GEOPHYSICAL PROSPECTING: SOME ELECTRICAL METHODS

BY

A. S. EVE and D. A. KEYS
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GEOPHYSICAL PROSPECTING: SOME ELECTRICAL METHODS

By A. S. Eve and D. A. Keys

INTRODUCTION

In a previous publication of the Bureau of Mines the writers gave a brief and elementary account of the principles involved in geophysical prospecting. As a next step in logical procedure it was deemed advisable to verify by experiment some of the methods described, particularly by using electrical apparatus which was simple, inexpensive, portable, and easy to obtain. In order to conduct the experiments under advantageous conditions, an area was selected that was known to be especially suitable for detecting ore bodies by electrical methods. The work consisted of making and comparing electrical surveys over this "proving ground" by as many methods as possible, rather than of searching for new ore bodies in unknown territory.

The results show that the existence of an ore body and a certain amount of valuable information as to its distribution can be obtained with equipment that is procurable with comparative ease by the practicing mining engineer. However, the means of detecting the ore are not equally adaptable under all conditions, and the principles underlying geophysical prospecting methods must be judiciously applied with a great amount of study and caution, as well as sound theoretical knowledge and extensive field experience. Even with these as background the methods in their present stage of development are not altogether reliable.

SITE FOR EXPERIMENTS

Upon the advice of Dr. C. A. Heiland, of the Colorado School of Mines, the site chosen for the major portion of the experimental work was on the northern slope of Caribou Mountain, 6 miles west of Nederland, in Boulder County, Colo., in a region that has been active as a mining locality since the discovery of gold there in 1858 and that has produced nearly $50,000,000 in gold, silver, copper, lead, and tungsten. The first mines at Caribou Mountain were located in 1869, and

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1 Work on manuscript completed April, 1928.
the district is known chiefly for the silver value in its ores. Titaniferous magnetite ore also occurs there in a porphyritic monzonite country rock, but the deposits are small and have no present and probably no future commercial value because the ore at best is of but medium grade and produces a very refractory slag when smelted. However, the excellent electrical conductivity of the deposits renders them particularly adaptable to electrical prospecting methods, and their strong magnetic properties enabled Doctor Heiland and J. A. Malkovsky to make a highly accurate, independent, magnetic survey with which the electrical surveys could be compared with confidence. All of these considerations, together with the fact that the geology of the region was well known, led to the selection of Caribou Mountain as the locality in which to test the various electrical methods of prospecting.

Studies of natural electric currents on the surface of the ground at Caribou Mountain, however, were not entirely satisfactory, due possibly to the complexity of the deposit and the slowness of magnetite oxidation. Hence additional studies were made at Ward, about 14 miles north of Nederland, where more readily oxidizable sulphides of iron and copper were known to exist near the surface of the ground.

APPARATUS

The essential needs of the apparatus used in the prospecting studies were: A source of electrical power, a means of applying the power directly or indirectly to the earth, and some means of detecting the effects produced. As already stated, it was highly important that the apparatus be simple, portable, and readily obtainable.

SOURCE OF POWER

In the experiments where direct current was used ordinary radio B batteries of 45 volts each served as a source of current. These batteries stood up well under more than two months of fairly constant use. Three of them connected in series gave a potential reading of 130 volts at the end of this period.

The source of alternating current was a complete United States Army signaling set purchased from the munitions branch of the War Department. The most essential element of this instrument is a convenient type of induction coil or buzzer, activated by a 10-volt secondary or lead battery, giving an alternating current with an audible frequency of about 1,000 to 1,300 cycles per second. The instrument was used during the World War for signaling through the ground and is known as the T. P. S. ("Telegraphie par sol" or telegraphy through the ground) transmitter, type S. C. R. 71. A diagram

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showing the construction of this rugged instrument is given in Figure 1. It has the advantage that the frequency of the vibrator, and thus of the alternating current introduced into the ground, may be altered over a considerable range of audible frequencies by adding weights to the vibrating hammer. In the experiments by the writers the frequency used was generally 1,300 vibrations per second, and this note was found very suitable for all purposes. To prevent burning the contacts, the buzzer was never left going continuously; an assistant sat by it and sent a signal, such as three dots followed by a dash, repeated only as long as readings were being taken. In this way the contacts were used for two months without serious fusing, although occasional filing of the points was necessary.

APPLICATION OF ELECTRICAL CURRENT TO THE EARTH

Two means were used to lead the current directly into the ground: Two electrodes, each comprising several stakes interconnected with stranded copper wire; and two parallel copper wires pegged to the ground every hundred feet.

In early experiments the stakes were 2-foot lengths of zinc-coated iron pipe 1 inch in diameter, with copper wires well soldered at the upper ends, and these stakes were quite satisfactory from an electrical point of view, but repeated driving into rather hard and stony ground gradually broke the ends. Hence the pipes were superseded by angle-iron stakes (see fig. 2) supplied with the Army T. P. S. set, which had the advantages of simplicity, strength, and convenience when the wires were attached to them.

The parallel bare copper wires were 600 feet long and were laid out along meridians 500 feet apart. The area between the wires was divided into squares, each 100 by 100 feet, and the lines of division were designated $U$, $V$, $W$, $X$, $Y$, and $Z$, from east to west, and 0, 100, 101290°—28—2
200, up to 600, from south to north. For convenience in transportation and handling of wires, special wooden reels holding a couple of thousand feet each were constructed at the Pittsburgh Experiment Station of the Bureau of Mines. With such a reel the wire was readily run out at the desired place and reeled up again when no longer needed, without any danger of twisting, kinking, or breaking. For the insulated wires similar reels were used, as well as the very convenient small type that could be carried on an attendant's back, supplied with the Army T. P. S. outfit. These latter were found especially convenient when only a few hundred feet of wire was required.

With the indirect method of leading the current into the ground, an induced current was produced through the use of a round or rectangular loop of well-insulated wire which was not in metallic contact with the ground.

MEANS OF DETECTING ELECTRICAL CURRENTS

For direct-current experiments non-polarizable electrodes were placed on the ground, or rather in small very wet holes, and wires were led to a portable Weston microammeter with a range of 1 to 100 microamperes and a resistance of 42.2 ohms. When working in a rough and mountainous country the convenience of a delicate instrument which is both portable and accurate can hardly be overestimated. A Weston voltmeter, reading from 1 to 150 volts with a resistance of 15,000 ohms, was used for measuring potential differences on the ground or of the batteries employed.

