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Geophysical Exploration for Ores

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Notice

Geophysical Exploration for Ores*

BY DR. MAX MASON,† CHICAGO, ILL.

(New York Section Meeting, October, 1927)

IN 1923 a Western mining company was experimenting with the device of an inventor designed to locate buried ores by radio. Because the progress was slow and the results were confusing, the company began to doubt the usefulness of the method and invited me to review the whole question of the application of physics to ore detection. I was fortunate in securing the cooperation of several physicists who had worked with me during the war on the problem of submarine detection. This group has been increased and has been studying the problem of physical exploration for ores since that time.

It was evident that the problem is a big one, with many angles of approach. Its general features may be set down, in rough outline, as follows: The soils, rocks and ores hidden beneath the surface differ one from another in many respects. These differences may be made to furnish a clew for the physicists working from the surface. To bring these differences into action the physicist creates some kind of an effect which penetrates into the ground and is distorted and reflected when it meets boundaries between different sorts of underground structure. In other words, he sends a message down, and the rocks and ore send back signals in reply. In picturing this process, we should not regard the ground as dense and impenetrable. The kind of messages used pass through the earth about as readily as a sound wave travels the air.

If, then, the fundamental procedure is to shout down questions in the hope that an orebody will hear and answer back to us, it is clear that a large part of the expert's study must relate to the kind of questions best suited to the temperament and intelligence of orebodies. It will be easier for the ore to reply to some of our questions than to others, and it is for us to find the right questions. In certain cases, we are spared the necessity of using a messenger, because nature has already provided one. For example, we already have a terrestrial magnetic field which automatically and continually conveys messages from underneath. We also have available the earth's gravitational field which furnishes us

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† President, University of Chicago.

information any time we care to record it. In other cases (which are in point of fact the most important ones) the ore is too polite to talk unless spoken to, and we therefore have to stimulate it with an artificial field. Whether natural or artificial, the utilization of the appropriate kind of exciting field is of the first importance in the process of physical ore detection.

It is equally apparent that we must be able to translate the message which the earth sends back to us in order that it may tell a story. This process of translation or diagnosis will often be complicated, for every part of the underground structure sends back its own answer, and we must

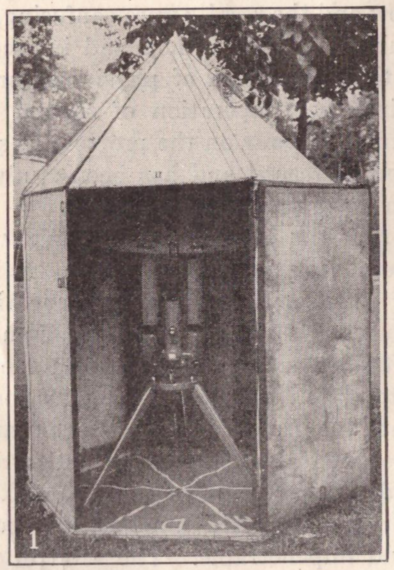

Fig. 1.—Eötvös balance in special heat-insulating hut.

separate one from the next and bring order out of a confusing babble of replies. This interpretation of the orebody's message is perhaps the most difficult part of the problem. One must know in what language the ground will speak, how to distinguish the Chinese of the surface soils from the Greek of the ore. It was obvious from the beginning of our work that the interpretation of messages was going to play a major rôle in ore detection, and our experience during the subsequent years has only emphasized this fact.

From the beginning of our work we adopted a policy of emphasis on the fundamentals of the project. We desired to explore all the possible paths which might reasonably be hoped to lead to results of practical significance. This involved a review of the prior work on geophysics, a study of theory and apparatus, and tests and comparisons in the field

and over known orebodies. We attempted to apply the fundamentals of physics in an unbiased investigation of all possible physical means of searching for ores. In the four years which have been devoted to this

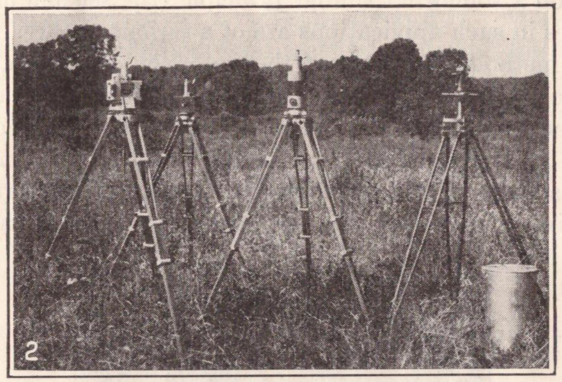

Fig. 2.—Two types of portable magnetometers.

work important progress on both the theoretical and practical aspects of the problem has been obtained, and as a result the whole situation has become greatly clarified in our minds. I hope I may convey to you

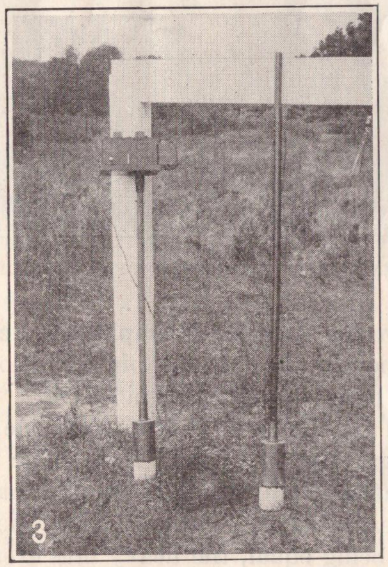

Fig. 3.—Equipment for self-potential surveys.

our conception of the work of the physicist in exploration, of the possibilities and limitations of his tools, of the manner in which practical success is being achieved, and of the present status of this development.

The acoustic method—which is, broadly speaking, the study of the echoes reflected by orebodies from incident sound waves—early proved rather disappointing. Perhaps the future will bring success with methods which work on a somewhat similar principle (the seismic methods), but the difficulties in such applications are of a serious nature. The seismic and acoustic methods depend upon the distortion, reflection, or change in velocity of an artificially produced small earthquake wave, or of a sound wave. In the neighborhood of most orebodies the rock conditions are complicated by fracture zones, by faults or folds, and, in general, by many irregularities. Such conditions will usually produce greater distortions in a seismic wave than the ore itself. In districts such as the oil

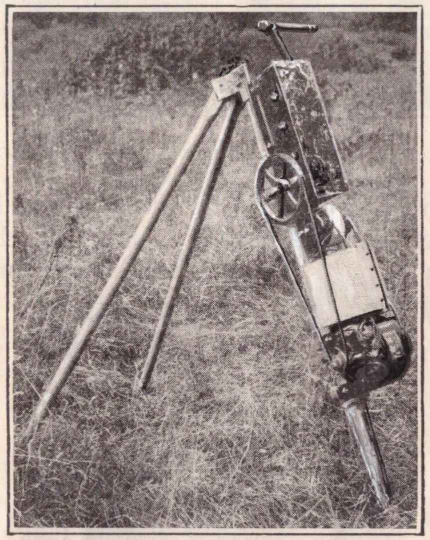

Fig. 4.—Hand-driven electric alternator for surface potential method.

fields of Texas, where the structure is simple, seismic methods have been successful in the discovery of oil domes, but extensions of these methods to ores have not yet been of practical significance.

Another physical method is the gravitational one, which makes use of the earth's natural gravitational field. Each cubic foot of rock, ore, or soil exerts a gravitational pull which is proportional to its weight, but which rapidly decreases as the distance from the observer becomes greater. Distances being equal, the heavy ores exert a stronger attraction. The instrument which is now most widely used in gravitational measurements is the torsion balance of Baron Eötvös. The instrument is called a "balance" for the following reason: It is so constructed that it gives no response when the subsoil beneath it is uniform in density or where successive horizontal layers are uniform. If there is an excess

or deficiency of density on one side or the other, the instrument becomes unbalanced and gives a reading. The Eötvös balance is of such extremely high sensitivity that it is necessary to set it up over ground which has previously been smoothed for a radius of about 6 ft. Moreover, a topographic survey of the neighborhood must be made and the effect of nearby surface irregularities computed and corrections made therefor. The balance is relatively expensive and slow in application, for one can obtain observations at only four stations per 24-hour day. Its usefulness is, therefore, greatly restricted and is confined chiefly to the confirmation

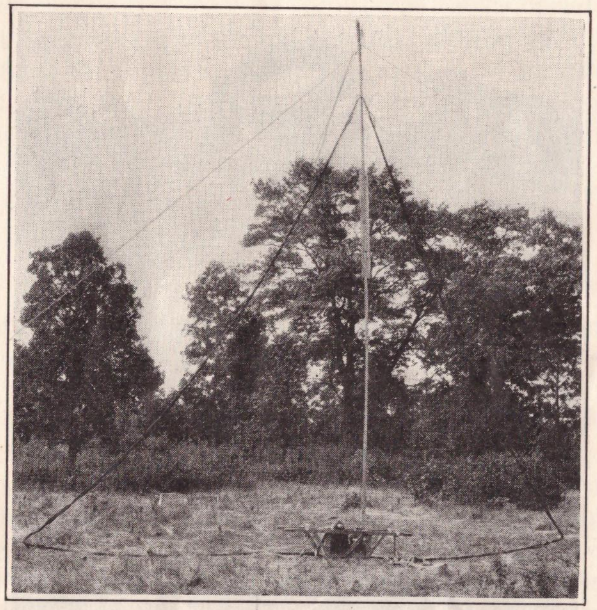

Fig. 5.—Sending equipment used in inductive method. Note the triangular loop.

and extension of the results of other methods, or for special purposes where relatively simple large-scale structures are of interest. It will thus be clear to you that the success of the Eötvös balance in such districts as the oil fields of Texas cannot be duplicated in most mining regions. We have made tests with the balance in two mining districts and believe that it has useful, though quite restricted, applications in ore work.

