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& the translator

Sherwin F. Kelly

STUDY
OF
UNDERGROUND ELECTRICAL PROSPECTING

BY **C. SCHLUMBERGER**

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TRANSLATED FROM THE FRENCH
UNDER THE DIRECTION OF THE AUTHOR
BY **SHERWIN F. KELLY**

PARIS 1920

With the compliments of T. A. Rickard
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Gift of Mr. T. A. Rickard

TO MY FATHER

whose persevering aid

permitted me to

pursue these researches.

C. S.

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INTRODUCTION

Magnetic permeability is the only physical property of rocks and minerals which has been used for underground investigation by means of observations made at the surface. Certain deposits of magnetite have been studied by means of the compass, by determining the disturbances in the intensity or direction of the earth's magnetic field which they cause in their vicinity. The other properties equally susceptible of being used in observations made at a distance, such as the density, elasticity, specific induction (1), transparency to X-rays, and electric conductivity, have given rise up to the present to relatively unimportant work which has not had any practical results.

Amongst the methods of prospection thus indicated, those based on the electrical conductivity are the most attractive.

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(1) The density of the rocks underground is mesurable by means of a pendulum, thanks to the attraction whose laws were enunciated by Newton. Thus the presence of a large body of pyrite (density 5) makes itself known by a slight diminution in the duration of oscillation of a pendulum. Unhappily, the very feeble perturbations thus produced are at the limit of the accuracy of observation; they are masked if the earth-surface is not horizontal, because mountains and hills also produce, by their mass, variations in the oscillation period.

The elasticity of rocks may be studied by measuring the rate of propagation of sound underground. This subject has only been studied from the point of view of the propagation to great distances of the seismic vibrations which affect the earth's crust at great depths.

The specific induction intervenes in the transmission of Hertzian waves.

They make use of precise measures, arrest the attention on a large variety of geological problems, and finally point directly to the metallic minerals, good conductors of electricity.

Thus it was in this field that I conducted a series of experiments (1), commenced early in 1912, interrupted in August 1914 by the war, and of which the present article has for object the brief explanation (2).

This study is divided into nine chapters.

Chapter I reviews the attempts at electrical prospection made by various experimenters before 1912.

Chapter II gives summary indications of the nature and relative order of electrical conductivity of various rocks and minerals.

Chapter III contains the theoretical exposition of the method applied under the name of "method of the potential-chart".

---

(1) In the course of this work, the efficient aid of numerous persons has greatly facilitated my task. Among my collaborators who experimented in the field I wish to cite especially my brother, Mr. Daniel Schlumberger. For theoretical questions, Mr. Liénard, assistant director of the School of Mines gave useful advice. Finally, I received a very cordial reception from various mining companies who authorised me to work upon their concessions and put at my disposal the necessary materials. I wish to mention and thank especially the Companies of: - Saint-Gobain, Penarroya, Châtillon-Commentry, Mines de Bor, Mines de Campanario, Hauts Fourneaux de Caen.

(2) For priority, and the eventual protection of the industrial applications of the methods studied, I have taken out several basic patents, notably: French patents, 460179 of September 27th 1912 and 457661 of May 8th 1913; German patent 269928 of November 5th 1912; American patents, 1163468 of January 2nd 1913, and 1163469 of September 25th 1913.

This part of the monograph does not contain the mathematical development, but has nevertheless a somewhat abstract theoretical character. It can be read over hastily by those who are interested principally in the practical applications, and to understand those need to remember only a few simple fundamental principles.

Chapter IV describes the method of operation employed. It indicates in detail the processes and apparatus.

Chapter V develops the manner of applying the potential chart to the study of disturbed strata, and illustrates the general considerations with the example of practical experiments made upon the Silurian of Normandy.

Chapter VI treats, under the same conditions, the case of the study of a mass of pyrite (conductor of electricity) and gives a resumé of the work done in this line upon the ore-body of Bor (Serbia).

Chapter VII gives the distribution of the current deep in the earth.

Chapter VIII deals with the different domain of "induced polarisation", that is to say, the phenomena of electrolysis that may be produced in the ground and finally used with profit in the prospection.

[illegible]

Chapter IV describes the [illegible] apparatus [illegible] in detail the [illegible] and [illegible].

Chapter V develops the [illegible] of applying the potential study of distributed [illegible], and [illegible] the results of practical experiments [illegible] location of [illegible].

Chapter VI treats, under the same [illegible] of [illegible] (conduction of electricity) [illegible] of the [illegible] upon the ore-body of [illegible].

Chapter VII gives the distribution of [illegible].

Chapter VIII deals with [illegible] "induced polarization", that is to say, the phenomena of [illegible] that may be produced in the ground [illegible] result in the prospection.

Chapter IX describes the phenomena of "spontaneous polarisation", consisting in the differences of potential that may be observed at the surface of the earth, especially in the neighborhood of pyrite deposits. The probable causes of these occurences and the practical applications which can result from measuring them, are studied with a certain amount of detail (1).

February 1920

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(1) I have, since October 1919, recommenced these studies in collaboration with my brother, Marcel Schlumberger. The new methods which we have adopted are not described in this article, as they have not been justified by sufficient field experimentation.

Chapter IX describes the phenomena of "spontaneous polarization", consisting in the differences of potential that are observed at the surface of the earth, especially in the neighborhood of pyrite deposits. The probable causes of these phenomena and the practical applications which can result from measuring them, are studied with a certain amount of detail (1).

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STUDY

OF

UNDERGROUND ELECTRICAL PROSPECTING

-:-:-:-:-:-:-:-:-:-:-:-:-:-:-:-

CHAPTER I

ATTEMPTS AT ELECTRICAL PROSPECTION BEFORE 1912 (1).

Method by Measurement of Resistance.- Brown patented in the United States in 1900 a process of prospection based upon measures of resistance, and later, numerous patents, in part due to Mac Clatchey, completed the original method (2). The following are the essentials.

By means of appropriate apparatus, the resistance is measured of the earth-circuit between two points A and B, situated at a predetermined distance from each other, such as 100 metres.

---

(1) These are all of the attempts that had been published at the time I undertook my experiments. Since then, during the printing of these pages, I have learned of important work done in Sweden and of which the reports were published during the war. The resumé of these studies will be found in an appendix at the end of this book.

(2) The following is the list of American patents covering the question: Nos. 645910, 672309, 686632, 727077, 736411, 817749.

[illegible]

[illegible]

-:-:-:-:-:-:-:-:-:-:-:-:-:-:-

CHAPTER [illegible]

ATTEMPTS AT ELECTRICAL PROSPECTING BEFORE 1910 (1)

[illegible] of [illegible] ion in 1902 a patent for prospecting [illegible], and later, [illegible] patents, in [illegible] the [illegible] method (2). [illegible] the essentials.

By means of [illegible] electrodes, the [illegible] potential between two points A and B, [illegible] distance from each other, [illegible]

---

1 There are all of the attempts that had been [illegible]

(2) [illegible] in the light of previous [illegible]

This base AB of constant length is then displaced and methodically explored by making a series of measurements of the resistances, which are then compared. The base is thus placed successively in the positions A_1B_1, A_2B_2, A_3B_3, (fig. 1) (3).

If, for a certain position A_3B_3 for example, a resistance particularly low is found, it is because, think the authors, between the points A_3 and B_3 should be found a conducting mass such as Z. Thus the position underground occupied by a mass of ore may be determined.

This process, very simple at first sight, as far as I know has given no practical results up to the present. Although it should not be absolutely rejected, it rests, as the patents show, upon an erroneous conception of the resistance of the earth-circuit.

If an electric current is passed through the earth between two points A and B, it does not travel directly from one to the other by the shortest route, but uses to the greatest advantage the entire section offered and distributes itself in the ground following a law which may be figured out if the earth is homogeneous. Figure 2 represents the distribution of the current as it is found in the vertical plane of symmetry passed through AB (1).

---

(3) (Translator's note) For all figures referred to hereafter, see the original in French, which should accompany this translation.

(1) For greater details see the discussion of the problem, page 21.

It is clear, and is supported by the evidence, that those lines of current come very close together at their extremities A and B, whereas in the intermediate portion they have a larger section, and some even an infinite section. From this it results that the resistance of the circuit AB, instead of being regularly distributed along the line between the two as in the case of a cylindrical conductor, is concentrated in the immediate neighborhood of the two contacts A and B. The nearer to the contacts the more pronounced is this action. Inversely, the portion of the earth where the section of these threads of current is large, hardly enters into the value of the resistance (2).

The practical conclusions which may be drawn from this observation are the following, also applicable to the case of heterogeneous earth: The resistance of the earth-circuit between two points A and B depends essentially upon the dimensions and forms of the earth-sections at the contacts and the nature of the ground in the immediate neighborhood; it is on the contrary almost independent of the constitution of the earth at a distance, and notably of the region between the two.

These facts limit considerably the practical value of the process.

---

(2) Taking two hemispherical sections of earth, A and B, with radii r_1 and r_2, very small compared with the distance AB, in homogeneous soil of specific resistance ρ, the expression for the resistance is $R = \rho \times \frac{1}{2\pi} \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$.

Under these conditions, the distance AB does not enter into consideration, and only the dimensions of the hemispheres are of importance.

Thus it is unnecessary to maintain for the base AB a constant length as the Americans authors wish to do.

[illegible] more than [illegible]

[illegible] resistance, [illegible]

[illegible] the line between the [illegible] of the [illegible]

[illegible], is concentrated in the immediate neighb[illegible]

[illegible] electrodes. The [illegible] to [illegible]

[illegible]. Therefore, the [illegible] of [illegible]

[illegible] the number of [illegible]

[illegible] of the resistance (13).

The [illegible] which may [illegible] from [illegible]

[illegible] of the [illegible], also [illegible] to the [illegible]

[illegible] the resistance of the earth-circuit between [illegible]

[illegible] depends essentially upon the [illegible] and [illegible]

[illegible] and the nature of the [illegible]

[illegible]

[illegible] of the earth [illegible]

[illegible] of the earth between the [illegible].

[illegible]

[illegible] hemispherical electrodes of earth, a and b, with [illegible] very small compared with the distance AB, in [illegible] of specific resistance ρ, the expression for the [illegible]

$$\frac{\rho}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right)$$

[illegible]

In reality, a conducting mass buried in the ground will not lower appreciably the resistance of the circuit except when it is very near one of the contacts A or B. And in such case its action will be practically the same whether it is situated between A and B or not. Moreover, and this is of importance from the point of view of application, the value of the resistance is in a large measure a function of experimental contingencies (disposition of the earth-contacts and condition of the soil at those points), so that the results of the measures are necessarily irregular and lack precision.

I think nevertheless that it is possible in certain cases to make use of the method. For example, when a thin regular bed of superficial earth (plant soil) covers rocks of different constitutions (sandstone, schist, igneous rocks), it should be possible to distinguish the nature of the rocks hidden by means of comparing the resistances.

TELEPHONIC METHOD (1) - Daft and Williams, abandonning resistance measures, made use of the following principle.

---

(1) The method is described in the following patents: American 817736, English 14124, (1902), German 152519. The texts differ somewhat, the German one being the most recent and the clearest. The experiments were especially made by an English Company, The Electrical Ore Finding Co., which was voluntarily liquidated December 19th 1905. An article in "Glückauf" (July 20th 1907), by W. Petersson gives interesting information. There is also some information in the number of the 8th of July 1908 of the "Revista Minera" (Experiments of Slade Olver). Finally, the book by Krusch ("Die Untersuchung und Rewertung der Erzlagerstätter") summarises the question on page 10 under the title "Die elektrische Schürfung".

By means of an insulated line L, (fig. 3), containing an induction coil C, they passed rapidly variable currents between two points A and B of the earth. By means of a movable line l, containing a telephone T, and touching the earth at a and b, they observed the passage of the currents in the earth, making use of the principle of telephoning through the ground.

The principal object of the authors was to study the distribution of the currents in the earth by following their lines with the telephone l. But they nowhere indicate with precision the method of application and seem to rest in a rather vague empiricism which is well shown in the following passage from their German patent. "The observer needs a great deal of experience and thought in order to draw correct conclusions from the sounds heard in the telephone, these varying like the human voice. He should therefore commence with the known and work little by little towards new phenomena".

The following is the method of procedure given in the articles treating this subject. The earth is explored by moving the telephone line, which should be of fairly short, fixed length (10 metres for example), parallel to itself . In homogeneous ground the sounds heard remain fairly regular and constant, whereas in heterogeneous soil they vary considerably from point to point. The different portions of the border of a heterogeneous section, ore body for instance, are characterised by sounds of different nature and amplitude.

Although experiments fairly complete have been undertaken, notably in Sweden in 1906 (see the article in "Gluckauf") and encouraging results were obtained, the method is at present well-nigh abandoned and the patent royalties are no longer paid. The cause of this failure seems to me partly attributable to phenomena of induction between the inducing circuit LAB and the induced telephonic circuit lab. This prevents the accurate study by means of the telephone line of the distribution of the current between the contacts A and B, as we shall see further on.

During the war the wide employment of ground telephoning and the methods of tapping enemy telephone conversations furnished a great number of observations, notably on the subject of the greater or less audibility in different soils. But I do not know whether or not these facts have been methodically grouped and studied from a geological point of view.

METHOD BY HERTZIAN WAVES.- The Hertzian Waves traverse dielectrics but are absorbed or reflected by bodies which are conductors. To apply them in the search for ore bodies is therefore logical. The practical methods of utilising them have been especially studied by Löwy and Leimbach who have taken out several patents and published a series of studies (1).

---

(1) Patents: English 11737, 14057 (1911); German 237944. Articles: "Oestreichische Zeitschrift für Berg und Huttenwesen", 18th and 25th of November and the 2nd of December 1911, 2nd and 9th Novembe 1912; "Annalen der Physik", vol. 36, 1911, p. 125; "Zeitschrift für praktische Geologie", 1912, p. 159.

[illegible] in 1916 [illegible]

[illegible] results were obtained, the method [illegible]

was abandoned and the patent [illegible] no [illegible]

[illegible] of this failure seems to be mainly attributable to [illegible]

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the constants a and b, as we shall see further on.

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METHOD OF DIRECTED WAVES.- The vertical waves [illegible] absorbed or reflected by [illegible]. The early ideas in the search for ore [illegible]. The principal methods of artificial [illegible] studied by [illegible] and [illegible] who have [illegible] and published a series of studies (1).

---

(1) [illegible]

For a conducting mass C situated in a mountain made up of insulating rocks (dry) and presenting steep slopes, the method of procedure is evident. It is sufficient to arrange a transmitting station E on one side of the mountain and to study by means of a movable receiving station R the waves which have traversed the mass (fig. 4). It should thus be possible to determine (judging at least from the theory of diffraction phenomena) the shadow-cones due to the interception of the waves by the opaque masses such as C.

For the ordinary case of flat or rolling country, Löwy and Leimbach propose to place the transmitting and receiving antennae in drill holes. To explore wide territory they think it possible to separate the antennae as much as 50 kilometres. No practical attempts have been made in this direction and it is certain that a good many objections could be made to such a project.

As far as conductors not vertical like veins, but horizontal like underground water strata, are concerned, the reflection of Hertzian waves should be of use. Löwy and Leimbach make use of an inclined transmitting antenna E and search for the proper position for the receiving antenna R, inclined in the opposite direction, to receive the reflected waves (fig. 5). The attempts seem to have given interesting results but the process has not entered into current practice as yet.

Löwy and Leimbach finally made experiments showing that the damping of oscillating currents from antennae depends upon neighboring bodies and especially, in subterranean work, on the surrounding ground.

It should be noted that the power of specific induction of the rocks enters into consideration, and thus it is possible to base methods of experimentation upon a property other than that of the electrical conductivity.

CHAPTER II

ELECTRICAL CONDUCTIVITY OF VARIOUS ROCKS AND MINERALS.

Before starting the examination of the method of the potential-chart it will be convenient to take notice of the relative order of conductivity of the various rocks and minerals.

Two sorts of conductivity should be distinguished. Certain minerals, not very numerous, conduct electricity in the same way as metals, that is to say, without the displacement of ions; they play therefore the role of metallic conductors. The other minerals, whether ores or sterile rocks, are insulators more or less perfect and owe their apparent conductivity to the absorbed water which they contain (1); they play the role therefore of electrolytic conductors.

The following experiment makes it easy to distinguish~~ed~~ between the two cases. The body to be studied, A, is immersed in water and connected with one side of an electric circuit (10 volts at least), the other side of the circuit being the second electrode B (fig. 6). If A is a metallic conductor, electrolysis will be produced on its surface of contact with the water and bubbles of gas will appear. In the contrary case the electrolysis will be produced at C, the extremity of the wire carrying the current.

---

(1) To be more precise it should be remarked that, if these minerals are actually conductors, this property is negligible as far as the phenomena here being studied are concerned, when compared with the conductivity of the absorbed water.

The principal ores usually metallic conductors are: a. Among the sulfides, the various pyrites, mispickel, galena, and copper sulfides; b. Among the oxides, magnetite and pyrolusite. It should be remarked that blende is an insulator, natural enough on account of its transparency. Stibine is also an insulator, in spite of its metallic aspect.

From the numerous experiments which I have made on various samples, it appears that Hematite, both massive and crystalline, does not conduct appreciable amounts of electricity, contrary to what various authors seem to admit.

The resistance of ores which are conductors, especially pyrites (1), is one ohm per centimetre per square centimetre (2). This value is analogous to that of the resistance of concentrated saline liquids or acids, and is 100,000 times as great as the resistance of ordinary metals. It is a question, therefore, of rather mediocre conductors which cannot be compared with metals.

The numerical order of resistance is the only interesting point. In fact, on one hand, the measures made upon various samples show a wide divergence, and on the other hand the value of the resistance of a crystal cannot be taken as showing the average of a of the same mass/subtance, notably because of the presence of gangue and of imperfect contact between crystals.

---

(1) Certain ores may be better conductors. I found for example, for a sample of chalcosine: = 0.005 ohms cm-cm^2. For galena a small fraction of an ohm is frequently given.

(2) (Translator's note) This expression means the resistance of a sample one centimetre long with a section of one square centimetre and will hereafter be written cm-cm^2.

[illegible]

[illegible] Among the oxides, magnetite and pyrolusite [illegible] remarked that oligist is an insulator, natural [illegible] transparency. Zincite is also an insulator, in spite [illegible] metallic aspect.

From the numerous experiments which I have made on [illegible], it appears that Hematite, both massive and crystalline, does not conduct appreciable amounts of electricity, contrary to what various authors seem to admit.

The resistance of ores which are conductors, [illegible] (1), is one ohm per centimetre per square centimetre. This value is analogous to that of the resistance of [illegible] liquids or solids, and is 100,000 times the resistance of ordinary metals. It is a question, [illegible] mediocre conductors which cannot be compared with [illegible] The numerical index of resistance is the only interest[illegible]. We have, on one hand, the measures made upon [illegible] wide divergences, and on the other hand the [illegible] of a crystal cannot be taken as equal to the [illegible] of the same substance, probably because of the presence of [illegible] contact between crystals.

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(1) Certain ores may be better conductors. [illegible] of conductivity 0.005 ohm [illegible] is probably [illegible]

(2) [illegible]

It should be noticed in this connection that in certain types of deposits the crystals are completly separated from each other in spite of their appearance of continuity and compactness, and their feeble gangue content. This is the case in certain iron deposits in the West of France, wherein small octahedrons of magnetite are envelopped by silica which prevents the conduction of electricity. On the other hand there are deposits of sulfides which are conductors throughout their mass, although the crystals are inclosed in a siliceous cement occupying a large part of the volume.

Carbonates and oxides have only, like rocks and earth, electrolytic conductivity, due to absorbed water; at least, if they are actually conductors it may be practically neglected. The quantity and composition of the absorbed water controls the phenomenon, but the fact that this water is retained by capillarity should not be lost sight of, and that therefore its properties are those of capillary water strata, which may differ appreciably from those of the water in the quarry.

