circuit matches the low impedance of the coaxial cable to the high grid impedance of the amplifier tube, and at the same time restores the pulse practically to its original voltage. The pulse is then amplified and fed into a clipper, which accepts only the pulses above a selected amplitude, rejecting any smaller pulses which might be noise picked up by the cable. The clipped pulses trigger the grid of a univibrator stage which serves to shape all pulses uniformly. The pulses are again clipped to an amplitude of about 5 volts and then are applied to the metering stage.

The metering circuit consists of two tubes in a "flip flop" arrangement, the first tube being normally conducting, and the second tube being normally cut off. When a negative pulse is applied to the grid of the first tube, the conducting state of the two tubes is instantly reversed, the first tube now being cut off and the second tube conducting. After a short time the circuit returns to its original state and remains thus until another negative pulse triggers it. The length of time the second tube conducts is determined by one of four RC values in its grid circuit which is selected by a range switch setting. A milliammeter and the measuring element of a strip-chart recorder are connected in series with the plate of the second tube, therefore, for a given input pulse rate, their readings are proportional to the length of time this tube conducts for each input pulse. If a small number of pulses per unit time are to be recorded, a long pulse is used in this circuit, and if a large rate is to be recorded, this circuit is adjusted for a short pulse. The integrating time of the meter circuit is determined by the size of capacitor which is connected directly across the meter and recorder.

Other circuits included in the unit are:

1. A low-voltage power supply that furnishes 6.3 volts a-c to the tube filaments and 150 volts regulated d-c to the tube plates.
2. A high-voltage supply that furnishes the Geiger-Mueller tube voltage. This voltage is variable from about 600 volts to about 1,500 volts, and to some extent is regulated for changes in load.
3. A calibrating pulse generator that is a multivibrator circuit adjusted to produce pulses at a rate of 5,000 per minute. It serves only as a rough check because it is subject to drift.

The ratemeter has four count-rate ranges plus a warm-up position on the range switch. These are ranges 0 to 100, 0 to 1,000, 0 to 10,000, and 0 to 100,000 pulses per minute. In its present form, the maximum count loss due to dead time of the instrument is about 10 percent at full scale on all but the 0 to 100,000 pulses per minute range where the loss is about 25 percent. This dead time in all but the highest range is due to the metering circuit, which is necessarily insensitive during the time the first tube is cut off, and which is equal to approximately 60,000, 6,000 and 600 microseconds respectively on the first three ranges. In the 0 to 100,000 pulses per minute range the dead time of the circuit is about 80 microseconds due to the pulse length of the pulse-shaping stage. The dead time of the

Geiger-Mueller tube is over 150 microseconds, which makes it the limiting factor at extremely high counting rates. The temperature dependency of calibration amounts to no more than three precent with a change of 60 degrees Fahrenheit in ambient temperature.

To calibrate the ratemeter the following general procedure is used:

1. The instrument is turned on and allowed to warm up for at least 30 minutes.
2. The voltage on the first clipper plate is adjusted by means of a potentiometer to eliminate all noise, and the voltage on the second clipper plate likewise is adjusted to furnish approximately a 5-volt pulse to the metering stage.
3. The cathode circuit of the metering stage is adjusted for a predetermined cathode voltage to provide stable operation.
4. Positive pulses are fed into the input of the ratemeter and each range is calibrated at 90 percent of full scale by means of the individual range potentiometers.
5. The readings are then checked against a known gamma-ray source using a selected Geiger-Mueller tube.

Tests in the laboratory on four representative instruments show the readings to be within plus or minus 3 percent of each other when using selected Geiger-Mueller tubes in known intensities of gamma radiation. However, during field use where they will be subjected to a variety of operating conditions and rather rough transport, the total error may be as much as plus or minus 10 percent, in addition to the statistical error inherent to radiation measurements.

GAMMA-RAY LOGING PROCEDURE

As the Geological Survey is engaged in routine gamma-ray logging of many drill holes for geologic studies and exploration of mineral deposits, a standardized procedure for operating the logging units has been established to ensure consistency and accuracy of results. This procedure includes features essential for the proper operation of the electronic and mechanical parts of the equipment.

All ratemeters are tested and calibrated in the laboratory before being used in the field. After a period of field use lasting from 2 to 4 weeks, and depending in part upon the number of hours operation, ratemeters are returned to the instrument shop for a thorough examination. Defective parts are replaced and each ratemeter is recalibrated before being reissued for field use. All Geiger-Mueller tubes are tested before they are issued for field use. These tests are designed to show that all tubes function properly within specified limits.

Components of the logging unit that become inoperative while in the field are immediately removed and repaired. Spare components such as ratemeters, probes, and Geiger-Mueller tubes are provided for field replacement. Minor mechanical repairs on reel assemblies, motor-generator plants, and other non-electronic parts of the logging units are made in the field. No repairs of electronic components are made in the field.

Power is supplied to the electronic parts of the unit for at least 15 minutes before a hole is logged. The performance of the electronic parts is then checked by placing the probe in an annular cylindrical container filled with radioactive material and noting the response of the ratemeter and the character of the strip-chart record. This test does not verify alinement and calibration of the ratemeter but frequently indicates faulty performance of the ratemeter, shorts in electrical circuits, and defective Geiger-Mueller tubes when these conditions exist. The internal pulse generator is also used to make a rough check on ratemeter performance when the Geiger-Mueller tube is detached.

The probe is lowered to the bottom of the hole and logging is acomplished as the probe is withdrawn. All slack cable and play in the cable drum is eliminated before logging starts. A cable speed of 5 feet per minute has been determined as the most practical when Geiger-Mueller tubes are used as counters. A time constant of approximately one second is used for all logging to obtain maximum definition of thin strata or layers of radioactive minerals. When it is impractical to log the entire hole from bottom to collar, accurate measurements are made of the length of the cable remaining in the hole and the hole depths for the top and bottom of the log.

CALIBRATION OF THE LOGGING INSTRUMENT

The principal objectives of the gamma-ray logging investigations were to establish a technique capable of measuring 0.01 percent equivalent uranium with a small degree of error and to calibrate the gamma-ray logs in terms of the equivalent uranium content and thickness of abnormally radioactive layers.

To establish a calibration that permits the interpretation of anomalies appearing on gamma-ray logs in terms of the equivalent uranium content some assumptions are necessary. Many deposits of radioactive minerals, especially those occurring in vein-type and supergene deposits, exist in an infinite variety of sizes and configurations. It is assumed that all anomalies appearing on gamma-ray logs, regardless of size, attitude, and configuration of the radioactive deposit, represent an equivalent layer of homogeneous material of finite thickness and infinite extent, and that the drill hole perpendicularly penetrates the equivalent layer. This assumption is necessary because as gamma-ray counters move through drill holes they merely respond to energizing rays without discriminating geometrical arrangements of the radioactive material. Most anomalies appearing on gamma-ray logs probably are caused by radioactive material exposed on the walls of the holes, although some anomalies may be caused by material separated from the walls of the holes by possibly as much as a foot of barren rock. Inasmuch as gamma-ray logs do not distinguish radioactive material exposed at the wall of a hole from material lying a short distance away and separated from the hole by barren rock, all anomalies are assumed to be caused by radioactive material exposed at the wall of the hole. Under such circumstances a gamma-ray log indicates an apparent grade that is less than the true grade of the material, and an apparent thickness that is a distortion of the true thickness. When precise measurements of the hole diameters are not made it is assumed that drill holes have uniform diameters throughout their lengths, and the effects of variable diameters are necessarily ignored.

Three possible methods of obtaining a calibration of the gamma-ray log in terms of equivalent uranium have been considered. These methods are (1) compilation of a calibration chart from data calculated mathematically on the basis of theoretical considerations, (2) an empirical calibration based on a comparison of radioactivity anomalies appearing on gamma-ray logs of holes drilled through radioactive mineral deposits with chemical assay data for core samples recovered from these holes, and (3) an empirical calibration based on gamma-ray logging of simulated drill holes through layers of known thickness and equivalent uranium content.

The mathematical calculation of calibration data was considered to be impossible because not enough basic information concerning absorption and scattering of gamma-rays in terrestrial materials is available to permit the calculations to be made. Most of the Geological Survey's work with gamma-ray logs pertains to the exploration of carnotite deposits, and these deposits are thin, a factor that complicates the mathematical considerations.

At the time the gamma-ray logging investigations were started, several hundred holes had been drilled in the Colorado Plateau area as part of the program for exploring and developing carnotite deposits. Many of these holes penetrate carnotite deposits, and core samples had been recovered and assayed. Gamma-ray logs were made of the holes. The counting rate and thickness of each of many radioactivity anomalies appearing on the gamma-ray logs were compared with the geologist's record of visual examination of core and with records of chemical assay of recovered cores to determine whether an empirical calibration chart could be compiled from these data. There was no systematic agreement of gamma-ray log data with the chemical assay data. Several causes of discrepancies were determined, none of which were involved in all the measurements. These sources of error were (1) incomplete recovery of core, especially in the soft, high-grade parts of the carnotite deposits, (2) variable character of the deposits whereby core samples are not representative of the larger volume sampled by gamma-ray logs, (3) radioactive disequilibrium in parts of carnotite deposits, (4) core sections selected for assay do not always precisely correspond to the radioactive layer, that is, the core sample may be greater or less than the thickness of the zone of the anomaly, (5) loss of material while preparing core samples for chemical assay, (6) chemists' errors, and (7) instrumental errors of the logging equipment. The lack of correlation between chemical assay data and radioactivity anomalies appearing on strip-chart records precluded the compilation of an empirical calibration chart from these data.

It became necessary to make an empirical calibration of the logging unit in terms of equivalent uranium with data obtained by logging simulated ore bodies. This procedure minimized the number of variables not accurately known.

The simulated ore bodies (fig. 4) were constructed inside of sections of iron culvert 4 feet in diameter which were placed on end to make vertical structures. An aluminum tube having an outside diameter of 2 inches and 1/64-inch wall thickness was placed at the center of each structure to simulate an open drill hole of about AX size and to help hold the loose filling material in place. A layer of sand approximately 4 feet thick was placed and tamped at the bottom of each structure.

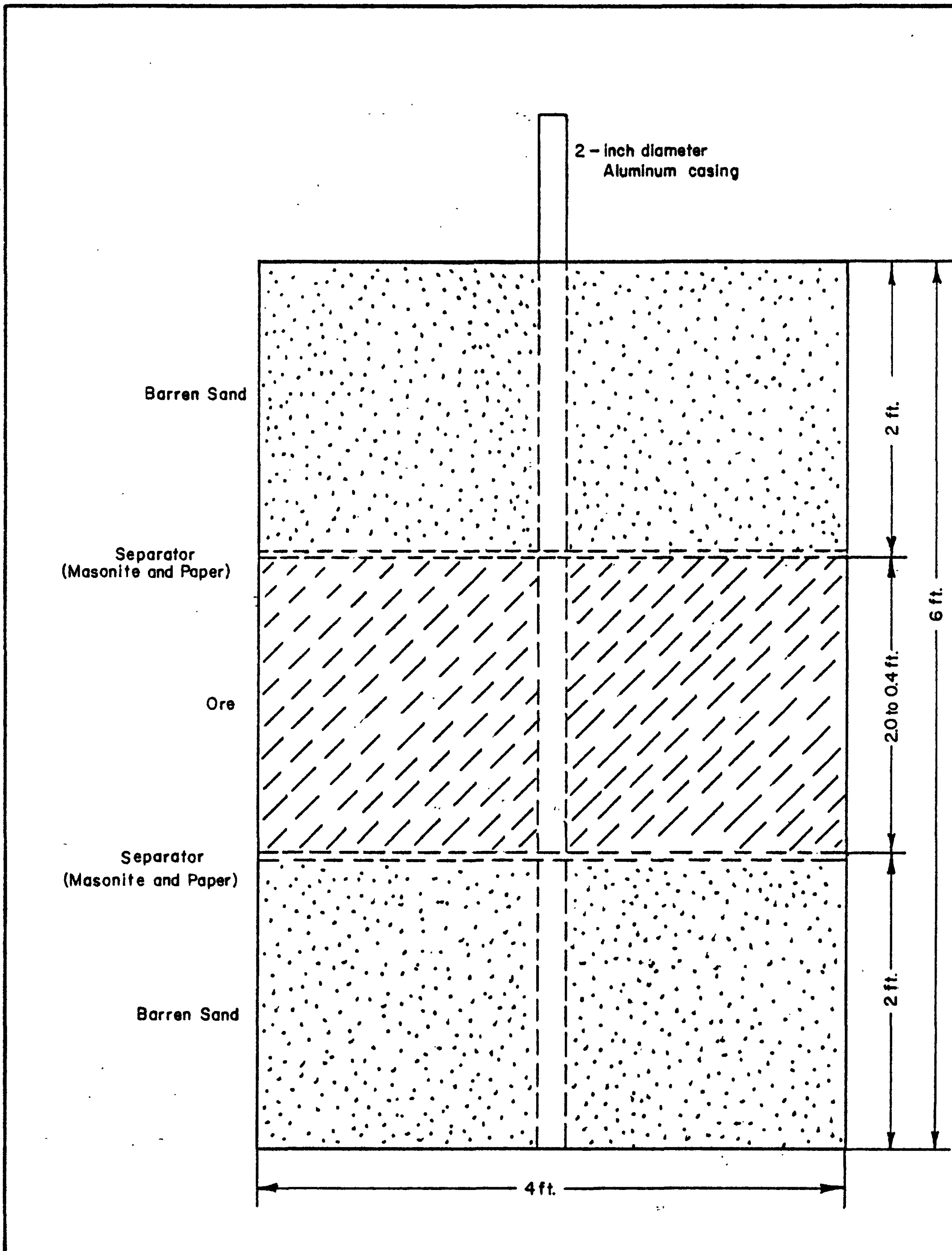

FIGURE 4. DIAGRAM OF SIMULATED ORE BODY.

Next, a layer of uranium ore of known grade and thickness was placed above the sand. Finally, a layer of sand approximately 3 feet thick was placed above the ore. Sheets of thin fiber pressboard were used to separate the sand and ore layers, and these sheets permitted the ore to be recovered undiluted with sand after measurements had been completed.

Carnotite-type uranium ores and uraniferous waste from carnotite mines, which had not been treated in any way except for crushing to less than ¼-inch, were used in the experiments. Lots were selected in which the uranium was in radioactive equilibrium or, near equilibrium, with its daughter products. Batches from each lot of ore and waste were used to make several set-ups, and all material in each lot was used repeatedly during the experiments. The ore or waste placed in each set-up was sampled carefully, and uranium and equivalent uranium contents were determined for each sample. After each set-up was constructed no gamma-ray measurements were taken for a period of at least two weeks. This lapse of time permitted radon to build up to approximately equilibrium concentration thereby compensating for the slight loss that occurred during handling of the material. Each set-up was logged 50 times or more and the average counting rate for the anomaly was determined. Use of the average value of a large number of tests reduced the statistical error inherent to counting rates.

Five grades of uraniferous ore and mine waste containing 0.009, 0.051, 0.32, 0.83, and 3.5 percent equivalent uranium were used in the tests. Set-ups having radioactive layers 0.4, 0.8, 1.2, 1.6, and 2 feet thick were constructed with each grade of uraniferous material. It was determined experimentally that increasing the thickness of the radioactive layer above 2.0 feet causes no significant increase in counting rate when the logging speed is 5 feet per minute.

The experimental data were used to compile a grade-thickness-counting rate calibration chart (fig. 5). When counting rates are plotted as ordinates and grade as abscissae, a family of curves can be drawn, each member of which represents a certain thickness of radioactive material. An infinite number of such curves can be drawn. During this work, experimental data were plotted to determine curves for thicknesses of radioactive material tested in the simulated drill holes, and curves representing intermediate thicknesses were determined by interpolation. Similar charts can be made for calibrating the logging unit in terms of equivalent thorium or potassium; however, these were not made during the course of the work being described.

A calibration chart of this kind is valid only for interpreting gamma-ray logs made with the same counter type and efficiency, same type of ratemeter, same control settings, and the same cable speed used for collecting the calibration data. Any substitution of parts or change in logging procedure that causes a shift of counting rate invalidates the chart. An individual chart is therefore required for each combination of critical parts and logging procedure.