The nonpolarizable electrodes were readily constructed by taking a porous pot (such as is used in a Daniel cell), placing a number of copper sulphate crystals at the bottom, and then inserting a rod of hardwood about 5 feet long and 1 inch in diameter, with a piece of stout copper wire running down its length to the bottom of the pot. This copper wire was insulated, except for about 6 inches at the bottom, and firmly fastened to the rod with friction tape. The porous pot,
was filled with a concentrated solution of copper sulphate, and a piece of toweling used as a plug at the top. To prevent water getting into the pot from above and also to prevent splashing and evaporation out of the top, a piece of oilcloth was wrapped around the upper half of the porous pot and fastened with friction tape both to the pot and to the rod which formed a handle for carrying the electrode. Such pots were placed in small holes scooped out of the earth, into which a cupful of water was poured to make good contact with the ground. When the pots were not in use they were placed in a basin of saturated copper sulphate solution to keep them filled and prevent evaporation. When two such pots were placed in the same hole and connected with the microammeter the readings seldom amounted to more than 1 or 2 microamperes, indicating that they were very nearly at the same potential.

To detect alternating current a pair of high-resistance head phones was employed, and the ends were connected to two stakes or wires that could be placed on the ground to make good contact. It was found that the body of the observer was a good conductor when alternating current was used; hence his two legs and a stake made three simultaneous contacts with the ground, with the result that no “silence” points could be found. When, however, a bare copper wire from one end of the head phones was wound around one rubber boot of the observer this wire served as a single contact, and the equipotentials could be found.

To detect the electromagnetic effect from two parallel wires, from two ground electrodes, or from insulated square and round loops, a special form of detecting coil was constructed at the Pittsburgh Experiment Station of the Bureau of Mines and hereafter will be referred to as the “Pittsburgh coil.” It consisted of a wooden frame 2 by 3 feet in dimensions, on which were wound 400 turns of No. 26 B. & S. gauge double-silk-covered copper wire, having a resistance of 174 ohms. This coil was held in a frame by two gimbles, so that it could turn about a horizontal axis through its center. The outside frame in turn fitted on the head of a transit tripod and could be turned about a vertical axis. A brass scale reading to $\frac{1}{2}^\circ$ was attached to the base, so that the azimuth of the coil could be read. A small graduated circle was also attached to the frame, so that the angle of dip of the inner coil could be measured to the nearest $\frac{1}{2}^\circ$.

The coil was first mounted on the tripod, and the latter was easily leveled by hanging a plummet from the center of the top of the frame and centering on a small brass plate with two lines intersecting at right angles directly beneath. As the base of the transit tripod was movable in every direction, the leveling process took but a few seconds. The coil had to be leveled at each station before readings were taken. The ends of the wire on the coil were soldered to two
terminals at the side of the frame, and these were connected to the head phones of the observer. Figure 3 is a photograph of the coil in use.

Where the induced currents in the coil were feeble a two-stage amplifier was used to magnify their intensities. The amplifier is diagramed in Figure 4 and was the set supplied with the Army T. P. S. outfit. It was found satisfactory and easy to transport. It is known as the United States Army two-tube amplifier, type S. C. R. 72. The plate potentials were obtained from small dry batteries and the filament current from a four-cell storage battery, also portable, of 100 ampere-hour capacity. Figure 5 shows this amplifier used in connection with the coil and observer.

![Figure 3](image)

*Figure 3.—Detecting coil in frame on tripod, which can be turned or tilted. Minimum reception is found by an observer using head phones, with or without amplifier. Site near Caribou mine*

Wherever possible "null" methods were employed; that is, the search coil was rotated into such a position that a minimum of sound was heard in the receiving telephone, or points on the earth were found at which no deflection of the galvanometer (microammeter) was observed. This is equivalent to a search for direction of the field.

The writers were, of course, under obligation to the pioneers of these methods and to their publications, particularly to Sundberg, Lundberg, and Eklund for the parallel-wire method, to Gella for the bipolar method, and to Schlumberger for the nonpolarizable

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electrodes (copper sulphate in porous pots with a copper rod leading to the solution).

**RADIO RECEPTION**

The tests of radio reception were made with a Victoreen superheterodyne set with nine electron tubes, which Guy L. Allen, of Boulder, had built for himself and with which he had received speech and music from such distant stations as London, Madrid, Lima, and Buenos Aires.

**ACKNOWLEDGMENTS**

The authors desire to make especial acknowledgment of their indebtedness to E. H. Denny, district mining engineer of the United States Bureau of Mines, without whose capable assistance the tests in Colorado could not have been carried out so smoothly. Mr. Denny made many of the necessary preliminary arrangements and obtained apparatus needed for the tests; moreover, he gave the authors the benefit of his intimate knowledge of the history of the region studied and of the mining methods in use therein. He also helped to prepare many of the illustrations.

Dr. C. A. Heiland and J. A. Malkovsky, of the Colorado School of Mines, gave valuable information regarding the Caribou proving field and loaned equipment from the school for use in the tests. Doctor Heiland selected the proving ground used in most of the experiments. One of the illustrations represents the results of a survey by these two investigators, whose conclusions were checked against those obtained by the authors' "leapfrog" method and other electrical surveys.
Acknowledgment is also made to the following: P. Sharp and T. A. Manhart (for illustrations); J. R. Roots and his son, L. S. Brock, P. A. Larson, W. G. Pauling, Guy L. Allen, J. G. Clark, H. K. Lidstone, Earl Bryant, and Mr. Martin.

ELECTRICAL SURVEYS

1. DETERMINATION OF EQUIPOTENTIALS IN A FIELD BETWEEN PARALLEL WIRES EXCITED BY DIRECT CURRENT

This method is the direct application on a large scale of the well-known elementary laboratory experiment in which the equipotentials between two parallel strips of metal in a tray of conducting water are determined. Two bare copper wires were laid on Caribou Mountain along the $U$ and $Z$ lines as described on page 3. The ends of the wires were connected to opposite poles of three B batteries joined in series, and a key was placed in the circuit so that the current could be applied to the wires only when desired. With the key depressed, an electric current flowed through the ground from one wire to the other. If the character of the ground had been uniform, the lines of current flow would have been parallel and would have had an east-west direction, while the lines of equipotential, which are perpendicular to the lines of current flow, would have

![Figure 5: Two similar detecting coils for comparative effects, one mounted on tripod, the other placed as desired; amplifier set on the ground.](image-url)
extended north and south—parallel to the copper wires. Since, however, there was a deposit of good-conducting ore in part of the area between the two wires, the lines of current flow were crowded into this good-conducting area and the lines of equipotential in consequence diverged, thus giving an idea of the conductivity of the ground and indicating the existence of the ore body.