In common with the gravitational method, the magnetic method is concerned with the reception and interpretation of messages which nature automatically supplies. It is the oldest and most familiar application of physics to mining exploration, but in recent years it has become of greater importance than ever before. The pocket dip needle of the geologist has found increasing application in the rapid and cheap survey of areas showing pronounced magnetic characteristics. Where the magnetic variations in the earth's field are small and where increased accuracy and sensitivity are desired, field instruments are now available which far surpass, in reliability, speed, and accuracy, those of a dozen years ago. The discovery and interpretation of concealed intrusives, faults, and structures in general, by magnetic methods, as well as the delineation of magnetic orebodies, have all undergone pronounced improvement as a result of the present increased interest in geophysics.

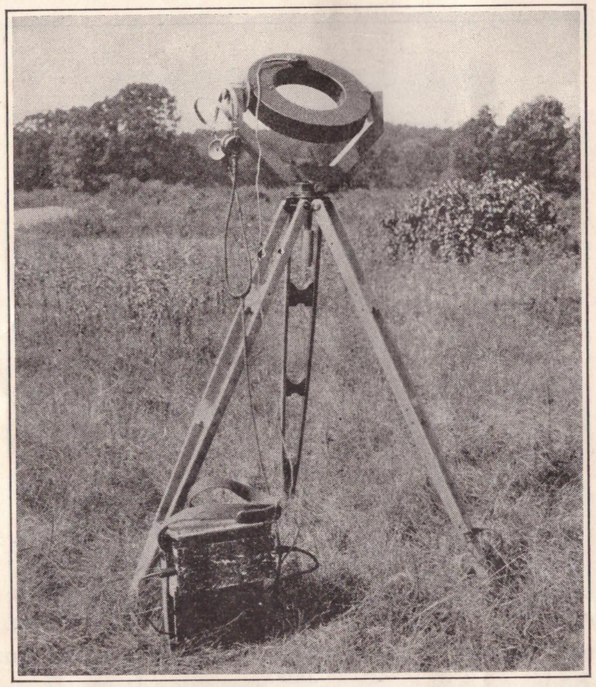

FIG. 6.—RECEIVING EQUIPMENT USED IN THE INDUCTIVE METHOD.

In many cases, magnetic methods offer a more powerful tool than any other in the exploration of hidden geological structures.

Besides the magnetic methods, the electrical methods alone are suited to reconnaissance exploration for metallic minerals, and I assume that you are chiefly interested in these methods. The electrical method which I shall first describe is similar to the magnetic and the gravitational methods, in that no artificial source is required to provoke a response from the ore. This is the self-potential method about which Mr. Kelly spoke to your society last May. Mr. Kelly explained, you will recall, that orebodies, particularly sulfides, undergo oxidation and that the upper zones are usually in a state of activity different from that of the

lower ones. The difference in chemical activity leads to a current flow tending to neutralize the difference of potential. This current spreads through the ground for considerable distances, but it is all supposed to pass through the orebody, just as all the current from an ordinary dry cell passes through the cell, regardless of the complications of the external circuit. In fact, the dry cell is the best simple analogy to an orebody supplying current in the manner mentioned by Mr. Kelly. By tracing the current it should be an easy matter to find the ore. The apparatus used in tracing the current flow is called the self-potential apparatus, because it measures the potentials naturally associated with the current flow.

The best early work with the self-potential method was done by Carl Barus in 1882 at the Comstock Lode. He applied the method almost in its present form. About 1913 Prof. C. Schlumberger, of Paris, revived interest in self-potential work and began a series of careful and extensive experiments in its theory and application, which contributed much to the knowledge of this method.

OTHER ELECTRICAL METHODS

All other electrical methods require an artificial exciting means in order to elicit a response from ores. Such methods may be divided into two main types, the surface potential and the inductive.

The exciting means in the surface-potential method is the flow of electric current through the soil. A dynamo may be used as the source; current from it is led into the earth at one point, and out at another, by means of grounded metal stakes called electrodes. The underground current flow follows the lines of least resistance, and tends to concentrate along any conductors, such as orebodies which may be in the neighborhood. The occurrence of underground concentrations is indicated by the nature of the current distribution at the surface.

Professor Schlumberger made creditable contributions to the study of artificial current distribution at the surface as influenced by ores. Hans Lundberg and his associates were also active pioneers in the development of this method, and introduced the use of straight extended electrodes, grounded at intervals along their length, instead of point electrodes. The current was thereby introduced into the ground evenly along the length of the electrode. The two electrodes roughly bounded the region of exploration, and were often very long, say 3,000 ft., and separated nearly as far, say 2,500 ft. The current paths at the surface between the long parallel electrodes are, in the absence of disturbing factors, straight and parallel; hence their distortions are readily apparent. Mr. Lundberg's extended electrode system has received wide application and has created much interest in electrical prospecting.

The Inductive Method

The other, or inductive type of electrical method, includes most of those special methods now in use. In this method an alternating magnetic field is created, which is similar to the natural magnetic field of the earth, except for the fact that it reverses periodically at a high frequency. This frequency is usually of the order of 1,000 cycles per second, or in the acoustic range, but it may be higher—as high as a radio frequency. The magnetic field penetrates the rocks and soils of the earth nearly as readily as it does the air above. However, when it encounters a conductor, let us say an orebody, a new magnetic field of the same frequency and general characteristics is emitted by the conductor. This new field radiates from the conductor in all directions in the same general manner as did the original one from the original source. It is called the secondary, or induced magnetic, field, and we therefore refer to this general method as the inductive method of electrical prospecting. The secondary field which is created through the presence of the ore constitutes its answer to our question, and is of course the one we wish to measure and study. At any point, however, both the primary and secondary fields are necessarily co-existent, and all we can do is to measure the total and then estimate what amount is due to the ore.

H. R. Conklin and others deserve credit, both for the early recognition of the possibilities of this method and for contributions toward its practical development.

Advantages of the Inductive Method

The inductive method has the following basic advantages over the other electrical methods:

1. It requires no grounded electrodes. Good electrical contact with the ground is difficult in rocky and barren regions, on ice-covered lakes and in deep snow, and in dry sand and gravel. The application of the inductive method is independent of such surface conditions.

2. A related advantage is important. With the surface-potential method, current flow must, of course, reach the ore, and be concentrated in it, in order to produce the desired distortion at the surface. If highly insulating layers exist below relatively conducting surface soils, nearly all the flow will be shut off from the deeper regions and be confined to the conducting surface soils. The ore will get no chance to indicate its presence. A similar situation may occur in the use of the self-potential method, for obviously the normal field of current flow as generated by the oxidization of the ore will be much modified by an intervening insulator. However, in the inductive method, the magnetic field penetrates an insulating layer nearly as readily as air and, therefore, the intervention of an insulating region is unimportant.

3. Both the surface potential and inductive methods depend primarily on the conductivity of the ore. This dependence is, however, of a fundamentally different type in the two cases. In the case of the surface-potential method it may be said that no absolute scale for the measurement of conductivity exists. To illustrate, let us assume a definite topography with the two grounded electrodes in position. Now, imagine the conductivity of every portion of the subsoil multiplied by the same factor, say one thousand. The current paths will remain unaltered by such treatment.[1] In other words, the current distribution is determined by the *ratio* of the conductivities of adjacent regions, not by the absolute values. Moreover, the influence of this ratio upon the distribution undergoes a saturation effect, in that higher values of the ratio produce only slightly greater concentrations. When the conductivity ratio exceeds 10 or 20, about 90 per cent. of the possible influence is realized, and higher values are of no appreciable avail in strengthening the indications caused by the conductor.