The width of an anomaly on the gamma-ray log for each particular radioactive layer is dependent upon the sensitive length of the counter, the time constant of the ratemeter, and cable speed. Any change in these instrumental factors causes the width of the curve to change. The position on a curve at which the true thickness of the radioactive layer can be measured varies with the thickness of the layer, and for any particular

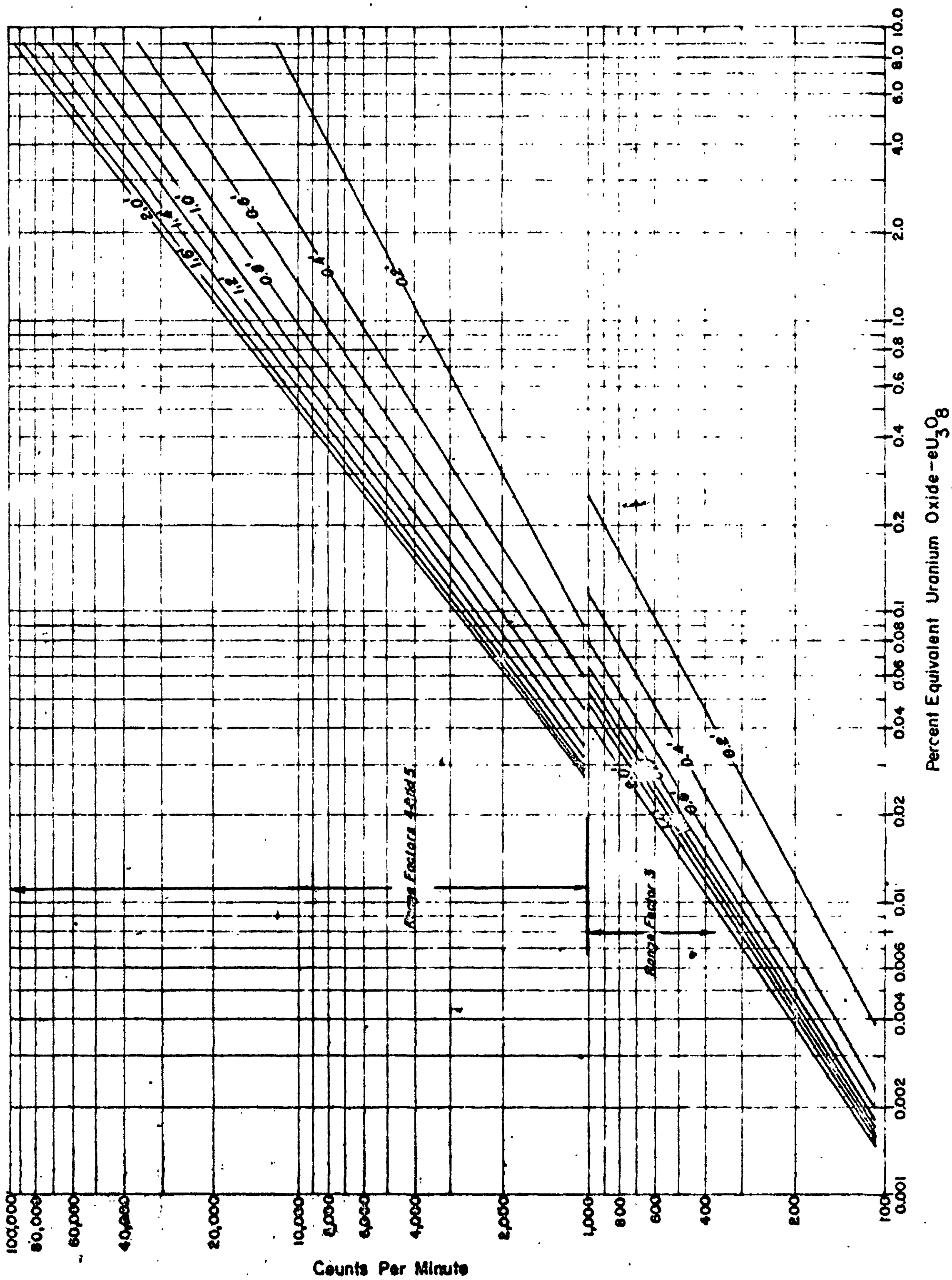

FIGURE 5. A CALIBRATION CHART.

thickness is constant with the same instrumental factors. Figure 6 is a plot of uranium ore thickness in feet versus percent maximum deflection of the curve at which true thickness is measured for a combination of Geiger-Mueller counter having an effective length of 7½ inches, a cable speed of 5 feet per minute, and ratemeter time constant of approximately one second. Experience in logging carnotite deposits shows that a reasonable estimate of true thickness can be made by measuring the width of the curve at 70 percent of the maximum counting rate. Many of the radioactive layers that can be distinguished on gamma-ray logs of holes drilled through these deposits are between 0.8 and 1.2 feet thick. It has been determined experimentally that the curves show the true thickness of these layers between 75 and 64 percent of the maximum counting rate (fig. 6). Width measurements at the 70 percent level are considered to be sufficiently accurate. Interpretations of logs of holes drilled through other kinds of deposits may require different width measurements.

The use of the chart for making grade estimates from anomalies appearing on gamma-ray logs involves a simple procedure. The maximum counting rate for the anomaly is read directly from the strip-chart record. The calibration chart is entered horizontally at the value of the counting rate. This value is carried across to the intersection with the line representing the estimated thickness; from this intersection the chart is then followed vertically to the edge where the value for percent equivalent uranium is read. Techniques for determining counting rates and for estimating thicknesses of radioactive zones are discussed in the section of this report dealing with interpretation of gamma-ray logs.

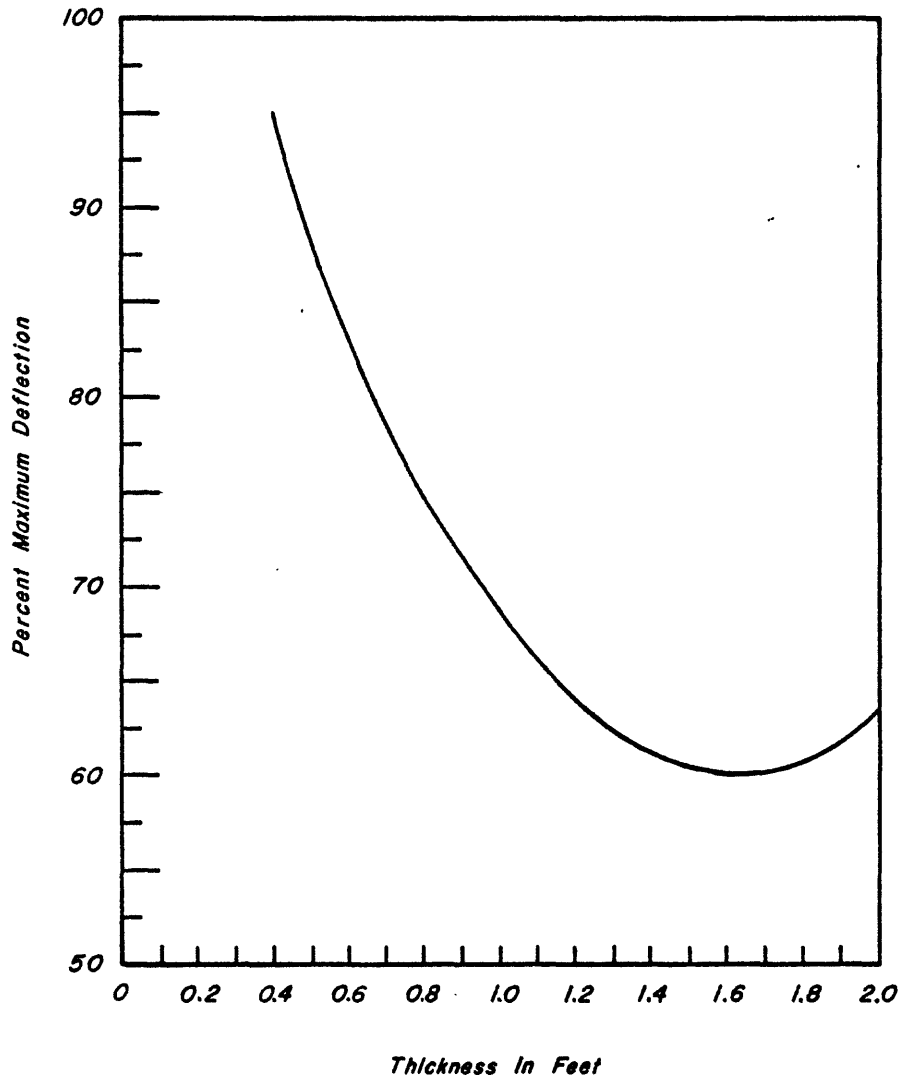

FIGURE 6. PERCENT MAXIMUM DEFLECTION AT WHICH CURVE SHOWS TRUE THICKNESS.

Other variable factors, in addition to thickness and grade of a layer of radioactive material, can significantly affect the counting rate recorded by gamma-ray logs. Metal casing placed in a hole substantially reduces the counting rate. A hole shows a lower counting rate when filled with water than when dry, and drilling mud causes a still lower counting rate to be recorded. Variations in hole diameter can cause increases or decreases depending upon sizes and shapes of cavities.

The gamma-ray absorption of combinations of standard-size flush-joint casing commonly used on core-drilling operations has been determined experimentally (table 1). The counting rate indicated on gamma-ray logs must be increased by the appropriate amount to compensate for absorption by various casing configurations when making grade estimates.

Percent absorption of gamma rays by water and mud in holes of various sizes was not determined experimentally. Absorption in water-filled holes of EX, AX, and BX sizes can be neglected without introducing significant errors into grade determinations. If the diameter of the hole is greater than the diameter of the probe by 2 inches or more, gamma-ray absorption in the water becomes a significant factor.

Table 1.--Gamma-ray absorption by drill-hole casing

Casing	Percent absorption
None	None
NX	23
NX + BX	35
NX + BX + AX	40
NX + BX + AX + EX	46
BX	20
BX + AX	32
BX + AX + EX	36
AX	13
AX + EX	26
EX	14

The effects of varying hole diameter upon counting rate have not been precisely determined. Preliminary tests with thin layers of radioactive material have shown that a decrease in the angle subtended from the exposed surface of the layer to the counter results in a decrease counting rate. A cavity within a thick layer of radioactive material can cause a higher counting rate to be recorded because of a greater surface of radioactive material exposed to the counter. The magnitude and sign of a change in counting rate caused by a cavity is therefore dependent upon the diameter of the cavity and the thickness of the radioactive layer. Unless a drill hole can be calipered throughout the section in which a gamma-ray log is made, there is no practical method of applying corrections for variations in hole diameter when making grade estimates.

INTERPRETATION OF GAMMA-RAY LOGS

THICKNESS AND GRADE ESTIMATES

Interpreting gamma-ray logs of drill holes in terms of grade and thickness can be resolved into two categories: (1) that pertaining to thick layers containing materials of nearly uniform grade, and (2) that pertaining to thin layers, -- especially to a series of thin layers whose successive members vary greatly in grade. Single homogeneous layers are represented by smooth curves on the gamma-ray log; irregular curves represent complex configurations. The first category includes most problems concerned with stratigraphic correlation and estimates of uranium content for such materials as uraniferous black shales and phosphatic deposits. The second category is concerned principally with deposits of radioactive minerals whose grades exceed 0.01 percent eU or 5.0 percent K_2O and change rapidly within a few inches.

Gamma-ray logs belonging to the thick layer category usually represent very low concentrations of radioisotopes. The term "thick layer" is used to denote a thickness of radioactive material such that the ratemeter reading reaches a maximum value maintained, except for normal statistical fluctuations, during the passage of the probe through the greater part of the layer. Thicknesses of uniform grade material that exceed approximately three times the length of the sensitive part of the counter belong to this category. The minimum dimension of a thick layer is therefore dependent upon the dimensions of the counter.

Interpreting gamma-ray logs of thick layers presents no difficult problem. When a log is made for stratigraphic correlation, and grade determinations are nonessential, the required data consist of the relative radioactivity of adjacent strata and the positions of the contacts. If the radioactivity of adjacent strata varies significantly, for example between many sandstone and shale layers, the contacts are represented by sharp breaks in the level of gamma-ray intensity indicated on the logs (fig. 7). Some knowledge of the stratigraphy of the area in which the holes are drilled and of the content of radioactive constituents in the formations penetrated is helpful in making complete and accurate stratigraphic correlations from gamma-ray logs.

Grade determinations for radioisotopes present in thick layers require a single value--the counting rate--to be taken from the log (fig. 8). An average value through the statistical fluctuations is used. The calibration chart is entered with this counting rate and infinite thickness to obtain the grade.

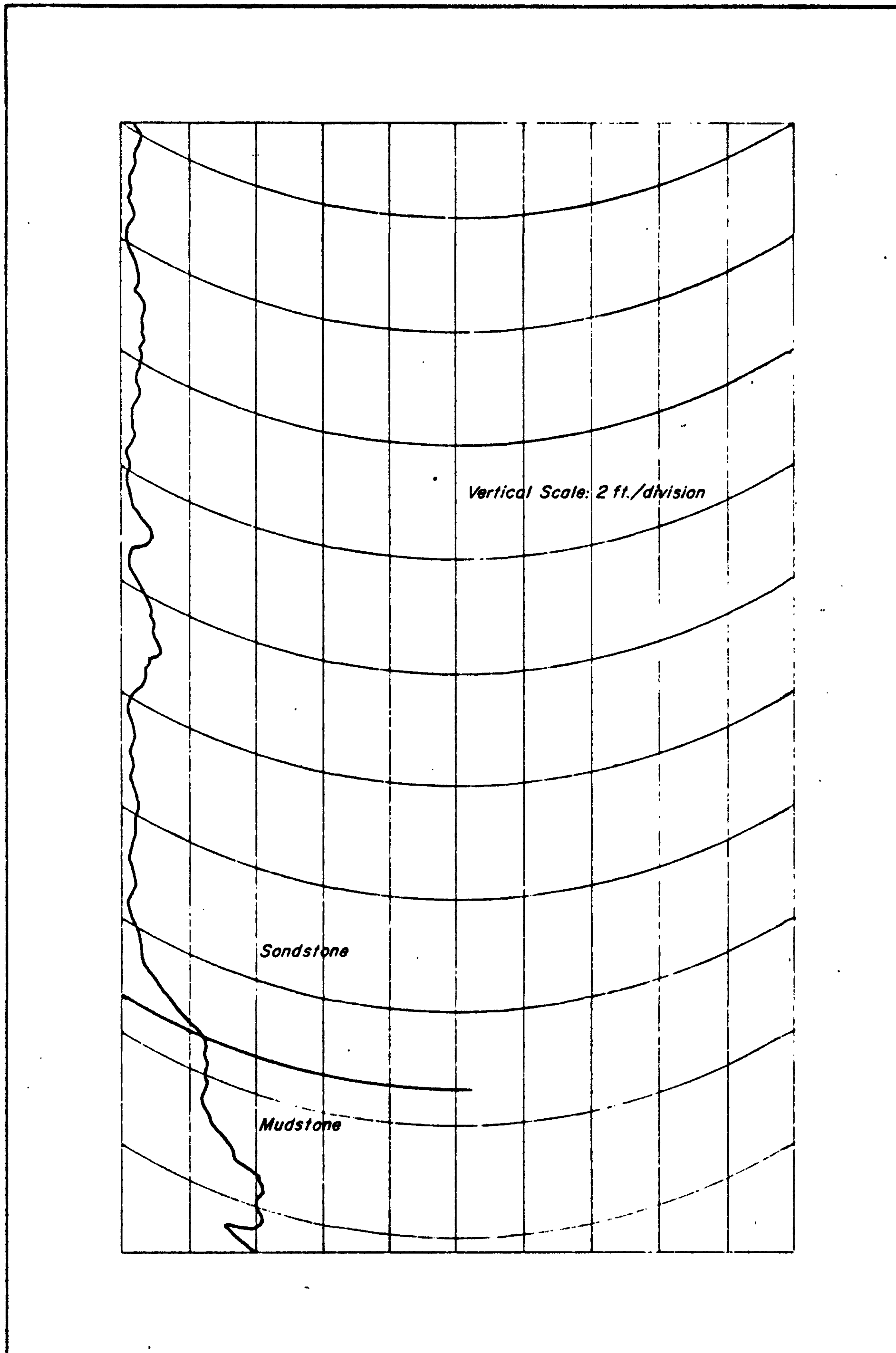

FIGURE 7. GAMMA-RAY LOG SHOWING SANDSTONE-MUDSTONE CONTACT, HOLE CM-584, CLUB MESA AREA, MONTROSE COUNTY, COLORADO.