The lines of equipotential were determined by the following procedure, which is described somewhat in detail, as it is more or less typical of all equipotential methods of geophysical prospecting: Two nonpolarizable porous-pot electrodes (see p. 4) were connected with the microammeter in series by a wire about 150 feet long. One electrode was placed at the V-0 point, for example, the other placed at some point on the 100-foot line, such as V-100, and the microammeter read to determine the “natural current.” (See p. 4.) Current was then supplied to the copper wires on the U and Z lines, and the microammeter read again. If the porous pots were not on the same equipotential line, a change in the microammeter reading resulted, in which case the electrode on the 100-foot line was then moved about along that line until a position was found at which there was no change in the microammeter reading when the current was applied to the U and Z lines, thus determining a second point on the ground having the same potential as the one at V-0. The first electrode was then moved to this point, and the second electrode advanced to the 200-foot line and the operation repeated. In this way a number of equipotential lines were produced throughout the entire region between the parallel wires, and from their distortion from directions parallel to the U and Z lines the position of the good-conducting regions was found. Figure 6 shows the equipotential lines obtained by this method at the proving grounds on Caribou Mountain. The crosshatched portion of this figure indicates the extent of the ore body as determined by the magnetic survey made independently by Doctor Heiland. Figure 7 (p. 11) is an enlarged outline of the extent of the ore body, determined by a geological survey made several years ago.\footnote{Bastin, Edson S., and Hill, James M., work cited (footnote 3), pl. 1.}

2. DETERMINATION OF EQUIPOTENTIALS IN A FIELD BETWEEN PARALLEL WIRES EXCITED BY ALTERNATING CURRENT

This method of determining equipotential lines was very similar to that just described, except that the wires were activated by the Army T. P. S. buzzer adjusted to a frequency of 1,300 cycles per second and that telephone receivers instead of the microammeter were used in detecting the flow of current through the ground. This method had the advantage that the porous-pot electrodes were not required, as enough contact could be obtained with a piece of copper wire wound
around one rubber boot of the observer; hence the man could walk along the east-west line until a silence point was reached. As the telephone receiver is a very sensitive instrument, the method is rapid and accurate. The results of this survey over the Caribou Mountain proving ground are shown in Figure 8.

![Figure 6](image)

**Figure 6.**—Equipotentials between parallel wires along $U$ and $Z$ lines excited by direct current. The crosshatched area indicates magnetite located by magnetic tests. The curved lines indicate electrical equipotentials, deflected by the ore

3. DETERMINATION OF MAGNETIC FIELD DIRECTIONS BY SEARCH COIL WITH AMPLIFIER AND TELEPHONE RECEIVERS IN A FIELD BETWEEN PARALLEL WIRES EXCITED BY ALTERNATING CURRENT

Method 3 used the alternating electromagnetic induction from the two wires from the $U$ and $Z$ lines excited by the T. P. S. transmitter with frequency 1,300 in determining magnetic field directions. The electric currents between the two wires generate an alternating magnetic field in the air that should be parallel to the wires if conductors
Figure 7.—Proving ground on Caribou Mountain, Colo., showing orientation, subdivision, relative contours in feet, and supposed outline of magnetite deposit.
in the ground do not distort the currents. Therefore, if a search coil, such as one of the Pittsburgh type, is placed between the two wires and the ground is uniform, no currents would be induced in the coil when in a plane parallel to the magnetic field, that is, when it parallels the wires. If the coil is set up at any point and adjusted for the minimum position of the current induced therein, the plane of the coil will be tangential to the direction of the magnetic field.

Directly over the wire the minimum position should be expected to be exactly or very nearly at right angles to the length of the wire, as the current oscillating up and down it at this point is very much stronger than that through the ground. This supposition was confirmed.
The Pittsburgh coil was set up at the various intersections of the 100-foot lines and the \( V \) to \( Y \) lines. The coil was kept vertical and its azimuth adjusted for the minimum positions. Figure 9 shows the readings at the various points. No amplifier was used. The sensitivity and accuracy of this method are shown by the results of an independent survey with the amplifier. (See fig. 10.) The agreement is remarkable, although the indication by this method is poor.

Similarity will be noted between the results with this method and those with methods 1 and 2, but there is one very striking difference. In those methods the equipotentials at the 500 and 600 foot lines on the east side tend to curve toward the center; in this search-coil method the lines of minimum reception seem to point toward the east.
or \( U \) line. A contour map of the region affords a ready explanation, however. The 100 and 200 foot lines are several hundred feet higher than the 500 and 600 foot lines, a change in level that no doubt alters the electromagnetic distribution. On the whole, however, the lines of minimum reception—at least those obtained on the more level section—appear again to diverge from the ore body, as did those determined by methods 1 and 2.

![Figure 10](image-url)

**Figure 10.**—Same as Figure 9, but repeated by another observer with amplification of reception

4. **DETERMINATION OF EQUIPOTENTIALS IN A FIELD EXCITED BY DIRECT CURRENT TO TWO GROUND ELECTRODES, USING TWO NONPOLARIZABLE ELECTRODES AND MICROAMMETER AS DETECTORS**

Placing long bare copper wires on the ground, as in methods 1, 2, and 3, may not always be practical, but an arrangement frequently employed in the laboratory may prove satisfactory. Two sets of four stakes each, at the four corners of a 2-foot square, connected by stout
copper wires, were driven into the ground 200 feet apart, and each set acted as a single electrode to distant points. (See fig. 11, A and B.) A and B were connected through a tapping key to the terminals of three B batteries connected in series, giving a difference in potential of about 135 volts. Reception was with two porous pots containing copper sulphate solution and copper leads, to a Weston microammeter. When the circuit was made a direct current flowed from A to B through the ground and was distributed symmetrically between these two electrodes if the ground was uniform. In fact, the lines of current flow were exactly the same as the lines of force if the electrodes were replaced by point charges of electricity of equal strength but opposite sign. Similar distribution would be obtained by a thin bar magnet with its north pole at A and its south at B.
The direction of the magnetic lines of force at any point in the region would then be that of the current in the test under consideration, the ground being, of course, uniform.

The equipotential lines were determined as described above—that is, with porous-pot electrodes and a microammeter—allowance being made for natural currents. Figure 11 shows the results of such a survey on the Caribou proving ground. If the ground had been uniform, distribution of the lines about a plane perpendicular to the line joining $A$ and $B$ through the middle point of $AB$ would be similar. It is quite noticeable that the distribution of lines about $A$ and $B$ is not the same. The presence of the ore body in the region shaded accounts for this asymmetry of the equipotential lines.

This method had possibly one advantage over methods 1 to 3, in that the lines of current flow were supposed to penetrate the ground farther; thus a conducting mass lying deeper would be detected. On the other hand, interpretation of results and recognition of the deviation of the equipotentials from normal distribution in homogeneous ground free from conducting masses of ore is difficult, even for one with considerable experience in making such calculations.