In practice, it is unfortunately true that ratios of conductivity of 10 or more are obtained between neighboring soils. The chief cause of such difference is moisture content; which in turn depends upon type of soil and upon topography. These differences, then, are about as effective in their influence upon the surface potential method as a difference of 10,000-fold between ore and soil. In the inductive method this difficulty is absent, for, in surface covers of high electrical resistance, the terrain response depends nearly directly upon the *absolute* conductivities and not upon the ratio of adjoining portions. Therefore, regardless of the value of the ratio, the entire response will be small whenever the conductivities are slight. Fortunately, the conductivity of cover is usually small, and thus the influence of topography is much less pronounced. The inductive method is thus better able to distinguish between the enormous conductivity differences between ores and cover and the far lesser variations occurring in barren land.

Of the six methods which I have outlined, we have been studying and using all except the seismic. Although our major interest has been in the development of the inductive method, we have found practical value in all the others. In most of our surveys we use the self-potential, magnetic, and inductive methods in combination with one another. The gravitational and surface-potential methods are reserved for special conditions, and as special checks.

I think you will now be interested in seeing pictures of applications of the methods I have described.

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[1] This is not rigorously true, but holds for the conductivities and frequencies customarily used in practical ore detection work.

Fig. 1 shows the Eötvös gravitational balance in its special heat-insulating hut. This equipment, as I have said, is limited in speed to about four stations per 24-hr. day.

Fig. 2 shows two types of portable magnetometers for the measurement of the terrestrial magnetic field. One is the Askanie balance, the other the Gepege. The Askanie balances are very satisfactory. They are reliable and rapid in use, and we often average 80 observations per day with them.

Fig. 3 shows equipment for self-potential surveys. The two electrodes are porous cups, filled with copper sulfate solution. The potential difference existing between the two electrodes which are placed on the ground is measured by a potentiometer, which is mounted above the left-hand electrode. You will observe how simple and portable is this equipment.

Fig. 4 shows a hand-driven electric alternator for supplying current to the ground for the surface-potential method.

Fig. 5 relates to the inductive method, which is our primary one in reconnaissance work. It shows the power source (at center), which is a light gas engine set, and the triangular sending loop. The entire equipment is readily portable by two men.

Fig. 6 shows the receiving equipment used in the inductive method. It consists of the rotatable coil mounted and leveled on the tripod, the amplifier in the box and the head phones. The direction of the magnetic field is measured with this equipment. For the measurement of intensity a more elaborate form of apparatus is required.

I do not wish to confuse the situation by illustrating equipment which is either in the experimental stage or suited only for specialized purposes. The equipment for the methods which I have mentioned is not cumbersome and complicated. It is of strongly constructed type, and capable of rapid use under most field conditions.

I shall now touch upon our customary type of survey, employing the magnetic, self-potential and inductive methods. These particular three methods are chosen, when conditions are suitable, because they are rapid and relatively economical, and because they are entirely independent of one another in the physical properties upon which they depend.

In the first place, it will do no harm to recall that the geologist must select and limit the area desirable for electrical exploration. The work thus begins with geology. Furthermore, it needs geology during its course in the field. Lastly, after the data are all taken, the important work of interpretation of results and of forming a logical and self-consistent picture requires all the aid geology can give. The conclusions must fit the known geological, as well as physical, facts.

In some cases the mining companies supply all the necessary geological assistance. Often, however, it will be expedient for geologists associated

with physical exploration groups to assume this responsibility. Such a course has the advantage of putting the whole exploration problem into the hands of one group, experienced in all phases of the work, and accustomed to studying together the various kinds of problems which arise. I think the advantages of such cooperation need no recommendation. Prof. Warren Meade, of the University of Wisconsin, is directing the geological phases of our work.

The area chosen for survey is laid out in long straight parallel traverses separated in conformity with the size of possible orebodies, such that at least one traverse will, in all probability, pass above any body large enough for commercial importance. Often a spacing of 500 ft. is suitable; sometimes it is much less. The observations are made at 100-ft. intervals along the traverse, and at each station readings with the three independent methods are usually taken—the inductive method, the self-potential method, and the terrestrial magnetic method. Our usual physical exploration thus involves brush-cutting, the transit survey of the traverses, and the chaining of the observing stations, together with the operation of the inductive method by two observers; of a magnetic balance by one observer, and of the self-potential apparatus by one observer and a helper. In all, excluding axemen, such a survey will require a personnel of five engineers and two assistants.

We have attempted to improve the speed and efficiency of exploration in the use of these three methods. In some hundred miles of traverses in the Sudbury nickel basin, near Sudbury, Ont., we have averaged 72 acres of reconnaissance work per day, with each of the three methods. The work was done in a period of about four months, and this average of 72 acres per day is the gross daily average for some 7000 acres, including time lost because of weather conditions and other unfavorable circumstances. At times 20,000 ft. of traverse have been done per field day with the inductive method, and this through heavily covered and rough country. This corresponds to about 250 acres per day. The methods may therefore be applied with speed.

The Physicist's Work

I have outlined the basic problem of physical exploration and described to you methods by which practical work may be carried out. A critical valuation and understanding of the real nature of these methods can be obtained only through the scientific studies to which they owe their birth and development. I should now like to view these scientific studies through the physicist's eyes, and to show you the means by which practical methods are evolved and by which progress in the basic problems of physical exploration is being attained.

In outline, we have seen that the physicist's problems are of two kinds —those of excitation and those of reception and interpretation. We are not here concerned about the details of apparatus for producing or receiving a field. The real limitations of ore detection lie in indications of suitable strength as compared with other disturbances similar in kind. We therefore ask: Granting perfect apparatus, what can physics do, and what can't it do, in detecting ores as they really occur?

There are three basic ways by which physics gathers information about the detectability of ores: (1) The mathematical method; (2) the laboratory and experimental method; (3) the knowledge gained from widespread practical field experience. Each is of prime importance.

Mathematics Applied to Detecting Ores

The first of these methods, the mathematical, tells us exactly what occurs when the source field which we create meets a postulated orebody, or other change in structure. This would appear to be all we want to know, but unfortunately there are difficulties. We find the mathematician cannot supply solutions except for a few simple cases. When we ask for the answer, he says he cannot give it, but can supply something nearly as good. He then changes our actual problem around so that he will be able to solve it. A lump of massive ore becomes to him a smooth sphere, the irregular cover becomes homogeneous, the hills and valleys are smoothed to a level surface. Or if the ore seems to occur as a sheet, it takes the form of an extended plane. Other shapes of bodies are approximated by various kinds of ellipsoids. The geometry must always be simplified.

Although the solutions available pertain only to such idealized cases, much useful information results from them. For they at least show us the best that may be hoped for under simple conditions, and how strong and of what character the message sent to us by certain simple orebody shapes will be. Moreover, we may approximate the answers for more complicated problems by a judicious combination and manipulation of the results for the simple cases.

In dealing with these idealized problems in ore detection, the physicist becomes impressed with the fact that his solutions pertain to more general problems than the particular one with which he started. There is, in fact, an interesting similarity between the gravitational problems, the terrestrial magnetic ones, the direct current ones, and electromagnetic or inductive ones. I have no doubt the same similarity can also be discovered in certain seismic applications. Thus the physicist is led to value a broad point of view in approaching the subject. It may be said, indeed, that the basic study in geophysics is the propagation and distortion of physical fields, whether they be gravitational, magnetic, or electromagnetic. To make my meaning clearer, let us consider the detection of a sphere by the various methods. We arrive at the following results: A

magnetic sphere in the earth's magnetic field, a conducting sphere in the field of flow of a direct electric current, or a conducting sphere under the inductive influence of a magnetic field, all give the same kind of mathematical solutions. The gravitational effect of a heavy sphere on the Eötvös balance is, moreover, closely related to the effects in the three cases.

Unfortunately, the inductive method of exploration, which we consider the most valuable one, is also the most difficult of mathematical analysis. The physicist at present has to make greater simplifications than he wishes, in order to get problems he can solve. However, he uses these answers, when obtained, chiefly as a guide book to show the general characteristics of the case, and employs additional aids, as we shall see, which make the situation better than it may appear.

I have said that the mathematician can predict the response of certain simple types of ore deposits to the fields we choose to impress upon them; and that these solutions may often be extended to tell us approximately what will happen under more complex conditions. I must now, unfortunately, mention a difference between such problems and the real ones of a survey. For we have been putting the question thus: Granted a buried sphere, or other deposit, can its response be predicted? Answer, "Yes." But we should have put the question other end to: Granted the field party turns in an observed response, can we determine exactly what caused the observed data? Answer, "No," strictly speaking, for we cannot solve the problem backward and so find the cause of the results. It is fundamental in electrodynamics that, to find out what is inside a region, one has to get measurements all around the boundary surfaces. Of course, the ground surface alone is accessible in electrical surveys. We cannot measure the fields below and at the sides of the ore.