Whatever may be the extent of this restriction relative to the capillarity, it is interesting to know in this connection the resistances of various natural waters, easily measured. Thus is found in ohms per cm-cm^2: 1000 for water containing selenium, 2000 to 3000 for water containing calcite, 5000 to 7000 for pure water. These figures are comparable to the following which refer to damp ground: 1000 for very wet, pyritic blue clay, 20,000 for an argilaceous sand, 30,000 for an argilaceous limestone, 70,000 for a granitic sand.

[illegible] crystals are [illegible]

[illegible] their appearance [illegible] the composition, [illegible]

[illegible] certain [illegible]

[illegible] of France, where a small [illegible] of water [illegible]

[illegible] which prevents the conduction of [illegible]

[illegible] other hand there are deposits of sulfides which [illegible] throughout their mass, although the crystals are [illegible] cement occupying a large part of the volume.

[illegible] and rocks have only, like rocks [illegible]

[illegible] conductivity, due to absorbed water; at least, [illegible] conductors it may be [illegible] neglected. [illegible] composition of the absorbed water controls the [illegible] that this water is retained by capillarity [illegible] and that therefore its properties are [illegible] water [illegible], which may differ appreciably from [illegible] water in the quarry.

Whatever may be the extent of this [illegible] it is interesting to know [illegible] of various natural waters, [illegible] measured. [illegible] in ohms per cm³; 1000 the water [illegible] to [illegible] for water containing [illegible], [illegible]. These figures are [illegible] to the following [illegible] ground: 1000 for very wet, [illegible] clay, [illegible] sandstone [illegible], 30,000 for argillaceous limestone, [illegible] sand.

Fresh, compact rocks give, even after absorbing water, figures considerably higher, in the neighborhood of 10 megohms in laboratory experiments made upon samples cut in the form of prisms (1). It should be noticed that such figures might not correspond at all to the average resistance of rocks in place, which, because of the numerous fissures which they contain are much better conductors. Measures made in the field and covering large masses are the only ones that give valuable results, in such a case. Unhappily the experiments can be made with ease only on rock outcrops, which of course are more or less altered. The figures which are found in practice vary in ground of average moisture from 50,000 to 200,000 ohms per cm-cm^2.

It should be remembered that the ratio of the conductivity of ores which are conductors to that of rocks is at least 1,000 and may easily attain 10,000 or 100,000. Also, that for different rocks the conductivities, rather variable, are frequently in the ratio of I to 10. Loose earth and superficial clay should in general be much better conductors than deep-seated rocks because of their high water content. The rise of temperature in depth which acts to increase the conductivity, has but slight effect at the ordinary depths to which investigation is carried (2).

---

(1) "Tables annuelles des constantes", vol. 1, p. 671.

(2) The resistance of water diminishes about 3/100 per degree, and falls therefore, to the half of its value at ordinary temperature, for a rise of 20 to 30 degrees Centigrade.

CHAPTER III

THEORY OF THE METHOD OF THE POTENTIAL CHART.

-:-:-:-:-:-:-:-:-:-:-:-

Principles of the Method.- If a difference of potential is applied to two points A and B of the earth, there will result between these points an electric current which will produce variations of potential in the earth, because of the latter's resistance. If for example, the current goes from A towards B, the voltage will drop in the same direction. To represent the distribution of potential in the ground, the simplest way is to consider the surfaces of equal potential, and to number them according to their value. In considering the superficial phenomena, the only ones that it is practicable to observe, it will be noticed that it is possible to trace curves of equal potential on the ground traversed by the current. These curves are the "outcrops" of the equipotential surfaces in the ground, and each may be numbered according to the value it represents. These lines constitute a map of the potentials of the region, analogous in principle to a topographic map wherein the elevations are traced by connecting points of equal altitude.

When the ground is homogeneous and flat, the distribution of the potentials between the contacts A and B may be calculated. That is to say that potential chart is known "a priori". When the earth contains rocks or minerals of different conductivities, this modifies the distribution of the potentials and produces perturbations which are reflected more or less in the form or value of the superficial equipotential lines . These latter may be easily traced and numbered in the field, the deformations figured out, and the provoking causes beneath the surface deduced. Such is the principle of the method.

[illegible]

-.-.-.-.-.-.-.-.-.-.-

[illegible] of the Current.- If a difference of potential is applied at two points A and B of the earth, there will flow between these points a telluric current which will produce a distribution of potentials in the earth, because of the different resistances. If for example, the current goes from A towards B, potentials will drop in the same direction. To represent the [illegible] of potentials in the ground, the simplest way is by curves of equal potentials, and in another [illegible] considering the geoelectric phenomena, the [illegible] considerable distance, it will be realized that it [illegible] curves of equal potentials on the ground, the [illegible] current. These curves are the "skeletons" of the equipotential surfaces in the ground, and both may be measured according to [illegible] requirements. These lines constitute a map of the [illegible], analogous in principle to a topographic [illegible] equipotentials are traced by connecting points of equal [illegible]

If the ground is homogeneous and rigid, the distribution of potentials between the electrodes A and B may be [illegible] way that potential would be known in general. When the ground is made up of materials of different conductivities, the [illegible] and the distribution of the potentials are [illegible] which are [illegible] [illegible] conductivity [illegible] the [illegible]

Theoretical Study of Flat, Homogeneous Ground.- The question is the following: Between two points A and B of flat, homogeneous earth, a current is passed, and it is desired to know what are the value and form of the equipotential surfaces below, and the equipotential curves at the surface.

This problem relative to the application of Ohm's law to a limitless conductor (1) is solved by the following formula (2):

$$V = \frac{\rho i}{2\pi}\left(\frac{1}{r} - \frac{1}{r'}\right) + \text{const.},$$

in which V represents the potential of a point M of the earth, ρ the specific resistance, i the intensity of the current, r and r' the distances of M from the contacts A and B (fig. 7).

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(1) The fact that the conductor is not unlimited in all directions, but does not extend above the plane of the surface, changes nothing because this plane is one of symmetry.

(2) To justify this formula, consider the immediate neighborhood of A, where on account of the symmetry, the equipotential surfaces are hemispheres centered at A and the lines of current are cones with their summits at A (fig. 8). The application of Ohm's law to the spheres of radius r and r + dr is written.

$$-dV = \rho \frac{dr}{2\pi r^2} i$$

which gives by integration

$$V = \frac{\rho}{2\pi r} i + \text{const.}$$

This expression is identical with the general formula, provided that r' is large compared with r.

The problem is, from the mathematical point of view, identical with that of the distribution of induced potentials in a medium of specific induction K, by two equal and opposite electrical charges + q and - q concentrated at the points A and B. The formula giving the potentials is then the well-known expression:

$$V = \frac{1}{K}\left(\frac{q}{r} - \frac{q}{r'}\right) + \text{const.}$$

The distribution of electrostatic or electrodynamic potentials is therefore identical, provided the relation $\frac{\rho i}{2\pi} = \frac{q}{K}$ holds.

The equipotential surfaces defined by the equation $\frac{1}{r} - \frac{1}{r'} =$ const. are of the fourth degree, and are of revolution about the line AB. They are of simple form in the neighborhood of A or B and midway between. In fact, near A it is possible to neglect $\frac{1}{r'}$ in comparison with $\frac{1}{r}$, so that the surfaces are hemispheres centered at A . Midway between A and B they are, because of the symmetry, planes perpendicular to AB.

The chart of the superficial potentials is reproduced in figure 9 (1). This also represents the sub-surface potentials. The equal potential surfaces in the ground being ones of revolution about AB, to obtain them it is but necessary to revolve half of the figure.

The numbering of the curves (or surfaces) has been done on the following principle. The unity of length chosen is 1/100 of the distance AB. The potential of the point α situated at the distance I from A is chosen as 100, and the potential of the point β at a distance I from B is taken as 0. This is equivalent to choosing as the unity of potential 1/100 of the difference of potential between α and β .

Under these conditions the fundamental formula becomes

$$V = 50.5 \left(\frac{1}{r} - \frac{1}{r'} \right) + 50,$$

which gives V=100 for (r=1; r'=99) and V=0 for (r=99; r'=1). The potential midway (r=r') and at infinity $\left(\frac{1}{r} = \frac{1}{r'} = 0 \right)$ is then 50, average between 0 and 100.

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(1) For the manner of tracing the lines of current and equipotential curves, see J.C. Maxwell, "Treatise on Electricity and Magnetism", Vol. I, Oxford.

[illegible] of the line AB, there are [illegible]

[illegible] and [illegible]

[illegible] $\frac{1}{r'}$ in comparison with $\frac{1}{r}$, so the

surfaces are hemispheres centered at A. Midway between A

and B, because of the symmetry, [illegible]

The chart of the [illegible] potentials is reproduced [illegible]

Figure 2 (1). This also represents the sub-surface potentials,

the equal potential surfaces in the ground being [illegible]

[illegible] about AB, to obtain them it is but necessary to [illegible]

of the figure.

The numbering of the curves (or surfaces) has been [illegible]

[illegible] principle. The unity of length chosen [illegible]

the distance AB, the potential of the point [illegible]

distance [illegible] from A is chosen as 100, and the potential [illegible]

[illegible] at a distance 1 from B is taken as 0. This [illegible]

[illegible] the unity of potential [illegible]

[illegible] between A and B.

[illegible] these conditions the fundamental formula becomes

$$[illegible] = 50 \left(\frac{1}{r} - \frac{1}{r'} \right) + 50,$$

[illegible] for [illegible] and the [illegible]

the potential midway (r=r') and at infinity [illegible]

is [illegible] 50, average between 0 and 100.

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(1) For the method of drawing the [illegible]

[illegible]

To put it in a more concrete fashion, the chart gives, very closely (2) with these conventions, the voltage that would be observed at each point in the ground if the sections chosen at A and B were hemispheres of I metre radius situated 100 metres from each other, and if a difference of potential of 100 volts were maintained between them.

The advantage of this relative notation is to give an invariable basis for making a potential chart of homogeneous ground. This graph translates a formula into numerical coefficients; it depends neither on the resistance of the ground, nor on the difference of potential applied, nor on the distance between the contacts, nor on the form or disposition of the latter. With regard to this last point, the section just at the contact must be ignored. All experimental contingencies are thus eliminated.

It is well to conserve, in the case of heterogeneous ground, the same conventions for evaluating distances and potentials. The chart, which will be disposed differently in each particular case, is independent of the difference of potentials applied, of the average specific resistance of the ground, and of the forms or dimensions of the sections being studied.

Distribution of the Current in the Earth.- The current is usually considered as the cause of the fall of potential.

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(2) The approximation consists in supposing that at I metre from A there will be, in the case of contacts exactly 100 metres apart, an equipotential surface, accurately hemispherical, centered at A.

It is thus often clearer to think of the distribution of the lines of current than of the potentials, although, in reality, the potentials alone are directly observable, as the current remains hidden and gives evidence of its passage under the surface by such observable phenomena as the fall of potential. One conception is easily translated into the other.

At each point the direction of the current is at right angles to the equipotential surface passed through that point. Thus the lines of current are trajectories perpendicular to those surfaces. The density δ of the current (intensity per square centimetre normal to its direction) is proportional to the drop $\frac{dV}{dn}$ of potential per unit of length (intensity of the electrical field) and in inverse ratio to the specific resistance, as Ohm's law is written $\frac{dV}{dn} = \rho\delta$. In homogeneous material the density of the current is greater when the surfaces are close together.

On the graph of potentials the dotted lines represent the currents (fig. 9). If the figure is revolved about AB to obtain the representation of what occurs at depth, these lines generate tubes of current. The lines I, 2, 3,.... have been traced in such a way that the corresponding tubes represent the following fractions of the total current: tube 1 a tenth of the current, tube 2 two tenths, etc. Tube 5 which conducts half of the current has a maximum transversal diameter attaining almost the double of AB.

[illegible] which, unlike electricity, [illegible] potentiality, although, in reality, [illegible] theoretically, as the [illegible] through the surface of [illegible] of the pressure [illegible] phenomena of the fall of potential, [illegible] distribution [illegible]

At each point the direction of the current is at right angles to the equipotential surface passes through that point, [illegible] of current [illegible] perpendicular to [illegible] of the current (intensity per square [illegible]) [illegible] is proportional to the [illegible] fall of potential (intensity of the electric [illegible]) [illegible] inverse ratio to the specific resistance, [illegible] = [illegible] conductance of electricity [illegible]

[illegible] these surfaces are given [illegible] the graph of potentiality [illegible] of the [illegible] as resolved [illegible] representation of what occurs at each, these lines [illegible] of current. The lines 1, 2, 3,..., have been [illegible] that the corresponding [illegible] represent the [illegible] of the total current [illegible] of the current, [illegible], etc. [illegible] half of the current [illegible]

It should be remembered, from the aspect of the figure, that in homogeneous ground the current does not flow from A to B in narrow paths concentrated about the line AB, but on the contrary spreads out from this axis and penetrates the ground widely and deeply. Near a contact (considered as a point) the current spreads out symmetrically in all directions, the current tubes before mentioned being in this case cones with their summits at the contact. The density of the current, and with it the intensity of the electrical field, varies inversely as the square of the distance from the contact. In the median region the current flows approximately horizontally by cylindrical lines of uniform density, throughout a zone deep and wide (1). In all this region the electrical field is, in consequence, nearly uniform.

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(1) The density of the current varies as follows for different points in the vertical plane of symmetry CD, perpendicular to AB (fig. 10).
The maximum density is at C and is $\delta_m = \frac{Ai}{\pi} \cdot \frac{1}{AB^2}$.

That would be the density of the current flowing from A to B, if it were distributed uniformly, in a section of diameter equal to AB. At a given point M in the plane, the density is $\delta = \delta_m \cos^3 \omega$, ω being the angle MAB. Going away from C, the density drops 1/10, if CM= 0.27AB, and 1/2, if CM=0.78AB. Calculating the radius CM of a circle described in the plane CD with C as center, so that a given fraction, x, of the total current passes within the circle, it will be found that it is defined by the angle ω given by the expression $\cos \omega = 1 - x$
For example, half of the current passes $\left(x = \frac{1}{2}\right)$ within such a circle that $\cos \omega = \frac{1}{2}$, $\omega = 60°$, which corresponds to a radius CM=0.87AB.

These figures show the effective manner in which the current spreads out from AB in homogeneous soil.

PROFILES OF POTENTIAL AND PROFILES OF ELECTRICAL FIELD.-

The potential chart with its equipotential curves is analogous, as we have seen, to a topographic map with its contours. It is useful to complete this chart with a graph showing the values of the potentials along a line traced from one point to another, exactly as a contour profile is drawn. Figure 11 shows such a graph along the line AB, with the conventional units chosen (2).

Instead of the potential, it is sometimes more convenient to represent the intensity H of the electrical field, or fall of potential per unit of length $\frac{dV}{dn}$. The field H being the derivative of the potential is naturally larger the faster the latter varies, that is to say, when the curves are closer together. To refer again to the topographical analogy, the field is comparable to the slope of the ground. Figure 12 gives the profile of the field along the line AB (1), always with the same units.

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(2) The equation of the curve is $V=50.5\left(\frac{1}{r}-\frac{1}{r'}\right)+50$, with $r+r' = AB = 100$. In the neighborhood of the contacts, the curve approaches an equilateral hyperbola. The figures on the curve are the values of the potentials at the distances 1, 10, 20, 30, ... from A.

(1) The equation of the curve is: $H=50.5\left(\frac{1}{r^2}+\frac{1}{r'^2}\right)$, with $r+r'=100$. Near the contacts the field drops rapidly, as it diminishes in inverse ratio to the square of the distance; in the middle region it rests nearly uniform however. The numbers on the curve are the values of the field at the distances, 1, 10, 20, 30, ... from A.

From the point of view of the practical applications, it is often necessary to consider the zone in which the field may be thought of as nearly uniform. This also corresponds to a uniform current density. It is convenient to take for this region a square PQRS (fig. 13), placed symmetrically with respect to AB, and having a side equal to $\frac{AB}{3}$. The depth to attribute to this zone of uniform field, is $\frac{AB}{6}$.

[illegible]

the potential [illegible] with the equipotential curves as [illegible] very, so a topographic map with its contours [illegible] useful to complete this chart with a graph showing the [illegible] the potentials along a line passes from one point to another, exactly as a contour profile is drawn. Figure 11 shows such a graph along the line AB, with the conventional units chosen. (1)

Instead of the potential, it is sometimes more convenient to represent the intensity F of the electrical field, or fall of potential per unit of length $\frac{dV}{dn}$. The field F being the derivative of the potential is naturally larger the faster the potential varies, that is to say, when the curves are closer together. To refer again to the topographical analogy, the field [illegible] the slope of the ground. Figure 12 gives the profile of the field along the line AB (2), always with the same units.

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(1) The equation of the curve is V=50.5 ([illegible]) [illegible] r' = AB = 100. In the neighborhood of the centers, the curve approaches an equilateral hyperbola. The figures on the [illegible] are the values of the potentials at the distances 1, 10, 20, [illegible] from A.

(2) The equation of the curve is [illegible] r+r'=100. Near the poles the field drops rapidly, as it is due in inverse ratio to the square of the distance; in the middle region it is nearly uniform however. The figures [illegible] are the values of the field at the distances 1, [illegible] from A.

From the point of view of the [illegible] application it is necessary to consider the zone [illegible] of an nearly uniform. This [illegible] current density, it is [illegible] (Fig. 13) [illegible]

PERTURBATIONS IN THE POTENTIAL CHART PRODUCED BY HETEROGENEITIES IN THE SOIL.- When the soil, instead of being homogeneous, contains zones of different conductivity, these affect the distribution of the potentials. The theoretical calculation of such distribution presents well-nigh insurmountable difficulties, even in the simplest case. Under such conditions an approximation giving a qualitative view of the perturbations must suffice.

Suppose, for example, that in the region half-way between A and B, where the equal potential surfaces are usually parallel, vertical planes, a conducting mass Z (fig. 14) is buried. In order to aid in understanding the deformation produced by this mass on the equipotential planes, consider first the extreme case in which Z is a perfect conductor (1). Under these conditions the mass is at the same potential throughout, the drop produced by the resistance being negligible. The entire volume of Z would then be enveloped by the surfacesof equal potential, these passing by one side or the other according to whether their potential is superior or inferior to that of Z. This may be summarized by saying "a conducting mass repulses towards its exterior the equipotential surfaces which tend to approach it". Passing to the case wherein the conductivity of Z, instead of being perfect, is merely superior to that of the surrounding territory, it will be noticed that the

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The approximation made by treating the field as uniform may be shown by looking at the following figures. If H_m indicates the value of the field at the center, then at D (minimum value) $H=0.97H_m$, and at E (maximum value) $H=1.4H_m$.

The field may be rendered considerably more uniform in the square PQRS, by replacing the contact A by two separate and distinct ones A' and A", placed as indicated in the figure, and replacing B by B' and B".

(1) Strictly, this amounts to supposing that the conductivity of Z is very large compared with that of the surrounding ground, because the ratios of specific conductivities alone enter into consideration.

[illegible] THE FIELD. When the soil, instead of being [illegible] neous, contains zones of different conductivity, these affect distribution of the potentials. The theoretical calculation of such distribution presents nearly insurmountable difficulties even in the simplest case. Under such conditions an approximate [illegible] a qualitative view of the perturbations must suffice.

Suppose, for example, that in the region half-way between [illegible] and B, where the equal potential surfaces are nearly parallel vertical planes, a conducting mass C (Fig. 14) is buried. To aid in understanding the deformation produced by this mass [illegible] the equipotential planes, consider first the extreme case in [illegible] C is a perfect conductor (1). Under these conditions the mass [illegible] the same potential throughout, the drop produced by its resistance being negligible. The entire volume of C would then be limited by the surfaces of equal potential, these passing to [illegible] side or the other according to whether their potential is [illegible] or inferior to that of C. This may be summarized by saying that [illegible] conducting mass repulses towards its exterior the equipotential surfaces which tend to approach it. Passing to the case where the conductivity of C, instead of being perfect, is merely [illegible] [illegible] that of the surrounding territory, it will be noticed that

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(1) [illegible] approximation made by treating the field as uniform may be shown by looking at the following figures. If E_m indicates the [illegible] of the field at the center, that at D (minimum value) [illegible] and at B (maximum value) $E=1.41E_m$.