5. DETERMINATION OF EQUIPOTENTIALS BY TELEPHONE AND TWO MOBILE ELECTRODES IN A FIELD BETWEEN TWO ELECTRODES IN THE GROUND EXCITED BY ALTERNATING CURRENT

In this method alternating current was employed and a telephone receiver with wires attached to a shoe of each of two observers, who walked about to find silence points. The method was simple in itself, but interpretation of the findings was difficult. The diagram obtained was almost the same as Figure 11.

6. DETERMINATION OF MAGNETIC FIELD DIRECTIONS BY SEARCH COIL, TELEPHONE RECEIVER, AND AMPLIFIER IN A FIELD BETWEEN TWO ELECTRODES IN THE GROUND EXCITED BY ALTERNATING CURRENT

Two sets of electrodes were driven into the ground 200 feet apart, as in method 4, and excited by alternating current from the Army T. P. S. buzzer. Conducting ore will distort currents in the ground from symmetrical distribution about electrodes $A$ and $B$. The equipotentials were not found in the ground; instead, a search coil was used and the plane of the coil adjusted at various points on the area where it would parallel the magnetic flux.

In the first set of experiments using method 6, the two electrodes were placed on the $V$ line at the 250 and 450 foot points. The Pittsburgh coil, with telephone and amplifier, was set up at the various stations shown in Figure 12. The coil was kept strictly vertical and the azimuth then found for the minimum induced current. The diagram indicates the direction of the magnetic flux at the various points. The minimum audibility lines are drawn as shown from these readings.
The above "lines" are asymmetrical about the 350-foot line, indicating that masses of conducting material are present at various points. In uniform ground the distribution of magnetic flux may be calculated from theoretical knowledge, and if the position of the lines found by experiment and by the theoretical distribution in a uniform area are compared, the presence of an ore body may be deduced; but these calculations are difficult.

The ore deposit may lie in such a position relative to electrodes A and B that it will not disturb distribution of the lines of minimum audibilities to a noticeable extent. In other words, the deposit might be symmetrically placed relative to the two electrodes. To counteract any error from this source another survey was made with the
electrodes at right angle to their former position. Figure 13 gives the results of such a survey over the same area when the electrodes were on the 200-foot line and 200 feet apart. The equipotentials again show dissymmetry, and shading indicates the location of the deposit, according to the magnetic survey. A small lump of strongly mag-

**Figure 13.**—Same as Figure 12, but with grounded electrodes, A and B, at right angles to their former position

netized magnetite will give a large indication on the magnetometer but may have little effect in an electrical survey, whereas a large deposit of highly conducting material which is not very magnetic would affect the electrical survey strongly but would not give a strong indication on the magnetometer.
7. DETERMINATION OF MAGNETIC FIELD DIRECTIONS BY SEARCH COIL, AMPLIFIER, AND TELEPHONES IN A FIELD WHEREIN A SQUARE LOOP IS EXCITED BY ALTERNATING CURRENT

These experiments were made to test the use of a loop method over a magnetite deposit. An insulated loop of wire, laid around a 500-foot square of the area investigated by other methods, is the outside of the diagram in Figure 14.

![Diagram](image)

**Figure 14.**—Directions of minimum audibility within square loop around proving ground, excited by alternating current, in a vertical plane determined with coil, amplifier, and telephone

The loop was excited by an alternating current from the T. P. S. buzzer, which was placed at the W-0 line, or well outside the area inclosed by the loop. The Pittsburgh search coil, amplifier, and telephones were used for reception.

Experiments were first made to see what could be deduced from the direction of the magnetic flux outside the loop. The coil was
kept strictly vertical, and the positions of minimum intensity found at various points in the loop indicated in the diagram. Interpretation of these results is very difficult, and the authors concluded from this experiment and others with loops (see pp. 21 to 24) that under these circumstances direction was very uncertain in indicating ore deposits.

It was found at once that an exceedingly slight dip of the search coil from the vertical caused a large difference in the minimum direction. Thus a dip of 1° from the vertical caused a change of several degrees in azimuth.

![Diagram](image)

**Figure 15.** Directions of minimum audibility near corner of square loop excited by alternating current. The arrows indicate azimuth of coil and dotted lines the directions of resultant magnetic vectors.

When over the loop itself the direction of minimum current in the coil was everywhere perpendicular to the direction of the wire. It was then desirable to trace the field directions for a short distance within the loop, particularly near a corner. To test this the field on an arc 50 feet away from the corner of the loop at the $U$ 100-foot point was explored. The results are shown in Figure 15. The lines of minimum audibility follow the diagonal; that is, they turn around and become asymptotic to the diagonal but always cut the loop wire at right angles. When it is known that the lines flow in this direction it is difficult, for instance, to interpret where the ore body must be to give the direction found at the $V$ 200-foot point in Figure 14.
magnetic induction from the loop stimulates an ore body, which in turn produces a field; hence the magnetic field at any point is the resultant of all disturbances reaching the point. The fact that these effects all arrive at various phases complicates the matter still further. The electromagnetic field at any such point will in general be elliptically polarized, tending to produce a broad rather than a sharp direction of minimum audibility.

This phase difference between the fields reaching the search coil at any point suggested an attempt to detect it. To do so another coil similar to that held on the tripod was placed on the ground, and these two coils were connected in opposition, the telephone being used as before. When the position of one coil was altered and the other kept in a constant position, only slight changes in intensity and no decided minima were noticed. When one coil was laid flat on the ground and the other placed directly on top and in opposition, silence was obtained, but under no other conditions.

Inserting resistance in the circuit of one coil to change the phase of its current and thus bring it into phase with that induced in the second coil was also tried, but this gave no definite results. No opportunity was afforded to try changes in capacity in order to eliminate the phase differences between the two coils.

As the location of deposits in the area investigated is known, it might be concluded that there was some indication that the coil pointed toward the deposits. The change in elevation between the 100 and 600 foot lines, however, rather complicates deductions by this method, so that more experiments on a larger scale with stronger currents in the loops are believed necessary before definite conclusions can be drawn regarding it.

8. DETERMINATION OF MAGNETIC FIELD DIRECTIONS BY SEARCH COIL, AMPLIFIER, AND TELEPHONE RECEIVER, WITH CIRCULAR LOOP BOTH ON AND OFF MAGNETITE DEPOSITS, IN A FIELD EXCITED BY ALTERNATING CURRENT

The experiments with the square loop described under method 7 indicated that a circular loop would give much better results. Considerations of symmetry made it evident that when a circular loop is excited by alternating current and a search coil, kept always vertical, is moved along a diameter its plane should remain along this diameter if there is no distorting effect due to unevenness of the ground.

A circular coil 100 feet in radius was laid out on the Caribou proving ground, with its center at V on the 200-foot line. This coil of insulated copper wire was excited by the alternating current from the Army T. P. S. buzzer, and the Pittsburgh search coil was set up every 25 feet along the two diameters, as shown in Figure 16. The coil was kept vertical and adjusted to the position of minimum current
and the azimuth measured. The minimum positions are given in the
diagram for each point on the two diameters.