How the Physicist Proceeds

In practice, the physicist is forced to proceed as follows: He obtains, digests and catalogs as many of the mathematical solutions of idealized cases as possible, being careful to check these solutions by appropriate experiments. Then he tries to fit the observed field data to the typical results in his file records, and draws approximate conclusions as to the shape and position of the ore. If he is led to believe the indications are caused by several different and separate conductors, he has to consider them separately by a process of subtraction.

In simple conditions his predictions will be closely correct, but it is always necessary to make some assumptions or guesses in the process of interpretation. Of course, geological knowledge, experience and common sense are at the bottom of such guesses. For example, the field data may indicate a deposit roughly spherical in shape. Then, if the physicist assumes that the topographical effects are either known or negligible, that the cover is uniform and disturbing factors are absent, he may accurately locate the center of the sphere from theory. It would also be useful to know how large a sphere had been discovered. Unfortunately, this question cannot be accurately answered. Before the physicist can do so he has to decide what the conductivity is, for radius and conductivity jointly determine the magnitude of the response.[2] One might hope that this difficulty would be clarified by the use of different frequencies for the impressed field, but unfortunately this will not help.

In brief the situation is this: The form of the response field at the surface will tell us that the source of the disturbance is a sphere, and also tell where its center is. Determination of the radius and conductivity is not unique, and estimates are therefore without logical basis. Although rigorous analysis is without avail, we may guess a reasonable value for the conductivity, and thereby obtain an estimate of the radius.

My purpose in spending so much time on this simple problem of the sphere is to show you that, even when conditions are exceedingly simple, there are difficulties in telling *all* about the case. You can imagine how much more complicated interpretations must become when several bodies are present or when shapes are irregular and structure is complicated. Some operators of electrical exploration methods offer to do things for us which are entirely outside the bounds of known science. They are the spiritualists of geophysics, and obtain messages which no others can decipher. The honest and informed physicist must admit the limitations of his science.

Under shallow cover, we may expect reasonably close delineation of the position of ores, but it will always be difficult to distinguish between the conductivity of the substance and the total amount present. Naturally these enter together, and it is hard to separate them. As the depth of cover increases, the determination of ore boundaries becomes more and more uncertain.

Use of Models

The second, or experimental, means of studying the basic detectability of ores is one which has proved indispensable in many other applications of physics. I refer especially to small-scale experimentations with models. We all know that the use of models in wind tunnels and in towing basins, for example, has contributed untold information to the science of the airplane, and to naval architecture. I believe that the use of models will play an important rôle in ore exploration. But before we can use models intelligently we must know the equations and laws which apply. The model is not simply a duplicate of the larger structure made on a reduced scale, as is sometimes thought to be the condition in

[2] It is theoretically possible to determine the conductivity and radius separately, but, practically speaking, sufficient accuracy and certainty are not yet attained.

ore-detection work. Account must be taken of the new values of the electromagnetic quantities when the scale is changed. In the towing of a ship model, or the test of an airplane wing in a wind tunnel, the resistance is not directly obtained through multiplying by the model scale. Similarly in ore models, where one factor, such as size, is changed, the other factors must be altered in correspondence. Models are models, but you must know how to work them.

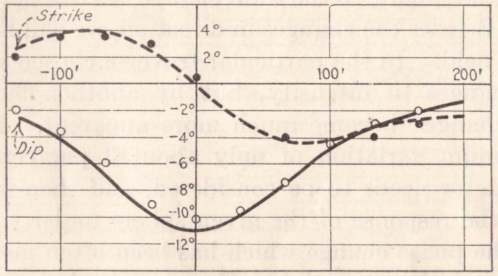

Fig. 7.—Curves showing the theoretical distortion of an electromagnetic field caused by a conducting sphere.

Models, when correctly used, serve to tie together in a valuable manner the exact predictions of mathematical theory, the extensions of theory based on judgment, and the actual experience in the field. They contribute new information which might easily pass unnoticed through studies of theory and practice alone.

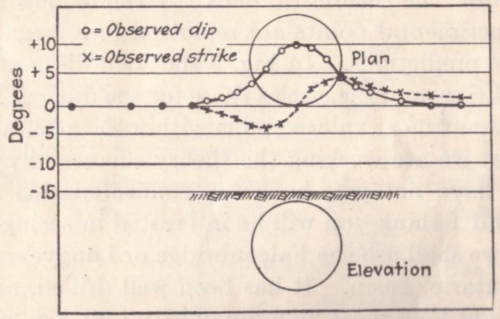

Fig. 8.—A model experiment, showing the distortion of an electromagnetic field caused by a conducting sphere.

I think I can make their value clearer by means of illustrations. We will again take the example of a conducting spherical orebody in the presence of an inductive field such as we use in practice. The mathematics for this case predicts the sort of curves shown in Fig. 7. Here the sphere is assumed to be 100 ft. in radius, with center under 120 ft. of cover, composed of solid pyrite. We suppose that our line of traverse passes, not over its center, but directly over its extreme outer edge, as shown in the plan. The energizing source is assumed to be far away—2,000 ft. to the left, and of 1,000 cycles frequency. Then theory predicts the following distortion in the incident magnetic field along the traverse. The field is normally horizontal, but is caused by the sphere to dip, as shown by the solid curve, until it obtains a maximum of 11 deg. opposite the center of the sphere. The dotted curve shows the change in the strike of the incident field. This is less, amounting to about 4 deg., but it reverses over the sphere, so the total change is 8 deg., or nearly as great as on the dip. Besides the changes in direction, we will have a change in intensity of the field. In the particular traverse chosen we will get relatively small changes in intensity, but by another choice of position the intensity changes become much more apparent. In the traverse shown, a maximum variation of only about 3 per cent. is obtained.

One other factor needs to be considered, and then we have told the entire story of the response of the given sphere under the given excitation. This is the phase change which has been often mentioned in connection with electrical prospecting. However, in the case of our present problem, the phase shift is small—of about 4 deg.—and is substantially constant in value at all points within a mile of the sphere. In this particular case the phase shift cannot be regarded as the primary indication.

Now let us see whether our theoretical solution is correct. We make up a model sphere of about 3 ft. diameter and we make small-scale measurements of the strike and dip of the source field in its neighborhood. The results of these measurements are shown in Fig. 8. It is clear that the curves resemble the theoretical ones. To show how good the agreement is, the experimental points are replotted to a large scale, for comparison with the predictions. In Fig. 9 the solid disks are experimental settings on the strike, and the circles those for the dip. The agreement is within 30 minutes at most values and is within the accuracy of the work. We see then that we are working the theory successfully and the models correctly. We have not yet, however, connected this subject with a real orebody, and I think you will be interested in seeing this next step. As an example, we shall use the Falconbridge or Longyear nickel body, in the Subdury, Ontario, basin. It has been well drilled, and is known to be a nearly straight long sheet, of a dip of about 90 deg., and probably of great extension in depth.

At the Edison Kettle hole, its shape is shown in plan and section at the right of Fig. 10, as drawn by Hugh Roberts from the drill data. A model of this orebody was made on a scale of about 300 to 1, and of a section shown at the left. This is roughly a mean between the two sections indicated by the drill. The cover is 60 ft., the thickness of the upper lip 40 ft. and at the widest part 120 ft. With this model, the distortion of the incident inductive field was measured, and the curves shown were obtained. The solid curve represents variations in dip; the dotted

one those in strike. Actual distortions obtained in the field are shown by the circles. It is seen that the model results and the actual data agree within a few degrees in most places. Moreover, by the model curves, a position for the quartzite-ore contact is indicated which agrees within five feet of the result obtained by Mr. Roberts. When we consider that

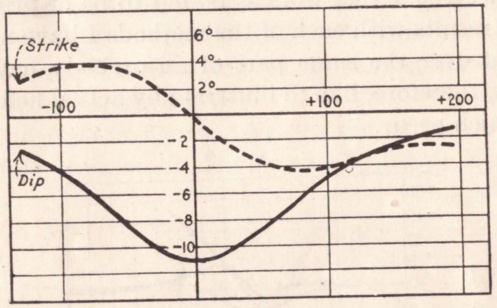

FIG. 9.—COMPARISON OF THEORETICAL AND EXPERIMENTAL DISTORTION OF AN ELECTROMAGNETIC FIELD CAUSED BY A CONDUCTING SPHERE.

the real orebody probably departs somewhat from the section assumed, the agreement is surely gratifying.