The field may be rendered considerably more uniform [illegible] using four poles, by replacing the contact A by two separate [illegible] as A' and A'', placed as indicated in the figure, and replacing [illegible] by B' and B''.

preceding deformation holds in principle, although in a less marked manner. There will still be the same repulsion of the surfaces, although they penetrate the mass, as indicated by the figure.

Observing now the reverse case, that of an insulating body, suppose first that its conductivity is nil (cavity in the ground) and reason this time on the lines of current. These pass around the space Z, obliging the equipotential surfaces to cut Z normally. The inflection which results is directed towards the interior of Z, as shown in the figure 15. Thus it is possible to say that "an insulating body acts as though it attracted the equipotential surfaces towards its interior". This attraction is less clear, but holds nevertheless, if Z instead of being a perfect insulator is merely a poorer conductor than the soil around it.

The perturbations that have been just analyzed are not solely local; they react at a certain distance from Z. If then this mass is not too deeply buried in the ground, it will produce the reaction above described on the equipotential curves on the surface. For example, in the case of a conducting mass, the chart of the equipotential lines will look something like fig. 16, making it possible to find the location, and to a certain extent the dimensions, of the buried mass (1).

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(1) It is possible, moreover, to get an idea of the depth at which the disturbing mass Z is buried (fig. 17), by placing one of the contacts A almost above it, in a convenient position.

Suppose the other contact B at a considerable distance, thus permitting the equipotential surfaces about A to assume the form of hemispheres centered at A. It is evident that the hemispheres with radii sufficient to reach A will be the only ones affected, those with shorter ones remaining approximately spherical. Observation of the average radii of the smallest curves presenting deformations will then give an idea, very rough it is true, of the depth of the disturbing mass.

The deformations of the potential graph often translate themselves particularly well on the profiles of the field. A profile along the line xy of the figure 16, for example, will have the form indicated in figure 18. At the extremities of Z, in the region of crowded lines, the field passes by the maximum values, whereas the minimum is above E, in the zone of widely separated curves.

REFRACTION OF THE EQUIPOTENTIAL SURFACES ON PASSING FROM ONE MEDIUM TO ANOTHER.- A case of deformation easy to calculate is that relative to the point of passage from one substance to another. It may be shown that a surface of equal potentials V, is refracted in traversing the plane P which separates two mediums of different specific resistances ρ and ρ' (fig. 19), and that between the angles α and α' which V makes with P in the two materials, the relation $\rho \tan. \alpha = \rho' \tan. \alpha'$, holds (2). The discussion of this formula leads to the following results: The refraction takes place in such a manner that the equipotential surface approaches the plane P in the poorer conducting substance; it is maximum when the surface encounters P at an oblique angle of incidence; it is on the contrary nil if the incidence is normal $\left(\alpha = \frac{\pi}{2}\right)$ or tangential

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(2) The demonstration of the formula is analogous to that of the refraction of lines of magnetic induction on passing from one material to another of different permeability.

$(\alpha=0)$ (1). The numerical calculations show that the angular change in direction produced by the refraction is considerable, even when the difference in specific resistances is small.

This bending has been studied in the foregoing as though it were a phenomenon localised at the point of traversing the separating plane, whereas in reality it commences by an incurving of the equipotential surface at a certain distance from the actual point of angular change. The surface, as shown in figure 20, bends in the medium which is the poorer conductor so that it encounters P at a small angle, bending back abruptly in the other substance (2).

THEORETICAL EXAMPLE OF PERTURBATION.- In the nature of an illustration, consider two terrains T and T', of different character separated by a vertical plane P, which is a frequent enough case in geology when the plane of separation is a fault. Suppose the contact A placed in the ground T, and the other contact B a long distance from the region being studied.

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(1) The incidence of maximum refraction is characterized by the fact that the bisector Ox of the dihedral angle formed by the two planes of V is inclined at 45° to the plane of separation P. For this incidence, $\tan.\alpha = \sqrt{\frac{\rho'}{\rho}}$, $\tan\alpha' = \sqrt{\frac{\rho}{\rho'}}$, $\tan(\alpha'-\alpha) = \frac{\rho-\rho'}{2\sqrt{\rho\rho'}}$. Take for example, $\frac{\rho}{\rho'} = 2$; the formula gives $\alpha'-\alpha$ =20°, which is a notable change in direction. More complete calculations establish that the deviation $\alpha'-\alpha$ remains greater than 15°, even when the incidence differs more or less from that giving the maximum refraction.

(2) It is, of course, the angles α and α' that P makes with the planes drawn tangent to the curved surfaces at the point where these latter intersect it, that it is necessary to substitute in the formula $\rho\tan.\alpha = \rho'\tan.\alpha'$.

The equipotential curves about A will be circular in homogeneous ground. In the present case it is possible to calculate their theoretical forms and values (1), a rare exception. They are represented in figure 21.

This has been sketched under the hypothesis that the region T is a much better conductor than T'. The application of the preceding principles is clear: 1. Attraction exercised by the relative insulator T on the curves situated within it, and which present a point towards T'; 2. Refraction of the curves on passing through the plane, P, of separation.

PERTURBATIONS DUE TO THE RELIEF OF THE GROUND.- The potential chart of homogeneous ground that has so far been studied refers to flat ground. More or less important disturbances result from sharp relief. A hollow, such as a valley, constitutes a lack of matter and acts the same as an insulating mass, attracting the equipotential surfaces.

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(1) The theoretical formula giving the potential V, of a point M situated in T is:- $V=100\left(\frac{1}{r}+\frac{\rho'-\rho}{\rho'+\rho}\,\frac{1}{r'}\right)$. ρ and ρ' are the specific resistance of the regions T and T', r is the distance MA, r' the distance MA', A and A' being symmetrical with relation to P. The unity of distance is 1/100 of that from A to the plane P. V=100 at the distance 1 from A, and V=0 at a great distance from A.

For points situated within T', the expression for the potential is simpler:- $V'=200\,\frac{\rho'}{\rho'+\rho}\,\frac{1}{r}$. The curves are circumferences about A as center.

In the case of the figure, ρ' being large in comparison with ρ the expression may be simplified and written:-

$$V=100\left(\frac{1}{r}+\frac{1}{r'}\right);\quad V'=\frac{200}{r}.$$

[illegible] investigated [illegible] ground. In the present state it is possible [illegible] theoretical curves and [illegible] exception, they [illegible] represented in Figure 31.

This has been sketched under the hypothesis that the [illegible] is much better conducting than T'. The application of the principle is almost a [illegible] attraction exercised by the conductor T on the current situated within it, and which [illegible] point counter C'; 2, the reaction of the current on passing the planes, P, of separation.

PERTURBATIONS DUE TO THE RELIEF OF THE GROUND.- The [illegible] of homogeneous ground that has so far been studied [illegible] ground. More or less important disturbances result from relief. A hollow, such as a valley, constitutes a lack of [illegible] and acts the same as an insulating mass, attracting the equipotential surfaces.

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(1). The theoretical formula giving the potential V, of a [illegible] situated in T is:- $V=100\left\{\frac{1}{AM}+\frac{\rho'-\rho}{\rho+\rho'}\cdot\frac{1}{r}\right\}$; ρ and ρ' are the specific resistances of the regions T and T', r is the distance [illegible] the distance MA', A and A' being symmetrical with [illegible] unity of distance is 1/100 of that from A to the plane [illegible] the distance 1 from A, and V=0 at a great distance from A.

For points situated within T', the expression for the potential is simple:- $V=200\ \frac{1}{\rho+\rho'}$ [illegible] The corresponding [illegible] A as center.

[illegible] the case of the figure, [illegible] expression may be simplified [illegible]

An elevation, such as a hill, corresponds to an excess of matter, and reacts in the opposite manner. These disturbances play a varying part, resulting in much trouble in rugged country. The difficulties are especially grave in view of the fact that it is not easy to evaluate, a priori, the quantitative importance of the deformation produced by a given relief.

ACTION OF VERTICAL CONDUCTIVITY.- One might think that, the potential chart representing phenomena in the horizontal plane, it could not translate any but the heterogeneities that present notable horizontal dimensions. A conducting body with its principal dimensions vertical, as for example, the casing of a drill hole or a narrow mineralised column, can nevertheless be marked on the chart, provided that it be sufficiently near one of the contacts. Consider, for example (fig. 22), a vertical conducting stem T, near the contact A. Its lower extremity being in contact with deep points of the earth, distant from A, this stem produces a diversion of the current downward, and to its summit are attracted the lines of current, which converge upon it. On the potential graph this is manifested by the presence about the summit of the tube of small, closed curves, formed out of the near-by ones by repulsion, as in the general case of conducting bodies.

Nothing of this sort would be observed in the region mid-way between A and B where the equipotential planes are vertical,and the tube would be without any action.

POSSIBLE DEPTH OF INVESTIGATION.- The question may be considered from two points of view.

Consider a conducting mass Z for instance (fig. 23), buried in the ground in the region where the equipotential surfaces would be parallel vertical planes in homogeneous soil, and imagine that this mass occupies the positions Z_1, Z_2, Z_3, deeper and deeper, retaining its dimensions and conductivity. It is evident that the deformations this body causes in the superficial equipotential lines will become less and less marked as it takes a deeper and deeper position in the soil, because such perturbations are only the surface reflection of the disturbances caused at depth to the vertical equipotential planes. A moment will come when they will be too indistinct to be perceptible, limiting the possible depth of investigation.

The problem, thus presented, requires a mathematical solution very complex, if not impossible, even in the simplest cases, because there is no way of calculating the form of the equipotential surfaces. The best way to get an idea of the relative sizes of the disturbances is to experiment in the laboratory, in miniature, on artificial ground. It happens, unfortunately, in my experiments that the perturbations in the potential-chart disappear rapidly as the depth of the disturbing body is augmented. As a concrete example, taking for Z (clayey ground) the form of a parallelopiped with dimensions 1 x 1 x 2 disposed as the figure indicates, with its conductivity 15 times greater than the surrounding soil (argilaceous sand), the perturbations of the chart become with difficulty perceptible when the thickness of the covering soil becomes greater than 1.

[illegible]

ordinary a conducting mass Σ for instance (fig. 21), buried in the ground in the region where the equipotential surfaces are parallel vertical planes in homogeneous soil, and imagine this mass occupies the positions Σ1, Σ2, Σ3, without any change maintaining its dimensions and conductivity, it is evident that the perturbations this body causes in the superficial equipotentials will become less and less marked as it takes a deeper and deeper position in the soil, because such perturbations are the surface reflection of the disturbances caused at depth in vertical equipotential planes. A moment will come when they will be too indistinct to be perceptible, limiting the possible depth of investigation.

The problem, thus presented, requires a mathematical solution very complex, if not impossible, even in the simplest cases, because there is no way of calculating the form of the equipotential surfaces. The best way to get an idea of the magnitude of the disturbances is to experiment in the laboratory, in a tank, on artificial ground. It happens, unfortunately, in all experiments that the perturbations in the potential-lines di rapidly as the depth of the disturbing body is augmented. As a con example, taking for Σ (clayey ground) the form of a parallelepiped with dimensions 1 x 1 x 2 disposed as the figure indicates, of conductivity 10 times greater than the surrounding soil (assumed homogeneous), the perturbations of the curves become with depth imperceptible when the thickness of the covering soil be

It must be concluded then, that the deformations produced in the equipotential surfaces are local and have no effect at a distance.

The problem may be considered from another point of view. Instead of placing the same mass Z at different depths, multiply all the dimensions by the same number simultaneously; that is to say, the depth of Z, its breadth, its length, etc., at the same time. The entire figure, and especially the graph of equipotential lines, remains similar, the scale only being modified. Thus it appears that a mass Z', twice as deep as Z, will appear just as distinctly on the chart of potentials provided that all the dimensions of Z' are double those of Z (1), that the contacts are twice as far apart, and that the chart embraces a region doubled in all its dimensions.

The study of deep-lying heterogeneities is perfectly possible, if their dimensions are comparable with their depth.

From the practical point of view, two difficulties are encountered. The first, very simple, is that in taking in a large superficial area so as to observe the major figure of deformation produced by Z, one also takes in the diverse rocks of the region which are not homogeneous with the rest of the terrain. From this there result parasitic disturbances with no relation to Z, and masking its action.

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(1) The cubical contents will then be 8 times as great.

[illegible] be considered then, that the [illegible] the [illegible] [illegible] surfaces are local and have no effect [illegible]

The problem may be considered from another point of view. Instead of placing the same mass Z at different depths, [illegible] all the dimensions by the same number simultaneously; then [illegible], the depth of Z, its breadth, its length, etc., [illegible] times, the entire figure, and especially the graph of [illegible] lines, remains similar, the scale only being modified. Thus [illegible] that a mass Z', twice as deep as Z, will appear [illegible] on the sheet of potentials provided that (1) the dimensions of Z' are double those of Z (1), that any [illegible] as far apart, and that the excess of mass [illegible] in all its dimensions.

The study of [illegible] interdependencies [illegible] their dimensions are comparable with their depth.

From the practical point of view, two [illegible] considered. The first, very simple, is [illegible] area so as to observe the major figure of [illegible] by Z, one also takes by the [illegible] which may not homogeneous with the mass of the [illegible] [illegible] would perceive [illegible] with [illegible] regarding the motion.

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(1) The [illegible] will then be [illegible]

The second difficulty comes from the fact that the current is, in general, denser in the superficial crust than at depth (1 , p.33) if the disturbing mass is deeply buried it will react on the lines of current of feeble intensity only, therefore on but a small part of the total current. This perturbation will be but feebly reflected, then, in the superficial curves of equal potential, which, on the contrary, are in a zone of great current-density.

Whatever the difficulties may be, investigations to great depths should be possible for phenomena sufficiently marked; it is possible, even, to imagine studies of the terrestrial crust carried to depths of several kilometres. This should furnish interesting documents relative to zones at present unexplorable by the usual processes. Such experiments would not present great difficulties of realisation.

RESUMÉ.- The potential chart, with its numbered curves or its profiles, gives in a simple and concrete manner ALL THE ELEMENTS permitting the study, at the surface, of the distribution of a current within the earth. The transmission of electricity produces, it is true, phenomena other than the drop of potential. It forms for example, a magnetic field, and produces heat, but these manifestations can not be mesured in practice.

The difficulty resides not in the making of the graph, which is fairly easy, but in the geological interpretation of the disturbances noticed. For this it is necessary to follow complicated abstract reasoning, or else experiment in the laboratory upon an artificial soil containing in miniature, the heterogeneities being studied in nature.

To study a given geological problem, as the location of a conducting mass, the two contacts A and B may be displaced at will with the respect to the point being examined. This makes possible the attack of the problem in different ways, so as to obtain needed verifications.

In practice, the potential chart presents two regions particularly favorable. First, near the section of ground A, the other section B assumed at infinity, the equipotential surfaces are spherical in homogeneous soil and their numbering, in inverse ratio to the distance to A, is simple. This zone is convenient for the study of the cases concerned with the vertical conductivity of the soil. When, on the other hand, the heterogeneities to be studied are horizontal, the section median between A and B is made use of, where the equipotential planes are normally vertical and equidistant.

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(1) It will be seen on page 70 how to study this fact experimentally. The concentration of the current near the surface of the ground, which exists even in homogeneous soil because of the fact that the contacts are on the surface, is particularly important if the superficial crust has a conductivity superior to the deeper rocks. There is every reason to believe this to be a general fact, as the deeper rocks are more compact, less altered, and in consequence drier.

CHAPTER IV

METHOD OF OPERATION FOR THE MAKING OF A POTENTIAL CHART.

-:-:-:-:-:-:-:-:-:-:-:-:-:-

GENERALITIES.- To cause a current to pass in the ground between two points A and B (fig. 24), they are connected by an insulated line L to the two poles of a generator D (dynamo or batteries). The differences of potential caused in the ground by the passage of the current is studied by means of a movable line l, which includes a measuring apparatus g (telephone, galvanometer, voltmeter), and touches the ground with two electrodes e and e'.

To trace a line C of equal potential, the electrode e is kept on a fixed point M (fig. 25), and the soil is touched at different points P, Q, R, with the other electrode e', while observations are made with the measuring apparatus g. When this gives no indication (no sound in the telephone, no deviation of the galvanometer), it is because the point touched, Q, is at the same potential as M and forms a part of the curve C searched for. One may determine thus a sufficient number of points Q, Q_1, Q_2,.... at the same potential as M, and connect them topographically, to obtain the trace of the curve C upon the potential chart.

To number the curves C,C', C", it suffices to measure, utilising an arbitrary unit, the differences of potential between them. To establish a profile of potentials, or intensities of the field, the differences of voltage are measured which exist between a series of points in the ground, disposed for example along a line at equal intervals.

CHAPTER [illegible]

METHOD OF OPERATION FOR THE TRACING OF A POTENTIAL CHART

-:-:-:-:-:-:-:-:-:-:-:-:-:-

GENERALITIES.- To cause a current to pass in the ground between two points A and B (fig. 24), they are connected by an insulated line L to the two poles of a generator G (dynamo, batteries), the difference of potential created in the ground by the passage of the current is studied by means of a circuit which includes a measuring apparatus g (telephone, galvanometer), and touches the ground with two electrodes e and e'.

To trace a line C of equal potential, the electrode e is [illegible] on a fixed point M (fig. 25), and the soil is touched at points P, Q, R, with the other electrode e', which [illegible] are made with the measuring apparatus g. When this gives no indication (no sound in the telephone, no deviation of the galvanometer), it is because the point touched, Q, is at the same potential as M and forms a part of the curve C sought. One may determine thus a sufficient number of points Q, Q', [illegible] at the same potential as M, and connect them topographically to obtain the trace of the curve upon the potential chart.

To number the curves C, C', C'', it suffices to measure [illegible] at arbitrary units, the differences of potential between them. To establish a profile of potentials, [illegible]

of the field, the differences of voltage are measured [illegible]

These measures, easy to make with a potentiometer on direct current, as will be seen later, may also be carried out by the method described below in the note. This latter scheme lends itself easily to the use of alternating current, and works well with the theoretical notion of relative numbering described on page 19 (1).

CHOICE OF DIRECT CURRENT.- A priori, it is possible to use either alternating current, with a telephone g, as indicating device, or direct current, with a galvanometer for making the observations. I started by experimenting with alternating, produced either by a powerful induction coil or by a 1,000-cycle generator, as I was tempted by the simplicity and sensitiveness of the telephone as receiving apparatus.

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(1) The curve numbered 100 (curve 1 metre from A, if the distance AB is equal to 100 metres) and that numbered 0 (curve 1 metre from B) are connected by a line α β containing a high resistance R, of about 100,000 ohms, for example (fig. 26). There will then be established in this line a slight diversion of the current flowing from A to B, which will produce therein a drop of potential due to the resistance. The potential will fall along the line R, from the value 100 where the current enters, to the value 0, where it leaves the line. If x is a point in R, such that there are 35,000 ohms between α and x, and 65,000 ohms between x and β , its potential will have the value 65 with our relative units. To determine the potential of a given point M in the soil, M is connected by means of a line containing a measuring apparatus (telephone or galvanometer) to the point x, movable along R. x is then moved until the point of equilibrium of the system is reached. The potential of x, read from the resistancescale, gives the potential of M, which is equal to it. If 65 is the potential of M, 65 will be the number of the equipotential curve passing through M.

But I ran against the following fundamental difficulty. The telephone included in the movable line l (fig. 24), is affected not alone by the difference of potential between e and e' produced by the resistance of the soil to the passage of the current. To this action, the only one we are concerned with here, are added the phenomena of induction between the circuits A-L-B-ground-A, the inducing line, and the telephonic circuit e-l-e'-ground-e, in which a secondary current is induced. These actions are not at all negligible when compared with the drops in potential caused by the resistance of the soil, when taking into consideration the relative dimensions of the circuits and current-frequencies which it is necessary to employ to obtain a sound in the telephone. It seems to me that this complexity, thus introduced, hinders greatly the making of precise measures (1).