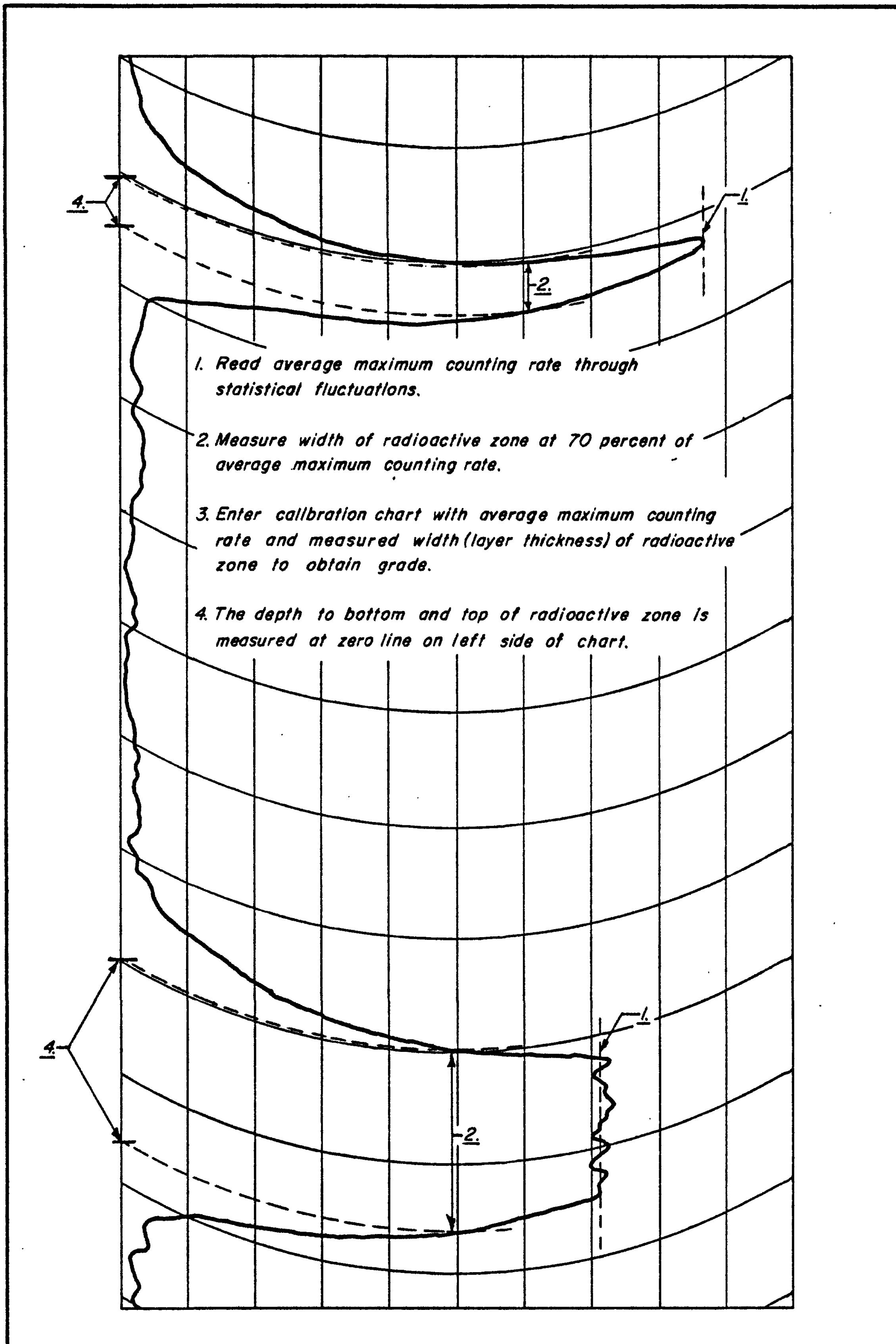

FIGURE 8. GRADE-THICKNESS DETERMINATIONS FOR THICK AND THIN RADIOACTIVE LAYERS.

The term "thin layer" is used to denote an interval in which the ratemeter reading does not maintain a maximum value during the passage of the probe through the layer; the entire sensitive length of the counter is not directly exposed to gamma radiation originating from within the layer; this radiation is partly shielded by adjacent layers. Thin layers are less than about three times the length of the sensitive part of the counter, and the maximum thickness therefore depends upon the length of the counter.

As the ratemeter reading does not maintain a maximum value, the peak reading reached lies within the limits of a statistical fluctuation. The effects of this fluctuation can partly be overcome by making several passes through the layer and by using an average value of the counting rate indicated for all passes. It usually is impractical to log a drill hole several times; therefore the peak counting rate indicated for a single pass is subject to a statistical error that directly affects the accuracy of a grade determination made from it.

Methods of estimating grade from gamma-ray logs of thin layers can best be explained by starting with a simple configuration. A single homogeneous layer of radioactive material enclosed in relatively nonradioactive layers (fig. 8) is the simplest configuration found when interpreting thin layers. Two values are needed to make a grade interpretation--the maximum counting rate of the anomaly, which is read directly from the strip-chart record, and the estimated thickness of the layer. The calibration chart is entered with these two values, and a grade estimate is read directly.

Interpreting gamma-ray logs of thin layers often becomes a complex process, especially when logs are made of holes that penetrate radioactive mineral deposits in which there are several alternating mineralized and gangue layer.

A succession of thin layers of radioactive material separated by layers of relatively barren material is represented on a strip-chart record as a series of anomalous curves (fig. 9). To make a grade-thickness interpretation each curve is treated individually as outlined above provided the nearly barren layers are thick enough to prevent the passage of significant gamma radiation from one radioactive layer to another and also to allow the ratemeter reading to drop to the background level between anomalies.

A configuration consisting of two adjacent thin layers of radioactive material confined in relatively barren material is shown by the solid line in the top part of figure 10. The interpretation of this configuration is complicated by the gamma radiation, which originates within each layer, passes through the common boundary and contributes to the total recorded for the other layer; the shape and apparent counting rate for each part of the anomaly as indicated on the strip-chart record is affected by the time constant of the ratemeter. If the two radioactive layers were so far apart that significant gamma radiation from one could not reach the other, and the ratemeter reading could drop to background level between the recording of anomalies, then two curves would appear on the strip-chart record as indicated in the bottom part of figure 10. If the two layers of radioactive material approach one another, the curves representing the two anomalies overlap. At a given depth, the effects of radiation from each

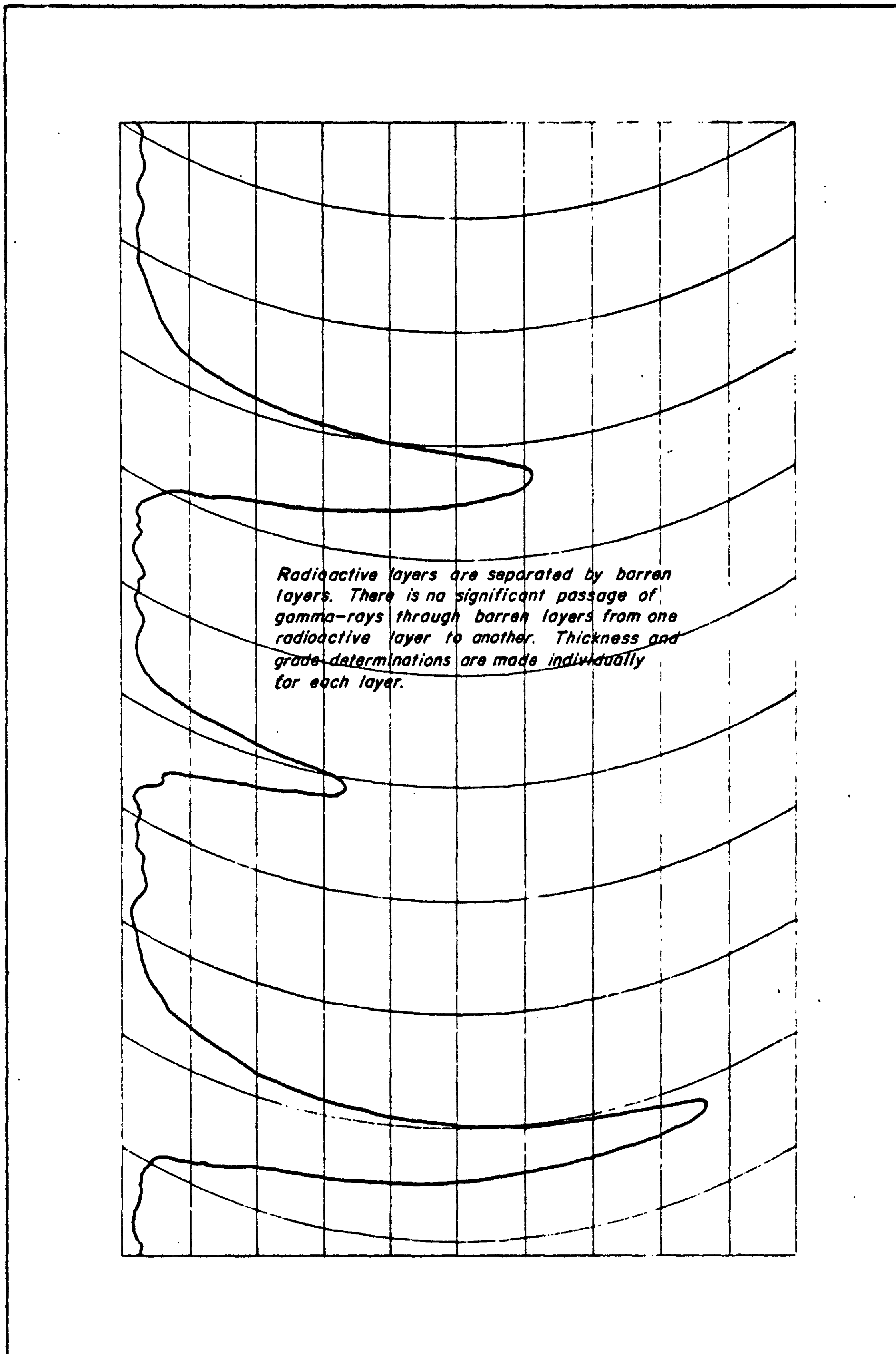

FIGURE 9. GRADE-THICKNESS DETERMINATIONS FOR RADIOACTIVE LAYERS SEPARATED BY THICK BARREN LAYERS.

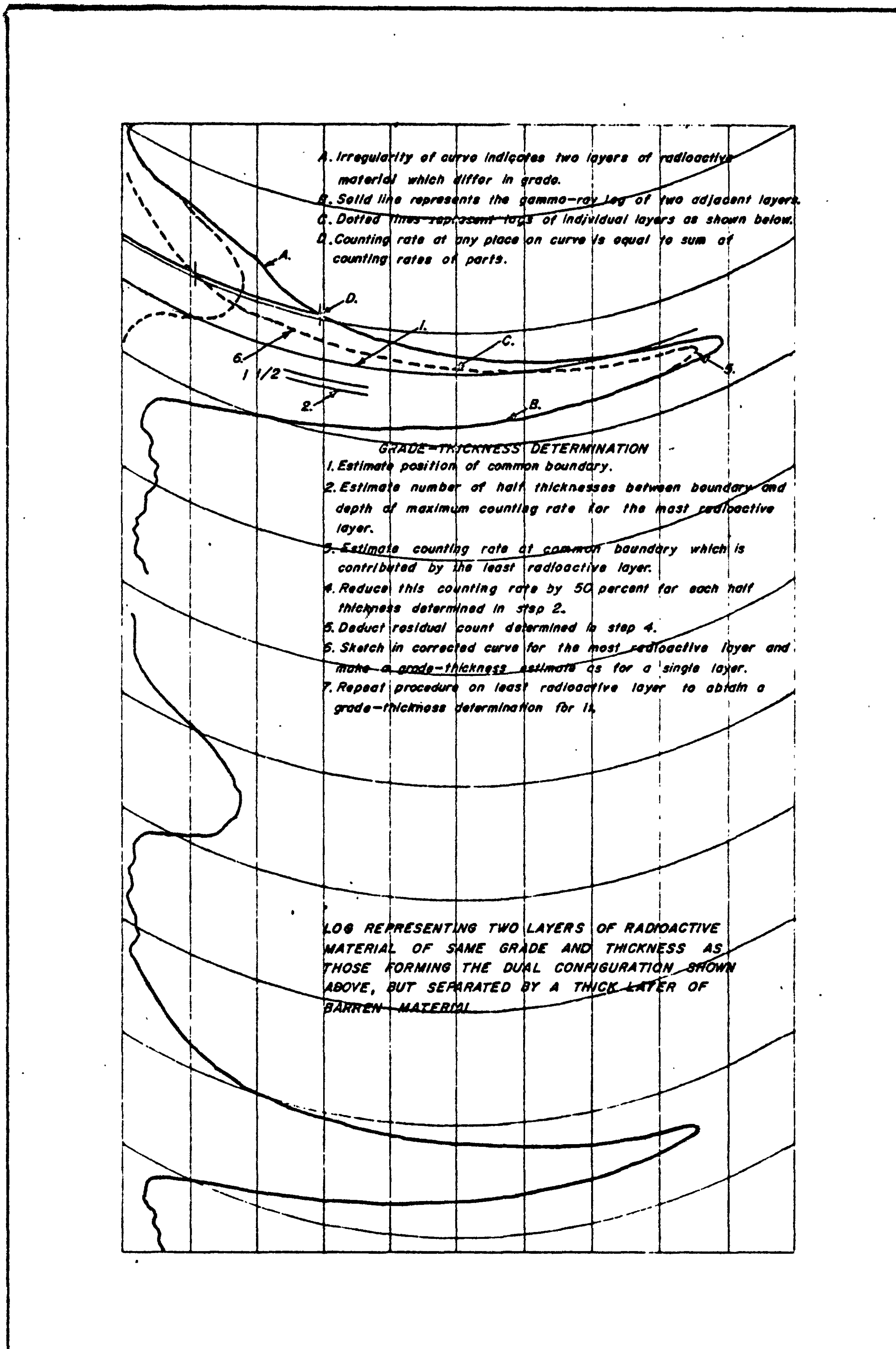

FIGURE 10. GRADE-THICKNESS DETERMINATIONS FOR ADJACENT RADIOACTIVE LAYERS.

of the two layers and time constant is added linearly by the ratemeter and appears on the strip-chart record as the sum of these components.

The addition follows the same pattern whether the two radioactive layers are separated by a thin barren layer or are in contact. Gamma radiation from high-grade layers tends to mask that from adjacent low-grade layers, and gamma radiation from thick layers tends to mask that from much thinner adjacent layers. When gamma radiation from one thin layer nearly masks that from another thin layer only a slight deviation from the shape of a typical curve for a single uniform layer may be noticeable. When a small difference exists between the grades of the two layers, both of which are comparatively thick, the configuration can be recognized easily because the curve consists of two parts, one showing a significantly higher counting rate from the other. Experience in examining drill-hole cores is helpful in recognizing the various configurations shown by gamma-ray logs.

If the curve representing a dual configuration deviates substantially from a theoretical curve for a single layer, or if determination of the grade for each layer of any dual configuration is desired, the curve must be separated into its component parts. A reasonably accurate separation can be made on an empirical basis. The contribution that each layer receives from its neighbor is greatest at the common boundary. Approximately 50 percent of gamma rays originating from the disintegration of the daughter products of uranium are absorbed in a thickness of 0.2 feet of most common rocks; therefore, if the maximum counting rate for a layer is indicated by the strip-chart record to be 1.0 foot or more from its boundary with another layer, this value can be used without correction.

If the maximum counting rate is less than 1.0 foot from the common boundary, a correction must be applied. The method of determining the correction is illustrated in figure 10.

When the corrected counting rate has been determined the curve can be adjusted as shown by the dotted line in figure 10, and the grade is estimated as for a single homogeneous layer. After the adjusted curve representing the most radioactive layer has been sketched, it is subtracted from the anomaly, an adjusted curve representing the less radioactive layer is sketched, and the grade is estimated. The most difficult part of the procedure is determining the counting rate contributed to each layer by gamma rays crossing the common boundary. With a little practice an interpreter can make sufficiently accurate estimates from trial sketches of adjusted curves. Grade determinations for adjacent layers made in this manner are approximations, but statistical errors of the counting rate and instrumental errors of the logging unit may be as great or greater than the errors of interpretation, and attempts to obtain greater accuracy appear to be unwarranted.

A set of curves showing the build-up and fall-off of the ratemeter reading for each of several counting rates distributed throughout the range of the instrument can be used advantageously while determining the shapes of curves representing individual layers of complex configurations. These curves can be made by feeding pulses into the ratemeter at a predetermined rate while the reading is building up from zero or background level. The curves are drawn by the strip-chart recorder moving at the rate used for making the logs being interpreted. The curve showing fall-off is obtained by shutting off the input and allowing the reading to drop to background or zero level. Pulses can be obtained from a counter exposed to a radioactive material or from a pulse generator. These build-up and fall-off curves show the effects of the time constant of the instrument. They do not include counts corresponding to those caused by gamma rays that originate in relatively barren layers lying on either side of a radioactive layer. They can be used to determine the shapes of curves representing individual layers of a complex configuration with a small error. If greater accuracy is required, additional adjustments can be made to compensate for increased counting rates during build-up and fall-off caused by the gamma rays which originate in layers enclosing the radioactive layer being considered. The effects of these increased counting rates can be determined by some tedious mathematical calculations, or curves including the effects of the time constant of the instrument and the penetration of gamma rays through adjacent layers can be obtained by logging simulated holes in which layers of radioactive ore are enclosed in other materials furnishing the counting rates for which adjustments are desired.

A weakly radioactive layer lying between two significantly more radioactive layers is a common feature of complex configurations. Grade determinations for each of the two enclosing layers are made in the same manner as described for dual configurations. If the weakly radioactive layer is more than 1.0 foot thick it can be assumed that no significant quantity of gamma rays from one high-grade layer reaches the other, and the only residual effects for which corrections are required appear in the curve of the upper layer as a result of the time constant of the instrument. If the weakly radioactive layer is less than 1.0 foot thick, then the curves representing each of the high-grade layers must be corrected for counting rate caused by gamma rays which originate in the other high-grade layer as well as for those which originate in the weakly radioactive layer. After adjusted curves for the two high-grade layers are drawn it is assumed that the part of the counting rate not accounted for by the presence of the two adjusted curves for the high-grade layers is due to the radioactivity of the weak layer. The procedure for making a grade estimate for this configuration is illustrated by figure 11.