Fig. 11 will illustrate another valuable rôle of the model. This illustration is much like that in Fig. 10, and represents a small continuous orebody of similar type 500 ft. long, 100 ft. deep, and under 40 ft. of cover. Now let us suppose the ore were disseminated through a thin, perfectly

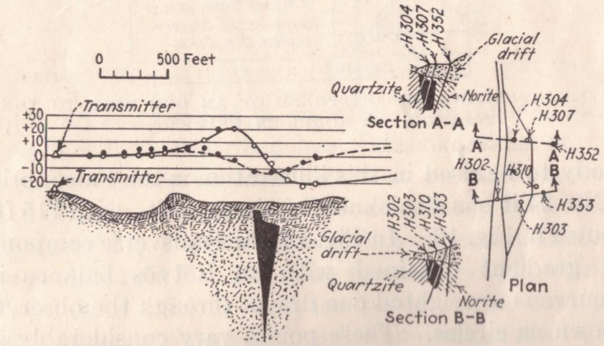

FIG. 10.—COMPARISON OF RESULTS OBTAINED FROM A MODEL WITH FIELD DATA GAINED IN APPLYING THE INDUCTIVE METHOD OF DETECTION TO THE LONGYEAR OREBODY.

insulating intrusive dike, and that the particles failed to make contact one with another. We know that under such conditions the inductive reaction would be enormously diminished, but the results of the tests are nevertheless striking. Let us, for example, preserve the same amount of ore, but cut it up into small squares, each one insulated from the next. Let the squares be of generous size, for a disseminated ore—say 9 ft. on a side. The resulting response is shown in the lower curve, taken from a model experiment. The curves become straight lines, and the response is essentially nil.

I need not dwell upon the utility of the third key to the ore-detection problem—namely, the information to be gained from practical field experience. As in everything else, the knowledge gained from first-hand contact with the actual work is bound to be of prime importance. Comparisons of results with each of the methods I have mentioned when they are applied over the same part of an orebody have seldom been given. I would, therefore, like to illustrate by actual field data the typical responses which occur.

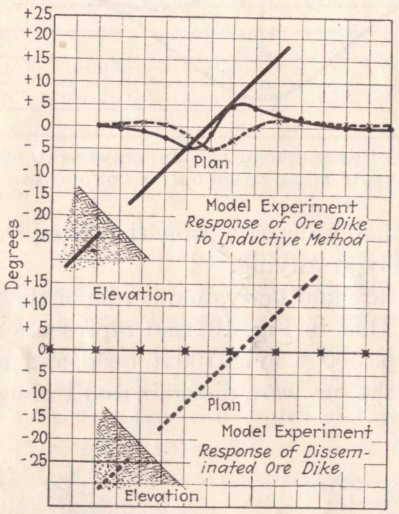

FIG. 11.—CURVES INDICATING THE RESPONSE OF AN ORE DIKE TO THE INDUCTIVE METHOD. A MODEL EXPERIMENT.

The orebody to be used in this illustration is the Falconbridge body. At drill hole No. 24 it has a thickness of about 30 ft., with 115 ft. of overburden, as shown in Fig. 12. In Fig. 13, the transverse component of the gravitational gradient obtained with an Eötvös balance is shown. The smooth curve is a weighted one drawn through the observed points, which are shown as circles. These points vary considerably about the curve, owing chiefly to the random effects of the large boulders of the glacial drift. In the absence of ore, the norite quartzite contact should give a symmetrical curve. The lack of symmetry in this curve may be attributed to ore, although results are not as definite as could be wished, because of the incidental variations caused by the presence of boulders. The curve in Fig. 14 illustrates the detection of this ore by the magnetic dip needle. Here the angle of dip in degrees is plotted against distance in feet along the traverse. It is evident that the well-defined peak furnishes an accurate determination of the position of the vein.

Fig. 15 shows two traverses over the ore at drill hole No. 24 taken by means of the self-potential method. The profiles are here flat and fail to indicate the ore. However, in order to show what this method can do over another part of the ore, another profile is shown in Fig. 16. This was taken about 3,000 ft. west in the Edison Kettle hole where the cover is 60 ft. thick and the ore 120 ft. thick at its widest part. It is a repetition of S. F. Kelly's traverse No. 5.[3] His curve is shown dotted. It is seen that our curve agrees well, though taken four years later. The negative peak occurs above the ore.

The next illustration figures refer to the surface potential method. Fig. 17 shows four equipotential ovals near drill hole No. 24. The black

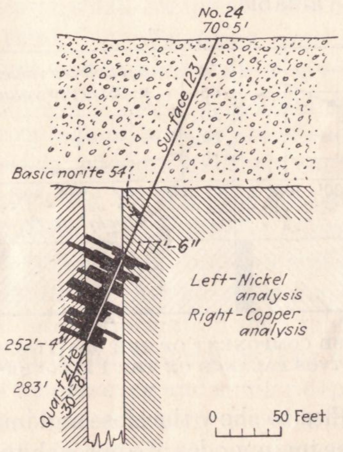

FIG. 12.—CROSS-SECTION OF DRILL HOLE NO. 24, ACCORDING TO THE LONGYEAR MAP.

bars and the arrows refer to a quantitative manner of interpreting the results, which will be described in a subsequent paper. In brief, the theory requires that the ore vein should lie between the four bars given. It is clear that the actual ore is to be found closely central between them.

Fig. 18 shows Mr. Lundberg's well-known extended electrode system as applied at drill hole No. 24. The spreading of the equipotential lines across this vein is evident, and locates its strike and position. The dotted curves are repetitions of the solid ones taken after a heavy rainfall. They agree sufficiently closely with the previous equipotential lines.

The inductive method at drill hole No. 24 was tested at several different frequencies. At 60,000 cycles the curve of Fig. 19 was obtained. These curves represent changes in the strike and dip of the magnetic vector obtained in a straight traverse across the ore. They localize the ore vein within some 50 ft.

The inductive method was also tested at 800 cycles, using a horizontal loop 200 ft. in diameter and situated 1,000 ft. north of the ore. Syste-

[3] *Engineering and Mining Jnl.* (Oct. 7, 1922).

matic changes of direction in both the strike and dip of the magnetic vector were obtained in crossing the vein.

Fig. 20 shows another traverse using a small vertical loop source and is of the same nature as the one previously shown in connection with the models over the Edison Kettle hole. The crosses and circles show the distortions in the strike and dip respectively of the incident field as the ore is crossed in a straight line traverse. These results are strictly in accord with expectations and have been confirmed by work with a model of the orebody. In fact, the results obtained with the model are shown by the dotted and solid curves. As in the previous model work, a satisfactory agreement is obtained. This form of the inductive method has proved especially valuable.

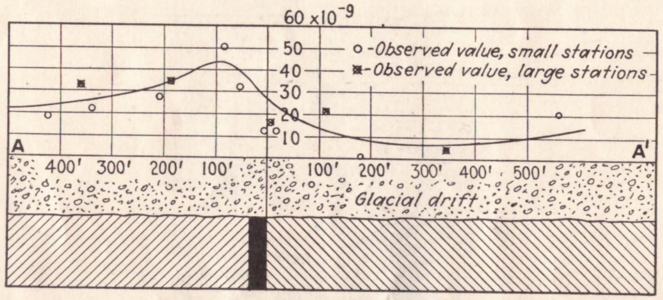

Fig. 13.—The transverse component of the gravitational gradient obtained with the Eötvös balance on the Falconbridge orebody.

I hope this will suffice to show the close and important relation which exists between the three main modes of approach to solutions of the basic exploration problem: the mathematical one; the experimental one, especially through models; and the practical field work. These three means, taken together, are competent to tell us much about the detectability of ores. They are the tools by which we investigate that difficult basic question, "What are the possibilities and limitations of physical methods of ore detection," or "What ores are to be regarded as detectable and why."

Detectability by Electrical Method—Four Factors

The detectability of orebodies by electrical methods is dependent upon only four factors: (1) electrical conductivity of the ores; (2) continuity of the orebody; (3) size of the orebody; and (4) the distance of the orebody below the surface.

1. Ores which have conductivity sufficiently high for successful prospecting by electrical methods have often been listed. They are the native metals and the sulfides (except sphalerite), the tellurides, arsenides and antimonides. The non-conductors are the carbonates, silicates and oxides, except magnetite and some of the oxides of manganese. It

will perhaps be well to add that the absence of conductors other than ore is desirable. For example, graphite is a good conductor, and when graphite slates are present results resembling the indications of ore may be obtained. The problem is naturally simplified if it is known that ores are the only conductors present.

2. The continuity of the mineralized parts of the orebody determines the effective conductivity of the whole mass in as important a way as the conductivity of the pure mineral itself. For it is clear that the orebody cannot constitute a conducting unit unless its mineralized sheets and veins form in the main a connected network. The mechanical nature of the mineral deposit in place is thus a vital consideration, and for this reason the conductivities of small samples of the ore are of less significance than one might think. A misleading conclusion may readily be formed about the actual conductivity of a given type of ore from consideration of its composition only. For example, some deposits containing only a small percentage of sulfides are of such a nature that contact between particles exists, whereas in others containing much greater percentages the rock completely envelops the ore particles, and the mass, as a whole, exhibits only slight conductivity. Disseminated ores may be classed as generally unfavorable, and massive sulfide deposits as favorable, for electrical exploration. Actual measurements of fair average samples of the ore afford more information than tables of conductivity of similar ores. A surer and better criterion will be obtained from underground investigations of neighboring and similar deposits—or, best of all, from actual experiments upon a known neighboring body. It will, of course, often be impossible to obtain the latter type of test.