The reader will notice at once that the minimum directions are
not along the diameters; thus there is some disturbing influence presen-
t. Close examination of the diagram indicates that the directions
all point to one locality in the lower left quadrant. The ground on
which the coil was laid was not flat, and the 300-foot line was about
25 feet below the 100-foot line. This does not, however, account

![Figure 16](image)

Figure 16.—Azimuths of minimum audibility within a circular loop excited by alternating
current; reception with vertical coil and telephone

for the fact that the azimuths all point to a fairly definite limited
area.

To allow further investigation, a 100-foot loop was placed on a
meadow in Caribou Valley that was very nearly level, although it
had a slight rise to the north. No surface indications suggested the
presence of an ore deposit near the loop. The loop was excited by
alternating current from the T. P. S. buzzer as before, and the Pitts-
burgh coil (kept vertical) was used to determine the azimuth of the
magnetic field at points 25 feet apart on two diameters, as shown in
Figure 17. Over the wire the coil was always along the radius, but
along the diameters the diagram in which the azimuths are given shows that here again their directions seem to converge to a definite region in the circle.

Another level meadow was found still farther down the valley, and a 100-foot radius circular loop was placed on this spot. The same general results were found at this location, as Figure 18 shows.

The following experiment was also performed here: The coil was kept with its azimuth along the diameter and the dip at which the intensity became a minimum read off. The diagram records the values found for the dip at every station and the nature of the soil immediately underneath.

The results of these experiments with circular loops indicate that the direction of the field depends upon several factors—slope of the ground, irregularities in the loop, angle of dip of the coil, and possibly the presence of ore bodies. The results do not appear definite enough to warrant the use of this method in geophysical prospecting for ore with the small currents that can be obtained with the Army T. P. S. buzzer used for exciting the loop.

\[\text{Figure 17.—Azimuths of minimum audibility within a circular loop excited by alternating current; reception with vertical coil and telephone}\]
Attempts to measure intensity in the exploring coil with a thermocouple and a microammeter were unsuccessful. When the exploring coil was placed directly over the wire of the loop and in the position of maximum intensity of the induced currents the greatest deflection obtained on the microammeter was one division. For measurements of intensity, much stronger currents must be used to excite the loop than those obtainable from the Army buzzer.

Figure 18.—Azimuths and dips of minimum audibility within a circular loop excited by 1,300-cycle alternating current; reception with vertical coil

9. DETERMINATION OF THE PRESENCE OF ORE BODIES BY THE "LEAP-FROG" METHOD

EVOLUTION OF METHOD

Parallel wires 600 feet long had been laid 500 feet apart and pegged to the ground every hundred feet. The writers thought it would be interesting to explore the drop of potential between the wires, and the latter were therefore connected to three B batteries which gave 131 volts between their terminals on open circuit and 122 volts on closed. When a porous pot containing copper sulphate solution was placed on the wire to the west and another on the ground a few feet away the voltmeter (joined between them) recorded about 26 volts.
When a pot was placed on a wire to the east the reading was about 65 volts.

The drop of potential per hundred feet in some of the ground between the wires was found to be only about 1 volt or even less—in fact, sometimes too small to be read on the voltmeter. Most of the fall of potential was, then, near the wires themselves, and the ground between them was in effect a huge conductor where the fall of potential (really the fall of electrical pressure) was naturally small. Moreover, the ground near the wire to the west contained much magnetite, an excellent conductor, whereas that to the east contained little.

Therefore the slight fall of potential indicated good conductivity in the vicinity and could be used to show the presence of ore bodies. A similar inequality was observed when the fall in potential between each of the electrodes (shown in fig. 11) and a point midway between them was measured.

Experiments were therefore made as follows: One porous pot containing copper sulphate solution was placed on the wire and connected through the voltmeter to a second porous pot similarly filled with electrolyte. The distance between them was varied, and the results are tabulated as follows:

<table>
<thead>
<tr>
<th>Distance, feet</th>
<th>Eastern wire at U-200 (voltage difference)</th>
<th>Western wire at Z-200 (voltage difference)</th>
<th>Distance, feet</th>
<th>Eastern wire at U-200 (voltage difference)</th>
<th>Western wire at Z-200 (voltage difference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>65</td>
<td>25</td>
<td>60</td>
<td>67</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>66</td>
<td>25</td>
<td>70</td>
<td>71</td>
<td>23</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>25</td>
<td>80</td>
<td>67</td>
<td>23</td>
</tr>
<tr>
<td>30</td>
<td>69</td>
<td>23</td>
<td>90</td>
<td>64</td>
<td>20</td>
</tr>
<tr>
<td>40</td>
<td>66</td>
<td>24</td>
<td>100</td>
<td>70</td>
<td>21.5</td>
</tr>
<tr>
<td>50</td>
<td>67</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There is no doubt then that the drop in voltage occurs mainly close to the wire, while the minor fluctuations shown in Table 1 are due to variations in conductivity around the second electrode.

**Theory**

Let the electrode (fig. 19) be a hemisphere of radius $a$, which is a good conductor and makes good contact with the ground, whose specific resistance or resistivity is $r$. Describe a concentric, hemispherical shell of radius $x$ and thickness $dx$. The resistance of this shell is proportional to its thickness and inversely proportional to its area and is in fact

$$\frac{rdx}{2\pi x^2}.$$
If this is summed from \( a \) to infinity, the total resistance \( R \) outward from the electrode is

\[
\int_a^\infty \frac{r \, dx}{2\pi x^2},
\]

so that

\[
R = \frac{r}{2\pi a},
\]

and the resistance is directly proportional to the resistivity (the resistance in ohms for 1 cm. length and 1 sq. cm. cross section) and inversely as the radius. When two electrodes are similar and some distance apart the resistance of the ground as determined in this way is approximately a measure of the resistivities of the underlying earth and rocks, not merely in their immediate vicinity but over a large region beneath and between them, and the fall of potential at or near an electrode is an indication of the approximate conductivity.

In Figure 20, therefore, if \( Y \) is halfway between \( X \) and \( Z \), if \( V_1 \) is the potential drop between \( X \) and \( Y \) and \( V_2 \) that between \( Y \) and \( Z \), and if \( r_1 \) and \( r_2 \) are a rough mean of the resistivities (specific resistances of the left and right regions), then

\[
\frac{V_1}{V_2} = \frac{r_1}{r_2}.
\]
DESCRIPTION OF METHOD

Three copper wires, $X$, $Y$, and $Z$ (fig. 20), each 100 feet long, are pegged well to the earth, and, if the soil is dry, water is poured around each peg. Three B batteries in series are connected to $X$ and $Z$, giving a potential difference between $X$ and $Z$ of 120 volts. A voltmeter is connected to $Y$ and $Z$, and the voltage between them recorded; the voltmeter is then connected to $X$ and $Y$ and the reading again taken. If the conductivity of region $A$ is twice that of region $B$, the voltage between $X$ and $Y$ will be half that between $Y$ and $Z$, and the readings will be: $Y$ to $Z$, 80 volts; $X$ to $Y$, 40 volts. Now the three pegs of $X$ are pulled up and moved forward, wire and all, to position $U$ (fig. 20), making a "leapfrog" jump over $Y$ and $Z$. The readings are taken for regions $B$ and $C$ by the voltages between $Y$ and $Z$ and between $Z$ and $U$.