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(1) Herewith are a few complementary observations. Suppose the two extremities e and e' (fig. 27) of the line l touch the soil at two points of an equipotential curve C (from the point of view of the resistance effect), as is the case in homogeneous ground if C is a cicumference centered on A, the other contact being far off. It is clear that the circuits A-L-B-ground-A, e-l-e'-ground-e, have a notable coefficient of mutual induction, as the lines L and l are parallel. A telephone inserted in the line l would then give out a sound under the action of L, although from a resistance point of view, which alone interests us, e and e' are equipotential. This parasite induction depends on the magnetic permeability and the power of specific induction of the rocks and, for the given points A, B, e, e', on the directions followed by the two lines L and l. This action is more important the higher the frequency, and becomes preponderant for high-frequency currents.

It should be added however, that operating in the laboratory on artificial soil covering a small surface, the tracing of the equipotential curves may be done accurately enough with the telephone; but the lines L and l are of different length and disposed differently than they necessarily are in the field.

[illegible] the [illegible] of the [illegible] [illegible] of the curves [illegible] (Fig. 29), [illegible] of the difference of potential between a and a' [illegible] the resistance of the soil [illegible] in the [illegible] action, the only curves we are concerned with here, are [illegible] phenomena of induction between the circuits A-l-B-ground-, inducing line, and the telephonic circuit a-l-a'-ground- in which a secondary current is induced. These actions are [illegible] negligible when compared with the drops in potential caused by the resistance of the soil, when taking into consideration the dimensions of the circuits and current-frequencies which it is necessary to employ to obtain a sound in the telephone. It is so that this complexity, thus introduced, hinders greatly the making of [illegible] measures (1).

---

(1) Herewith are a few complementary observations. If, [illegible] the points a and a' (Fig. 29) of the line l touch the [illegible] points of an equipotential curve C (from the point of view of resistance effect), as in the case of homogeneous ground in circumference centered on A, the other contact being far, it is clear that the circuits A-L-B-ground-A, a-l-a'-ground-a, [illegible] [illegible] coefficient of mutual induction, as the lines L and l [illegible] parallel. A telephone inserted in the line l would then give a sound under the action of L, although from a resistance [illegible] view, which alone interests us, a and a' are equipotential. [illegible] [illegible] induction depends on the magnetic permeability [illegible] [illegible] specific induction of the rocks and, for the given [illegible] L, l, on the directions followed by the two lines L and l. [illegible] action is more important the higher the frequency, and [illegible] preponderant for high-frequency currents.

It should be added however, that operating in [illegible] artificial soil covering a small surface, the tracing of equipotential curves may be done satisfactorily enough [illegible] provided that the lines L and l are of different [illegible] [illegible] [illegible].

These difficulties disappear with direct current, which I have in consequence adopted. The direct moreover, presents the two following advantages. The galvanometer g (fig. 25), placed in the movable line, indicates the direction of the current traversing it, that is to say, the direction of the difference of potential existing between its two extremities e and e'. On touching the ground at the points P, Q, R, with movable electrode e', it may be determined whether the point touched is within or without the curve C, and which way it is necessary to move it to encounter that curve. This can not be done with the telephone, which is merely an indicator of the zero point. The second advantage, of greater importance, is that it is possible to place in the circuit 1 with the galvanometer, a volmeter, permitting the measure , by a method of equilibrium, of the difference of potential between the points e and e'. Thus quantitative measures may be made instead of merely qualitative observations. The numbering of the curves of equal potential and the establishing of the profiles of potential or intensity of field is greatly expedited, whereas with alternating current the more complicated method described in the note on page 35 must be adopted.

NON-POLARISING ELECTRODES.- The employment of direct current carries with it also certain causes of grave error, which must of necessity be eliminated.

On touching the soil with two metallic electrodes e and e', connected by a wire 1, a battery is formed of which the moist soil is the electrolyte (fig. 28).

[illegible] supplied. The direct method, however, presents [illegible] following advantages: the galvanometer gives, not only [illegible] movable line, indicates the direction of the current [illegible] that is to say, the direction of the difference of [illegible] between the [illegible] a and a' in reaching [illegible] of the points [illegible], with opposite [illegible] whether the point reached is [illegible] which may [illegible] necessary to [illegible]. This cannot be done with the telephone, [illegible] indication of the same point. The second advantage, of [illegible], is that it is possible to place in the circuit of the galvanometer, a voltmeter, permitting the measure [illegible] value, of the difference of potential between [illegible]. Thus quantitative measures may be made [illegible] qualitative observations. The numbering of the curves of [illegible] potential and the establishing of the profiles of potential [illegible] intensity of field is greatly expedited, whereas with [illegible] current the more complicated method described in the text on page 87 must be adopted.

NON-POLARIZING ELECTRODES.-- The employment of direct current with it also certain causes of error, which [illegible] it be eliminated.

In [illegible] the cell with two metallic electrodes [illegible] [illegible]

The electromotive force of this element, zero with two identical electrodes in ground perfectly regular, is greater the less similar are the two metallic contacts. In practice, even with inattackable metals (gold-plated rods), the electromotive force easily amounts to several hundred millivolts. The greater part of it comes from the polarisation produced, at the contact of the metal with the soil, by the current flowing in the line 1, a current which must necessarily exist in these measures. This electromotive force is considerable, but also quite variable, and in actual practice with metallic electrodes, measures at the surface of the ground can not be made closer than a hundred millivolts.

To remedy this defect, recourse must be had to non-polarising electrodes. I have used the following type. A tube T of copper (fig. 29), is inserted in a porous container V containing a concentrated solution (with an excess of crystals) of copper sulphate. Only the container touches the ground. The electrodes thus made do not become polarised, since the flow of current through them causes opposite reactions, and does not change the composition of the bodies in contact (1).

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(1) This is a question of approximate equilibrium, as the reactions are not established either instantaneously or exactly. For example, the concentration of the film of liquid on the cathode diminishes at first, due to the deposit of copper, and a certain time is necessary for it to recover its value by dissolving the excess crystals. These reactions should be reduced. which may be accomplished by augmenting the metallic surface upon which the electrolytic deposit is formed.

They do not give rise on the other hand, to appreciable, permanent electromotive forces, since they are nearly identical. Thus it is possible by choosing appropriate electrodes, to prevent such a force becoming greater than a millivolt, and to keep it at about this magnitude during prolonged experiments (1).

The differences of potential that may be measured correctly at the surface by this means are at least a hundred times smaller than those that can be measured with ordinary metallic electrodes. This permits the reduction of the power necessary for the circuit in the ratio of 10,000 to 1 (2). This big reduction makes possible the employment of storage batteries or light generators, an indispensable condition for practical work.

That is the advantage of using a tube instead of a rod. The surface of the copper utilised in our type of electrode exceeds 200 square centimetres. The currents observed yield several tens of microcoulombs. Thus it is seen how much the reactions are reduced, and with the zero-method, always utilized, the currents are now in one direction, now in the other.

Remark that, in this theory, notice is being taken of the electromotive forces between the electrolytes and the metals only, and not of those which may exist at the contact between the electrolytes (sulphate of copper and water absorbed from the ground in this case). There should result from this the existence of electromotive forces of polarisation, but the good functioning of the apparatus in practice shows their effect to be minimum. (See page 84).

(1) With properly porous earth a semi-permeable partition is formed, probably by the precipitation of copper oxide. As a result of this, the electrode immersed in water absorbs the liquid under the action of the osmotic pressure of the solution of copper sulphate. The porous containers dry out by evaporation, but moisten themselves again gradually in this manner, and may be used several months without recharging.

The joint between the receptacle and the stem is sealed with an adhesive poured hot. The tube is about 1 metre long. The electrode is used like a cane, and requires no special precautions, being solid enough.

(2) The power needed is Ri^2, R being the resistance of the earth-

[illegible] potential factor, unless they are nearly identical, [illegible] [illegible] by choosing appropriate electrodes, to prevent [illegible] [illegible] exceeding greater than a millivolt, and to keep it [illegible] [illegible] throughout long-period experiments (1).

The differences of potential that may be measured [illegible] at the surface of this earth are at least a hundred times greater than those that can be measured with ordinary metallic [illegible]. [illegible] permits the reduction of the power necessary for the [illegible] in the ratio of 10,000 to 1 (2). This big reduction makes [illegible] the employment of storage batteries or light generators, an indispensable condition for practical work.

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(1) With properly porous earth a semi-permeable partition is formed, probably by the precipitation of copper oxide. As [illegible], the electrode immersed in water absorbs the [illegible] the action of the osmotic pressure of the polarity of [illegible] plate. The porous containers dry out by evaporation, [illegible] themselves again gradually in [illegible], and may be used [illegible] without recharging.

The joint between the receptacle and the stem is [illegible] [illegible]; the tube is about [illegible] metres long, the [illegible] is used like a cane, and requires no special [illegible] [illegible].

ELIMINATION OF ERRORS DUE TO SPONTANEOUS POLARISATION AND TO EARTH-CURRENTS.- A second difficulty inherent in the use of direct current, is due to differences of potential which exist spontaneously between any two points of the earth, and which superpose their action on that of the current being studied. These differences are of two types. The first, constant and due to chemical or electro-capillary phenomena, are studied at the end of this book under the title of "Spontaneous Polarisation". The second are variable and due to the earth-currents which flow in all directions in the globe's crust (1). These two causes of error, which would be annoying in certain cases (long lines, proximity of pyrite deposits), are eliminated by opening and closing the principal circuit at regular intervals and paying attention, in the reading of the galvanometer, only to the deviations thus produced (2).

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circuit, and i the intensity of the current flowing through it. The drop of the potential between two given points of the ground is proportional to i. Reduce this drop to 1/100 of its value, and the result is a reduction of the intensity to 1/100 and of the power to 1/10000.

(1) In regular earth the spontaneous polarisation does not exceed about ten millivolts, but near a mass of pyrites may amount to 500 millivolts. Earth currents, extremely irregular, cause differences of potential usually smaller than 1 millivolt per 5 metres.

(2) Instead of interrupting the current it is better to reverse it. In fact, an inversion of the current reverses the direction of deviation of the galvanometer, which amounts to doubling the amplitude of displacement and hence the sensitiveness.

ELIMINATION OF ERRORS DUE TO SPONTANEOUS POLARIZATION AN[illegible] EARTH-CURRENTS.- A second difficulty inherent in the use of [illegible] current, is due to differences of potential which exist spontaneously between any two points of the earth, and which superpose their action on that of the current being studied. These differences are of two types. The first, constant and due to chemical or electro-capillary phenomena, are studied at the end of this book under the title of "Spontaneous Polarization". The second are variable and due to the earth-currents which flow in all directions in the globe's crust (1). These two causes of error, which would be annoying in certain cases (long lines, proximity of pyrite deposits), are eliminated by opening and closing the primary circuit at regular intervals and paying attention, in the reading of the galvanometer, only to the deviations thus produced (2).

[illegible] and I the intensity of the current flowing through the [illegible] the drop of the potential between two given points of the ground proportional, to I. Reduce this drop to 1/100 of its value, the result is a reduction of the intensity to 1/100 and of the power to 1/10000.

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(2) Instead of interrupting the current it is better to [illegible] it; an inversion of the current reverses the [illegible] deviation of the galvanometer, which amounts to doubling the amplitude of displacement and hence the [illegible] reading.

GENERAL INFORMATION CONCERNING THE APPARATUS.- Each of the contacts A and B is formed of several metallic pegs (1 to 8) driven into the ground, several metres apart and usually arranged in a circle (1). The resistance of the earth-circuit between them varies considerably according to the nature of the soil, especially the ground near the contacts. In a territory of average dampness it is usually between 30 and 300 ohms, varying most often between 50 and 100 ohms. A sufficient sensitiveness for observations of the potentials at a great distance from the contacts (several hundred metres), is obtained by passing a current of 2 to 5 amperes. For this the difference of potential at the generator should be between 100 and 200 volts (2), and the power delivered between 300 and 1500 watts, for example.

As source of current, I use either a gasoline-driven dynamo, or a set of storage-batteries.

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(1) Too closely placed, the pegs no longer give the sum of their conductivities. For pegs separated by at least 5 times their length, there is no great error in adding their conductivities. Put in another way, a contact formed by 5 pegs has 1/5 the resistance of that made of 1. This is true only in homogeneous soil. If there is a thin layer of earth overlying compact rocks the pegs destroy each other's action, and must be separated still more.

(2) A higher tension presents several dangers.

[illegible] APPARATUS, [illegible]

[illegible] several metres apart and [illegible]

[illegible] (Fig. 11). The resistance of the earth-[illegible]

[illegible] considerably according to the nature of the

[illegible] the ground near the electrode. [illegible]

[illegible] between [illegible] and 500 ohms, [illegible]

[illegible] sufficient [illegible]

[illegible] the potential at a great distance from the [illegible]

(several hundred metres), [illegible] obtained by [illegible]

[illegible] that the [illegible]

[illegible] should be between 100 and 200 watts [illegible]

[illegible] between 500 and 1000 watts, for example.

[illegible] source of current, [illegible] either a [illegible]

[illegible] of storage batteries.

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(1) Two closely placed, the pegs no longer give the [illegible] characteristics. For pegs separated by at least [illegible] times [illegible] length, there is no great error in [illegible] their [illegible] But in another way, a contact formed by a peg [illegible] resistance of that made of 1. This is true only [illegible] earth. If there is a thin layer of earth overlying [illegible] the pegs destroy each other's action, and must be [illegible] more.

(2) A higher tension presents several [illegible].

The movable line, with the non-polarising electrodes just described, at each terminal, is about 50 metres long, and is provided with a reel, for winding up the wire, on each of the copper stems of the two electrodes.

The galvanometer included in the line carries a scale and pointer sensitive to one division per microampere. It weighs about a kilogramme and may be carried on a cord over the shoulders. For making the readings, resting the galvanometer on one of the electrodes, held vertically, gives a sufficiently solid support.

The voltmeter is a very simple type, weighing about 300 grammes and attached beneath the galvanometer. It is arranged to give a reading of 200 millivolts by fractions of 10 millivolts.

With this ensemble it is possible to measure differences of potential as small as a millivolt, if the ground is not too dry. In the latter case the resistance of the movable line circuit becomes too high, and the deviations of the galvanometer are distinct only for several tens of millivolts.

ACCURACY OF THE RESULTS.- Within the limits of power and sensitiveness indicated, it is possible to trace equipotential curves with great precision over a wide extent of territory. Thus in favorable ground, such as clay not too dry, at a distance of 400 metres from the contact A (the other contact being far off), it is possible to determine by succesive steps, equipotential curves having a developed length of 2 1/2 kilometres, and to close the curves with an error of only a few metres (1).

---

(1) 100 metres from the contact A, the accuracy would be 16 time greater, since the intensity of the electric field which governs it, varies in inverse ratio to the square of the distance, and is hence 16 times stronger.

[illegible]
potential, if such exists, is about 50 metres long, [illegible]
person with a reel, for winding up the wire; on each [illegible]
[illegible] of the two electrodes.

The galvanometer included in the line permits easy [illegible]
moderate sensitive, of one division per microampere. It weighs
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In the latter case the resistance of the movable line circu
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tinct only for several tens of millivolts.

ACCURACY OF THE RESULTS.- Within the limits of possible
sensitiveness indicated, it is possible to trace equipotenti
curves with great precision over a wide extent of territo
Thus in favorable ground, such as clay not too dry, at a dis
of 800 metres from the contact A (the other contact being
it is possible to determine by successive steps, an equipote
curve having a developed length of 2 1/2 kilometres, and
trace the curves with an error of only a few metres. (1

[illegible]

The measures with the potentiometer of potential-differences between two points of the earth, are slightly less satisfactory, especially as it is difficult to maintain a constant current throughout a long experiment (1). Nevertheless it seems to me possible, taking everything into consideration, to avoid errors relatively greater than 1/10, or even 1/20. One may count on that order of precision in the establishment of the profiles of potential or of field.

SUMMARY.- The apparatus for studying the earth seem to be well developed. They permit the complete and precise study of the surface distribution of potentials over an area of several square kilometres around the contacts A and B. This requires the expenditure of about one kilowatt of power for the electric current.

I wish to add that these measuring instruments are adapted for the observation of all sorts of slight differences of potential in the ground. They would be especially suitable for the study of stray currents (tramways), or for that of earth currents.

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(1) The resistance of the contacts varies because of gaseous deposits on the surface of the pegs and the polarisation of the earth itself, as will be noted later on. The variations of the current would be of importance if the method described in the note on page 35 were employed.

CHAPTER V

APPLICATION OF THE POTENTIAL CHART TO THE STUDY OF TILTED STRATA.

-:-:-:-:-:-:-:-:-:-:-:-:-:-:-:-

The method of the graph of potentials which amounts to, as has been indicated, the study of the distribution of an electric current within the ground by means of measures made at the surface, has a variety of applications. Theoretically, it permits the consideration of all problems of earth-investigation in which rocks or minerals of unequal conductivity intervene. Practically, it is necessary to choose the cases in which it may render service.

From this point of view, I shall examine successively in chapters V and VI, two problems which I have experimented on in the field. They are, the study of tilted strata, and of the form of a buried conducting mass. For these two cases, I shall commence by studying the theory, then I shall describe the method of application adopted, and the results obtained.

The study of tilted strata which I am considering, presents a practical interest only when direct observations are rendered impossible by overlying soil. I suppose it to be a case, so frequent in nature, where there is a more or less thick cover of recent sediments, or where it is simply soil or debris, which hide the rock in place.

I shall first examine how to determine the horizontal direction of stratification, the direction of dip of the beds, and then how to follow a given stratum of rock from place to place, discover the faults and measure their movements.

DIRECTION OF STRATIFICATION.– Consider a terrain of tilted strata, composed of an alternating series of different rocks, schists and sandstones for example, as is the usual case in the older deposits. In its entirety, such a series acts like an anisotropic body, possessing an electrical conductivity greater in the direction of bedding than perpendicular to it. This holds no matter what the nature of the layers, provided that they have different specific resistances.

This property will be made clear in the consideration of the following extreme case. Alternating layers of insulating and conducting substances, such as tin-foil and waxed paper of a condenser, conducts electricity parallel to the sheets, but perpendicular to them it is an insulator. This anisotropy would remain, but less marked, if the sheets of paper were conductors, but poorer ones than the metallic layers (1). It may be added that the conductivities of the conducting leaves act together longitudinally (sum of the conductivities of conductors in parallel), whereas the resistance of the insulating leaves intervenes transversally (addition of the resistances of conductors in series).

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(1) The following is the strict reasoning for the case of a mass formed of two sorts of rocks of specific resistances ρ and $x\rho$, disposed so that the first is in the proportion of 1 (thickness of the beds), and the second in that of y. Under these conditions the average resistance ρ across the beds is: $\rho_t = \rho \frac{1+xy}{1+y}$. The average longitudinal resistance ρ_l is given by the expression $\rho_l = \rho \frac{x(1+y)}{x+y}$. The ratio of the resistances is $z = \frac{\rho_t}{\rho_l} = \frac{(1+xy)(x+y)}{x(1+y)^2}$. This function z of the two variables x and y represents the amount of anisotropy of the earth with respect to its electrical conductivity. It does not change in replacing x or by their reciprocals $\frac{1}{x}$ or $\frac{1}{y}$. This shows that only the

[illegible]

[illegible]

[illegible] resistances for [illegible] is the [illegible]

[illegible] deposits, is theoretically such a [illegible] with the [illegible] uniform body, possessing an [illegible] conductivity [illegible] the direction of bedding than perpendicular to the [illegible] no matter what the nature of the layers, provided they have different specific resistances.

This property will be made clear by the consideration [illegible] bedding extreme cases: alternating layers of insulating [illegible] conducting substances, such as tin-foil and waxed paper [illegible] however, conducts electricity parallel to the sheets, [illegible] perpendicular to them it is an insulator. This [illegible] ment, but less marked, if the sheets of paper were [illegible] poorer [illegible] than the metallic layers (1). It may [illegible] that the conductivities of the conducting leaves are [illegible] tically [illegible] of the conductivities of conductors in [illegible] whereas the resistance of the insulating leaves [illegible] (addition of the resistances of conductors in [illegible]

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(1) The following is the strict reasoning for the case [illegible] of two sorts of rocks of specific resistances [illegible] [illegible] so that the first is in the proportion of x (thickness [illegible]), and the second in that of y. Under these [illegible] the average resistance [illegible] across the beds is: [illegible]

The average longitudinal resistance [illegible] is given by the [illegible] [illegible]

[illegible]

[illegible]

It is evident that we are dealing here with an average property, and that a terrain can not be compared to a homogeneous, anisotropic body, except when considering a territory so large that the thickness of the individual beds is very small. In practice, the anisotropy is accentuated by the fact that the moisture, instead of being evenly distributed, is concentrated in parallel strata. That is the case for example, in limestones which include between their beds thin layers of wet clay.