3. The last two factors of size and depth of burial must be considered together. However, in considering the inductive method, we must at times regard size in a rather novel way. Here the effective volume is not merely that filled with ore, but is more properly that around which the ore forms a complete conducting perimeter. For example, a thin ore vein in the form of a continuous closed loop (should one by chance exist) is nearly as effective as though the ore formed a continuous sheet over the area bounded by this loop. For the inductive method, then, the size of the ore may at times be considered the size of the picture frame, whether or not the picture be present.

Depth Frequently Overstated

4. The depth to which ores may be detected commonly tempts overstatement. We agree with Mr. Lundberg's statement of last May that "The greatest depth to which an orebody may be reached under favorable conditions cannot be generally given." This statement may be somewhat developed. It is a law of electrodynamics that the direction

and relative intensities of the electromagnetic quantities are preserved unaltered at corresponding points, when the scale of the geometry is uniformly changed. Therefore, a deep body is theoretically exactly as detectable as a shallow one, *provided* it occurs on the same relative scale.

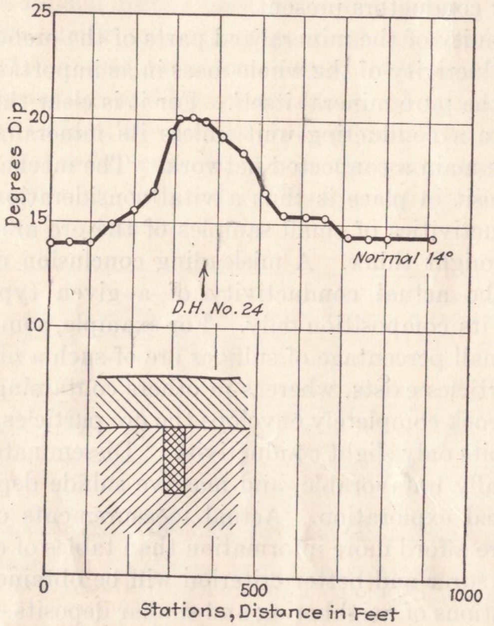

FIG. 14.—CURVE ILLUSTRATING THE DETECTION OF THE FALCONBRIDGE ORE BY THE MAGNETIC DIP NEEDLE.

This is illustrated by Fig. 21. Here all the spheres are tangent to the same cone, with apex at the surface, and all are equally detectable at the surface. The law of detectability of ores with respect to distance is an

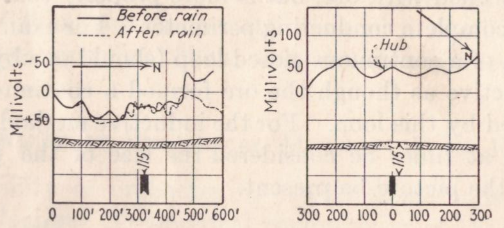

FIG. 15.—RESULTS OF TWO TRAVERSES OVER THE ORE AT DRILL HOLE NO. 24 TAKEN BY THE SELF-POTENTIAL METHOD.

inverse cube law, for the magnetic, gravitational (torsion balance), surface potential, and inductive methods. Some investigators seem to have been misled upon this topic, for two of the active operators of electrical methods claim in their descriptive pamphlets that an inverse square law is applicable to their methods.

If you will carefully examine the list of successes with electrical methods you will find the vast majority have been obtained at covers of less than one hundred feet. One can see, by the following example, how slight is the chance of detecting ore at a depth of 500 ft.: Assume a solid pyrite body of a tonnage of 5,000,000. Let it be under 500 ft. of cover and roughly of a spherical form. Then the mean diameter of the mass will be nearly 400 ft. Now, if this mass is excited under the most favorable circumstances of a uniform inductive field, its own reaction at the most favorable point at the surface will be less than 2½ per cent. of the value of the exciting field. Such a small value will prove very difficult to recognize. It is true that the mass would be more easily found if in the form of a large plane sheet, but my general point still holds: that, for detection, deep bodies must be enormously large. I would, therefore, advise skepticism when working ranges of 500 ft. or more are claimed.

A Practical Rule

From our experience, with theory, models and practical field work, we should give the following rule: "It will, in general, not be economical

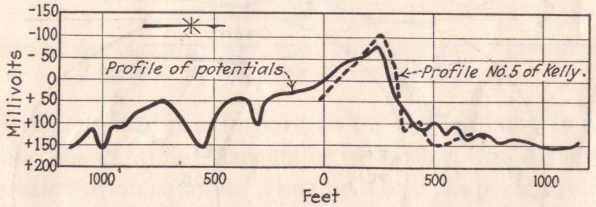

FIG. 16.—A PROFILE, TAKEN IN THE EDISON KETTLE HOLE BY THE SELF-POTENTIAL METHOD, COMPARED WITH THAT OBTAINED BY S. F. KELLY.

to search for massive conducting ores unless two dimensions of the expected orebody approximate the depth of cover." In other words, if the body is lenticular, each of two perpendicular dimensions of the lens should roughly equal the depth of cover. Actual survey conditions are so largely unknown that mathematical refinements in such rules have no place. The statement made will, therefore, serve to give a satisfactory idea of what, in general, constitutes a detectable orebody. As a rougher but simpler rule, which has exceptions under certain conditions, we should advise that physical explorations be confined to regions where the orebodies are expected to approach within 200 ft. of the surface.

Difficulties of Interpreting Results the Great Obstacle

The difficulties in extending the practical limits to which ore may be detected are of a fundamental type. It is not that more sensitive or more accurate receiving apparatus is needed, nor that more powerful sources are required. The difficulty arises from the existence of the extraneous efforts of the unknown ground conditions, and is really one of interpreting results. Of course, when the ore is relatively near, it responds in a loud voice, and drowns out all else. When it is further away the inevitable babble of all the other differences begins to become confusing, and finally the small voice of the ore is completely masked by other messages. It will do no good to use a loud speaker, for this will simply increase the static along with the message. The problem is one of selection rather than of sensitivity. In its basic feature it is like the sub-

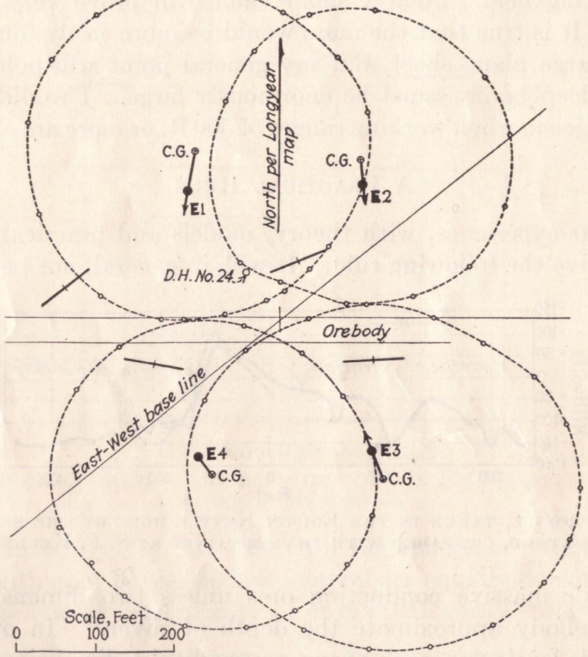

FIG. 17.—EQUIPOTENTIAL OVALS OBTAINED NEAR DRILL HOLE No. 24 WITH SELF-POTENTIAL METHOD.

marine detection problem. There the game was to hear the submarine without hearing your own boat. Here, we must hear the ore without the response from near-by surface conditions. There are, then, natural limits in working range which offer increasing resistance to attempts toward their extension.

ECONOMIC ASPECTS

The business of mining has always involved its own peculiar risks, not found in other branches of commerce and engineering. Evaluation of such risks by intelligent analysis, and the reduction of uncertainties by engineering studies, have helped the industry to proceed along sound

lines. The history of the mining business has been the history of the replacement of the "risk all, gain all" attitude of the speculator by policies founded upon the discovery and analysis of facts.