In practice green twisted pair wire is very convenient for all battery and voltmeter connections. The three batteries are carried forward in a suitcase in one hand and the voltmeter in the other hand. The work can be done swiftly if poor contacts are avoided. In practice it is wise to reverse the battery wires and voltmeter to check accuracy. The "leaps" are conveniently taken as 100 feet for a preliminary survey and 50 feet for detailed work.

SINGLE LEAPFROG

When looking for a vein or running along a definite line of country, wires need not be 100 feet long. Single pegs, as at $X$, $Y$, and $Z$ (fig.
21), can be driven, the connections made, and the readings taken, exactly as described before. Table 2 is a set of readings from the field book. They read upward.

**Table 2.—Specimen readings by leapfrog method**

<table>
<thead>
<tr>
<th>Item</th>
<th>Region</th>
<th>Reading</th>
<th>Merit mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>9...</td>
<td>ST</td>
<td>77-76</td>
<td>300</td>
</tr>
<tr>
<td>8...</td>
<td>KS</td>
<td>67-67</td>
<td>750</td>
</tr>
<tr>
<td>7...</td>
<td>RR</td>
<td>49-49(93-93)</td>
<td>875</td>
</tr>
<tr>
<td>6...</td>
<td>PQ</td>
<td>77-70(22-22)</td>
<td>3,700</td>
</tr>
<tr>
<td>5...</td>
<td>OP</td>
<td>33-43</td>
<td>6,580</td>
</tr>
<tr>
<td>4...</td>
<td>NO</td>
<td>22-22</td>
<td>1,800</td>
</tr>
<tr>
<td>3...</td>
<td>MN</td>
<td>94-95</td>
<td>370</td>
</tr>
<tr>
<td>2...</td>
<td>LM</td>
<td>50-48(84-86)</td>
<td>104</td>
</tr>
<tr>
<td>1...</td>
<td>KL</td>
<td>50-52</td>
<td>100</td>
</tr>
</tbody>
</table>

1The numbers of the table are proportional to the resistances in the intervals, whereas the conductivity of the interval is the index for conducting bodies. The relation between the two is a reciprocal one expressed as follows:

Conductivity of region = \frac{1}{\text{resistance of region}} = \frac{1}{\text{readings above}}

Give region KL an arbitrary value of conductivity of 100.

Then region LM conducts 4 per cent better, since

\[
\frac{\text{Conductivity of new region LM}}{\text{Conductivity of standard region KL}} = \frac{LM}{KL} = \frac{1/49}{1/51} = 104.
\]

Therefore LM has a mark of 104, which is 4 per cent greater than KL. Now compare LM to MN. LM is \( \frac{84+86}{2} \), or 85, and MN is \( \frac{24+23}{2} \), or 23.5; therefore \( \frac{MN}{LM} = \frac{1}{123.5} \), and MN becomes \( 104 \times \frac{85}{23.5} \), or 397. Proceed upward, using a slide rule.

![Figure 21.—Profile of leapfrog circuit, as in Figure 20](image-url)

The letters in the second column denote stations—K, L, M, etc.—50 feet apart. KL and LM are compared. KL reads 50 volts and 52 on reversal, and LM reads 50 and 48 on reversal, so the region between L and M conducts 4 per cent better than that between K and L. When MN is compared with LM it is found to conduct much better, and with a slide rule the “merit” mark is determined to be 370. The highest score is attained by OP, a region underlain by a vein. The diagram of results can be quickly plotted and is shown as Figure 30. (See p. 37.)
A "single leapfrog" was next run from the proving ground (station U–200) across a magnetite outcrop at the north corner of Caribou Village across a meadow, marsh, and small stream. Results are plotted in Figure 22. The stream and marsh proved to be nearly as markedly conducting as the magnetite, but this result was confirmed on other occasions. Water is an electrolyte rather than an insulator, and it cements rocks and earth together, making them highly conducting. Many people who would have been safe standing on dry rock or cement have received severe shocks by touching a live wire when standing on damp earth or cement. Geophysicists attempting prospecting by the methods described herein are warned to interpret their results with care; otherwise they may believe they have located ore bodies, whereas they have found water.

The next step in the authors' investigations was to make leapfrog jumps across the proving area from east to west and to assign values to every square on each line. By running a line north and south
these squares were tied together, and with the help of a slide rule a number that would be a measure or indication of the conductivity of the ground under the area was assigned to every 50 or 100 foot square. When east and west surveys across a proving ground are made and numbers indicating the relative conductivities for every square in each run are obtained it is possible to tie all these squares together to a common basis by running only one north and south line. This can be done in a few minutes with a slide rule and involves elementary arithmetic only.

The results (see fig. 23) of this electrical survey corresponded closely with Doctor Heiland's accurate magnetic survey. In Figure 23 the numbers of larger size indicate relative conductivities as determined by the leapfrog method, and the smaller numbers the relative vertical magnetic intensities. It was therefore clear that the leapfrog method had earned a place among other electrical methods of prospecting for ore. These surmises were confirmed by the tests at Ward, Colo. (See p. 33.)

**Tests in Quebec**

Through the kindness of the owners and with the assistance of Dr. E. S. Bieler, one of the writers tested the leapfrog method at the Alderson-Mackay mine in the Rouyn district, northern Quebec. The terrain consists of rocky ridges alternating with marsh and swamp over clay and glacial beds, and the bedrock underneath contains ore bodies of pyrite and chalcopyrite. The conductivity of the marshes masked that of the ore bodies beneath, so that the leapfrog method which was so efficient on the dry mountain slopes of Colorado proved useless. This result indicates the necessity of suiting the method to local conditions. New methods have been evolved that are more adapted to geophysical prospecting in northern Quebec and Ontario, and it is hoped that these will be described in a forthcoming report.