Many complex configurations consist of several layers whose successive members differ significantly in radioactivity. Such configurations can be broken into groups consisting of two adjacent layers or of two relatively high grade layers separated by a weaker layer. Grade estimates for each group are made as outlined above.

While making grade estimates it may be necessary to adjust counting rates indicated on gamma-ray logs for varying counter efficiencies when nonstandard counters are used. The most practical method of effecting this adjustment is to determine the counting rates given by each counter when exposed to the identical gamma-ray intensity and from these figures calculate percentage-wise corrections to be used to convert all counting rates to a predetermined standard base. If the thickness of a layer of radioactive material is less than the length of the sensitive part of the counter it cannot be determined accurately from a gamma-ray log because the counter is exposed to the maximum gamma-ray flux for an effective distance equal to its own length as it moves past

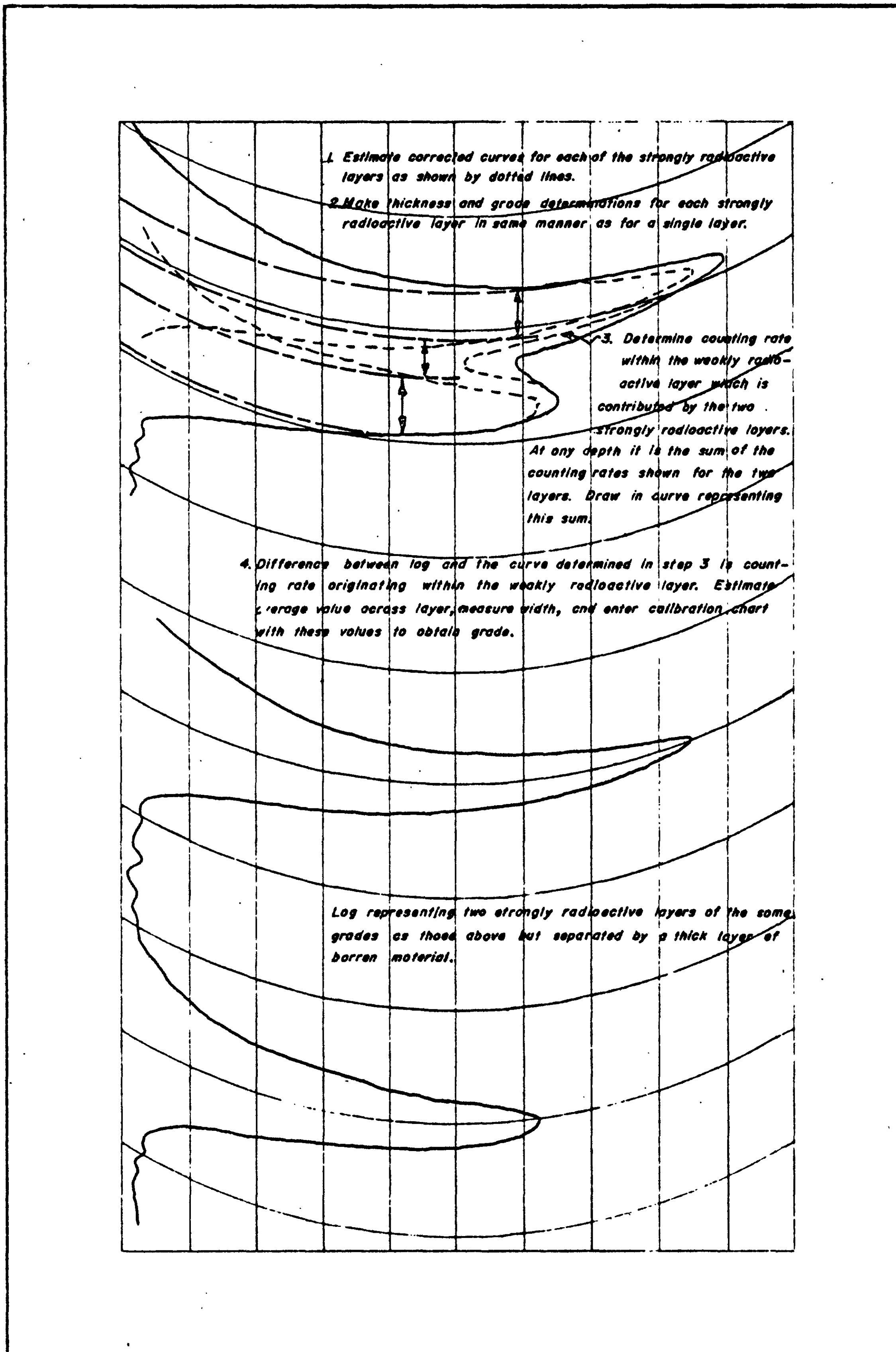

FIGURE 11. GRADE-THICKNESS DETERMINATION FOR A WEAKLY RADIOACTIVE LAYER BETWEEN STRONGLY RADIOACTIVE LAYERS.

such layers. The minimum thickness that can be estimated from gamma-ray logs is dependent on counter length, and the greatest differentiation is made by the shortest counters.

RECOGNITION OF DEFECTIVE GAMMA RAY LOGS

Accurate determinations of thickness and grade can be made only from gamma-ray logs that show the profile of radioactivity along a drill hole exactly to scale in both vertical and deflection directions. Any defect or malfunctioning of either mechanical or electrical parts of the logging unit that causes the strip-chart record to deviate from an exact scale invalidates the log. Defects and malfunctions of all parts of the logging unit must be recognized and corrected immediately. Some of the commonest causes of defective logs are short or open circuits (fig. 12), defective Geiger-Mueller tubes, loss or improper adjustment of the high voltage to the counter tube, intermittent transmission of signal, erratic running of the strip-chart recorder (fig. 13), lack of free movement of the strip-chart pen (fig. 13), and slippage of the cable-measuring device.

CONTAMINATION OF DRILL HOLES

During drilling operations, part of the cuttings and also fine-grained fragments that slough off the walls of holes may adhere to the walls above the zones of origin rather than being carried out of the holes by drilling fluids or air. Gamma-ray logs of holes thus contaminated do not show accurately the radioactivity profiles of the rocks in place along the walls if such adhering particles are radioactive. This contamination is most likely when deposits of soft or claylike minerals such as carnotite are penetrated. Contamination generally is greatest immediately above the deposit of radioactive mineral and gradually decreases upward.

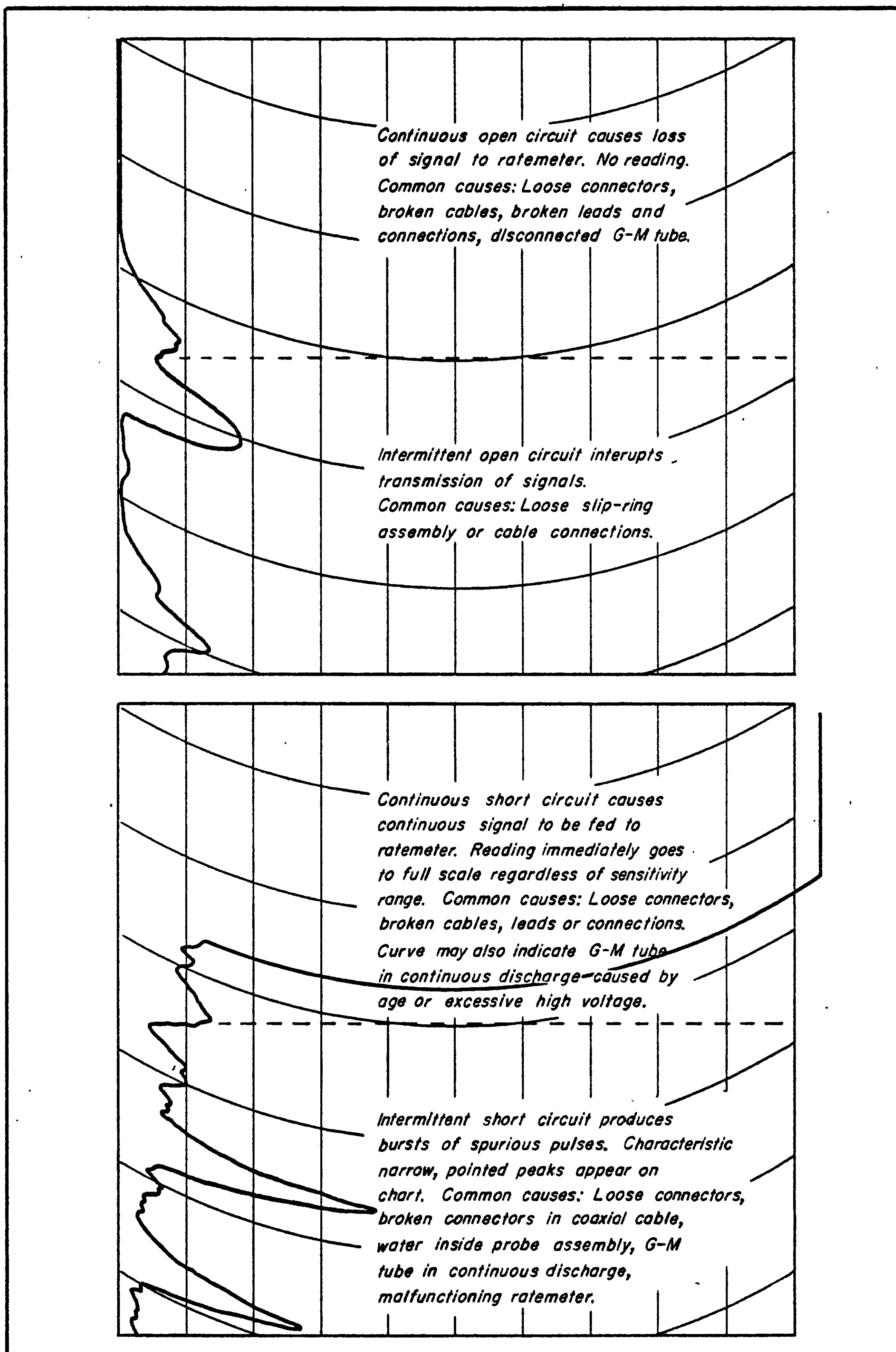

FIGURE 12. DEFECTIVE GAMMA-RAY LOGS CAUSED BY OPEN AND SHORT CIRCUITS.

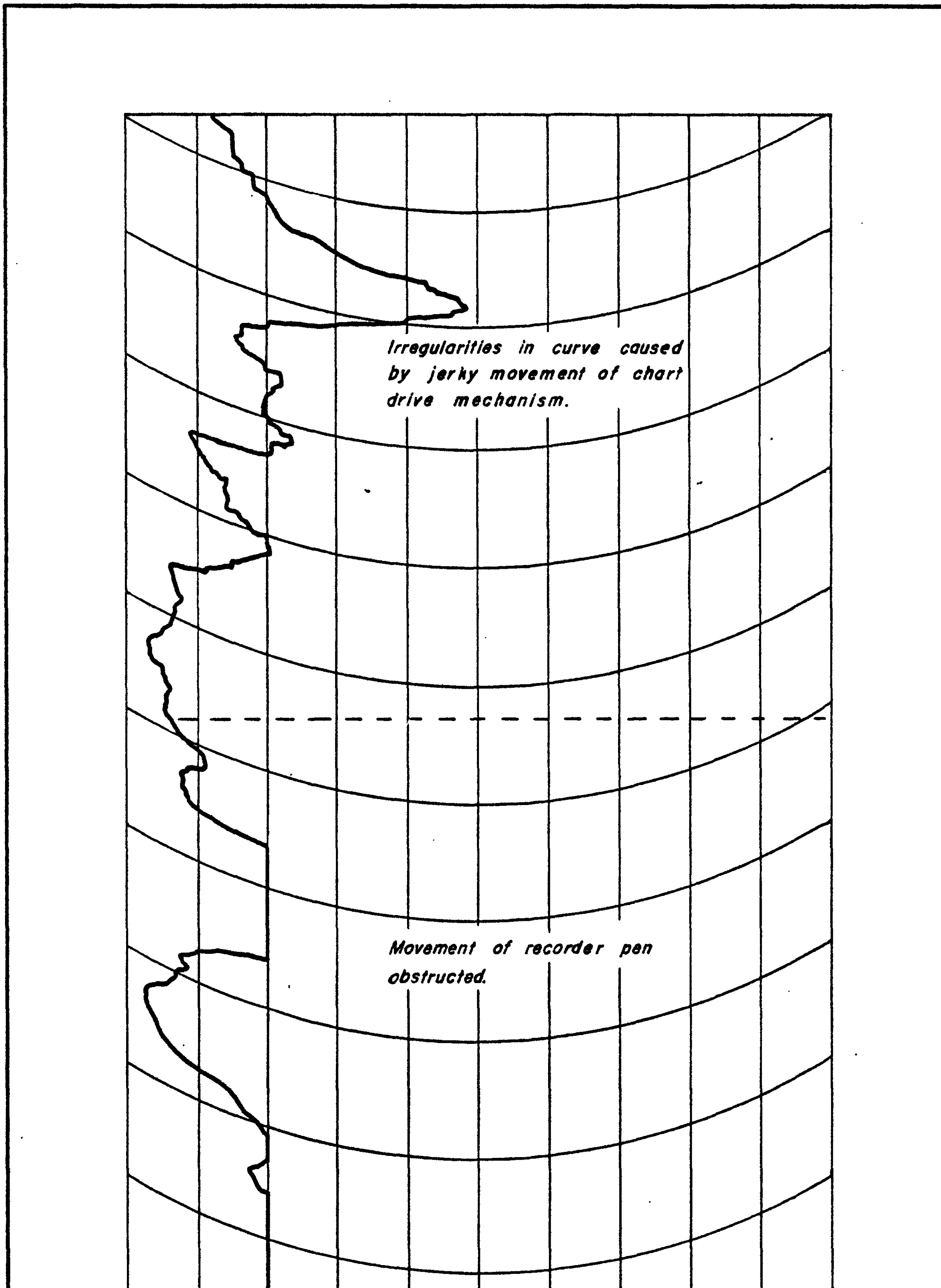

FIGURE 13. DEFECTIVE GAMMA-RAY LOGS CAUSED BY OBSTRUCTED PEN AND BY MALFUNCTIONING CHART DRIVE.

Gamma-ray logs of contaminated holes indicate anomalous radioactivity for the mineralized and contaminated zones. Such logs have features that either indicate or lead one to suspect contamination. Generally, the highest radioactivity is indicated at or near the bottom of the anomalous zone and marks the position of the radioactive mineral deposit. Usually it is possible to make satisfactory estimates of grade and thickness of the mineralized zone. Generally, the anomalous radioactivity falls off in a normal manner at the upper edge of the mineralized zone but does not reach the background level of unmineralized rock because of the contamination, and then it gradually decreases to the background level. Depending upon the amount of contamination, this decrease may take place through a short distance or through many feet of drill hole above the mineralized zone. The radioactivity profile of the wall rock is obscured and generally its character cannot be determined in the contaminated zone. A section of a typical gamma-ray log of a contaminated hole is shown by figure 14.

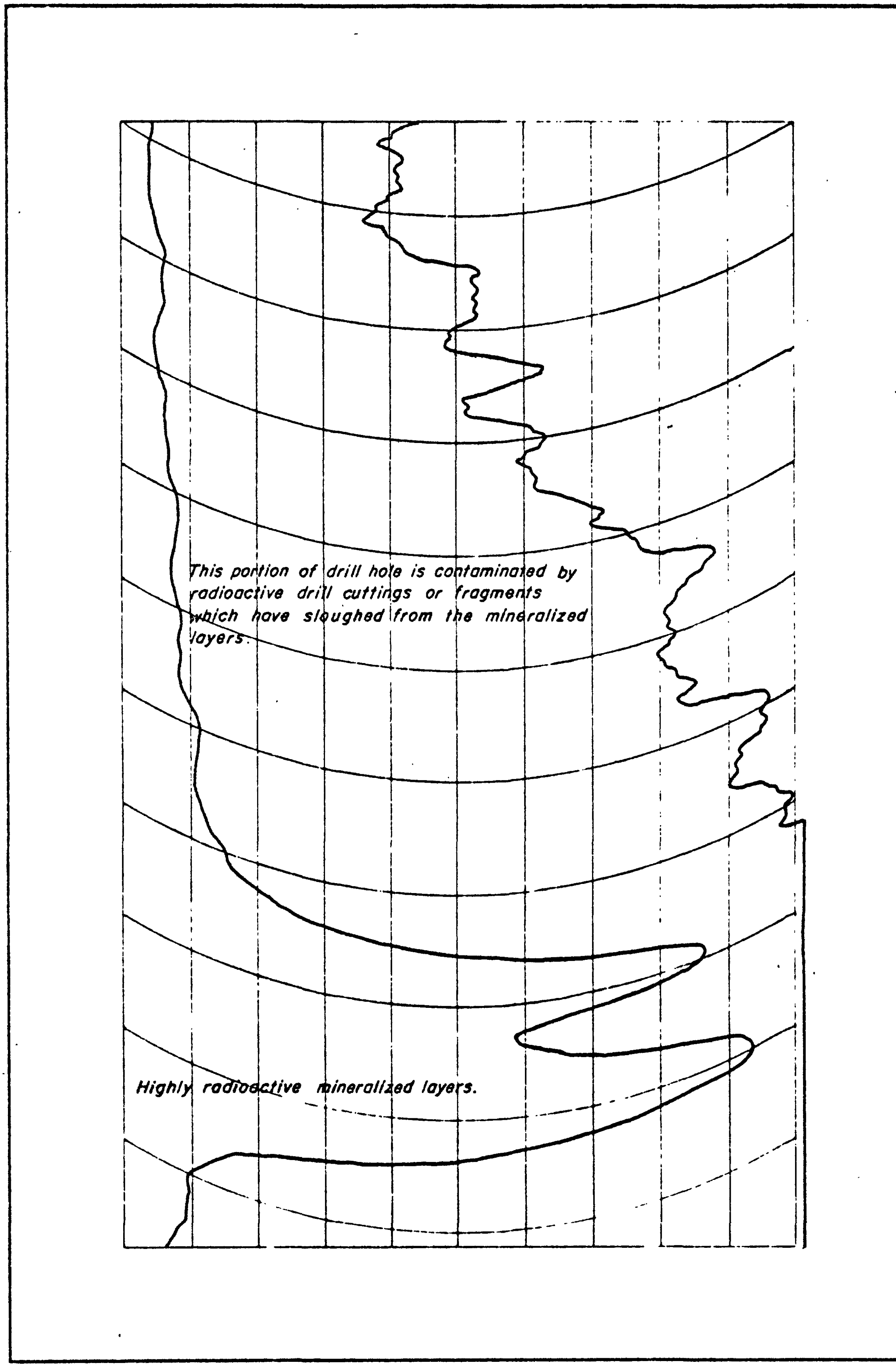

FIGURE 14. SECTION OF A GAMMA-RAY LOG OF A CONTAMINATED DRILL HOLE.