The greatest uncertainties are those met in the exploration of virgin lands for new orebodies. This division of mining is obviously an essential

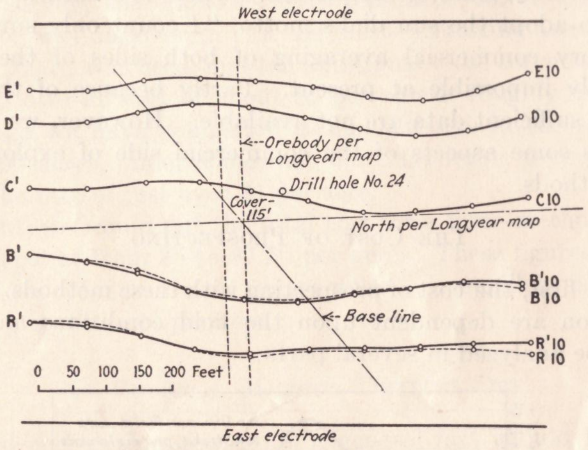

FIG. 18.—RESULTS OBTAINED BY APPLYING THE LUNDBERG EXTENDED ELECTRODE METHOD AT DRILL HOLE No. 24.

part of the business, and it is important for the industry to eliminate, as far as possible, the gambling aspects of its exploration expenditures, and to put exploration upon as sound a business basis as present circumstances

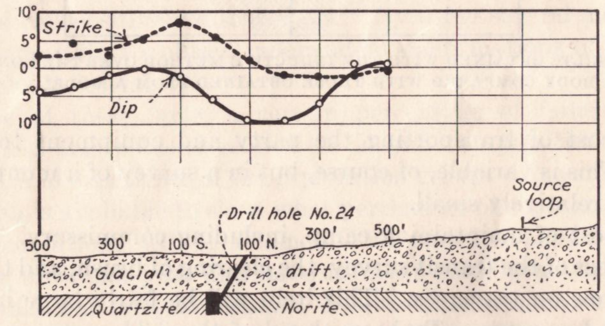

FIG. 19.—CURVE OBTAINED OVER THE LONGYEAR OREBODY WITH THE INDUCTIVE METHOD, USING A FREQUENCY OF 60,000 CYCLES.

will permit. Not only this, but foresight for the future demands that a fund of data be collected concerning the relation of the newer exploration methods to the possibilities and economics of exploration work. As in all questions in which probability and chance strongly enter, conclusions must be founded on a large fund of experience. It is, therefore, especially important to obtain a statistical view of the results of exploration with the physical methods, and to avoid being misled by success or failure in a few single instances.

The question is, "What is the cost of the failures in physical ore exploration, compared to the value of the successes?" We must be careful to get both sides of the picture. There is a natural tendency in this work to adopt the sun dial's motto, "I count only sunny hours." A satisfactory commercial averaging of both sides of the picture is unfortunately impossible at present. Partly because of the youth of the subject, sufficient data are not available. However, we may profitably discuss some aspects of the commercial side of exploration with physical methods.

The Cost of Prospecting

There is, first, the cost of prospecting with these methods. The costs of exploration are dependent upon the field conditions and location. They may be analyzed in several parts:

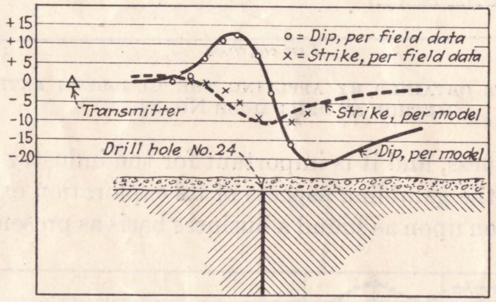

Fig. 20.—Results obtained with the inductive method over the Longyear orebody compared with those obtained from a model.

1. The cost of transporting the party and equipment to the field location. This is variable, of course, but in a survey of a month or more it is usually relatively small.
2. The cost of maintaining camp, including commissary.
3. The cost of the transit survey, the clearing of brush, and the staking out of stations on traverses. This item will be fairly large in difficult, brush-covered country. To keep ahead of the field party we have had to maintain at times three axe crews of four men each, who cut through about 15,000 ft. of traverse per day. In the region near Sudbury, Ont., transit costs have averaged, in over 100 miles of traverse, about $25 to $35 per mile, including all costs for brush cutting.
4. The other costs are those directly involved in taking the data of the physical survey. In our usual type of exploration, they are divided between the inductive, the terrestrial-magnetic, and the self-potential

methods, about as the ratios of 4 to 1 to 1. The inductive method is naturally the more elaborate and expensive.

In one survey of 22 working days near Sudbury, Ont., the total field costs for the self-potential, magnetic and inductive methods, apart from travel and shipping expenses, were under $5 per acre.

In this survey, the traverses were separated 50. ft. except where mineralization was discovered. In the most interesting areas, a separation of only 200 ft. was used, and ten additional cross traverses were run.

The total over-all cost of about $5 per acre is roughly typical of the area, although we have completed similar surveys in the same region totaling 4,000 acres, under somewhat more favorable topographic conditions, at the rate of just over $4 per acre.

At present, we would put the total cost for a three-method survey of the above type, at from $5 to $7.50 per acre. These figures, of course, apply only to surveys of several square miles. In smaller ones, the fixed charges bring up the cost per acre.

No Physical Method Detects Ore

In considering exploration costs, a general fact should be borne in mind, which is sometimes neglected by enthusiasts: No physical method detects ore, but only some physical characteristics, usually, but not *exclusively*, associated with ore. There are conducting ores, but also conducting graphitic slates. There are heavy ores, but also heavy rock formations. There are ores showing chemical activity, and a resulting earth current, but many other ground conditions lead to current flows. No method can positively discover ore. By using several methods, it is sometimes possible to obtain independent confirmations of indications, but not absolute certainty.

Because of these facts, a certain percentage of failures must be expected, and this percentage will be dependent upon the intelligence, knowledge, and experience of the exploration group. As yet no adequate fund of data is available to show what percentage of success, under given operating conditions, will be attained. We ourselves have done research exclusively until last year and have thus far made practical surveys of only nine different mineral regions. Four of these were over known ore, used by us for experimentation. In each of these four cases our results agreed with ore known to exist. Of the remaining five areas, only one has thus far been drilled. Here a mineralized fault was discovered in the position indicated by us, with commercial ore in spots. It is not yet known whether a sufficient quality exists for a mine. One of the other locations was trenched, with the resulting discovery of non-commercial sulfides near the surface. In the course of time experience will permit a clear statistical representation of the probabilities of success in physical prospecting and of the degree of the risk involved. It will, however, be impossible to predict the composition, or type, of the suspected orebody, and the drill and underground work must be considered as indispensable as ever. Physical prospecting, like geology, can simply indicate favorable positions for drill holes.

Underground Exploration an Attractive Field

It is obvious that returns from investments in physical prospecting will be highly dependent upon the success in choosing areas favorable for their use. Because of this fact, we believe underground explorations in producing mines will be an attractive field for future applications of

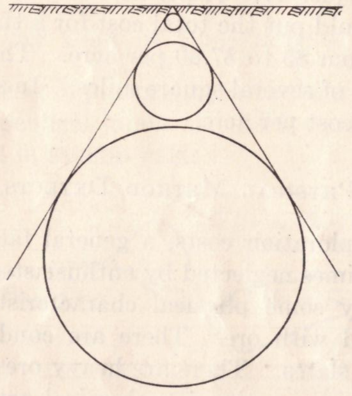

Fig. 21.—These spheres are all equally detectable at the surface.

physics. Since it is a well-known fact that about nine-tenths of all new discoveries of ores are near existing mines, one can feel sure that such areas are highly favorable for electrical prospecting. Furthermore, operations underground are likely to be much nearer the ore, hence the limitations of range are not so serious. In many instances, it would be most valuable to determine whether ore exists within a radius of 100 ft. of certain drifts and crosscuts.

The progress which the future will bring should be continuous and gratifying, but it will not be spectacular in the sense that any glorified witch-hazel wands will be discovered. Improved technique and increased knowledge will be attained through the same process of intelligent and energetic research to which all the important applications of physical science owe their birth. Although physical exploration for ore is a scientific development which can claim only a short history, its economic value has already been demonstrated in many areas. The present accomplishments and technique in this field warrant serious consideration by mining men in laying any sound policy and program of ore prospecting. When conservatively and intelligently applied, in

regions suited to their nature, I believe that physical prospecting methods will amply repay investments.

DISCUSSION

A. M. Bateman, New Haven, Conn.—What is your opinion as regards the possible application of these methods to underground workings in existing mines?

M. Mason.—Directly as developed today there possibly is no application, but there are physical possibilities for obtaining much information from essentially the methods of today. There will be variations due to the immediate presence of the conducting masses within which you are working.

I am impressed by analogies with the things that one sees in physics. If 25 years ago even a well-trained physicist had seen the negative on which was traced a curve such as one gets in ionization and been told that out of it the structure of the atom would be discovered, he would have laughed. But by working from the simpler cases and with a number of thoroughly intelligent, scientific and honest-minded investigators in groups at this problem, I am convinced that as one goes from simple cases to the more complex ones, those minor variations which now disturb in our readings will be interpreted, and that we will be able to know structure as well as ore deposits and the application of all of these methods to the determining of structure to aid the geologist. Looking at the future of 25 or 30 years from now, I am completely optimistic over the enormous use to which this tool will be put when further knowledge of interpretation and formal processes of interpretation have been studied and carried out.