**10. Determination of Presence of Ore Bodies by Natural Electric Currents**

The fact is now accepted that bodies of sulphide ore, such as pyrite, when oxidized by rain, surface waters, and air, behave as batteries, so that an electric current flows upward from their base or lower regions through the earth to the top or upper parts of the ore body, completing the circuit through the ore. An attempt was therefore made to discover whether such currents could be observed and measured over the known magnetite deposits on Caribou Mountain by a slight modification of Schlumberger's method. Iron or galvanized-iron rods or pipes were first driven into the ground and connected to a Weston microammeter by flexible wire. The deflections that ensued were large, uncertain, and variable, due, as was expected, to polarization of the iron by surface moisture and water.
Figure 23.—Leapers survey at Caribou Mountain, showing plan of stations on northern magnetite deposit. Approximate conductivities of every 50-foot square of the proving ground. The results of the leapers methods were in good agreement with the magnetic survey.
To remedy this condition, porous pots (filled with copper sulphate into which dipped copper rods) were placed firmly in small holes and used as electrodes. The readings then became steady and repeatable. If, however, new holes were made only a few feet or inches from the original ones, the readings of the microammeter often showed wide variation. Much work had been done before this was explained. Under the earth were many veins, some continuous, some isolated, and also stray pieces of magnetite, and on the surface there was loose "float." The latter was slowly oxidizing to various extents, so that

![Figure 24. Diagram of natural currents between a point (V-200) and eight points each 50 feet away from it. Arrows indicate the direction and magnitude of natural currents, numbers in microamperes. (Four microamperes of current equivalent to 1 millivolt of potential difference)](image)

the surface of the ground really became a large assemblage of electric cells connected by a complicated network of conductors. Into this maze electrodes were introduced at random, and the readings depended on the particular place where these electrodes were introduced. Two examples are given: 1, Figure 24, where vectors show the strength of the currents, for 50 feet between electrodes, toward eight main points of the compass, from a central electrode; and 2, Figure 25, a careful survey around a negative center at various distances (5, 10, 25, 50, and 100 feet), with average values 9, 11,
16, 14, and 14 microamperes, all directed to the center. The writers measured the resistance of their circuit (two porous pots and a microammeter), and the total was about 250 ohms (precise values are not attainable in practice) so that 4 microamperes of current correspond to about 1 millivolt of potential difference. (Microampere = \(1.000 \times 0.000\) ampere; millivolt = \(1.000\) volt.)

Some trouble was taken to get a current "vector" for a given point as the resultant of the north-south and of the east-west components, but the attempt had to be abandoned. Nevertheless, if a line is run by Schlumberger's method, the currents will be feeble over regions where there is no ore or no conducting water and well marked when a sulphide vein is crossed. Examples of such effects are cited under method 11 and need not be introduced here. It may be well, however, to record the readings by a diagram along a west-east direction on the 200-foot line at Caribou. (See fig. 26.) The variations indicate well the presence of magnetite as determined by other methods, electric and magnetic. The figure of merit by the leapfrog method is also shown, and the two results confirm each other.
The natural current method for detecting ore is excellent when enough ore is being oxidized to produce natural currents at the earth's surface. Furthermore, just as the compass cannot detect nonmagnetic ores like pyrite, the electrical method cannot detect poorly conducting minerals like zinc sulphide.

11. WORK WITH SULPHIDE ORE BODIES AT WARD, COLO.

The natural electric currents on the surface of the ground on Caribou Mountain were caused by exceedingly slow chemical changes in the magnetite as it was decomposed by rain and surface water. In some instances the black magnetic ore had turned rusty looking on exposure. The measured currents were of the order 0 to 30 microamperes for 50 feet between the electrodes. Results were repeatable between two given points but very erratic in direction and magnitude from place to place. Each porous pot had a resistance of about 100 ohms, so that in the circuit used, counting the resistance of the microammeter, 1 microampere of current corresponded to about 4 millivolts of potential difference,
The writers were, however, anxious to find a place where there were sulphides of iron and copper that would oxidize more readily near the surface than magnetite, so that the ore bodies would resemble batteries with the electric currents flowing toward the ore near the earth's surface. The place selected for the tests was Ward, Colo., about 14 miles north of Nederland.

Two types of apparatus were used: 1, The most simple and easily carried—the Schlumberger porous pots, copper sulphate electrodes, and microammeter; and 2, the single leapfrog apparatus, consisting of twisted pair wire, three iron stakes to drive into the ground, three B batteries, and the Weston voltmeter. Five men who were conversant with the position of the principal ore bodies near Ward joined the party and gave guidance and information, which the authors acknowledge with gratitude: J. R. Roots and his son (formerly of the Colorado School of Mines), L. S. Brock, P. A. Larson, and W. G. Pauling.

![Graph: Comparison of leapfrog and natural current methods, Baxter mine, Ward, Colo.](image)

By moving forward 50 feet at a time the position of the vein was readily determined by the natural current method; the survey was then repeated and confirmatory results obtained. (Fig. 27.) Tests were made with equal success at two other positions. Next day the leapfrog method was tried over the same course, and the indications were equally well marked. (Figs. 28 and 29.)

An explanation of these figures is desirable. When the natural currents arising from oxidation of the iron sulphides are measured, it will be remembered, they flow toward the vein, hence direction reverses as the vein is traversed. (Fig. 27.) In Figure 29, however, two veins are in close proximity, and there is accordingly a double reversal. The leapfrog method, described as method 9, gives a measure of the conductivity of the ground not merely on the surface but for some depth beneath; hence the position of the vein indicated by
two different methods may not coincide, particularly if the vein has a considerable dip.

Figure 30 illustrates the most successful results attained in this exploration. A line was run along an old railway, and location was made by Schlumberger's (porous-pot) method and confirmed by a run in the reverse direction. The leapfrog method indicated the presence of a conducting body in the same position. One of the members of the party who knew the location of the vein confirmed the accuracy of this determination. The vein here was near the surface, but in Figure 31 the same vein was located under 20 or 30 feet of overburden.

Results were uniformly successful, for at the Rose Dalton mine, 2 miles south of Ward, the writers failed to locate a well-marked vein of iron pyrite by the natural current method. This failure was easily explained, for above the vein was 60 feet of very dry overburden, and the vein itself was shining and so well inclosed in rock that oxidation was not taking place; under such circumstances the chance of natural currents was indeed remote. The leapfrog method was not tried at this point.