GEOPHYSICAL APPLICATION OF SUBSURFACE GAMMA-RAY MEASUREMENTS

INTRODUCTION

Gamma-ray measurements can be utilized in geophysical prospecting for deposits of uranium, thorium, and potassium minerals. All terrestrial materials contain traces of radioisotopes. Certain strata, soils, and rocks contain characteristic quantities of radioisotopes and can therefore be determined and correlated by gamma-ray measurement. Gamma-ray measurement is widely used to define plutonic rock masses and to aid in correlating stratigraphic rocks. Developing an aid to stratigraphic correlation has been one of the minor objectives of the Geological Survey's investigations. Less time and study have been given to this objective than have been given to developing techniques applicable to exploring for mineral deposits because the latter has been the more essential objective.

Gamma-rays are absorbed by thin layers of terrestrial materials; therefore their utilization in geophysical methods is severely limited. A thickness of approximately 1 foot of rock, or a slightly greater thickness of some soils, forms a mask which absorbs more than 95 percent of the gamma rays that initially penetrate it. Because of this absorption most of the gamma-ray radiation measured by a geophysical instrument originates 1 foot or less within a cover of terrestrial materials or originates during the disintegration of gaseous radiosotopes that have escaped into the atmosphere.

Some covered deposits of radioisotopes are surrounded by halos of radioactive daughter products or by radioisotopes leached from the deposits by ground waters and redeposited nearby. The radioactive halos or redeposited radioisotopes may be detected with radiation instruments, but the detected radiation originates from within a cover of approximately 1 foot or less, and not from deeply buried deposits. Knowledge of the geology of the area and the application of geologic principles are required to extrapolate the information to the parent deposit.

Radiation-detection instruments used for geophysical work are classified as surface or subsurface instruments depending upon how the detector is used. Airborne instruments are specially adapted surface instruments. Subsurface instruments are used to make measurements in soil or rock penetrated by drill holes or wells. Surface-type instruments are used for making above-ground measurements and can be used in mines, tunnels, shafts, and caves.

Most of the logging for uranium exploration has been done with small Geiger-Mueller tubes, which give low counting rates, because (1) nearly all holes have been drilled with an AX size core bit thereby limiting the maximum external diameter of the probe to approximately 1¼ inches, and (2) counters having low counting rates, when exposed to high-grade uranium ores, do not have outputs that exceed the capacity of the ratemeter. The combination of a small Geiger-Mueller tube and the type of ratemeter used for this work provides strip-chart records that are highly satisfactory for making estimates of grade and thickness for carnotite deposits, but this equipment usually does not provide the detail necessary for completely satisfactory stratigraphic correlation.

Gamma-ray logging of drill holes for stratigraphic correlation generally is concerned with very low levels of radioactivity as contrasted to the high levels of radioactivity associated with radioactive mineral deposits. Small Geiger-Mueller tubes such as those used by the Geological Survey for holes drilled through radioactive mineral deposits give counting rates usually not exceeding 200 counts per minute when exposed to nonmineralized rocks, such as most layered rocks and sediments. Large statistical fluctuations inherent to very low counting rates tend obscure any small variations in radioactivity which may exist between adjacent rock layers; therefore, gamma-ray logs made with small counter tubes generally do not differentiate stratigraphic features.

The counter used in making gamma-ray logs for stratigraphic correlation must give a high counting rate when exposed to rocks having low levels of radioactivity. If Geiger-Mueller tubes are used, increased counting rates can be obtained by using larger tubes

or by using multiple anode tubes. These tubes must be enclosed in large probes which cannot be used in AX- and BX-size holes usually drilled during exploration of mineral deposits. Scintillation counters now available give considerably higher counting rates than Geiger-Mueller tubes when exposed to the same sources but also have the disadvantage of requiring a probe too large to permit the logging of AX-size holes. Counting rates from scintillation counters are highly satisfactory for making logs to be used for stratigraphic correlation but are too high for logging through many ore-grade uranium and thorium deposits because ratemeter capacities are exceeded. If it were desirable to obtain data for stratigraphic correlation and for grade estimates from the same drill hole, two logs might be required, one with a high-sensitivity counter, and the other with a low-sensitivity counter.

Geophysical prospecting for radioactive mineral deposits by gamma-ray logging drill holes and wells with subsurface instruments has the following limitations:

(1) Completion of drill holes and wells is a prerequisite to logging; therefore, considerable expense and labor is required before the method can be used.

(2) Only radioactive minerals within approximately 1 foot of the wall of the hole can be detected.

The practical applications of gamma-ray logging of drill holes and wells include:

(1) Verifying the presence or absence of radioactive mineral deposits on or near the wall of the well or drill hole shortly after completion of drilling.

(2) Detecting radioactive halos and redeposited leached radio-isotopes which can be used as a guide to further exploration.

(3) Obtaining data with which to make estimates of grade and thickness of radioactive mineral deposits penetrated by drill holes and wells.

(4) Establishing stratigraphic correlation.

EXPLORATION OF MINERAL DEPOSITS

Gamma-ray logs are used to aid prospecting and exploring for mineral deposits by: (1) indicating immediately upon completion of drilling whether a hole has penetrated a radioactive mineral deposit, (2) indicating the thickness and grade of any radioactive mineral deposit penetrated, and (3) furnishing geologic data that will aid further exploration.

Any deposit of a radioactive mineral that includes a gamma-ray emitter among its constituents will be detected by gamma-ray logs. The kind of host rock and type of deposit do not affect the validity of the logs. Uranium, thorium, and potassium are the most abundant and most sought-after radioactive elements. The potassium K^{40} isotope and some of the daughter products of uranium and thorium are gamma-ray emitters; therefore, gamma-ray logging is a highly useful tool in the search for and exploration of mineral deposits containing these elements. The lateral extent, thickness, grade, and tonnage of deposits of radioactive minerals can be estimated from information furnished by gamma-ray logs of drill holes spaced in a pattern normal for core-drill exploration.

Some deposits of radioactive minerals are surrounded by halos of radioisotopes that have diffused or transported outward from the parent bodies; other deposits have been partly leached by ground water with trains of radioisotopes deposited down-dip or down-grade from them; these halos and trains of redeposited radioisotopes can be detected by gamma-ray logging and thereby can indicate the presence of nearby radioactive mineral deposits.

Some deposits of nonradioactive minerals are accompanied by small amounts of radioactive elements--for example, phosphate deposits carrying uranium--which can be utilized in the exploration for the nonradioactive host mineral. Gamma-ray logs furnish information concerning thickness and extent of such deposits, but, of course, they cannot be used for making quantitative determinations of grade for nonradioactive constituents. If, however, the ratio of the nonradioactive material to the radioactive trace element is consistent within a district, gamma-ray logs may indicate qualitatively, the grade of the nonradioactive material. A consistent ratio may exist between uranium and calcium phosphate in some phosphatic formations.

Most of the gamma-ray logging by the Geological Survey in connection with exploration of mineral deposits has been in carnotite-type uranium deposits in sandstones; therefore, techniques that have been devised for using the logs as an aid to further exploration probably are especially adaptable to sandstone-type deposits and may be less useful when applied to other types of deposits.

Field use during drilling operations

A gamma-ray log of a drill hole can be made within a short time after the drilling has been completed and while the drill equipment is still in position over the hole. The logging unit can be set up, and a log of a hole 100 feet deep can be obtained in approximately 30 minutes. An additional 20 minutes logging time is required for each additional 100 feet of hole.

By observing the ratemeter and recorder, the logging unit operator or geologist can determine, while a gamma-ray log is being made, whether a hole penetrates a radioactive deposit. Immediately upon completion of logging the strip-chart records can be used to determine depths to radioactive deposits and approximate grades and thicknesses of these deposits. This information is especially helpful when core recovery is incomplete, and it is essential when noncoring equipment is used. It can be used advantageously in selecting sites for additional holes and in selecting portions of core to be saved for chemical assay.

In the field office, data from gamma-ray logs can be used to compile isoradioactivity contour maps and cross sections to be used as aids in planning further exploration. Grade and tonnage estimates of radioactive mineral deposits can be made on the basis of complete interpretation of the logs.

Leached and redistributed radioisotopes

Shortly after the start of routine gamma-ray logging of drill holes in the Salt Wash member of the Morrison formation in the search for carnotite deposits, weak radioactivity anomalies were observed in some places at the contact of ore-bearing sandstone strata and underlying impermeable mudstone or shale strata; furthermore, these anomalies were found only at short distances from carnotite deposits. Investigation of these anomalies in the Calamity area by K. G. Bell and A. S. Rogers, U. S. Geological Survey (written communication, 1950), and in the Legin Group area by Rogers (written communication, 1951) showed that the anomalies exist at the contacts of ore-bearing sandstones and underlying impermeable mudstones or shales that occupy positions stratigraphically below and down-dip from carnotite deposits. In these two areas investigated, the anomalies were less than 300 feet from known carnotite deposits. The radioisotope responsible for the anomalies has not yet been identified because a satisfactory sample from the zone of an anomaly has not been recovered. When a coring bit passes from hard sandstone into soft mudstone or shale a small amount of rock, which includes the contact, is pulverized, and no core is recovered from this zone. Pulverization, which is accentuated at places where ground water seeps along the contact, is considered to be the principal cause of core loss in the zone of the anomalies.

The radioisotope responsible for the radioactivity anomalies at the sandstone-mudstone contacts is believed to have been leached from carnotite deposits by ground water, and carried downward to the upper surfaces of impermeable mudstone or shale strata and then down-dip along the contacts. Only a few anomalies of this kind are found up-dip from carnotite deposits; these may be associated with other carnotite deposits lying farther up-dip. These anomalies are not associated with all carnotite deposits, nor are they found in all localities in which carnotite deposits exist. They are most abundant in localities where ground water is moving or has moved recently.

Inasmuch as radioactivity anomalies on sandstone-mudstone contacts are not always associated with carnotite deposits, they serve only as localized aids to further exploration. When such anomalies are found, continued exploration up-dip from the point of initial observation may lead to the discovery of carnotite. A section through three holes drilled in the Yellow Cat area, Grand County, Utah (fig. 15) illustrates typical conditions existing in the vicinity of these anomalies. McDonald has devised a procedure whereby amplitudes of the anomalies indicated on the strip-charts are used to make an isoradioactivity contour map and areas indicated to be radioactive highs are tested by additional drilling. This procedure has been used with considerable success in the Yellow Cat area, Grand County, Utah, and is described in the case studies section of this report.

Nearly all the drilling done in the Salt Wash member as a part of Geological Survey exploration projects up to 1954 has been within the zone of oxidation. Within this zone, ground-water movement has aided

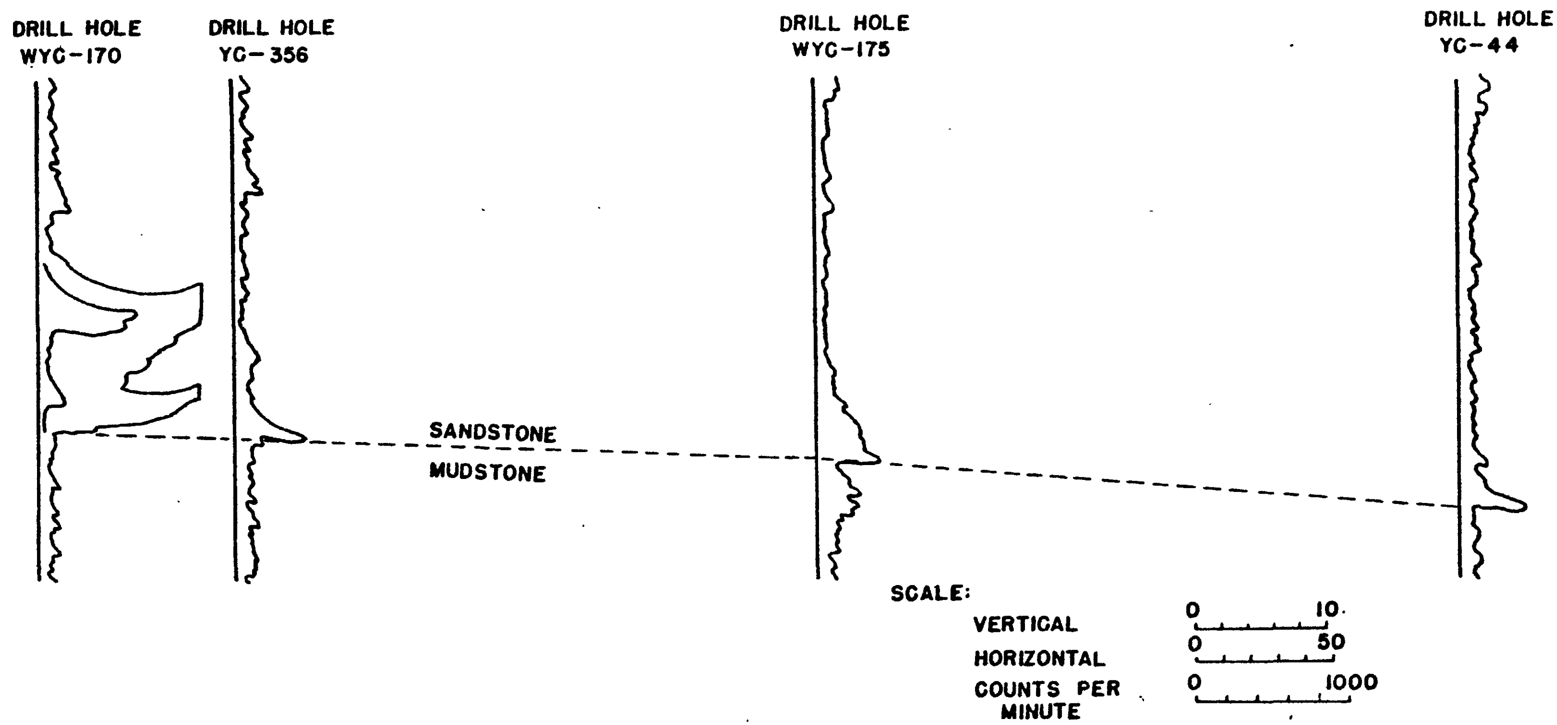

FIGURE 15. GAMMA-RAY ANOMALIES ON MUDSTONE CONTACT, YELLOW CAT DRILLING PROJECT, GRAND COUNTY, UTAH.

in altering primary uranium minerals and has redistributed uranium and its daughter products. The redistribution continues in localities where ground-water movement occurs, and in these localities radioactivity anomalies or sandstone-mudstone contacts are common. A few holes have penetrated to depths below the zone of oxidation where primary uranium minerals have been found. Whether the original radioisotopes have been significantly redistributed since the initial deposition has not been determined, and drilling has not been extensive enough to indicate whether anomalous radioactivity exists on sandstone-mudstone contacts in the unoxidized zone.

Gamma-ray logs of a few holes drilled through the Shinarump show that in the vicinity of carnotite deposits similar radioactivity anomalies exist on the upper surfaces of shale partings and at the contact with the underlying Moenkopi formation. This drilling also has been done within the zone of oxidation.

There was no opportunity during the course of this work to test areas surrounding other types of uranium deposits for leached and redeposited radioisotopes. Leached and redeposited radioisotopes may be present in the vicinity of all uraniferous deposits accessible to ground water, and the gamma-ray anomalies resulting from the radioisotopes may be utilized during extrapolation.