Place a contact A in a stratified mass, supposing the stratification to be vertical, the other contact B having been placed at a great distance (fig. 30). The equipotential surfaces in the ground about A are no longer spheres, as is the case in an

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relative proportion of the two rocks and the ratio of their specific resistances, enter into consideration, and that it is of little importance whether the more resistant of the two is the more abundant or not.

The discussion of z demonstrates that this function is larger for a given value of x the nearer y is to unity. The maximum anisotropy of strata composed of two series of rocks is when these rocks are present in equal quantities (y=1). Under these favorable conditions, if the ratio x of the specific resistances has a value of about 6, the anisotropy z will have the value of 2. Thus it may be said that a mass made up of equal quantities of schist and sandstone for example, will be twice as good a conductor longitudinally as transversally, provided that the schists are six times better conductors than the sandstones. The same value 2, of anisotropy, is also realised in a region of parallel, water-filled fissures, provided the thickness of the fissures is 1 millimetre for 1 metre of rock (y=1,000), admitting that the conductivity of the water is 1,000 times that of compact rock (x=1,000).

isotropic substance. It may be shown that they are flattened ellipsoids of revolution about Ax as axis , which is perpendicular to the plane of stratification (1).

In considering, not the underground equipotential surfaces, but the superficial curves of equal potential traced around the contact A, it will be noticed that they are ellipses elongated in the direction of stratification. The elongation is greater the greater the anisotropy of the ground, that is to say the more accentuated the difference between the longitudinal and transversal conductivities of the beds. It is possible to make exact calculations, as is explained in the note below, and express the ellipticity of the curves in terms of the various parameters of the earth.

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(1) The demonstration that the equipotential surface in an anisotropic substance is an ellipsoid, is the same as that by which is established the fact that an isothermal surface about a source of heat (the source being reduced to a point), is an ellipsoid. In the present case the ellipsoid is one of revolution about Ax, by reason of symmetry. The short axis of the figure is parallel to the direction of least conductivity, following Ax, perpendicular to the stratification. It is therefore a flattened ellipsoid of revolution. It may be shown that the ratio of the larger axis a, to the smaller b, is equal to the square root of the ratio of the conductivities (reciprocal of the specific resistances) lengthwise and across; then

$$\frac{a}{b} = \sqrt{\frac{\frac{1}{\rho_l}}{\frac{1}{\rho_t}}} = \sqrt{\frac{\rho_t}{\rho_l}} = \sqrt{Z} \ ,$$

z being the function already studied.

The superficial equipotential curves, which are the traces on a horizontal plane of the flattened ellipsoids, are ellipses with axes a and b. Their departure from the spherical may be measured by the ratio $\frac{a}{b}$, which is equal to $\sqrt{Z}$; it is zero $(\frac{a}{b} = 1)$ when the ground is isotrope (z=1); it commences to be appreciable $(\frac{a}{b} = 1.1)$ when z=1.2, and becomes notable $(\frac{a}{b} = 1.41)$ if z attains the value 2.

If the stratification of the beds, instead of being vertical is merely inclined to the horizontal, the elongation of the ellipses is less pronounced, and disappears entirely when the layers are actually horizontal. In the latter case the curves are circles, as is required by the symmetry, and there is no cause moreover, to speak of the direction of stratification (1).

To summarise; when equipotential curves are drawn around a contact placed in stratified rocks sufficiently inclined to the horizontal, these curves are elongated in the direction of stratification, so that the observation of such deformation permits the discovery of the desired direction. In rocks of the same dip the elongation will depend on the properties of each particular terrain, and thus permits the characterising of the different beds.

When the strata are covered by thick sediments, in order to get accurate results, the equipotential surfaces should penetrate deep enough into the underlying rocks for the resulting deformation, to have a pronounced effect (fig. 32). Therefore it is necessary to experiment on large curves whose radius is double the thickness

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(1) If the strata make an angle of θ with the horizontal, the ratio between the axes of the equipotential ellipses is $\sqrt{1+(z-1)\sin^2\theta}$. When $z=2$ (case already considered) this ratio is $\sqrt{1+\sin^2\theta}$, which for $\theta=27°$ gives 1.1; the elongation of the equipotential curves is then appreciable. It should be noticed that these calculations are only approximate and that the curves are not exactly elliptical.

In the case of horizontal strata, the equipotential ellipsoids within the rocks have their axes of revolution vertical, as indicated in figure 31. The flattening is vertical.

of the covering. As already remarked, the latter intereferes more with the deformation studied, in this case the elongation, the better a conductor it is compared with the underlying strata, so that no precise rule can be given (1). In practice, the overlying sediments are often horizontal and present few irregularities in the relief; they then cause no deformations in the curves, but act merely as a more or less opaque screen.

As a result of the necessity of operating with curves of large radius, such as several hundred metres, only the general direction of stratification can be studied over a wide territory. That is not a great inconvenience in practice, as it is usually more important to view the beds in their entirety than to follow them in detail.

DIRECTION OF DIP.- Although I have not obtained any conclusive practical results from the study of the determination of the direction of dip, the following discussion will show the possibility of solving the problem.

Consider the contact A placed in tilted strata, as indicated in figure 33. If it were not necessary to take account of the plane of the surface which limits the terrestrial conductor, the surfaces of equal potential would be flattened ellipsoids of revolution about Ax, centered at A. The meridian of one of these ellipsoids would be the ellipse abc, with Aa=Ac. But the presence of the plane of the surface results in a deformation whose nature it is easy to note. As the superficial lines of current are necessarily horizontal, it follows that the equipotential surfaces, being normal to them,

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(1) The covering sediments are often argilaceous or aquiferous, and as a result are good conductors.

must "outcrop" vertically. The arc of the ellipse abc will be deformed into the curve a'b', so that Aa' < Ac'. What will be the resulting effect on the equipotential lines that may be traced about A? Instead of being ellipses centered at A and elongated following the stratification, they are curves such as a'dc'e, always elongated, but NOT centered at A. The direction of this decentering is the same as the direction of dip.

Thus the latter may be discovered by observing the former.

The practical difficulty encountered in such an attempt comes from the lack of homogeneity of the soil. It is possible to have a displacement opposite to the dip, occasioned by the proximity of a good conducting or insulating body, which deforms the curves in its vertical plane. This inconvenience is the more serious the feebler is the normal decentering of the curves by the dip.

When the existence of a drill hole S, permits the making of a contact deep in the earth, such as A, it is possible to discover the direction of the dip by the direction of decentering of the surface equipotential curves with respect to the point vertically above A. These curves are displaced as indicated in figure 34, which is self-explanatory. It should be remarked that the determination of the dip may be of practical interest, even after drilling the hole, because of the difficulty of discovering the correct orientation of the cores which, though they give the amount, do not give the direction of dip.

LOCATING A GIVEN BED OF ROCK.- Suppose the stratification vertical or nearly so, as the phenomena are the clearest in this case, becoming less and less distinct as the dip becomes less marked.

[illegible] plane of [illegible], [illegible] the [illegible] the [illegible] drill, so that each one, [illegible] will [illegible] on the equipotential line that may be traced [illegible] instead of being ellipses centered at B and elongated [illegible] direction, they are curves such as a [illegible] eccentric [illegible] of [illegible] centered at A. The direction of this eccentricity is [illegible] the direction of dip.

Thus the latter may be discovered by observing the curves.

The practical difficulty encountered in such an attempt [illegible] from the lack of homogeneity of the soil. It is possible to [illegible] displacement opposite to the dip, occasioned by the [illegible] good conducting or insulating body, which deforms the curves [illegible] vertical plane. This inconvenience is the more serious the [illegible] the normal deformation of the curves by the dip.

[illegible] the existence of a drill hole S, permits the making [illegible] deep in the earth, such as B, it is possible to [illegible] the direction of the dip by the direction of eccentricity of [illegible] equipotential curves with respect to the point [illegible]. These curves are displaced as indicated in Figure [illegible] is self-explanatory. It should be remarked that the [illegible] the dip may be of practical interest, even after [illegible] because of the difficulty of discovering the [illegible] the sound which, though they give the amount [illegible] direction of dip.

[illegible] BY THE USE OF [illegible].— Suppose the [illegible]

[illegible]

Assume the bed of rock to be studied, PQ (fig. 35), to be more resistant than the surrounding material, having for example double the specific resistance, which can very well be the case when a layer of sandstone is included between two beds of schist. In order to locate such a stratum it is possible to make use of two processes, one depending on the establishment of a profile of the electric field (page 23) and the other upon the refraction of the equipotential curves (page 26).

Operating by means of the electric field profile (fig. 35), the two contacts A and B are placed each at a great distance (1,000 metres to 2,000 metres for example) from the bed PQ, and on opposite sides thereof, the line AB being approximately perpendicular to the strike of the beds, as near as can be determined beforehand. The profile $\alpha\beta$ is then determined along the line AB, in the region where it is desired to discover the limits PQ; this profile, which will be a nearly horizontal line in homogeneous soil, presents a hump above the bed PQ. In fact, since the density of the current is very nearly constant throughout the entire region, the electric field is proportional to the resistance (1) and has, vertically above the sandstone, a value double for example, what it has above the schist. A simple inspection of the profile indicates the location searched for, the thickness of the stratum, and to a certain extent the relative value of the specific resistance of the rock of which it is constituted.

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(1) The problem is the same as that of the "Wall of Fourier". The lines of current are horizontal cylinders.

To employ the method of refraction (fig. 36), the contacts are placed at A' and B', the line A'B' being inclined at about 45° to the strike. Any line of equipotential is then traced in the region half-way between the two. In homogeneous ground the line will be nearly a straight one xy, perpendicular to A'B'. The bed of sandstone PQ, an insulator, refracts this line which is bent to form an S following xzty, so that it traverses PQ more obliquely than xy. Such a deformation is in practice very apparent on the ground, if the line is staked out and sighted along from one of the ends.

Nothing has been said of the covering that is supposed to mask the ground to be studied. Its action is, as usual, to suppress the phenomena to a certain extent. The bump on the profile will be flattened and lowered, the points of the refracted curves of equipotential will be rounded. In order for the deformations to remain perceptible, the difference between the specific resistances of the two rocks must be great enough, and the thickness of the layer PQ must be sufficiently large in comparison to the thickness of the covering. As always, the deep-lying phenomena are perceptible only on condition that they are pronounced.

It should be remarked that when the overlying material is irregular a great difficulty is introduced, as there are added to the perturbation due to the deep strata, those due to the surface material, and the two causes are extremely difficult to separate.

Actually, in the presence of irregularities in the overlying material, it is very easy to erroneously attribute an augmentation of resistance to deeply buried rocks, when in reality it comes merely from a dimunition of thickness of the covering, a better conductor than the substrata.

Note that the problem just studied is very general in the determination of the contact (supposed vertical or decidedly inclined) between any two rocks of different nature . Its solution is simple provided there is a sufficient difference (ratio of 1 to 2, for instance) between the specific resistances of the rocks, and provided that the covering that masks the contact is regular and relatively thin in proportion to the deposits being studied (page 28).

DETERMINATION OF FAULTS AND THE MEASURE OF THEIR HORIZONTAL MOVEMENTS.- Since it is possible to note the point of passage from other rocks to a given bed PQ by means of the profile of the electric field, to find the points where such a formation has suffered dislocation, it is but necessary to follow along it from place to place. However, the simpler way is to attack the question directly.

Suppose, for example, that the poorly conducting layer of sandstone PQ, intercalated in the schists, to be displaced to the position P'Q' by a fault F (fig. 37). The following is the method of finding the location of the fault and at the same time measuring the amount of movement. The contacts A and B having been placed on opposite sides of PQ, as for drawing the profile, an equipotential line xy is traced approximately above PQ. This line will follow

the layer in its various sinuousities along part of its length, so that at z it is itself subjected to the movement of the fault F (1). All that is necessary then, is to note the location of the break and its magnitude of displacement to solve the problem.

EXPERIMENTS IN THE IRON REGION OF CALVADOS.- In 1912, 1913, and 1914 I carried on a number of experiments in the region of Calvados that may serve as a practical illustration of a stratigraphical study, based on the above theoretical principles. The Silurian beds studied consist of the compact Armoricain Sandstones at the base; next above are the Calymene Schists containing iron ore (2) and having a thickness of about 100 metres; above are the layers of May Sandstones and the Upper Silurian, which are differentiated from the Armoricain Sandstones by alternating schists and sandstones. The Silurian beds are generally tilted and covered by horizontal Jurassic limestones; the relief of the surface is not pronounced.

Experiments at Fierville-la-Campagne.- These experiments were carried on in a region of relatively thick overburden, where the older strata wore well known through a series of drill holes. The Silurian is nearly vertical; the Jurassic, which is rather argilaceous, an unfavo-

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(1) For this it is necessary that the bed PQ be sufficiently thick, and that its specific resistance be notably different from that of the enclosing material.

(2) It consists of hematite and the carbonate of iron, and has not an especially high conductivity, so I think it plays no part in the experiments described.

rable condition (page 33), has a thickness of 60 to 90 metres.

The direction of stratification was studied by means of equipotential curves. In the upper part of figure 38 is given the profile of the beds in question, as determined in seven drill holes aligned perpendicularly to the strike. The lower part of the figure shows several equipotential curves, traced around three successive contacts A_1, A_2, and A_3, while the other contact B remained fixed at about three kilometres from the region being explored. From these curves may be drawn the following observations.

The contact A_1 is placed above feldspathic sandstones of the Lower Silurian. They produce the curves C_1 and C_1', which have a radius of 250 to 500 metres and are approximately circular (1). From that it may be concluded that the mass is sensibly isotropic, therefore but slightly fissured in the direction of stratification, without alternations of differently constituted layers.

The contact A_2 was placed near a drill hole which had encountered the Calymene Schists and the iron ore. The curve C_2 of 100 metres radius is nearly circular, because the corresponding equipotential surface does not penetrate far enough into the Silurian, and so is under the influence of the horizontal overburden. The curve C_2' commences to show a slight ellipticity, but this is clearly manifested only for C_2'' with an average radius of 400 metres,

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(1) The crosses marked on the curves show the points determined in the field, their positions were then noted in relation to the topography and finally, joined with a continuous curve in the drawing.

table condition ([illegible] 3), has a thickness of 50 to 60 metres

The direction of stratification was studied by means of equipotential curves. In the upper part of Figure 36 is given rofile of the beds in question, as determined by seven drill lined perpendicularly to the strike. The lower part of the igure shows several equipotential curves, traced around three uccessive contacts A_1, A_2, and A_3, while the other contact B was laced at about three kilometres from the region being rom these curves may be drawn the following observations.

The contact A_1 is placed above feldspathic sandstones of ower Silurian. They produce the curves C_1 and C_1', which have adius of 250 to 350 metres and are approximately circular. rom this it may be concluded that the mass is sensibly isotropic herefore but slightly fissured in the direction of stratification ithout alternations of differently constituted layers.

The contact A_2 was placed near a drill hole which had en tered the Calymene Schists and the iron ore. The curve C_2 of etres radius is nearly circular, because the corresponding quipotential surface does not penetrate far enough into the nd so is under the influence of the horizontal overburden. urve C_2' commences to show a slight ellipticity, but this is learly manifested only for C_2'' with an average radius of [illegible]

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(1) The numbers marked on the curves show the relative n the field, their positions were then noted in relation he topography and finally, traced with a [illegible]

much greater than the thickness of the Jurassic, which is about 100 metres. The curve C_2''' presents the same deformation, and its length is more than 3.5 kilometres. The region is therefore anisotropic, its maximum conductivity (that is to say the direction of stratification) being parallel to the long axis of the equipotential ellipses.

The contact A_3, over the Upper Silurian, also gives very definitely elongated equipotential curves C_3 and C_3', Therefore it may be concluded that the series is made up of beds of different nature (schists, sandstones).

These various results are in conformity with those given by the drills. Notably, the strike of the Silurian coincides very exactly with the direction of elongation of the curves.

Near the iron-ore deposits the contact of the Calymene Schists with the Armoricain Sandstones, which constitutes a very definite geological horizon, was searched for by refraction of the curves, and by the electric field profile.

The refraction of the curves was visible in the field, but was not very clear and might have escaped observation if the result had not been known beforehand.

The indications given by the profile of the electric field were more satisfactory. They are represented in figure 39. The two contacts A and B having been placed on opposite sides of the contact being searched for and at a distance of about a kilometre from it, three profiles were drawn, following the lines x_1y_1, x_2y_2, x_3y_3, parallel to the direction AB. In each one of these the field presents a marked discontinuity at the points P_1, P_2, and P_3,

corresponding closely to the juncture hunted for. The Armoricain Sandstones being of higher specific resistance than the schists, indicate their presence by a sharp rise of the field, that is to say of the rate of fall of the current, due to the resistance per metre (1).

It is interesting to note the rapidity with which these profiles may be established. With a personnel of two operators, two assistants, and a chauffeur, six and a half hours sufficed to place the line AB, pass the current and trace the three profiles, which determine, at three different points, the desired contact within about fifty metres. This point of view of the experiment presented an especial interest, for no less than seven drill-holes, distributed along a line some 1100 metres in length, were needed

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(1) I think that these variations of the electric field are due in a large part to the specific resistance of the Silurian rocks, the sandstones being more resistant than the schists or beds of sandstone and schist. It is certain that the changes in thickness of the overburden, better conductor than the Silurian, also play a role. It should be especially remarked that the Armoricain Sandstones, hard and compact, nearly always project into the Jurassic, thus accentuating their apparent resistance. For example, the thickness of the overburden as determined by the drills, was only 60 metres over the Armoricain Sandstones, but attained 90 metres over the schists. The two causes are therefore concordant in the present case. They ought to be, in general, because the resistance to erosion is determined by the hardness of the rock, which goes hand in hand with the compactness, and the latter determines the resistance to electricity. From the point of view of practical application, merely discovering the relief of ancient terrains, now covered up, would render service.

The profiles of the field were determined by using a movable line of 50 metres and measuring the number of millivolts between its two ends. The intensity of the current between the two contacts A and B, 2 kilometres apart, was 4 amperes.

corresponding closely to the structure looked for. The Armori

sandstones being of higher specific resistance than the

indicated their presence by a sharp rise of the field, that is

say of the rate of fall of the current, due to the resist

metre (1).

It is interesting to note the rapidity with which these profiles may be established. With a personnel of two operators as assistants, and a chauffeur, six and a half hours sufficed place the line AB, pass the current and trace the three profiles which determine, at three different points, the desired [illegible] ability about fifty metres. This point of view of the experiment presented an especial interest, for no less than seven drill distributed along a line some 1150 metres in length, were

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(1) I think that these variations of the electric field are due in a large part to the specific resistance of the Silurian, the sandstones being more resistant than the schists or [illegible] schistone and schist. It is certain that the changes in this the overburden, better conductor than the Silurian, also [illegible] role. It should be especially remarked that the Armorican slopes, hard and compact, nearly always project into the [illegible] thus accentuating their apparent resistance. For example, the mass of the overburden as determined by the drills, was [illegible] metres over the Armorican Sandstones, but attained 30 metres the schists. The two causes are therefore, concordant in the present case. They ought to be, in general, because the resistance to erosion is determined by the hardness of the rock, which goes hand in hand with the compactness, and the latter determines resistance to electricity. From the point of view of practical application, merely discovering the relief of ancient formations covered up, would render service.

The profiles of the field were determined by using [illegible] line of 50 metres, and measuring the number of millivolts between the ends. The intensity of the current between the [illegible] A, B, [illegible] to find the Calymene Schists, and with them the iron deposits. This uncertainty is explained by the difficulty in distinguishing between the cores taken from the May Sandstone, above the schists, and those from Armoricain Sandstone, below the schists.