Experiments at Ward, Colo., confirmed the agreement between the two methods and strengthened the opinions formed at Caribou. It was surprising that the sulphide veins did not give much stronger currents than did the magnetite at Caribou, but at the latter place the ore was greater in quantity and nearer the surface. Further work, using potentiometer methods, also appears advisable.
Figure 29.—Leapfrog and natural current methods used below Baxter mine
12. EXPERIMENTS WITH RADIO

While the writers were at Caribou they tested penetration of radio waves into the earth with a nine-tube superheterodyne set, built by Guy L. Allen, of Boulder, that had successfully picked up broadcasting from Europe and South America. The facilities of the Caribou mine were offered by J. G. Clark, president and general manager of the American Mining & Prospecting Co., and by H. K. Lidstone, the mine superintendent; the tests were begun on the morning of August 17. Mr. Allen first tested his set in the shaft house; at a depth of 220 feet, as measured by an altimeter, reception with a loop was strong and clear of a concert from KFEL (247.8 meters), Denver, 50 miles away. The maximum intensity was obtained when the loop pointed about

![Diagram](image)

**Figure 30.**—Comparison of leapfrog and natural current methods at Monitor vein, Ward, Colo.

S. 53° E., while the actual direction of Denver is S. 63½° E. The experiments were made at the point marked X in Figure 32, and it will be noted that the nearest conductors (rails) were 66 feet away. There was the remote possibility that the effect came down shaft S and turned along the crosscut SX, although the loop did not point in that direction.

The wireless set was then taken to a measured depth of 550 feet below the shaft house, at the end of a crosscut reached after making many turns and 200 feet from the main shaft; it must be noted that a pipe down the shaft ran through the tunnel up to 80 feet from the point of observation. Figure 33 shows its position. At this point indications of the reception of carrier waves were obtained, but no clear speech or music could be detected during the daytime. At 9.20 p.m., however, the voice of the station announcer, songs, and instrumental music were heard with the loud speaker from KLZ, Denver (267.7 meters). Reception was of the type sometimes called "mushy" but was no more so than that at Mr. Allen's home earlier in the
evening. The loop again pointed within a few degrees of Denver for maximum intensity. Mr. Allen believed that he could receive at points 200 or 300 feet deeper.

The authors acknowledge the courtesy of Earl Bryant and Mr. Martin, who made the facilities of the mine available for both day and night experiments.

Do the results of these tests prove that radio waves will penetrate 500 feet of rock? In experiments on underground communication previously made by the Bureau of Mines in mines near Pittsburgh, Pa., it was at first concluded that radiation and induction would
penetrate rock for considerable depths. Subsequent studies indicated that the supposed penetration through the rock may not have taken place, but that the air in the shaft, metallic circuits in the shaft, and circuits extending from the shaft bottom may have acted as conductors; in drift or slope mines electric circuits and tacks may have assisted the air and acted as conductors in a similar manner. Bureau of Mines Technical Paper 433, Experiments in Underground Communication Through Earth Strata, by L. C. Ilsley, H. B. Freeman, and D. H. Zellers, describes many of these tests.

At Caribou the radio waves may have excited the conductors in the shaft and these in turn excited rails and pipes, bringing the radiation within 70 feet of the apparatus; the strong amplification of the radio apparatus thus enabled the radiation to bridge the gap. This is improbable but not impossible.

![Diagram](image)

**Figure 33.** Plan of Caribou mine 500 feet below the surface, showing place of radio reception (X)

On the other hand, the loop did not point toward neighboring conductors or along the tunnels, but at both the 220 and 550 foot levels it did point within a few degrees of the source at Denver. The evidence is therefore strong, but not absolutely conclusive, that wireless waves will penetrate 500 feet of rock to an extent enabling them to be received with powerful amplification. These investigations should, however, be followed up by further research.

Reference may be made here to some preliminary work in the 1-mile tunnel of the Canadian National Railway at Montreal, which runs under 700 feet at the most of igneous and other rocks. The tests were made by Major Steele, of the Royal Canadian Signal Corps; Mr. McEwan, head of the radio department of the Canadian National Railways; Dr. E. S. Bieler; and one of the authors. Short waves (40 meters) could be detected outside the tunnel at both ends. Reception was obtained for only a few hundred feet within the tunnel. Broadcasting waves were, however, received throughout the tunnel.
but decreased in intensity at the center. Longer waves (1,400 meters) were more strongly received. The results of these interesting experiments were not published, partly because of the uncertainty as to whether the received signals came through the rock, along the rails and electric cable, or through the air.

The experiments at Caribou mine tend to confirm the theory that the radiation passes through the rock, with, of course, much attenuation. It is known that radio signals will just penetrate through a good conductor like sea water to a maximum depth of about 50 or 60 feet, and there is no reason why radiation should not penetrate to ten times that distance through a poor conductor like dry rock.

Penetration by radio waves from a distance exceeding many wave lengths and by radio waves generated at a distance less than a wave length are still to be compared. This question involves the somewhat arbitrary distinction between radiation and induction, and some investigators are ready to claim much penetration for induction and little for radiation. The matter can be settled only by extensive tests, for present theories lead to results open to doubt or question. The point at issue is important to geophysical prospectors because one company at least claims to be able to stimulate a long ore body, even of disseminated ore, up to a depth of 500 feet. It is claimed further that this ore will reradiate the induced high-frequency currents or oscillations, which will pass to the surface with enough strength to be detected by a suitable search coil, so that the direction of the source can be deduced. Such claims can be verified only by searching experiments.

**SUMMARY AND CONCLUSIONS**

1. A proving ground was selected at Caribou Mountain, Colo. (fig. 7), where there was a magnetite deposit with strong magnetic properties, good electrical conductivity, and high density.

2. A magnetic survey and electrical surveys by many simple and direct methods were made over a selected area. In addition to making a magnetic survey, Dr. C. A. Heiland investigated the use of the torsion balance in this mountainous region.

3. The magnetic and electrical surveys agreed very satisfactorily in locating the ore body; the various electrical surveys also give concordant results.

4. Although the seven electrical methods all gave indication of the ore body, some were much more easily interpreted than others.

5. In the district examined the most effective methods were:

(a) Methods 1, 2, and 3, in which parallel conductors were connected to earth and excited by either direct or alternating current, reception being by galvanometer (microammeter) or telephone.
(b) Method 10, in which the direction of natural currents is determined by suitable electrodes and microammeter.

(c) Method 9, a new method christened the "leapfrog," in which conductivity of the soil is compared step by step.

6. Methods must be adapted to local conditions. Damp ground, or that underlain by springs, may give misleading results.

7. Methods 9 and 10 were tested with success at Ward, Colo., over known ore veins; the locations determined by the two methods were in agreement and were correct.

8. Experiments were made at 220 and 550 foot depths in the Caribou mine on the penetration of radio waves into rock, indicating the probability that they can be received at depths exceeding 500 feet.

9. Further experiments are desirable on the following phases of the subject:

(a) The depth of penetration into the ground of induced currents and radio waves.

(b) The magnitude, direction, and phase of induced currents from underground ore bodies due to the use of large insulated loops and of smaller vertical loops excited by alternating currents of audible and radio frequency.

(c) Also currents excited by electrodes.

(d) Measurement of the depth of ore deposits beneath the ground. Several physicists are making notable progress on the last three phases of the question.

10. Simple, direct electrical methods of geophysical prospecting are available for judicious use by geologists and mining engineers.