Radioactivity halos

Some, and possibly all, carnotite deposits in sandstones are partly or completely surrounded by halos of one or more radioisotopes. The constituents present in the halos may have been deposited originally as thin edges of the deposits, may have been leached from the primary deposits by ground water and thus redistributed, may be gaseous radioisotopes that have moved outward from the parent deposits by diffusion, or may have reached their present positions through combinations of any of these processes. Weak radioactivity anomalies are indicated on gamma-ray logs of drill holes penetrating these halos. Proper interpretation and utilization of this information are useful in further exploration.

The most practical method of utilizing the radioactivity halos around carnotite deposits as an aid to exploration appears to be through the medium of isoradioactivity contour maps compiled from gamma-ray log data. Preliminary work on this method was accomplished by personnel of the Exploration Division, Grand Junction Operations Office, AEC, and has been described in reports by Hinckley (1952) and Teichman (1952). Several holes must be drilled to obtain the data necessary to compile an isoradioactivity contour map. These holes can be drilled on a fairly wide-spaced grid pattern, and complete utilization of the information available from them will probably result in a reduction in the number of drill holes required to explore the area adequately.

At least two procedures can be used to compile data for isoradioactivity contour maps. First, the maximum counting rates for anomalies indicated on the strip-chart records can be plotted on the maps, or second, the areas enclosed by the curvesrepresenting the anomalies can be measured with a planimeter and these data plotted on the maps. Inasmuch as the curves representing the radioactivity anomalies are the only significant parts of the strip-chart records, planimeter measurements must be restricted to the areas under these curves and must not include the background radioactivity of adjacent relatively nonradioactive rock. Inclusion of background radioactivity from adjacent rock reduces the significance of the anomalies proportionally to the amount included in the measurements and leads to erroneous interpretations. Only those parts of the curves which enclose the estimated thickness of each anomalous zone should be used for compiling the data. The recommended procedure for determining values to be plotted is illustrated in figure 16. After data obtained by either method have been plotted on maps, radioactivity contours are drawn at selected intervals. Isoradioactivity contour maps of parts of the Salt Wash member in three widely separated localities have been made by the two methods. Comparison of the two maps for each locality shows only minor differences. Inasmuch as the use of maximum counting rates involves less work, this method is recommended.

The data used for making isoradioactivity contour maps are most useful when obtained from thin layers of ore-bearing sandstone. However, if the sandstone unit is thick, it should be divided arbitrarily--when no suitable basis exists for making a separation on stratigraphic features--into layers about 10 or 15 feet thick, and an isoradioactivity contour map should be made for each layer. In some localities carnotite deposits are concentrated along two or more thin layers in thick sandstone; therefore, using only data from the thin layers tends to present a clearer picture of local distributions of radioactive material. Maps made on transparent sheets can be superimposed to present the overall picture.

Contour intervals should be selected to separate probable barren ground from that in which continued exploration may be profitable. The background radioactivity characteristic of the sandstone layer being explored must be considered. It can be determined from the strip-chart

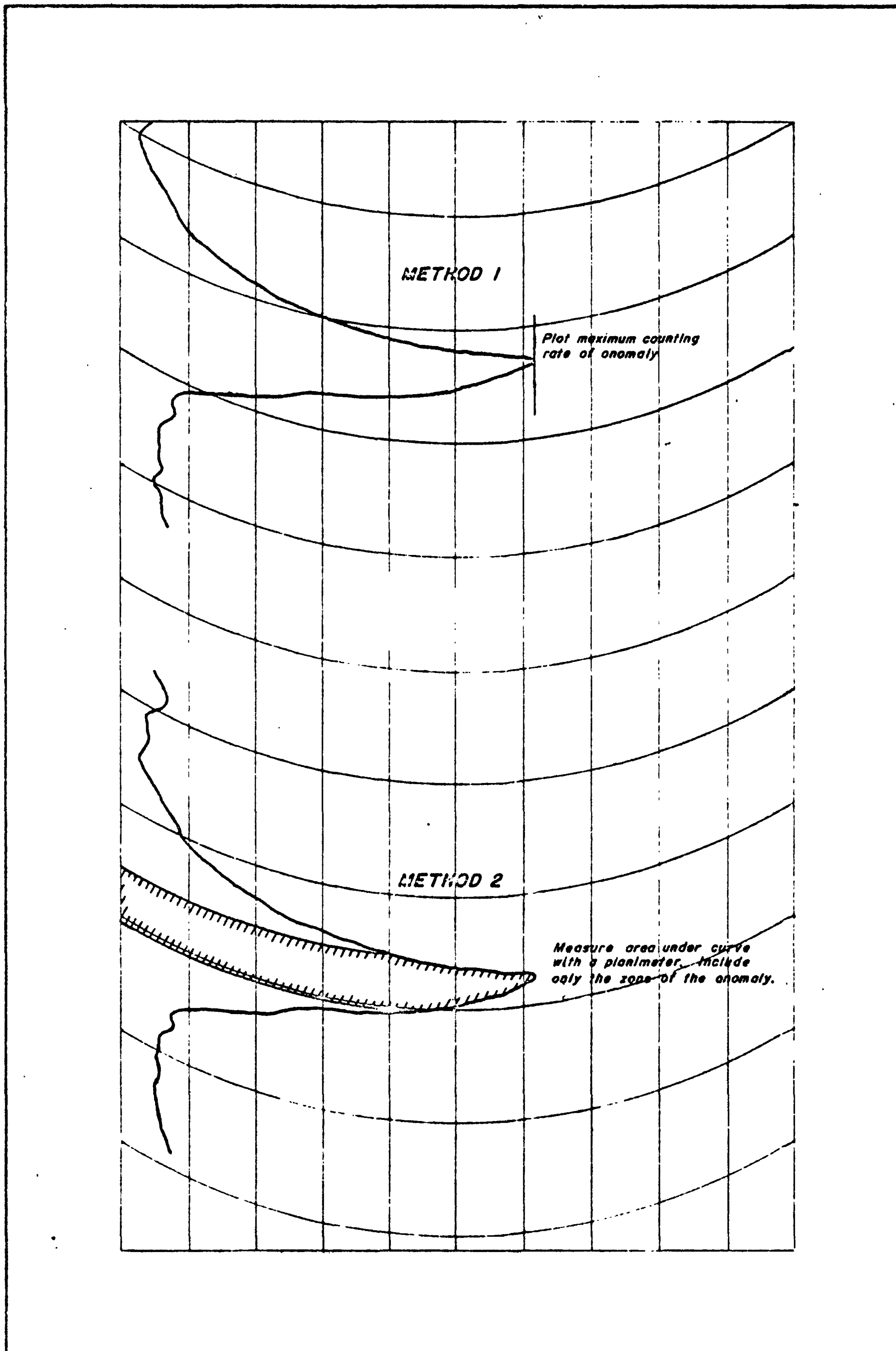

FIGURE 16. METHODS OF DETERMINING DATA FOR ISORADIOACTIVITY MAPS.

records while compiling data to be plotted on the map. The contour separating unfavorable from favorable ground should be set at a level of radioactivity slightly higher than that of the barren rock. This level can be expected to vary from one locality to another, but three or four times background would be used as a starting basis.

An isoradioactivity contour map for the Gramlich claims and some of the adjacent ground in the La Sal Creek district, Montrose County, Colo., is presented in figure 17. Although this area was not drilled on a grid pattern, and although holes distributed haphazardly--as in this area--are not the best sources of data for compiling isoradioactivity contour maps, the utilization of the data nevertheless is satisfactorily demonstrated. Exploration in this area was completed prior to compilation of data used for making the map. The ore-bearing sandstone is a part of the Salt Wash member and ranges in thickness from about 50 feet to about 100 feet. It crops out over approximately the south two-thirds of the area and elsewhere is covered with a thin layer of Brushy Basin shale. Only anomalies appearing in the bottom 30 feet of the sandstone were considered while compiling data. The maximum counting rates of the anomalies were used to construct the map. All counting rates of 200 counts per minute or more over background for barren sandstone were considered to be anomalies. Contours are drawn at 200, 400, 600, and 1,000 counts per minute levels. The map indicates that the southeast and northwest parts of the area are below the 200-counts-per-minute level, and a belt 500 to 600 feet wide in which the radioactivity generally is above the 200-counts-per-minute level extends across the area from the northeast to the southwest. There are small ore bodies within the 200-counts-per-minute contour. A few anomalies lying in the upper part of the sandstone, which were not considered when this map was made, should be plotted on a second sheet because there appear to be two rather distinct mineralized stratigraphic levels.

If the Gramlich claims and adjacent ground had been drilled on a fairly wide-spaced grid pattern, for example at intervals of 200 feet and an isorad map made with the data available from these holes, most of the favorable ground which lies within the 200-counts-per-minute contour could have been separated from the unfavorable ground. The favorable ground then could have been drilled on a closer-spaced grid to locate ore bodies.

There does not appear to be any rigid rule that can be applied to the initial spacing of drill holes in a grid pattern when data for isoradioactivity contour maps are desired. In some localities a spacing of 1,000 feet may be adequate whereas in others a spacing of 200 feet may be required. Carnotite deposits vary greatly in size and shape, and the distribution of radioactivity halos about them is equally erratic. It probably is impractical to attempt to make isoradioactivity contour maps for areas that are extensively faulted and include breccia zones. Applying experience and judgment is a necessity when gamma-ray or other geophysical data are used for exploration.

Radioactive halos around carnotite deposits are characteristic features of the zone of oxidation. Ground-water movement, either past or present, may have had a part in forming the halos, but whether halos are associated with the deeper uraniferous deposits is not definitely known. Deposits which are believed to consist wholly or predominantly of primary uranium minerals are found under impermeable shale covers or below the zone of normal ground-water movement. To the end of 1953 no unoxidized deposit had been thoroughly explored by drilling; however, it seems probable that radioactive halos surround these deposits because gamma-ray logs of holes drilled in the vicinity of the deposits show anomalous radioactivity.

CASE STUDIES

Uranium deposits in sandstone - Colorado Plateau

In 1948 the Geological Survey started a systematic exploratory drilling program on the Colorado Plateau, which had as its objectives the location of ore-grade uranium deposits, the preparation of grade and tonnage estimates for these deposits, and the collection of information pertaining to the habit of these deposits that could lead to determining geologic criteria useful for further exploration. In 1949 gamma-ray logging of all holes drilled was started as a routine phase of the program.

All the uranium deposits of the Colorado Plateau area are found in sandstones, conglomerates, or sandy shales. Around the edges of the plateau area, or at short distances from it, some deposits are found in limestones.

Until the summer of 1953 all exploratory drilling by the Geological Survey in the Colorado Plateau area was directed towards the search for uranium deposits in the Salt Wash member of the Morrison formation. Exploration in the Shinarump member was started in the summer of 1953.

The Salt Wash member was deposited in a fluviatile environment. In the districts where the greatest number and largest uranium deposits have been discovered, as for example the Uravan, Slick Rock, and Yellow Cat districts, the Salt Wash member consists of three sandstone layers separated by several feet of unconsolidated mudstones. The sandstone layers are not continuous over the entire extent of the Salt Wash. They consist of lenticular strata in which there are scour-and-fill structures and channel structures. The lateral extent of individual lenses commonly does not exceed a few hundred yards, and scour-and-fill structures and channel structures tend to be narrow and sinuous. Some parts of the sandstone layers contain thin mudstone splits, and other parts are mixed with considerable quantities of clay and clay galls. The sandstone varies from fine- to medium-grain and has porosity as high as about 20 percent. Most of the known uranium deposits lie in the upper sandstone layer in places where it locally thickens and scour-and-fill or channel structures exist. The mudstones, even when present as splits a few inches thick, are impervious or nearly impervious to ground-water movement. Those parts of the sandstones which contain uranium deposits are generally sufficiently porous to permit the passage of ground water.

Most of the uranium deposits that had been found in the Salt Wash member up to the end of 1953 lie within the zone of oxidation. Carnotite is the most abundant uranium-bearing mineral and in many deposits is the only such mineral. These deposits are irregularly shaped tabular bodies, generally lying horizontal or nearly horizontal, and ranging in size from small blebs to masses having an areal extent of a few thousands of square yards and thicknesses that in places may reach a maximum of approximately 20 feet. The average size of the deposit mined for uranium ore is about 100 feet in greatest horizontal dimension and about 2 feet thick. A few deposits of partly oxidized ore have been found in localities where the deepest holes have been drilled or where the deposits are protected by shale impervious to water or by mudstone caps. Nothing indicates that the size and shape of partly unoxidized deposits differ significantly from those of oxidized deposits. Most of the oxidized deposits are above the present ground-water table. The habit of oxidized and unoxidized deposits, other than relations to ground-water tables and the character of the cover, appears to be the same.

Information concerning grade and thickness of the deposits has been considered to be more essential than stratigraphic detail obtained from gamma-ray logs. It has not been practical to make a second log to get stratigraphic detail because (1) compensation to drilling contractors for keeping equipment at the hole sites during extra time required for making the second log becomes excessive, and (2) core recovered from the holes has already furnished information for stratigraphic correlation.

The differentiation of mudstones and shales from sandstones in the Salt Wash member of the Morrison formation on the Colorado Plateau by means of gamma-ray logs made for uranium grade estimates has been moderately successful. Throughout much of the Salt Wash member the thick sandstone layers enclose many mudstone seams as much as a foot in thickness and are separated from one another by mudstone layers as much as 15 feet in thickness. Mudstone layers exceeding these thicknesses are found locally. Inasmuch as uranium deposits are generally in those parts of the sandstone that are comparatively free from mudstone seams and disseminated clay, information concerning minor stratigraphic detail is essential for evaluating the locality being explored. The standard Geiger-Mueller tubes used for logging holes drilled through uranium deposits in the Salt Wash member give counting rates as high as 100 counts per minute for the sandstone layers and in the range of 150 to 200 counts per minute for most mudstone and shale layers. This difference is great enough to permit identification of mudstone and clean sandstone layers from gamma-ray logs. The differentiation cannot be made positively when the sandstone layers are contaminated with substantial amounts of clay. In some places the sandstone layers are locally mineralized with uraniferous minerals or with redeposited radioisotopes leached from nearby uraniferous deposits. When this condition exists, sandstone and mudstone layers cannot be distinguished by means of gamma-ray logs; however, a counting rate significantly higher than that normally associated with the mudstones can be considered to be indicative of mineralized sandstone. A portion of a gamma-ray log of hole LP-289 drilled in the Long Park area, Montrose County, Colo., is shown in figure 18. This hole did not penetrate any deposits of radioactive minerals. Mudstone and sandstone layers are indicated by the illustrated portion of this log.

Several geophysical methods used successfully to locate deposits of other minerals have been tested in the Colorado Plateau area to determine whether they can be utilized in prospecting for carnotite deposits. Electrical resistivity methods have successfully located the channel structures and scour-and-fill structures that are favorable sites for carnotite deposits. Electrical resistivity methods do not locate the deposit, merely the structure favorable for the deposit. Gamma-ray logging is the only geophysical method developed to date that gives a direct indication of the presence of carnotite deposits.

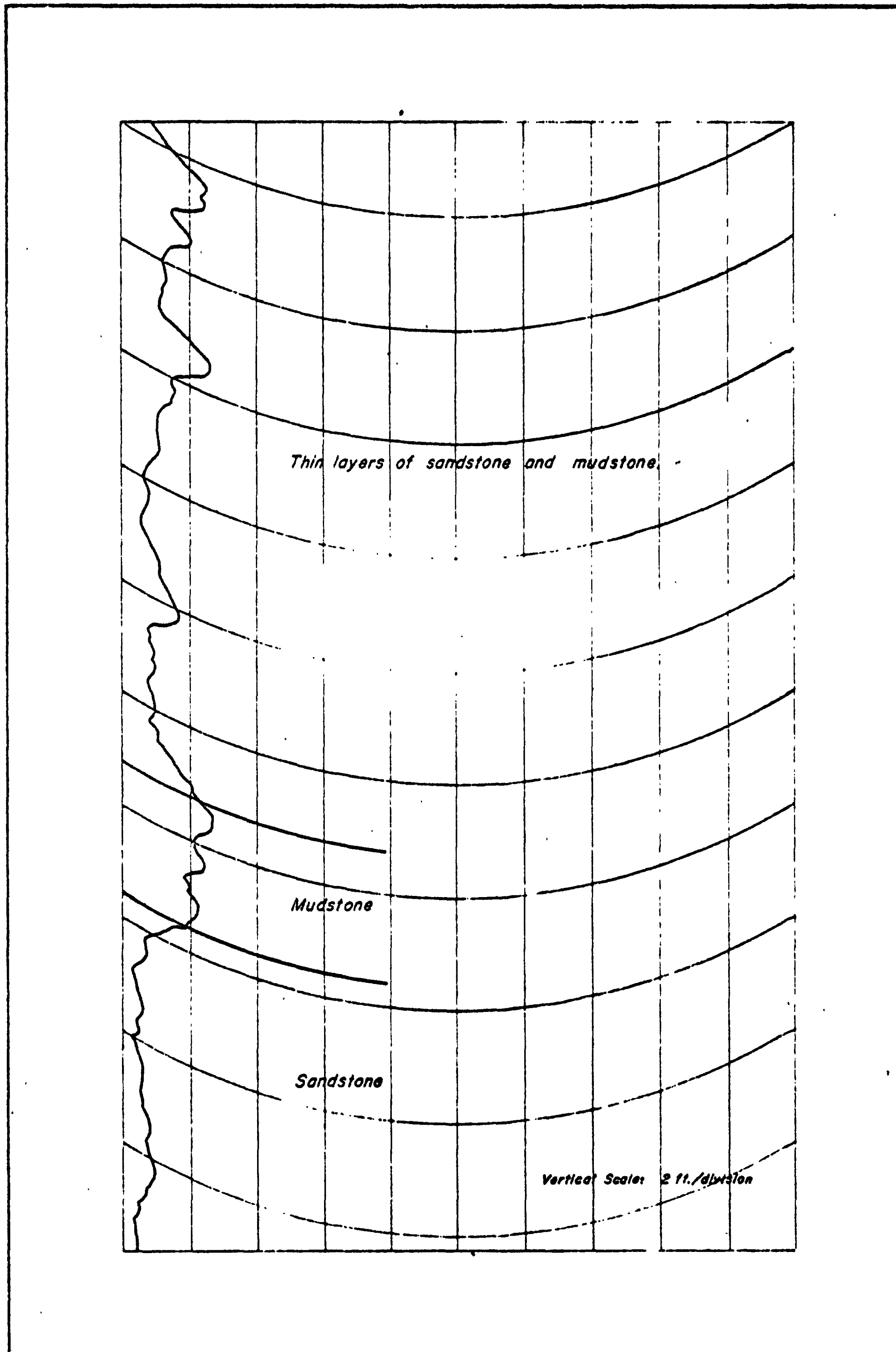

FIGURE 18. SECTION OF GAMMA-RAY LOG SHOWING DIFFERENTIATION OF SANDSTONE AND MUDSTONE IN SALT WASH MEMBER, MORRISON FORMATION, HOLE LP-289, LONG PARK AREA, MONTROSE COUNTY, COLO.