Experiments at Soumont.- The region of Soumont, studied in 1913, is in the prolongation of a mine exploiting iron-ore of the Silurian age, and whose workings at the time had encountered a fault F, at the west end (fig. 40). The object of the research was to study the region beyond the fault with the idea of seeing to what extent the underground work would later, on passing the dislocation, verify the prognostications made by means of the electrical prospection.

The Jurassic covering has a thickness varying from 25 metres to 40 metres; it is generally not very wet (1), and but slightly argilaceous, so therefore not a good conductor, which is an advantage as its masking effect is thereby reduced. Beneath the limestone, the Silurian has a dip of 30 degrees only, a condition good enough for the determination of the contacts (page 50). The beds of Armoricain Sandstone, Calymene Schists P-Q, layers of sandstone and schist Q-T, and May Sandstone are superposed, as indicated in the cross-section. The corresponding outcrops beneath the Jurassic are drawn in dotted lines on each side of the fault, in the zone actually known through development work.

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(1) Except at the west of the fault, where moreover, it is thicker.

The potential chart gives rise to a number of observations.

The contact B having been maintained at a great distance (2.5 kilometres to the south), the equipotential curves were traced around the three centers A_1, A_2, A_3, placed respectively upon the Armoricain Sandstones, the Calymene Schists, the May Sandstones. The curve C_1 around A_1 is nearly circular, showing the isotropy of the rock and hence the absence of either water-fissures following the stratification, or of different beds alternating with each other. The curves C_2 and C'_2, around A_2, are elongated parallel to the elliptical form of one in anisotropic, stratified rocks. Other curves not shown confirm this evidence, analogous to that obtained at Fierville-la-Campagne.

The curve C'_2 presents a very clear decentering, the southern branch (left of the figure) being nearer the center A_2 than the northern. One might be tempted to deduce from it the direction of dip (page 49), which is to the north, as would be expected from the direction of displacement. This conclusion, though, is invalidated by the other curves (C_3 for example). In reality it is a local deformation produced by the bed of Armoricain Sandstones.

The curve C'_2 has a slightly rectangular shape, with a sharp break especially visible towards the south east. This bend is the result of the refraction on traversing the contact P between the Armoricain and the schists. The curve flattens itself against the contact in the resistant material (sandstone), and cuts the better conductor normally (schists) (page 26).

The [illegible] chart given from a [illegible] of observa-
[illegible] (current A having been sent along [illegible]
kilometres to the south), the equipotential curves were traced
around the three centres A_1, A_2, A_3, placed respectively on the
Armoricain Sandstone, the Callovian Schists, the May Sandstone.
The curve C_1 (around A_1) is nearly circular, showing the isotropy
of rock and hence the absence of either water-bearing fissures
or stratification, or of different beds alternating with each other.
The curves C_2 and C_3', around A_2, are elongated parallel to the
elliptical form of the [illegible] electrotropic, stratified rocks. Other
curves not shown confirm this evidence, analogous to that observed
at Vierville-la-Campagne.

The curve C_3' presents a very clear deformation, the southern
portion (left of the figure) being nearer the vertex A, than the
northern. One might be tempted to deduce from it the direction
of dip (page 40), which is to the north, as would be expected
the direction of displacement. This conclusion, though, is con-
tested by the other curves (C_3 for example). In reality it is
deformation produced by the bed of Armorican sandstone.

The curve C_3'' has a slightly rectangular shape, with the
lines especially visible towards the southeast. This was the
result of the refraction on traversing the contact between
Armorican and the schists. The curve flattens itself against the
contact of the resistant material (sandstone), and [illegible]
conductor normally (schists) (page 40).

The same phenomenon was studied methodically farther west, by means of a series of curves R, R', R", R'" carried obliquely across the contact, following the method explained on page 52 The two contacts, placed about 1600 metres apart, were located on opposite sides of the juncture of the two rocks. The refraction is very evident: inflection at the contact, path oblique across the resistant bed, normal across the conducting bed. The curve R', which closes towards the south-east, shows the S deformation particularly well.

The contact P' of the sandstones and schists west of the fault, is thus located approximately by means of the refraction (1). Although the real position of this contact is not yet known exactly, the work so far done shows that the determination is well-nigh exact (2).

Finally, the same contact was studied by means of profiles of the electric field traced along the lines x_1y_1 and x_2y_2, with the electric contacts situated one to the north, the other to the south. These profiles are indicated by the hatched sections along $\alpha_1\beta_1$ and $\alpha_2\beta_2$ (3). They show a very clear increase of the

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(1) It should not be forgotten that when the beds have a dip of 30° the contact is poorly defined in horizontal projection.

(2) It should here be noted that the May Schist-Sandstone contact, which I have not studied very much, is not sharply defined by the resulting phenomena. This is due to the presence of a sandy-schist transition stage between the two . Moreover, the May Sandstones are slightly schistose.

(3) Distance between the contacts, 1800 metres; intensity, 4 amperes; scale of ordinates of the profiles, 100 metres (at the scale of the drawing) for 80 millivolts drop of potential per 50 metres of line.

electric field on crossing the Armoricain Sandstones (page 51). From this it may be deduced that the contact should be found towards p_1 and p_2, which corresponds well with the other indications of the chart and with the underground discoveries.

The amount of horizontal movement of the fault was evaluated by the method described on page 53 . Thus the curve DD' was traced, it being made up of two lines D and D', displaced about 50 metres with respect to each other, which should be the amount of strike-slip. The underground workings reached the fault several months after these experiments, and verified exactly this conclusion. The curve C_2' shows a deformation just like that of DD'. It should be noted that the points of inflection are a little to the south of the location indicated for the fault. This comes, I think, from the fact that the fault is not vertical, having a dip towards the west, so that the point where it is encountered in the underground workings is west of the outcrop.

This schematic reasoning has a weak point already indicated. It is concerned solely with the Silurian and neglects the overburden, which is supposed to be perfectly regular, hence without influence except to render the phenomena less distinct. Perhaps this hypothesis is rather inexact, and one might argue, paradoxically, that it is only these variations in thickness that cause the perturbations in the equipotential curves.

CONCLUSIONS.- The experiments made in the Calvados show a way in which electrical prospection seems capable of rendering

service in the study of regions not containing good conducting ores. It is only applicable if the strata are tilted, and the indications are clearer the more nearly vertical are the beds. This is of advantage, since it is precisely in such a case that the drill-holes need to be placed with the greatest precision. It must be remembered: 1 - The facility with which the average strike of strata over a wide area may be determined; 2 - The possibility of following from place to place a known and conveniently chosen geological horizon.

It may be that the regularity of the Normandy Silurian, the considerable thickness of its beds, and the nature of the overburden constitute particularly favorable circumstances. I think that they are not isolated. Other and analogous cases should be found in which the thin covering material would permit the rapid planning of a drilling campaign (1).

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(1) In 1914, in the Orne, I studied a similar problem. No drill-hole has as yet been put down however, to verify the predictions made with the aid of electrical prospection.

CHAPTER VI

STUDY OF THE FORM OF A CONDUCTING BODY (1)

-:-:-:-:-:-:-:-:-:-:-:-:-:-

PRINCIPLES.- Suppose that a point of a conducting ore is known either by outcrop, any sort of exploration work, pit, gallery, or drill. Let it be, for example, a body Z of pyrite (2) touched by a drill-hole S at a point A, as is indicated in the plan and elevation of figure 41. In order to determine the approximate form of the deposit, the process is as follows: The contact B having been placed anywhere at a distance, the ore at A is chosen as the second contact and the equipotential curves are traced at the surface of the ground, above A (3). Because its conductivity is much superior to that of the surrounding ground, the ore-body is at about the same potential throughout its entire mass. The equipotential surfaces envelope it fairly closely therefore, and their outcrops, following the lines C_1, C_2, are centered on the deposit (4) and follow its form more or less exactly.

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(1) I am leaving aside here the study with contacts OUTSIDE the deposits, which are carried on following the principles explained in the generalities and apropos of the perturbations produced in the potential chart by a conducting mass (page 24).

(2) Or a mass of magnetite, pyrolusite, etc.

(3) If there are underground workings, the observations, which will permit the determination of the form of the equipotential surfaces in the ground, can just as well be made in them.

(4) The center is, in principle, the point where the deposit comes nearest to the surface (translator's note, == apex).

CHAPTER [illegible]

STUDY OF THE FORM OF A CONDUCTING BODY (1)

-.-.-.-.-.-.-.-.-.-.-

PRINCIPLES.- Suppose that a deposit of a conductive ore is known either by outcrops, any sort of exploration work, etc., [illegible] it. Let it be, for example, a body X of pyrite (2), cut by a drill-hole S at a point A, as is indicated in the plan and elevation of figure 41. In order to determine the approximate form of the deposit, the process is as follows: The contact B being placed anywhere at a distance, the one at A is chosen as the second contact and the equipotential curves are traced at the surface of the ground, around A (3). Because its conductivity is much superior to that of the surrounding ground, the deposit is at about the same potential throughout its entire mass; the equipotential surfaces envelope it fairly closely; therefore their outcrops, following the lines C_1, C_2, are centered on the deposit (4) and follow its form more or less exactly.

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(1) I am leaving aside here the study with magnetic [illegible] [illegible], which are carried on following the principles [illegible] to the generalities and errors of the perturbation caused in the potential chart by a conducting mass (page 64).

(2) Or a mass of magnetite, pyrrhotite, etc.

(3) If there are underground workings, the observations permit the determination of the form of the equipotentials in the ground, and just as well as [illegible].

(4) [illegible]

To determine which of the equipotential, concentric curves coincides most nearly with the apparent horizontal contour of the mass, two cases are distinguished. If, by means of work already done, one point M of the horizontal limit is known, a curve C_2, passing near the point vertically above M,is chosen as the apparent contour, admitting that it encloses the deposit at a practically constant distance (1). If nothing is as yet known, measures of potential above the mass are made. For example, a profile of potentials is laid out along a line xy, which cuts across the curves diametrically. As is represented in figure 42, the values V of the potential are laid out as the ordinates, with the surface of the ground as zero. Thus a profile such as $\alpha\beta$ is obtained. The body Z being sensibly equipotential, it corresponds in the profile to a flat portion terminated by two zones where the potential falls rapidly, due to the considerable resistance-drop which the passage of the current produces in the surrounding poorly conducting material. The limit of the deposit is taken at the points where this sudden drop is produced (2).

The preceding is the simplest case, where the mass Z is nearly horizontal and distinctly limited by vertical sides. In general, the deposits have a more or less steep dip and taper out in ragged fringes without a well-defined horizontal contour.

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(1) As the curve tends to center itself on the contact A it will be farther from the mass at Q, in the neighborhood of A, than at P, in the region opposite.

(2) In practice, the profile of potential is not traced, but a profile of the field H (or fall of potential per metre). Thus a curve $\alpha'\beta'$ is obtained, in which the two maxima characterise the limits of the deposit.

The potential-chart is then subject to more doubtful interpretation. Take the simple case of a dipping lenticular mass Z (fig. 43). The profile of the potentials will not be symmetrical, having a more abrupt slope on the side X than on the side of the dip, y. As a result, the equipotential curves will be more closely crowded at x than at y. Evidently, in practice it would be impossible to limit the mass precisely down the dip.

The practical difficulties come from:-

1. The relief of the surface, which may cause notable perturbations.

2. Lack of homogeneity of the soil.

3. Accidents in the mass, such as faults, quartz dikes, etc., which interrupt the electric conductivity, although the deposit is continuous from the miner's point of view.

EXPERIMENTS AT BOR (SERBIA).- In order to verify these diverse theoretical conclusions, I made some experiments in September 1913, upon the mass of cupriferous pyrite at Bor.

The ore is very special, the copper being usually found in the form of covellite with some enargite, no chalcopyrite, about 45 % of pyrite and 40 % of silica. The mass is in a large vein of andesite; in plan, as shown by the exploration done, it is roughly elliptical (200 metres long and 100 metres wide) and dips towards the south-east, but has not been explored down the dip. The overburden, made up of a quartz gossan, is very irregular because of the discovery work which has been carried on in it. Its thickness is about fifty metres, where the earth has not been dug away.

Conductivity of the Mass.- By using the two following methods, I found out that the body acts as a conductor buried in a mass of non-conducting material.

The contact A having been made in the mineralized mass Z (see fig. 44, which is purely schematic), and the other contact B having been placed at a great distance, by means of measures of potential along the gallery G, I assured myself that the entire mass was sensibly equipotential. Except in the immediate neighborhood (a few metres) of A, the drop of potential in a length of 50 metres was less than 1 millivolt, although the current expended was more than 10 amperes. On coming to the incaseing ground the drop of potential, due to the resistance, was about 100 millivolts per metre, which shows that the specific resistance of the rock was at least 5000 times greater than that of the ore, with its average composition in the deposit (1). Nevertheless, no precise measure was made to permit the fixing of an upper limit for this figure.

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(1) To obtain precisely the relation between the specific resistances ρ and ρ' of the ore (average composition) and the rock, a profile of the electric field $\alpha\beta$ must be established along a straight gallery G, traversing the ore-body. The field, which has a value nearly uniform either in the ore or in the country-rock, passes brusquely from one value to the other on crossing the contact, as shown by the dotted line in figure 45. Since the density of the current is sensibly uniform throughout the region, the field is proportional to the specific resistance. The ratio between these resistances is therefore equal to the ratio between the two values of the field on opposite sides of the contact, $\frac{\rho}{\rho'} = \frac{H}{H'}$.

The second process employed consisted in tracing equipotential curves on the surface above the deposit and noteing that these curves remained the same when the contact within the conducting mass was displaced. This takes for granted the line of reasoning followed on page 63. The method is evidently very sensitive, because of the precision with which the equipotential curves may be traced. It has the inconvenience of giving no quantitative value of the ratio between specific resistances of the ore and the rock.

Figure 46 indicates the results obtained by placing the contact successively at A_1 and A_2, and tracing around these two positions two curves C_1 and C_2, with a common point 0 of departure. The curves C_1 and C_2 are but slightly different (1).

It should be added:

1. The region between A_1 and A_2 is lean, so a poor conductor.
2. The point of departure 0 was taken in a region where the equipotential curves were crowded together, and the invariability of form of the curve would have been better assured if the point had been chosen where the fall of potential was less rapid.

To summarize, the ore-body of Bor acts as an entirety whose conductivity is very great compared with that of the surrounding rock.

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(1) To determine the deformation of a curve of fixed origin 0, resulting from the displacement of the contact from A_1 to A_2, when the earth is homogeneous, it is sufficient to consider the portion of the arc diametrically opposite to 0 (fig. 47). This arc undergoes a displacement M_1M_2 which is twice that of A_1A_2. In the case of the ore-body of Bor the amount of this deformation is 50 times less than it would be in homogeneous ground.

An objection can be made with regard to this evidence. The deposit, although but slightly worked on the level where the contacts were made, is nevertheless pierced by galleries which cause a slight oozing of water where they cross the fissures. This water is charged with copper sulphate, which may notably increase the conductivity. I do not think so, in view of the slight importance of these infiltrations, but only an experiment upon an unexploited deposit could avoid this criticism (1).

Form of the Lens.- The hatched area of figure 46 indicates the horizontal section of the lens of ore, containing the two contacts; the dotted border corresponds to the extreme limits known (in September 1913) and still in ore; the solid line gives the contact with the country-rock. It seems that the dotted line is not so far from the sterile ground, according to knowledge gained in other levels.

As may be seen, the curves give a reasonhable approximation of the form of the deposit. One should not be surprised at a few discrepancies. They come, in the first place, from the fact that the body is not a cylindrical solid with vertical sides and a rigorously defined horizontal contour; the southern limit of the ore at a level lower than the one considered passes noticeably

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(1() The presence of rails in the galleries plays no great part in the distribution of the current, at least if the contact is not placed near one. A theoretical discussion would show it, and an experiment verify it very easily. It is established that the potential of the ground does not vary appreciably on approaching any point in a track, which would not be the case if the rails were conducting a current of any size.

outside of the drawn contour. In the second place the ground is very rough. The contacts A_1 and A_2 were situated about seventy metres below the level of the ground, and the latter presents differences in level of fifty metres between the east and west borders. The surprising thing is, that under these conditions it is possible to get so faithful a representation of the apparent contour in horizontal projection.

Conclusions.- In short, from these experiments it seems possible to discover easily (in one or two days) the approximate form of a conductor of which a point has been reached, by determining the equipotential curves around this point as contact. These conclusions would in any case be invalidated if it were to be established that, either the real form of the Bor deposit escaped me, or that this mass constitutes an exceptionally favorable case that could not be found again, because of the nature of the ore and that of the encaseing country-rock.

I wish to add that the indications thus given refer to the form of the deposit in horizontal plane only, and that the vertical disposition (depth of the shoots and their locations), escapes discovery entirely, or nearly so, which is a grave disadvantage.

CHAPTER VII

DISTRIBUTION OF THE CURRENT AT DEPTH IN THE GROUND

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One of the fundamental questions which intrudes itself in the application of the methods already described, is to know to what extent a region of nearly regular geological composition will behave as though effectively homogeneous from the point of view of its electrical conductivity.

This latter is but due to the absorbed water. There are then three levels to be distinguished: first, a thin superficial bed, dry or damp according to the season and the climate, and hence of variable conductivity; below, a zone situated near the water-table and the very wet regions, so regularly a conductor; farther down, the zone of deep-lying rocks, but slightly fissured, compact and in general of high resistance, except in the water-fissures.

In consequence the current should not be distributed at depth according to the law in homogeneous ground, but be localised near the surface and circulate there as though in a flat conductor. Everything depends on the thickness of this plate. Is it very thin, thus masking completely the underlying material, or is it thick emough to include the regions interesting to prospect? In all probability, there are great differences between the various sorts of cases, and each one should be examined separately.

Herewith are two processes which I applied in attacking methodically the problem of the distribution of the current at great depths.

Underground Observations.- I hunted for the form of the equipotential surfaces within the ground by taking a contact M, in a gallery or pit, and determining the location of an equipotential point M' at the surface (fig. 48). In all the cases studied (1), I found that the equipotential surfaces penetrate vertically at the surface, and are practically spherical, if not too distant from the contact A.

These observations are favorable to the hypothesis of homogeneous ground at depth, or, more precisely, are not opposed to such an hypothesis. Too absolute conclusions should not be drawn from them. Ground made up of beds more and more resistant as one goes deeper, should give rise (2) to surfaces in the form of flattened bowls, as one penetrates into the layers, but this deformation is probably not strongly accentuated.

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(1) Figure 49 summarizes the observations made in this connection in the coal mines of Saint-Eloy. The subterranean point M, for which the corresponding point of same potential M' was hunted on the surface, was taken in a gallery 220 metres below the surface. The contact A occupied successively the three positions A_1, A_2, A_3, the other contact B remaining far away. For A_1, situated exactly 220 metres below M, the point of equal potential M_1' was found 225 metres from A_1; therefore the equipotential surface is probably nearly spherical, as shown in the drawing, without an appreciable flattening. For A_2 the distances are: A_2M=290m.; A_2M_2'=350m. Here there is a slight departure from the spherical. For A_3 the figures are: A_3M=360m.; A_3M_3'=400m., which corresponds to a deformation in the same direction.

(2) The following reasoning, based on the phenomenon of refraction of the surfaces when traversing the juncture of two different media, permits the understanding of why the deformation acts to flatten the curves. In fact, when the equipotential surface V passes from one substance (1) into another which is a poorer conductor (2), the refraction which it undergoes bends it towards the plane of separation P, as indicated in figure 50.

A succession of beds (1), (2), (3),....... of increasing resistances as the depth increases, will then transform a surface spherical in homogeneous earth, such as S, into the form of a flattened bowl, such as S' (fig. 51).

It should be added that it is as easy to trace the profiles of potential in the underground galleries as it is at the surface.