Mr. Parks.—I was engaged during the war in the detection of submarines, using the method which is based upon electrolytic action. We found it possible to detect the immersion of metals in saline solutions such as sea water at very considerable distances. The method offers great possibilities and, I think, might be used in connection with orebodies.

Dr. Mason referred to the currents which occur between the upper portions of oxidized orebodies and the unoxidized portions below and I think it might be possible to develop methods along that line for detecting the electrical energy which is passing out of, or actually detecting the radio energy which comes from certain classes of minerals which we know, such as uranium. Has any work been done along these lines?

I must confess that when I talk about detecting pieces of iron at distances of 40 ft. in sea water with absolutely no connection between iron and the water and I show a deflection across the scale as wide as that screen which you have before you, the uninitiated would think I could also show the magnetic effect and superimposed upon that the electro-chemical effect or the radiation effect.

M. Mason.—Radio-active minerals will show effect readily. An effect corresponding in distance to that you have spoken of, I should think would be quite hidden in the earth due to the great amount of earth current normally present and I should doubt the value of anything more delicate than the self-potential method which has been applied so widely by Mr. Kelly, particularly in this country.

Dr. von Buelow-Trummer, New York, N. Y.—Our company is working with all the different kinds of methods—with the magnetometer, with the seismograph and with the electrical methods. I agree with Dr. Mason that it remains to be found out before actual work is started what kind of a tool we have. It is not possible, generally speaking, to say, "Use a torsion balance." It is seldom that you have occasion to use a torsion balance. For practical use the torsion balance is too slow to detect.

We frequently cross-check electrical measurements with magnetic measurements and have thus had the opportunity to be more sure that the indications we get are in a certain way coming from the orebody. We do not claim success unless at the places where we have had indications actual drilling has proved the presence of the ore. There are very many places where we have had this opportunity and have been quite successful.

The greatest depth that can be obtained with any actual electrical measurements is about 400 or 500 ft. We have had one opportunity of finding a very large orebody by starting in on a known orebody which was 650 ft. below the surface. It was a very large body and very good ore and even though the surface conditions are very bad the orebody showed up very nicely. We went ahead with these measurements and found other indications exactly similar to those on top of the orebody, but no drilling has been done and I do not claim it to be a success as yet.

A large amount of work has been done in Canada during the past month. Unfortunately some failures have taken place in the opinion of people not quite familiar with the work and who think that what we find is the ore. We find indications. We believe that the indications should be checked against other measurements and with geological features and then drilling resorted to.

The use of these measurements is that unnecessary drilling is spared and you know about what drill holes cost if they have to go down, say, 400 ft. The electrical measurements, as well as the geophysical measurements, will cover the entire area.

G. C. Riddell, New York, N. Y.—It would seem that one of the major ore districts of the country is ideally adapted to the use of these methods in accordance with the conditions described by Dr. Mason. I refer to the Missouri sheet deposits which exist from 100 to 200 ft. deep, are dense in character and I presume a great deal of work has been done there with these methods.

M. Mason.—I understand that the deposits are very poorly adapted to the method as being not highly conducting and not sufficiently continuous.

Mr. Schlichter.—I think the reason the methods have not been successful in the tri-State district is that the ore is nearly all sphalerite and that is the only sulfide which is an insulator. On that account the electrical methods are not successful as far as I know in that district, and the orebodies are, moreover, of complicated shape and not of great density.

Mr. Rogers.—Mr. Riddell refers to the southern district where the lead is. I will say that we have done a great deal of testing on those ores in a laboratory way and we find the mineralization in not heavy enough. Furthermore, another objection is that ground water is a very high conductor.

H. A. Guess, New York, N. Y.—A year or so ago we used a torsion balance in the tri-State field, not with the idea that we would delimit it to orebodies particularly, but with the thought that we might broadly show the flint areas within which drilling might be profitable as compared with the surrounding series. By the torsion balance we did get broadly a fair amount of information. To our surprise it gave a lower general specific gravity than it did in the surrounding rocks due to the presence steadily throughout that area of so many vugs.

We have used in Newfoundland the surface potential method of Mr. Lundberg. We began in August, 1926, and, perhaps due to the fact that the ore that we found was quite close to the surface, we have been quite successful up there in opening up (it was all done within a few months) a very considerable tonnage of complex sulfide ore containing lead, zinc and copper. We are continuing the work this year and plan to continue for some time, but have not been as fortunate this year as last, possibly because of the area in which there is no ore.

Mr. Gilbert.—I am with the Radior Company and we use an electrical prospecting method that is based on the inductive system using high frequency current. We use a vertical loop and direction-finding coils. Our method has been worked out so that we not only locate the plan view position of the conductors but approximately the depth as well. During the past few months we have entered Canada, having sent two crews there in June. We now have five. In the past two months four different conductors not previously developed have been drilled and have all checked. In addition to that some seven or eight conductors have been trenched and all checked. At the present time the five crews are contracted through until some time in February.

I quite agree with Dr. Mason that one of the chief difficulties with electrical prospecting is teaching our customers what they can expect as well as what they cannot expect. I have great difficulty in preventing them from getting over-enthusiastic.

Basically, it is quite true that electrical prospecting will only tell you the position of the electro-conductive areas or zones and you must resort to other measures to determine the character or the values of those areas. It has been our experience in the past three years with the conductors that have been proved up, after having been located by our method, that so far we have only located sulfide zones.

Some question has been raised from time to time as to whether we would not locate or indicate areas which were better conductors than adjacent areas, but which might not be sulfide. I think the answer probably lies in the ratio of conductivity. The ratio of the average sulfide body of any considerable extent is so much greater over the adjacent material, it is so enormous, you might say, that only in those cases will you positively locate them electrically, and where the difference in conductivity is very small or slight, the reaction that is obtained is so slight that it is not noted as a rule.

H. T. F. Lundberg, New York, N. Y.—In the laboratory work which we have carried on in Sweden and here also, we have found that in the ground we have more complicated conditions than we ever could imagine when we started. In fact the ground itself is sometimes a very good conductor, especially if we are in sedimentary regions. The mud is porous and carries solutions which have a rather high conductivity. This will sometimes prevent the possibility of finding any ore in such regions. An example of that is the Mississippi Valley, previously talked about.

Therefore, we have found that it is necessary not only to investigate all data on the ore, but also on the rock and on the rock in different places of the area, the water conditions and the conductivity and electrical conditions of the water. Furthermore, it is necessary to investigate the petrographic conditions, the arrangement of the minerals, the arrangement of the conducting minerals as well as the arrangement of the non-conducting minerals. By doing so it seems possibly to elaborate methods by means of which certain indications may be selected as being due to more homogeneous sulfides, for instance, as distinguished from shales, slates, graphitic slates and schists.

Thus by further research and further work in the laboratory and in the field, it will be possible and sometimes already is possible to eliminate many of these so-called indications from sulfide mineralization, and from the knowledge of the locality to eliminate them as very certainly barren and of a character unencouraging for drilling. Of course, there remain many doubtful cases and they have to be drilled, but that is the course that we think the methods will take so that they do not encourage too much useless drilling and too much useless exploration work.

Member.—Is the method suitable for prospecting anthracite coal?

M. Mason.—I should hesitate to make any such promise.

H. T. F. Lundberg.—Some of the anthracites are oxidizing and under certain conditions they are surrounded by electrical fields that can be detected, but they have to be rather close to the surface. Some anthracites and some coals are conductive and if within reasonable reach it might be possible to trace them, but most of the electrical work in coal has failed.

* Member.—The only work I know on coal has been done at Wilkes-Barre, Pa., by Mr. Kelly and some that has been done in the French Alps. Some of those coals are sufficiently insulating to be detected by the potentiometer, but as far as I know not a great deal of work has been done along this line. I should prefer to emphasize that much of this work has been done in the Saar coal basin by the Schlomburger method but this is out of the subject on account of the fact that it is stratigraphical work.

I quite agree with Dr. Mason upon his subject and especially upon the fact that what we need most in electrical prospecting is experience. Many discoveries are made every month or every week, but not all of them prove to be orebodies or to be real discoveries.

My company made a discovery in Serbia in 1913 and obtained drillings in 1923. The orebody was one of importance and is now one of the biggest copper mines in Europe. We located it under a mountain of a very large orebody. In the instance of another discovery made by us, in Canada, in 1924, results were obtained two years later. As explained by Dr. Mason, many people are skeptical and some are over-enthusiastic. The difficulty is to convince people of the results that you can mathematically and physically obtain.

* 1928. E. G. Leonardon

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