Utilization of gamma-ray data as a guide to ground favorable for carnotite deposits in the western part of the Yellow Cat area, Grand County, Utah

During the period June through September 1952, studies were made to determine if gamma-ray logs of drill holes could be used to define ground favorable for carnotite deposits in the western part of the Yellow Cat area, Thompson district, Grand County, Utah. This area was selected because it provided a suitable coverage of drill holes and because gamma-ray logging instrument calibrations had been standardized before gamma-ray logging started in the Yellow Cat area.

The carnotite deposits in the Yellow Cat area are found in the basal conglomeratic sandstone of the Brushy Basin member and the top three sandstone lenses of the Salt Wash member of the Jurassic Morrison formation. These carnotite-bearing sandstones have been assigned numbers that increase stratigraphically downward; the conglomeratic sandstone of the Brushy Basin is called the No. 1 sandstone, and the three carnotite-bearing sandstones of the Salt Wash are called the No. 2, No. 3, and No. 4 sandstones, respectively. The carnotite deposits in this area are in irregular tabular or pod-shaped masses tending to be elongate toward the northeast or east and roughly parallel to the bedding (D. C. Alvord, U. S. Geological Survey, written communication, 1952)

The studies described in this report were confined to the No. 4 sandstone, because it is continuous over the area studied, and because it contains known ore deposits.

The first study was based on a volumetric comparison of the gamma-ray activity of individual drill holes with respect to the ore deposits in the No. 4 sandstone. A relative value of radiation intensity per volume was derived by dividing the area under the curve showing intensity of gamma radiation on the gamma-ray log for each drill hole by the thickness of the ore-bearing sandstone penetrated in that hole. All anomalies of mudstone seams within the sandstone were deducted from the gross area because of their relatively high radioactivity. Holes were selected to give a fairly uniform grid pattern on the map; other holes were disregarded. A contour map was drawn using the values determined for the holes selected in the grid. This map showed no halo effect around the deposits, and this result is attributed to the fact that areas under curves lose their significance when prorated over the entire thickness of sandstone, which varies from one hole to another.

A second study was made of the gamma-ray anomalies at the contact between the No. 4 sandstone and the underlying mudstone. These small anomalies are found in many holes drilled in the vicinity of carnotite deposits (A. S. Rogers, written communication, 1950), and probably are due to the gamma radiation of materials that have been leached from overlying or adjoining mineralized rock and concentrated along the contact of the sandstone with the relatively impermeable mudstone. A contour map (fig. 19) was made using the maximum gamma-ray counts per minute at this contact for each selected hole. These anomalies shown by the gamma-ray logs were correlated stratigraphically by comparing the geologic log with the gamma-ray log of each hole. Ground having more than 150 counts per minute at the mudstone contact was considered favorable for ore deposits, because all ground inside the contour of 150 counts per minute contained most of the holes in mineralized material (material containing 0.02 percent or more U_3O_8 or 0.10 percent or more V_2O_5 by chemical assay, or that registers gamma-ray values of 0.020 percent or more eU_3O_8), and all the known deposits.

To determine if the gamma-ray data on the mudstone contact would be useful as a guide to deposits, 18 additional holes were drilled. Fifteen of these holes were drilled on sites considered favorable for deposits on the basis of both geological and gamma-ray data and the other three holes were drilled on sites considered favorable on the basis of the gamma-ray data only. Of the 15 holes drilled on the basis of geologic and gamma-ray criteria, 3 penetrated ore (material 1 foot or more thick containing 0.10 percent or more U_3O_8 or 1.0 percent or more V_2O_5 by chemical assay, or registering gamma-ray values of 0.10 percent or more eU_3O_8), and 6 penetrated weakly mineralized material (contains less than 0.10 percent U_3O_8 or 1.0 percent V_2O_5 by chemical assay, or registers gamma-ray values within the range from 0.02 to 0.099 percent eU_3O_8 or less than 1 foot thick, if higher grade). Of the three holes drilled on the basis of gamma-ray criteria, one penetrated ore and one penetrated weakly mineralized material. Of the 18 holes drilled, 11 (or 61 percent) penetrated mineralized material. This is about twice the percentage of the moderately spaced holes that penetrated mineralized material from sites selected on the basis of geologic criteria alone, to search for deposits in the No. 4 sandstone.

Although too few holes were drilled and logged to determine the reliability of using gamma-ray data to supplement geologic information for exploring carnotite deposits, the results are encouraging. This method of applying the gamma-ray data from the mudstone contact below ore-bearing sandstones as an additional guide to deposits may be applicable to other uranium-exploration projects on the Colorado Plateau.

Land-pebble phosphate district, Florida

The so-called land-pebble phosphate of the Bone Valley formation, Polk and Hillsborough Counties, Fla., is an example of a mineral deposit in which the exploited mineral is nonradioactive but is accompanied by a small amount of uranium. This circumstance makes possible the utilization of gamma-ray logs in exploratory work in this deposit.

The phosphate deposits lie at shallow depths and are mined by open-pit methods. From the surface downward the units distinguished in mining operations are (1) overburden, (2) a leached zone containing aluminum phosphate minerals, (3) a zone of calcium phosphate minerals called "matrix" by the producers, and (4) limestone bedrock of the Hawthorne formation. The overburden and limestone are not significantly radioactive. All the phosphatic material is accompanied by a small amount of uranium. The calcium phosphate layer, or matrix, contains the higher phosphate values, is the producing part of the formation, and contains about 0.2 to 0.4 pounds of uranium per ton. Gamma-ray logs of drill holes indicate that the matrix is significantly radioactive. In the leached zone some of the calcium phosphate has been removed, and the remainder has been altered to aluminum phosphate, but uranium has become enriched. The leached zone contains as much as 0.10 percent uranium, and is significantly more radioactive than the matrix. A typical gamma-ray log of an exploratory hole is shown in figure 20. The overburden, leached zone, and matrix vary in thickness from place to place. A leached zone does not everywhere overlie the matrix.

Gamma-ray logging in the district was initially started to obtain information for a preliminary evaluation of uranium potentialities.

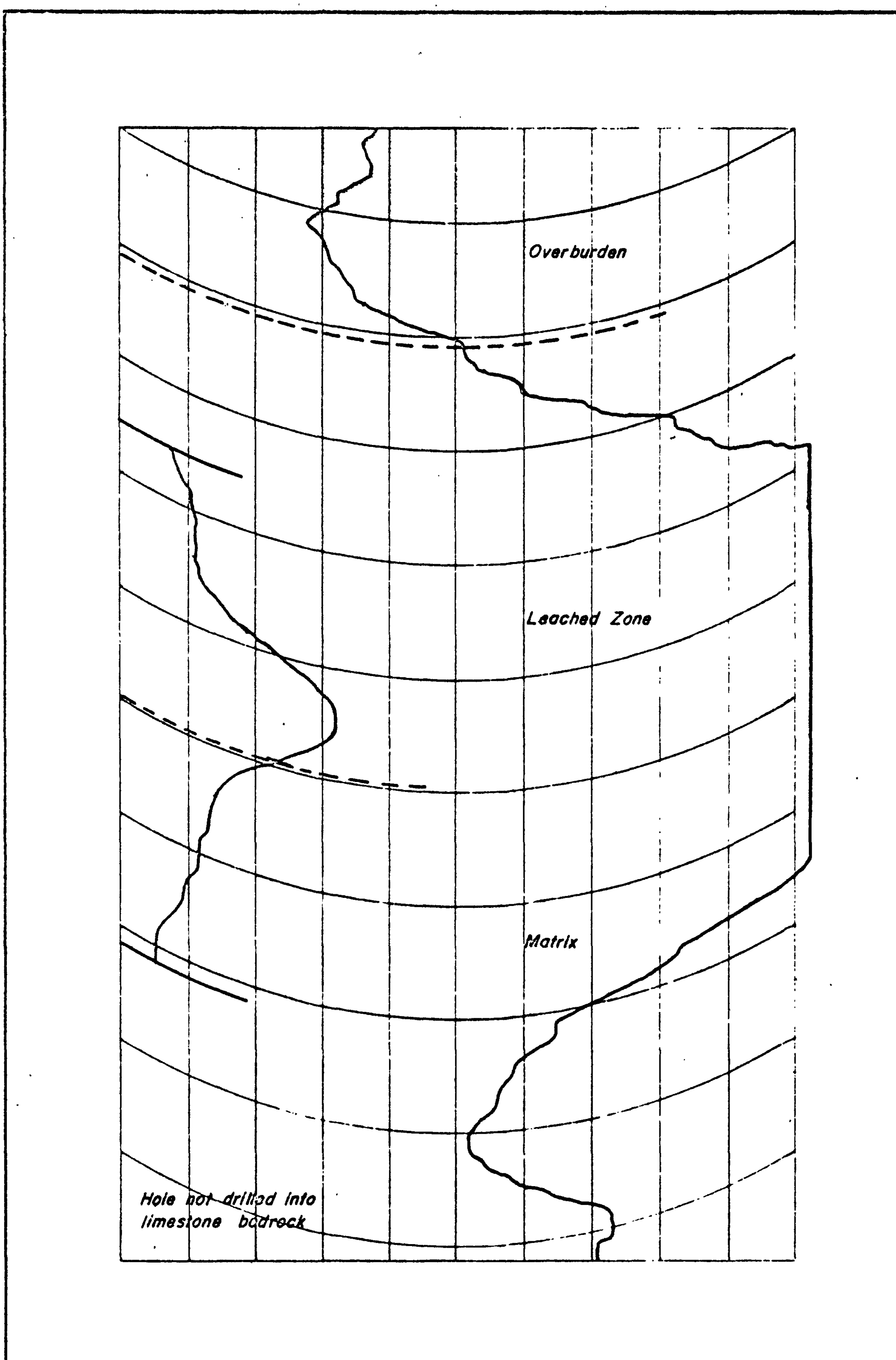

FIGURE 20. GAMMA-RAY LOG OF HOLE DRILLED THROUGH THE PHOSPHATE-BEARING BONE VALLEY FORMATION.

The many exploratory holes drilled by the phosphate producers offered a rapid and economical method of obtaining information. Gamma-ray logs of holes drilled down to the limestone bedrock also have been useful for showing presence or absence of the leached zone and for indicating the thickness of each mining unit. Each of the three units removed in mining operations generally exceeds 2 feet in thickness; therefore, gamma-ray logs of the holes are interpreted as thick-layer problems.

The mining units in the Bone Valley formation are similar to stratigraphic units in that they are layered and exist over wide areas. The first few gamma-ray logs made in the district showed conclusively that the radioactivity of adjacent mining units differs significantly. The thickness of each unit and the positions of contacts are shown in the same manner as for a sequence of variable strata. Depth and thickness data obtained from the logs are now used to determine where to cut drill-hole cores to separate matrix from leached-zone material preparatory to making up samples for assay. The accuracy of sampling is improved thereby because core from the two units often is so nearly identical in appearance that it is impossible to locate the contact by visual examination. The logs furnish data on thickness and depth, which can be used in making preliminary tonnage estimates.

Gamma-ray log data cannot be used directly for making quantitative determinations of the phosphate content of the formation, although there seems to be at least a semiquantitative relationship between uranium content and phosphate content in both leached zone and matrix. Investigations are underway to determine whether uranium-phosphate ratios are constant, or nearly so, for substantial parts of the district. If the ratio proves to be nearly constant, then semiquantitative values for phosphate content may be calculated from uranium grades indicated by gamma-ray logs. Values for phosphate content obtained in this manner might be suitable for preliminary reserve estimates.

Gamma-ray log data can be used to make estimates of the uranium contents of both leached zone and matrix provided a large area is considered and several holes within it have been logged. The eU/U ratio varies somewhat and has been shown by a large number of assays to be slightly greater than 1.0. The conditions causing the variations and general slight excess of eU have not been determined, but they may be due in part to variable amounts of heavy minerals, including monazite and zircon. The matrix and leached zone both are as much as about 30 feet thick. When the matrix is less than 3 feet thick, which is uncommon, it loses its economic importance. Within each unit, equivalent-uranium grades are variable, but they do not fluctuate within distances of a few inches.

Grade-thickness-counting rate calibration charts used for making estimates of equivalent uranium from gamma-ray logs of the holes drilled into the Bone Valley formation consist of a single curve. Calibration charts for this work were compiled empirically using data obtained by chemical and radiometric assay of core samples and counting rates from gamma-ray logs of the holes from which the cores were taken. An example of a chart of this kind is shown in figure 21. The dispersion of the plotted experimental points results partly from statistical fluctuation of the counting rate and partly from undetermined causes.

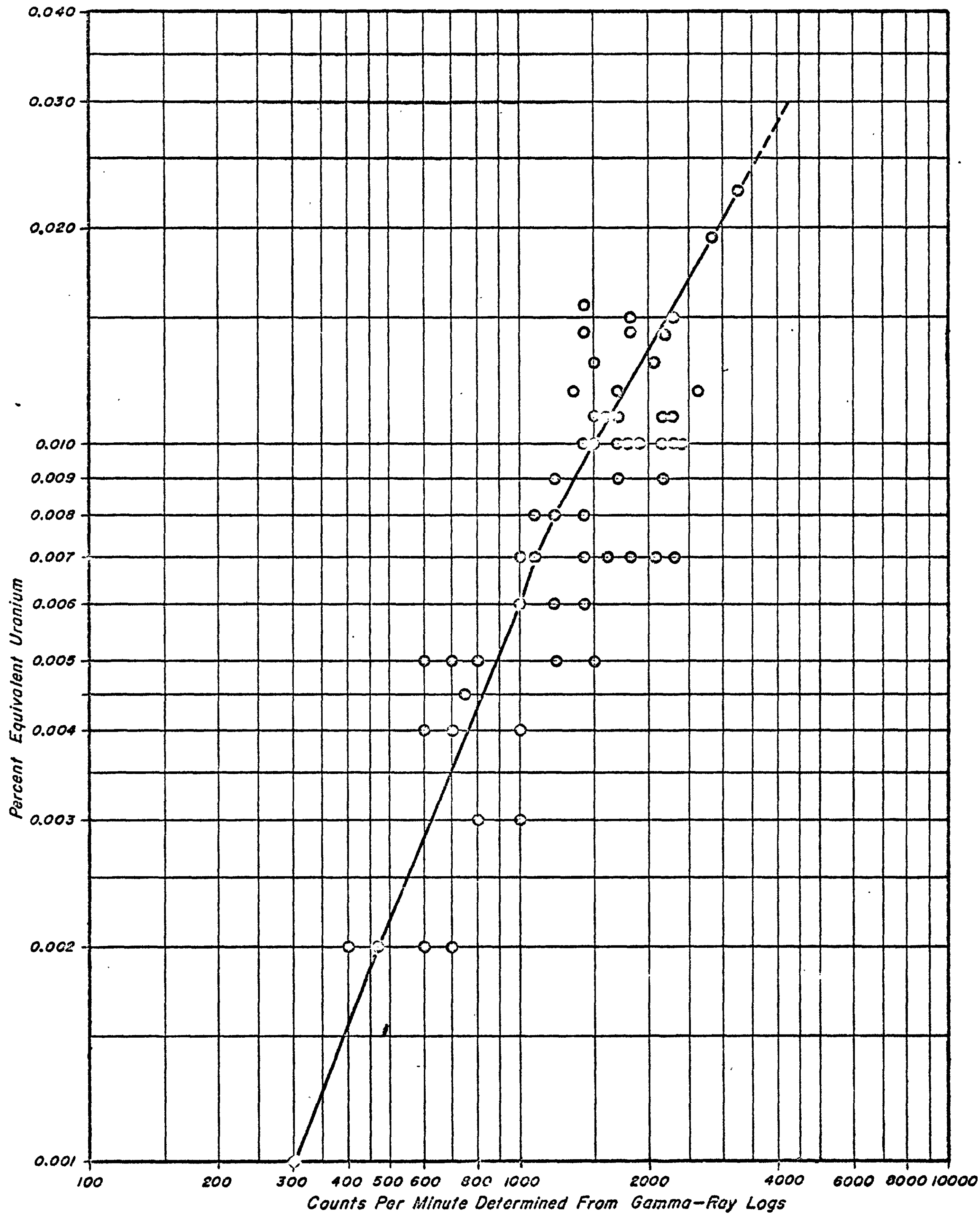

FIGURE 21. CALIBRATION CHART FOR THICK LAYERED MATERIAL, BONE VALLEY FORMATION.