Profile of the Field.- The method of establishing a profile of the field between the two contacts A and B seems more efficacious. Figure 52 gives such a profile:

1. In the case of an indefinite homogeneous conductor (curve C_1).

2. In the case of a conductor in the form of a thin plaque (curve C_2).

The minimum field, at the center of AB, was chosen as unity for the drawing of the two curves. These are very different (1). To know in any real case which of the two hypothesis will apply the more closely, it is sufficient to determine the profile of the field, always taking as unity the value of the field at the middle point, and then deciding which of the two curves C_1 or C_2, corresponds closer to the one obtained.

If the contacts are so disposed that the distance AB is clearly less than the thickness of the conducting layer of ground, the profile will have the form of C_1; if, on the contrary, AB is much

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(1) The equations for the curves are

$$C_1 \quad \frac{dV}{dn} = 1250 \left(\frac{1}{r^2} + \frac{1}{r'^2}\right)$$

(r=distance to A; r'=distance to B; r+r'=AB=100)

$$C_2 \quad \frac{dV}{dn} = \frac{2500}{rr'}$$

greater than that thickness, the profile will resemble C_1 only in the neighborhood of A and of B, and at a certain distance from these points it will follow the shape of C_2, with of course a transition point between the two forms. The place at which this change occurs should be at a distance from the contacts roughly equal to the thickness of the conducting layer. Thus we have a method of determining whether the propagation of the current in the ground is deep or superficial, and too evaluate approximately, in the latter case, the thickness of the conducting layer involved.

The experiments along this line thus far carried out are insufficient, and they should be pursued further.

MEASURE OF THICKNESS OF A SUPERFICIAL CONDUCTING BED.- As complementary to the preceding considerations, and to give an example of how varied may be the applications, consider the method of measuring the thickness, h, of a conducting bed, in the simple case where the layer is homogeneous and rests upon insulating ground (1), as would be realised in the case of regular and moist alluvium resting on a compact rock (fig. 53).

The contact B having been placed at a considerable distance, two measures are madeof the electric field: one at C, at a distance r from the contact A, small in comparison with the thickness h of the layer; the other at D, at a distance r' from A, large compared with h.

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(1) As usual, it is a question of relative amounts. The underlying rock needs merely to be resistant in comparison with the superficial layer.

Near A the equipotential surfaces are approximately spheres centered at A, and Ohm's law, applied between two equipotential spheres of radii r and r+dr, gives

$$(1)\quad \frac{dV}{dr} = \rho \frac{i}{2\pi r^2 h} ,$$

wherein ρ designates the specific resistance of the conducting bed and i the intensity of the current expended,

Far from A the equipotential surfaces have the form of vertical cylinders whose axes pass through A. The same law of Ohm leads to the following formula for the drop of potential dV' between two cylinders of radii r' and r'+dr'

$$(2)\quad \frac{dV'}{dr'} = \rho \frac{i}{2\pi r' h} .$$

Dividing (1) and (2) member by member, and simplifying, the following expression is finally obtained for the value of the thickness (1) looked for:

$$h = \frac{\frac{dV}{dr}}{\frac{dV'}{dr'}} \; \frac{r^2}{r'} .$$

I have not as yet had necessity, by means of this formula, to make any practical determination in the field.

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(1) If measures are made at C and D of the drops of potential ΔV and $\Delta V'$, not over short distances, but over considerable lengths Δr and $\Delta r'$, the formula is more complicated, and becomes

$$h = \frac{\Delta V}{\Delta V'} \; \frac{r^2\left(1+\frac{\Delta r}{r}\right)}{\Delta r} \; \text{Nap. log}\left(1+\frac{\Delta r'}{r'}\right).$$

C H A P T E R VIII

INDUCED POLARISATION

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This chapter treats of a subject very different from those already considered, namely of differences of potential existing temporarily in the earth following the passage of an electric current. The greater or less conductivity of the rocks enters into the phenomena studied in a purely accessory manner.

The object I had in mind, in undertaking these experiments, was to locate deposits of metallic conductors, such as pyrite, pyrolusite, or galena, by observing the phenomena of polarisation caused on their surfaces by the passage of a direct current through the ground.

In fact, a mass Z of metallic conductivity buried in the ground acts like a bit of metal submerged in water. If a direct current, i, is passed between the two contacts A and B, as indicated in figure 54, it decomposes the water in the enclosing rocks. There results a deposit of hydrogen on the part P where the electricity enters the mass, and a deposit of oxygen over the entire region Q where the current leaves the ore.

The polarisation of the ore-body is thus produced, that is to say, the latter transforms itself into a veritable storage battery. As soon as the electrolysing current i is turned off, this battery discharges itself through the ground (dotted arrows), P acting as the positive pole and C as the negative one. Observations at the

surface of the potentials due to this discharge of current (1) should permit the locating of the conducting mass Z. The entire work is done with the usual apparatus already described (movable line, non-polarising electrodes, galvanometer and voltmeter).

Let it be said at once, however, that I have not as yet obtained really satisfying results in the field, but the difficulties which I encountered, on the other hand, enabled me to make two interesting observations.

The first, to be studied in the following chapter, is that all pyrite deposits are spontaneously polarised and act permanently like great batteries, without there being any necessity to make use of an electrolysing current. These forces of spontaneous polarisation therefore hide, in the case of pyrite, the phenomena of induced polarisation.

The second observation was of the following fact. When a current, i, is passed through any given ground between two contacts A and B in the direction from A to B (fig. 55), on interrupting the current, by opening the circuit L, there remains for a certain time a residual difference of potential in the ground, the region around A remaining positive with respect to that around B, just as though the line L were continuing to discharge a small current in the original direction. These residual differences of potential do not exceed a fraction of a volt. They disappear progressively of themselves, the speed of dying out being the faster the shorter the length of time the current i was flowing. The same thing happens

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(1) These differences of potential should be very weak. In fact, the total electro-motive force of the battery should not exceed 1.5 volts, and of this, a fraction only would be perceptible at the surface of the ground in the form of resistance-drop of potential of the discharging current.

when using pure water instead of wet ground, provided that convection currents do not interefere by mixing the different parts of the liquid.

These phenomena are not caused by the <u>surface</u> polarisation which takes place at the contact of the metallic pegs with the moist earth (1), but in a polarisation of <u>volume</u> involving the entire mass of electrolyte around the contacts. There is not a simple diffusion in the ground of the oxygen and hydrogen disengaged at the metallic pegs, because the phenomena is established instantaneously at a great distance; but the appearances are comparable to those that would be given by a battery containing gas thus formed. There seems to be a movement of ions which creates a disymmetry between the two regions surrounding the electrodes A and B. The residual action is more intense and prolonged the stronger and more prolonged was the current that provoked it, which appears to imply an electrolytic action.

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(1) This polarisation of the pegs operates as follows: when, instead of interrupting the circuit L, the source of the current i is disconnected, there is established in the line a current i', opposite in direction to i. This discharge of current i' produces differences of potential in the ground, due to the resistance, and the neighborhood of A appears <u>negative</u> with respect to B, which is just the reverse of the phenomena actually studied.

CHAPTER IX

SPONTANEOUS POLARISATION

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GENERALITIES.- Studying the lens of pyrite of Sain-Bel in 1913, I noticed that near it the soil presented, spontaneously, easily measurable differences of potential (1). This observation has

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(1) Since then I have hunted for observations that may have been made on this subject by other authors. The first studies of electrical phenomena in metallic deposits were conducted from 1830 to 1848 by R.W. Fox, in the veins of Cornwall, using the decidedly rudimentary technique known at that period (See especially: Henwood, "Sur les courrants electriques observés dans les filons de Cornouailles", Annales des Mines, 3rd series, vol. 11, 1837, p. 585; Reich, "Notiz über elektrische Ströme auf Erzgängen", Annales de Poggendorff, vol. 48, 1839, p. 287). Then there must be mentioned the very interesting observations collected by Carl Barus in 1880 at the Comstock Lode and at the Eureka Mine, which should have lead their author to important results if he had not been handicapped by the imperfect apparatus in use at that time. Finally, in the laboratory, a number of experimenters have studied the polarisation of various minerals in contact with different electrolytes. Among the works of this nature the most recent and most remarkable is that of Mr. R.C. Wells: "Electric Activity in ore deposits", U.S. Geological Survey, Bulletin 548, 1914. This publication contains a detailed bibliography of those works anterior to it.

To summarise the status of the question in 1914, I quote the last paragraph of the Preface to the work of Mr. R.C. Wells, written by Mr. George Otis Smith, Director of the Geological Survey:

"It should be emphasized that results thus far obtained afford no adequate basis for any method of electric prospecting nor any promise of development of such a method by connecting the presence of ore deposits with readily or definitely measurable electric activity. Nevertheless, the data here presented are believed to possess value in the broader investigation of ores, for even feeble currents might exert a directional influence on ore deposition, and chemical conditions, even at a distance, might be a factor in determining mineral association".

been confirmed since, for pyrite deposits, by an entire series of investigations (1) in the course of which no exception was encountered. The fact may be considered as absolutely general as far as pyrite and pyritic minerals are concerned.

For veins of galena, differences of potential are observed when the ore contains pyrite (as at Villemagne, in the Gard); but it seems that the phenomenon does not exist, or at least is too feeble to be clearly observed, when pyrite is entirely lacking, as is the case for the veins in the Penarroya district (mines of Villanueva de Duque).

I think that mispickel should be active, but have not had the occasion to make conclusive experiments in the field along that line. Magnetite and pyrolusite give no results (2), and it is the same for the non-conducting ores (blende, carbonates, etc...). Iron buried in the ground (pipes, rails) on the contrary, causes phenomena analogous to those resulting from masses of pyrite (3).

From this simple enumeration it may be concluded that the metallic conductivity and oxidation of the ore seem to be two essential factors in "spontaneous polarisation".

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(1) Here is the list of the principal pyrite deposits studied: Sain-Bel, Rhône (pure pyrite); Vaux, Rhône (magnetic pyrite); Saint-Félix-de-Pallières, Gard (pyrite with galena and blende); Herrerias and Campanario, Andalousie (cupriferous pyrite); Bor, Serbia (pyrite and covellite).

(2) The experiments were made upon the magnetite of Normandy and upon the oxides of Romanêche (Saône-et-Loire).

(3) Thus it would be possible to find buried pipe-lines, as though they were pyrite deposits, except that the action is not so clear.

DESCRIPTION OF PHENOMENA OBSERVED.- Herewith is the manner in which these things are observed in a large lens of pyrite, such as that of Sain-Bel, of Bor, or of Andalousie.

When the soil is touched with a movable line containing a voltmeter and galvanometer and terminated by two non-polarising electrodes, on approaching the deposit regular differences of potential will begin to be noticed several hundred metres away from the ore (300 metres for example), the electrode nearest the lens being nearly always negative to the other. The difference of potential thus observed increases as one advances, and may even attain several millivolts per metre (1). In the region above the ore the potential is nearly constant, then after traversing the deposit new differences are observed but in the opposite sense from the preceding.

The results of these potential measures, usually made along a line, are easily translated into a profile in which the distances are laid out as abscissae and the potentials as ordinates (page 23). The maximum of separation between the summit of the line and the distant points may be as great as 500 millivolts. It is very easy to trace the equipotential lines, and it will then be observed that they follow approximately the outlines of the deposit, surrounding a center of negative potential just above it.

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(1) The most marked effect noticed in this connection was a difference of potential of 400 millivolts in a line 100 metres long, making an average of 4 millivolts per metre (northwest border of the ore-body of Bor).

Moreover there is frequently, in the wetter part of the deposit, a center of positive potential of small extent and naturally surrounded by the curves. Generally, the equipotential lines of spontaneous polarisation close well, with about the same precision as the measures are made (several millivolts). They seem to be as stable as the profiles, that is to say that one finds them unchanged on making the measures over again after a certain length of time.

To summarize, making use of the topographical image again, a dome of negative potentials is found above pyrite deposits, of which it is easy to trace the profiles, or the curves of equal altitude. The summit of this dome and its general form coincide in general with those of the ore-body.

As far as the apparatus used is concerned, note that the galvanometer should be sensitive and that the non-polarising electrodes are indispensable. In fact, the differences of potential to be measured are very small, and an error of more than ten millivolts becomes notable. Moreover, the phenomena are permanent and it is impossible to eliminate the parasite electromotive forces, as may be done by reversals of the current when studying conductivities (page 40) (1).

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(1) Nor is the action of earth currents avoidable. The equipotential curves of spontaneous polarisation are not exact except in the case of curves drawn with reversed current. Also, one gets greater errors of closure.

Figure 56 represents the potential-chart of spontaneous polarisation, with the equipotential lines and the profiles, as established at Sain-Bel in 1913. The hatched area indicates the deposit at level 106, about 100 metres below the average level of the surface, which is very rough in this region. It will be noticed at once that taken all together, the curves of equal potentials envelope the ore-body very closely. This coincidence would be more striking by taking into account the higher parts of the deposit, where the exploitation is within 40 metres of the surface (1). The vein presents a certain departure from the vertical, which causes the wider separation of the curves from the mineral at the right.

The central part of B is very important. It has a length of 1 kilometre and a width of 500 metres, which means that an area of more than 50 hectares is involved in these phenomena. The difference of potential between the distant points and the negative center attains a value of about 220 millivolts, as is evident from the profile (2) established along the line xy across the deposit. The curves C_1 and C_2, traced at the levels γ_1 and γ_2 of the profile, are 50 and 100 millivolts below the summit of the potentials.

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(1) Except at the two extremities A and D where the ore comes much nearer the surface, causing the two little centers of independent polarisation A and D, with closed equipotential curves.

(2) In the profile of potentials, 1 metre at the scale of the drawing represents 2.3 millivolts.

Below the mine there is a road passing over a pile of waste 15 metres high, made up of transported earth and detritus of all kinds.

It should be noted that a profile of potentials traced along this road shows no anomalies. This proves that the nature of the immediately underlying soil plays no part.

At the extremity E of the deposit a positive center appears, a region where there is a difference of potential, but where the interior of the curves is positive to the exterior, a reversal of the general rule. I have not got definite enough information to interpret this, but it seems to me that the positive regions usually correspond to faulted portions, near the lenses of pyrite, wherein there is a strong circulation of water .

The positive center E gives 75 millivolts difference of potential from the distant points.

EXPLANATION OF THE PHENOMENA.- In order to understand the mechanism of spontaneous polarisation, I conducted the following experiments in the laboratory.

If a piece of pyrite is immersed in water and the liquid is explored with non-polarising electrodes, differences of potential will be noticed around the mineral. There are, in the water, negative and positive centers with respect to the pyrite (1).

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(1) A negative center is one where the potential of the water is negative to a distant region where the potential is taken as zero. In a negative center, then, the current flows towards the mineral , thus giving in the electrolyte a resistance-drop in the desired direction. For a positive center the reverse holds true.

[illegible] the mine there is a road passing over a hill [illegible] [illegible], made up of transported earth and detritus [illegible]

It should be noted that a profile of potentials [illegible] [illegible] road shows no anomalies. This proves that the nature of the immediately underlying soil plays no part.

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[illegible] the potential [illegible] [illegible] region where the potential [illegible] [illegible] the deposit [illegible]

Negative ones correspond with oxidized zones. Notably, as soon as the pyrite is attacked with an oxidizer (HNO_3, CrO_3, Cl, $KMnO_4$), the point attacked becomes negative.

A bit of iron or of zinc plunged in water gives rise to the same phenomena, as well as a fragment of pure galena, which leads me to suppose that deposits of this latter mineral should also be active under suitable conditions.

These experiments may be completed by making a battery with pyrite electrodes, thus permitting the accurate measurement of the electromotive force. Two bits of mineral A and B, connected by a wire C, are placed in the two compartments of a receptacle with a porous dividing wall (fig. 57). One of these compartments A contains an oxidizing agent, such as a weak solution of $KMnO_4$, the other contains pure water. It will be observed that in the wire the current flows from A to B, and in consequence from B to A in the electrolyte. Therefore the electrode A is the positive pole of the battery, according to the usual convention. However, one should not lose sight of the fact that when the measures are made in the electrolyte (as is the case at the surface of the ground), the portion of A which is submerged in the liquid and towards which the current flows, appears to be a region of negative potential, and B is then the positive center.

Note that the direction of the current is such as to liberate hydrogen where the pyrite is in the process of being oxidized, producing thus an effect opposed to the cause.

As a result of these experiments I think it possible to adopt provisionally the following explanation for the spontaneous polarisation of ore deposits. A body of pyrite buried in the

[illegible] positive [illegible] A,
[illegible] with solutions [illegible]
[illegible] attracted because negative.

[illegible] of iron or of [illegible] in water give a [illegible]
[illegible] as well [illegible] of pure [illegible]
[illegible] that [illegible] the latter [illegible]
[illegible] positive particles.

These [illegible] may be [illegible] by making a battery
[illegible], then [illegible] the [illegible]
[illegible] the electrodes A and B, [illegible]
[illegible] in the [illegible]
[illegible] wall [illegible], one of these [illegible]
[illegible] water, and [illegible] solution
[illegible] contains pure water. It will be observed that
[illegible] the current [illegible] from A to B, [illegible]
[illegible] the electrolyte, therefore the electrode A is the
[illegible], according to the usual convention.
[illegible] not lose sight of the fact that since the [illegible]
[illegible] the electrolyte and in the case of the [illegible]
[illegible] in the [illegible]
[illegible] Fig. [illegible]
[illegible] the positive current.
[illegible] the direction of the current is such [illegible]
[illegible] where [illegible] is the [illegible]
[illegible] in the [illegible].
[illegible]
[illegible]

earth is always more or less humid, and acts as though it were immersed in water (fig. 58). The upper part A is in the process of being oxidized, more intensely where there are workings which permit water to infiltrate. The deeper part B, on the contrary, rests intact. Because of this disymmetry the deposit forms a battery which causes current to flow from B to A in the surrounding ground, the circuit being completed from A to B in the mineral. The summit A, towards which the current flows from beneath, thus constitutes a center of negative potential, the differences of voltage being due the drop resulting from the resistance of the soil.

From this hypothesis there should be, at depth and surrounding B, a positive region from which the current emanates. The proof of the existence of such a region, which seems easy enough to establish with underground workings properly disposed, has not yet been established in spite of several efforts (1). On the contrary, the observation of positive centers above faults serving as water veins through the deposit, is actually a confirmation.

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(1) It is necessary to call attention to the fact that a cross-cut encountering the ore at G (fig. 59), is hardly serviceable, because of rapid oxidation of the mineral as soon as it is exposed to the air, this producing a secondary negative center. In fact, all the attempts in drifts or cross-cuts across the ore-bodies have shown negative potentials on approaching the mineral. Do not forget that the presence of rails in the tunnels of a mine always a little humid, cause grave perturbations by reason of the differences of potential resulting from the iron itself.

In fact, these currents of water act as excellent conductors, uniting depth and daylight by a path which may serve as an electric circuit, the electricity on arriving at the surface flowing out in all directions, thus creating a positive center. The potential at depth has been brought to the surface by the liquid conductor, so to speak.

In the case frequently encountered, of an ore-body containing pyrite and galena at the same time, there is added the action of a battery made up of water-pyrite-galena-water, with dry contact between the galena and the pyrite. The current goes from the pyrite to the galena by the dry contact. Electrolysis of the water then liberates hydrogen on the pyrite, with the result that, conforming to the law of moderation, the effect (deposit of hydrogen and reduction of the pyrite) is opposed to the cause of the current (oxidation of the pyrite).

I do not think that the many little batteries oriented in all directions, contained in a deposit wherein the two minerals are intimately mixed, as is the usual case, could give rise to a general current clearly observable. On the other hand, an exceptional case might be encountered where a column of pyrite is in dry contact with galena at its base, these two mineral masses giving rise to a battery of considerable importance in humid soil.

Note that the action of the little pyrite-galena elements is to oxidize the galena, thus carrying over to this mineral a part of the oxidizing action that would otherwise be concentrated on the pyrite. In other words, galena should be more easily oxidized in a mixture with pyrite than when alone.

[illegible]

[illegible] galena [illegible] which may serve as a [illegible] perpendicular to the [illegible] of the surface [illegible] thus creating a positive center. The potential [illegible] has been brought to the surface by the liquid [illegible] to appear.