Potential uranium reserves of the district are calculated from gamma-ray log data. The thickness of the unit, either matrix or leached zone, is determined from gamma-ray logs. Tons of uranium per acre are determined by multiplying tons of material per acre by percent eU_3O_8 as taken from the calibration chart for corresponding counts per minute shown by gamma-ray logs. Percent eU_3O_8 can be multiplied by 0.848 to obtain percent eU. A comparison of uranium reserve estimates made from gamma-ray data with estimates for the same areas made from chemical assay data has shown that the radiometric estimates are higher than the chemical estimates by about 20 percent. The reason for this difference has not been determined.

Alluvial deposits, Salt River Valley, Arizona

Several water wells in the Salt River Valley, Maricopa County, Ariz., were gamma-ray logged during February 1952 to determine whether the positions of highly porous aquifers could be determined from the logs. The wells are approximately 1,600 feet deep and are drilled through unconsolidated alluvial deposits. All wells are cased and the casing is perforated in the zones of highly productive aquifers. Diameters of the bores are not the same for all wells logged; one well had a diameter of 24 inches at the top and was reduced in several steps to a diameter of 8 inches at the bottom; another well had a straight 6-inch diameter bore. The character of the sediments penetrated ranges from coarse boulder beds to fine-grained silts and so-called clays.

A 2 x 20-inch Geiger-Mueller tube was used as a counter. Other components of the logging unit were the same as are used for the logging of holes drilled through radioactive mineral deposits.

Gamma-ray logs of several wells showed no significant variations in levels of radioactivity that could be attributed to stratigraphic changes. The only significant changes on the logs occur at points where successive strings of casing were used, and at the surface of the water. These were not the results expected because the wells are reported to penetrate interstratified layers of clay and coarse-grained clastic sediments. The positions of aquifers could not be determined from a study of the logs even though the very meager records kept by drillers showed that several kinds of clastic sediments were penetrated during drilling.

The lack of significant changes in recorded radioactivity in these wells is attributed principally to the compositions of the sediments, and partly to the circumstance that large-diameter water-filled holes do not form ideal environments for making gamma-ray logs. All the sediments comprising the valley fill were probably derived from a rather small erosional area and have essentially the same mineral composition. Examination of a series of samples baled from a well being drilled at the time the logging was done showed that some of the materials being called clay by the drillers were fine-grained silts. Also, drillers and geologists working in the area stated that water flowed from all strata, including the so-called clays, but that the volume varied greatly. This observation verifies the conclusions that the fine-grained strata contain very little clay. Inasmuch as successive strata vary principally in grain size, and only slightly in mineral composition, significant differences should not be expected in the levels of radioactivity between coarse- and fine-grained strata.

Water wells in northeastern Arizona and northwestern New Mexico

Gamma-ray logs were made during February 1952 of three deep water wells in northeastern Arizona and northwestern New Mexico. One well is located at the Wide Ruins School approximately 20 miles north of Chambers, Ariz., another is located at the Cheechilgeetho Day School approximately 20 miles south of Gallup, N. Mex., and the third well is the Hunters Point Tribal Well located approximately 5 miles east of Oak Springs, Ariz. These wells penetrate sandstone and shale formations of Cretaceous and older age. This experimental logging had two objectives: to ascertain whether the major stratigraphic units could be identified by gamma-ray logs and to determine their usefulness as an aid in locating aquifers. Some of the formations penetrated by these wells carry uranium deposits in other areas; therefore, it was desirable to check these wells for anomalous radioactivity. A 2 x 20-inch Geiger-Mueller tube was used as a counter. The logs show good differentiation of major stratigraphic units.

Thorium deposits in Wet Mountains, Custer County, Colorado

During the period of November 1951 to April 1952 gamma-ray logs were made of 11 holes which had been drilled into a thorium-bearing vein traversing the Haputa Ranch, Custer County, Colo. Geologic studies of thorium deposits in the district were being made by the Geological Survey, and exploration of one of the deposits by core drilling was a part of the program.

The radioisotopes accounting for most of the radioactivity in this locality are thorium (Th^{232}) and its daughter products. According to Christman and others (1953), "The thorite and rare-earth minerals occur as fracture fillings, as coatings on fractures, and as replacement bodies in sheared rock," and "The thorium minerals occur in northwest-trending shear zones that contain barite-sulfide veins and cut a pre-Cambrian complex * * *." The principal radioactive mineral had not been identified at the time the report was written, but had been tentatively identified by X-ray pattern as thorite. "Spectrographic analyses of two specimens show that the mineral contains a large number of minor constituents. The material contains more iron and less uranium than normal thorite and may be the variety known as ferrothorite."

The thorium deposit on the Haputa Ranch serves as a typical example of a vein-type radioactive mineral deposit. The kind of information furnished by gamma-ray logs of holes drilled into this deposit can be obtained for all vein-type uranium and thorium deposits. This information includes depth to the radioactive zone, thickness or radioactive material penetrated by the hole, and grade. The logs do not indicate the position of the vein when the hole penetrates at a point where no radioactive material is present.

Inclined holes were drilled through the shear zone, which is nearly vertical, to test for thorium-bearing veins at various depths. The wall rocks consist of several varieties of igneous intrusive rocks and metamorphic rocks, none of which are significantly radioactive. In the area tested the only significant quantities of radioactive minerals are found in veins, but not all veins or all parts of the same vein carry radioactive minerals. A section through drill holes HA-3 and HA-7 and logs of these holes are shown in figure 22. The logs show the position and thickness of radioactive material penetrated. The deflections of the curves representing the anomalies indicate the grade.

Quantitative interpretation of grade in terms of equivalent thorium (eTh) requires the use of a calibration chart based on thorium standards or conversion factors with which to convert equivalent uranium (eU) data to equivalent thorium (eTh) data. An eTh calibration chart has not been compiled by the Geological Survey, and factors for converting eU to eTh have not been determined. To obtain some tentative figures concerning grade and tonnage of the thorium deposit the gamma-ray logs were interpreted in terms of eU_3O_8 using a calibration chart based on uranium standards, and the figures were multiplied by 2.5 to give an approximate grade in terms of $eThO_2$. The grade figures obtained by this method may be too high. It was not possible to make direct comparisons with chemical assays on recovered core samples. The assays which were made are considered to be unreliable because no satisfactory analytical procedure was available for accurately determining thorium in the presence of some other elements contained in the samples, principally barium and rare-earths.

Chattanooga shale

During 1952 and 1953 exploration work was done in the Youngs Bend area, DeKalb County, Tenn., to obtain information on the uranium content of the Chattanooga shale. The formation was tested by several core holes drilled by the U. S. Bureau of Mines. Gamma-ray logs were made of all holes. Geologic studies and gamma-ray logging were done by the Geological Survey.

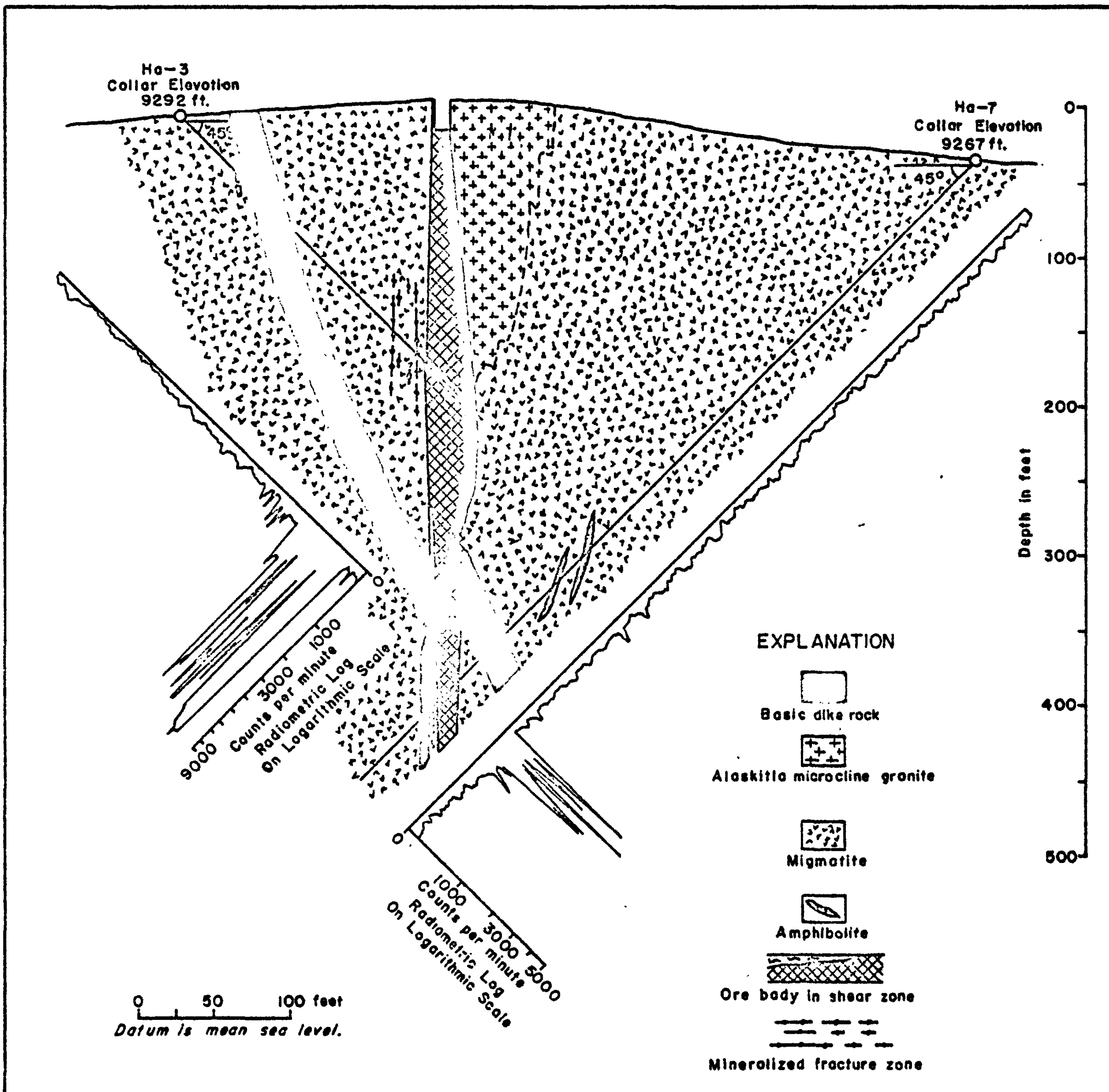

FIGURE 22. SECTION THROUGH HOLES HA-3 AND HA-7, CUSTER COUNTY, COLORADO. (REPRODUCED FROM USGS CIRCULAR 290)

In this district, the Chattanooga shale contains a small amount of uranium. The uraniferous black shale ranges from about 25 to about 35 feet in thickness and overlies nonuraniferous limestone. The Maury formation overlies the black shale and is represented by a bed of phosphatic shale ranging from 1 foot to 4 feet in thickness. The Fort Payne chert overlies the shales. Neither the phosphatic shale nor the chert is significantly radioactive.

Gamma-ray logs were used to show stratigraphic detail and for making qualitative estimates of the uranium content of the shale. Quantitative determinations of equivalent uranium content were not made from gamma-ray log data because the low concentration of radioactive material produces low counting rates and large statistical errors. A section of a gamma-ray log of the lower part of the Fort Payne chert, the Maury formation, and the upper part of the Chattanooga shale is shown in figure 23.

Exploration at the Old Leyden Coal Mine, Jefferson County, Colorado

A uraniferous deposit at the site of the Old Leyden coal mine, Jefferson County, Colo., in which carnotite-type minerals are found in a brecciated, silicified coal bed and adjacent sandstone was tested by core drilling in 1951. Preliminary geologic studies of the area have been described by F. A. McKeown and A. J. Gude (written communication, 1951) and the results of the drilling by Gude and McKeown (1952). The holes were gamma-ray logged to obtain information on the distribution of radioactive material. Gamma-ray and lithologic data of one of the holes are shown in figure 24.

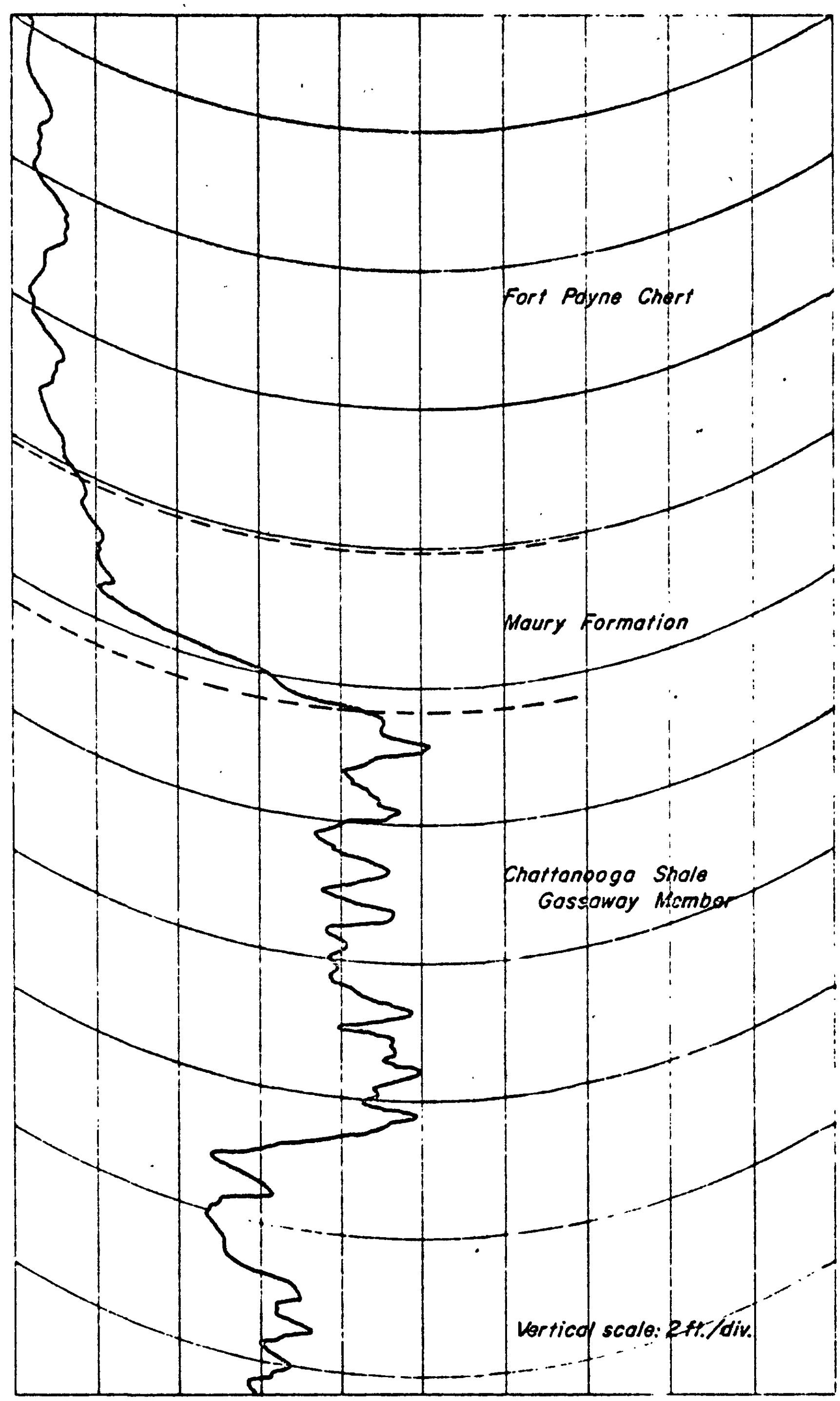

FIGURE 23. GAMMA-RAY LOG SHOWING UPPER CONTACT OF THE CHATTANOOGA SHALE, HOLE YB-22, YOUNGS BEND AREA, DEKALB COUNTY, TENNESSEE.

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