In the case frequently encountered, of an ore-body where pyrite and galena at the same time, there is added the action of a battery made up of pyrite-galena-water, with contact between the galena and the pyrite, the current [illegible] the galena by the dry contact. Specimens [illegible] which [illegible] liberated hydrogen on the pyrite, with the [illegible] conformity to the law of [illegible], the [illegible] and reduction of the pyrite) is opposed to the [illegible] current (oxidation of the galena).

I do not think that the very little batteries [illegible] containing a deposit wherein the two [illegible] are intimately mixed, as in the usual case, would give [illegible] current clearly [illegible]. On the other hand, [illegible] be [illegible] where a column of pyrite is [illegible] will [illegible] at its base, these two mineral [illegible] a battery of considerable importance in itself [illegible] that the action of the little pyrite-galena [illegible] the [illegible], thus carrying over in [illegible] the oxidation [illegible] would otherwise be [illegible] should be [illegible]

These remarks apply evidently to all complex ores made up of different minerals possessing metallic conductivity.

Since there is a permanent current in the ground, the chemical reactions should face a continual consumption of energy (1). Let us see if the thing is possible, as far as the order of magnitude is concerned, for a lens of pyrite. The intensity of the total current expended by a deposit is unknown, but having given the observed drops of potential and the volume of ground involved, it is possible to estimate it roughly at about an ampere, which corresponds to an expenditure of 100,000 coulombs per day. We are ignorant of the exact chemical reactions of this complex battery, at least those producing the current. Take as a basis merely the oxidation of iron, and admit that to oxidize a gramme-atom of iron, which is trivalent, 300,000 coulombs are necessary. Under these conditions there will be oxidized each day 0.3 gramme-atoms of iron, or about 40 grammes of pyrite. To maintain the curront, a consumption of 15 kilogrammes of mineral is then necessary per year,or 15 metric tons per thousand years. It is easy to conceive that the oxidation of the gossan, or "iron-hat" found on pyrite deposits, has furnished without difficulty

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(1) I am leaving aside the other sources of energy which, to me, do not seem to intervene appreciably. It might be imagined for instance, that one is confronted with a thermal couple, functioning under the action of the difference of temperature between the base and the surface.

[illegible] metallic conductivity.

Since there is a permanent current in the ground, it [illegible] reaction [illegible] constant [illegible] (1). [illegible] is possible, on [illegible] of magnitude [illegible] of pyrites [illegible] the total current produced by a deposit is unknown. [illegible] the observed drops of potential and the volume of [illegible], it is possible to estimate it roughly at about [illegible] which corresponds to an expenditure of 100,000 coulombs [illegible] most important of the direct chemical reactions of this [illegible], at least those producing the current, take as a [illegible] the oxidation of iron, and apply them to [illegible] consumption of iron, which is [illegible], 300,000 [illegible]. Under these conditions there will be oxidation [illegible] consumption of iron, or about 60 [illegible] of pyrites, [illegible] a consumption of 10 kilograms of [illegible] necessary [illegible] year, or 15 [illegible] be supposed that the [illegible] of the [illegible] by the [illegible] deposits, [illegible] without [illegible]

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(1) [illegible]

the energy necessary to maintain a permanent current throughout the geological ages.

PERTURBATIONS DUE TO VARIOUS PHENOMENA.- The differences of potential found at the surface of the ground do not all come from the presence of pyrite or other mineral. There is a whole series of other causes, which may be grouped under three heads:-

1. Earth-currents
2. Chemical reactions, or more generally, the contact of substances of different chemical composition.
3. Electro-capillarity.

Earth-Currents have their origins at a distance, are perhaps even cosmic (1), they are very irregular, and it is impossible to separate exactly, in the difference of potential observed between two points of the ground, the part due to the resistance-effect of such a current. Only a prolonged study of the entire question could eliminate the perturbations by reason of their very irregularity. However, in the researches I am considering, where the operations are carried out over short lines and but a small area of the ground, the errors committed under this head are not grave, the drop of voltage produced by the earth-currents seeming not to exceed a maximum of 0.2 millivolts per metre. If the experiments

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(1) I am leaving aside the stray currents produced by trolley cars, etc.

are carried out, on the contrary, over lines several kilometres long, it will be the differences of earth-current potentials that will predominate and mask the other phenomena (1).

In chemical actions or effects of contact, must be classed the case of pyrite buried in the ground. The other chemical actions of the soil, it seems to me, give rise in general, solely to phenomena much less marked. In fact, numerous measures in the field have revealed no appreciable difference of potential between two disimilar rocks, as for example granite and limestone. These studies are still incomplete, however (2).

The following experiment shows that the acidity or salinity of the water plays a role. Let A and B be two containers filled with water and united by a siphon (3) (fig. 60); let e and e' be two non-polarising electrodes of copper sulphate, mounted upon a voltmeter G and touching the liquid in A and in B. It will be observed that if the water in B is acidified, or better, if any electrolyte (KOH, NaCl) is dissolved in it, B becomes negative to A; the difference of potential may be as great as 100 milli-

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(1) It appears that up to the present, in the study of earth-currents, nobody has been impressed with the necessity of employing non-polarising electrodes at the ends of the wires.

(2) As a matter of detail, note that peat may present very clear negative centers, with total differences of potential as great as 200 millivolts and a fall of 2 millivolts per metre. This polarisation is perhaps linked with the oxidation of pyrite contained in the peat, because it was noted at the points studied, that there were abundant deposits of yellow iron oxide.

(3) Porous walls should be avoided for the separation of the liquids, because of the electro-capillary phenomena that they produce.

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(1) It appears that up to the present, in the study of earth-currents, nobody has been impressed with the necessity of employing non-polarizing electrodes at the ends of the wires.

(2) As a matter of detail, note that peat may present very intense positive centers, with total differences of potential as great as 300 millivolts and a fall of 8 millivolts per meter. This chemical action is perhaps linked with the oxidation of pyrite scattered in the peat, because it was noted at the points of the centers there were abundant deposits of yellow iron oxide.

(3) [illegible] should be avoided [illegible] siphon [illegible]

volts for moderate concentrations (1). In consequence, it is possible that sulphuric waters produced by the oxidation of the minerals may enter into the spontaneous polarisation of pyrite deposits.

Electro-Capillarity is important.- It is known that the circulation of any electrolyte, such as water, through a dielectric in the form of a powder, as sand for example, causes differences of potential in the direction of flow or opposite thereto, according to the nature of the bodies in contact. This effect, which depends essentially on the nature of the elements involved, is inversely proportional to the conductivity of the electrolyte and proportional to the pressure provoking the flow, at least if one may speak of pressure, which is notably not the case in capillary absorption by a porous body.

The following experiment is easy to make. A small cup of porous earth A is placed in a bath of water (fig. 61). It becomes wet on the inside because of the capillary ascension of the water. It may then be observed, always with non-polarising electrodes, that a difference of potential of several tens of millivolts exists between the interior of A and the water in B surrounding it. Evidently such phenomena intervene continually in the ground, with the resulting risk of error in the study of polarisation.

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(1) Note that this measurement does not give the electromotive force of the contact of the two liquids: water-acidified water, but the total electromotive force of the entire chain: copper sulphate-water-acidified water-copper sulphate. The result then depends on the nature of the electrodes e and e'.

Water circulation may have two origins. It is due either to gravity (infiltrations in faults, along beds of river sand), or to capillarity (ascension (1) to the surface where the moisture escapes by evaporation (2)). Gravity does not provoke, it seems, notable differences of potential because the pressure operating is too weak, seldom exceeding a few metres of water (3), but there are,nevertheless, capillary actions. Herewith are a few observations on this subject. If one electrode is immersed in water and the other touches the neighboring ground, the water appears positive (capillary ascension as in the case

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(1) Except in the case of rain, when the absorption takes place from above downwards.

(2) The water which evaporates from the ground is therefore electrified, and of opposite sign from the sand through which it rose. If, in evaporating, this water carries along part of its charge, the ground should become electrified and a difference of potential established between the earth and the vapor in the atmosphere (condensed or not). Perhaps these electro-capillary phenomena play an important part in all questions of atmospheric electricity.

(3) See Quincke "Annales de Poggendorff", 1850-1860, on the differences of potential produced by the pressure of filtration. From the figures given, which are especially notable for quartz sand, there could be differences of potential of only a few millivolts. My experiments on filtration through sand, although very incomplete, confirm the slightness of the phenomenon.

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[illegible] (1) at the surface where the relative
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(3) See Quincke "Annales de Poggendorff", 1860-1880, on the differences of potential produced by the pressure of filtration. From the figures given, which are especially notable for [illegible] sand, there could be differences of potential of only a few millivolts. My experiments on filtration through sand, still very incomplete, confirm the slightness of the phenomenon.

of the cup). Along sea-beaches a difference of several millivolts may be observed between the potential of the high and low portions of the sand-beds (1). Between a field freshly cultivated, where evaporation causes a rapid ascension of deep-lying water, and one not worked, there is normally a difference of about ten millivolts.

To summarize, differences of potential of electro-capillary origin play an important role. They necessitate much care in the study of the polarisation of deposits. Their principal inconvenience is to limit the sensitiveness of the method of study, and to prevent in practice the registering of slight differences of potential.

APPLICATION TO PROSPECTING.- Observation of the phenomena described seems, at first sight, to be susceptible of rendering signal service in the prospection for various pyritic minerals. Their measurement requires only light apparatus, easy to handle; it is extremely rapid; the action of the deposit is distinguishable at a considerable distance, at least for those that are of importance. Thus it is possible to search the ground thoroughly,

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(1) The sea-water, in my experiments, was negative to the sand. This change of sign from that usually observed might be due to the fact that the water was salty, or that the movement of water in the sand is towards the sea (gravity), and not due to evaporation (capillary ascension). The differences of potential are small, because of the good conductivity of the water. Two puddles of sea-water in the rocks always show a difference of potential between them of about ten millivolts, for example. The measures appear concordant and correct.

hectare by hectare, with a speed that I calculate to be, in favorable ground, at least 20 hectares per day, with two men, a prospector and an assistant. As the work leaves no trace, absolute secrecy may be maintained, even with respect to the assistant, who does not see the instrument readings. Finally, where the region is indicated as interesting, it may be more thoroughly studied by means of the method of conductivities, which should permit, with or without drilling, the formation of an idea of the importance and form of the deposit. All of this constitutes a tempting method of prospection. Experience will show how much of this first optimism is justified.

Let us discuss at once two grave objections that may be made at present.

It seems that pyrite grains disseminated in the rock may show polarisation (1). It is thus that I encountered a long band of ground, giving in places notable differences of potential (200 to 300 millivolts), and which appeared to correspond to a series of schists strongly pyritized, although the exploration work has not yet shown them. How can one distinguish such a zone, lacking in interest for the miner, from a large deposit, compact and of great value. Certainly the general action of the phenomena, the accentuation of polarisation at certain prominent points where the infiltration of water promotes the oxidation of the pyrite, should serve as guides. Nevertheless, the hazard remains.

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(1) I have not yet succeeded in realising, in the laboratory, the equivalent of pyritized ground showing polarisation. Moreover, I do not see any satisfactory explication for such a phenomenon.

[illegible]

[illegible] conditions of [illegible], in the [illegible]

[illegible] this method may be maintained, even with respect to [illegible] who have not [illegible] importance [illegible]. This [illegible] the method is indicated as interesting, it may be [illegible] studied by means of the method of [illegible], could permit, with or without drilling, the formation of an [illegible] the importance and form of the deposits. All of this [illegible] method of prospection. Experience will show [illegible] optimism is justified.

[illegible] discuss at [illegible] groups of [illegible] that [illegible] to support.

[illegible] pyrite [illegible] polarisation [illegible]. It is [illegible], [illegible] in [illegible] potable differences of [illegible] ([illegible] millivolts), and which appeared to correspond [illegible] of schists strongly pyritised; although [illegible] has not yet shown them, [illegible] the [illegible] in interest for the miner, [illegible] of great value. Certainly the general [illegible], the accentuation of polarisation at [illegible] where the facilitation of [illegible] the [illegible] the pyrite, would serve as [illegible].

[illegible]

The second objection concerns the slight activity which even a virgin deposit, near the surface, might show. All the measures I made (Sain-Bel, Bor, etc.) were upon lenses already being exploited, or at least known by several galleries. It was, moreover, a condition necessary to enable me to know if the results of my observations agreed with the reality. In a mine, even slightly worked, there are always infiltrations, and these cause an energetic oxidation (1). If this is the only cause of the phenomenon it is probable that the polarisation of new deposits, the only ones that interest a prospector, is of little importance, and risks falling to the magnitude of experimental error (10 to 20 millivolts). This is the more likely the deeper the mineral is buried in the ground, and the more compact and impermeable is the surrounding rock.

I summarize my present opinion as follows. Although at the beginning of the attempts I thought to appreciate easily the importance of a deposit by the amplitude of its polarisation (2), today I fear that a virgin deposit, or even one already developed, signals its presence by but localised polarisation near its summit, and that will be perceptible only when the mineral comes near the surface (10 metres, for example) at least

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(1) Sufficiently violent, sometimes, to cause heating and combustion of the pyrite.

(2) The difference between the large lens of Sain-Bel and the little, near-by masses, is striking from this point of view.

[illegible] a single deposit near the surface, might once, [illegible] the [illegible], [illegible], etc., were upon lenses already [illegible], or at least known by borings galleries, it was, however, a condition necessary to enable me to know if [illegible] of my observations agreed with the reality. In a mine, actively worked, there are always infiltrations, and these an energetic oxidation (1). If this is the only cause of [illegible] it is probable that the polarization of new de[illegible] the only ones that interest a prospector, is of little im[illegible] and risks falling to the magnitude of experimental error [illegible] to be eliminated). This is the more likely the deeper the mineral is buried in the ground, and the more compact and impermeable is the surrounding rock.

I summarize my present opinion as follows. Although at the beginning of the attempts I thought to appreciate easily the importance of a deposit by the amplitude of its polarization (2), today I fear that a single deposit, or even one already developed, signals its presence by but localized polarization very [illegible], and that will be perceptible only when the [illegible] near the surface (10 metres, for example, [illegible]

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(1) Sufficiently violent, sometimes, to cause heating and combustion of the pyrite.

(2) The difference between the [illegible] [illegible] [illegible] [illegible] [illegible] means, in [illegible] [illegible]

if the porosity of the soil and the position of the water table do not favor oxidation. Finally, one risks confounding a pyritic terrain with a deposit of massive pyrite.

For the exploration of ancient workings, prospecting by polarisation would be excellent.

EVIDENCE OBTAINED AT SAIN-BEL IN 1920.- At the moment of giving the order to print this work, I had occasion to make the following important observations on the Sain-Bel vein.

At the southern extremity of the deposit (region A on the map, page 76 of the French text), underground work, conducted during the war, encountered a small lens of very good pyrite at 40 and at 50 metres below the surface. This coincides exactly with the curves of spontaneous polarisation, determined in 1913, and which present at this point a small negative center. The mineralisation is 50 metres long. Its thickness, not yet known, seems not to exceed several metres. The pyrite probably comes very close to the surface, but is hidden by the overlying soil, and so is invisible.

These underground workings are two years old. They have not in the least modified the polarisation of the ground, which was identical in March 1920, to what it was in 1913. The water seeping in through the galleries plays no sort of role, then.

In resumé, these proofs show the perfect possibility of discovering, by observation of spontaneous polarisation, a virgin deposit of pyrite, provided that it is not too deep.

FINAL CONCLUSIONS

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It is not yet possible to be sure of the services that the various methods of prospection already described are capable of rendering in their present form. Certain pronouncement can not be made until after many experiments have been followed by exploration work.

Nevertheless, the great adaptability and wide application should be noted. There is every reason to suppose that, among the innumerable problems presented by the mining industry, hydraulic researches and studies of the earth's crust, certain ones will present themselves in a favorable manner to be solved conveniently. I add, that the studies I have undertaken since November 1919, and which are not explained here, have strengthened my previous optimistic opinion.

Electrical processes will probably never give certain and precise results. Their domain is to furnish more or less clear indications, serving as guide for the orientation of researches by drill, shaft or gallery. This role of auxiliary should have its interest. Underground work gives exact information upon the composition of the rocks traversed, but it does not explore, so to speak, more than a sole point of the deposit, and the deductions that are made therefrom have the disadvantage of being extrapolations; its execution is slow and costly. Electric prospection seems to present the opposite properties: lack of precision, but

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Electrical processes will probably never give certain and precise results. Their domain is to furnish more or less close indications, serving as guide for the orientation of researches (drill, shaft or gallery). This role of auxiliary should have its interest. Underground work gives exact information upon the composition of the rocks traversed, but it does not explore, so to speak, more than a sole point of the deposit, and the [illegible] [illegible] therefore have the disadvantage of being [illegible] along; its execution is slow and costly. Electric prospecting seems to present the opposite properties: lack of precision, the possibility of studying wide spaces rapidly, economically, and of giving a view of the terrain in its entirety.

These opposite and complementary characteristics are affirmed at other points. The current reveals well the vertical heterogeneities (faults, veins, tilted strata) which escape drill-holes so easily. It seems on the other hand, to be nearly powerless to aid in the study of horizontal sedimentary strata (coal-beds, potash deposits), which the drills cut with a minimum of hazard.

As far as the depth attainable is concerned, I think that the electric method retains a wide field of application, even if the investigation beneath the surface is but of slight depth, not exceeding for example, twenty metres. It is, in fact, beyond a doubt that many deposits or rock-arrangements at present unknown, are masked by but an insignificant covering of alluvium or soil, especially in equatorial countries or regions of but slight relief.

The present study constitutes merely a beginning. Perfections, or other analogous methods, present themselves to mind, and seem to merit serious investigation. When one thinks of the formidable sums wasted every year in useless search, especially in metal mines, one hopes that important efforts will be undertaken to discover and perfect methods of prospection at a distance, even if their field of action be limited to depths of but a few metres.

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APPENDIX

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ELECTRIC PROSPECTION WORK DONE IN SWEDEN.- Mr. Gunnar Bergström, Engineer of Mines, and Mr. Carl Bergholm, Doctor of the University of Upsal, gave, in the course of two conferences held the 14 of November 1918, at Stockholm, interesting information concerning the work on electric prospection carried out in Sweden since 1913. These conferences were published in the "Teknisk Tidskrift, Kemi och Bergvetenskap" 1918, book 12. They complete a more summary account of "Sveriges Geologiska Undersökning, Arsbok 7" (1913), no. 6.

The method adopted consisted essentially in the tracing of equipotential lines, making use of an induction coil as source of current, and a telephone in the circuit of observation. It is therefore derived directly from the technique of the process of Daft and Williams (page 8), which was last applied in Sweden by Mr. Slade Olver (1906).

The conference of Mr. Bergholm has a theoretical character. The author insists especially upon the employment of straight, parallel wires, laid along the ground, as contacts. This gives the equipotential curves the form of straight, parallel lines, in homogeneous ground, as far as the contact with the ground is even and regular throughout the length of the wire. The appearance of the deformations which should be produced in the equipotentials by a conducting vein is discussed in detail, and several different cases are considered.

A P P E N D I X

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Mr. Bergström renders an account of the attempts at electric prospection made in Sweden up to 1913, then he describes the work that he himself undertook in the field, in collaboration with Mr. Bergholm, at the initiative of the Society "Svenska Diamantbergbornings Aktiebolaget". The figures represent curves in the four following regions: Västra Mansgrufan at Norberg (iron mine with magnetite); Anggrufvan Salsta Grufvor (iron mine with magnetite); Orkla Gruber, at Lökken, Norway (mine of cupriferous pyrite); Hufvudmalmen, at Lökken. The authors used contacts either pointed, linear, or in the mineral. The figures show some very notable deformations of the equipotentials; the precise interpretation of these perturbations is not given.

The Swedish investigators do not seem to be interested in the numbering of the curves, that is to say, in measures relative to the drops of potential. They have produced in the laboratory certain phenomena observed in the field, but operating not upon an artificial soil of three dimensions, but merely upon a plane conductor (wet blotting-paper).

Although this work does not seem to have resulted as yet in the discovery of new deposits verified by underground workings, the authors are full of confidence in the efficacy of the methods. It is certain that their researches constitute, for clarifying the question of electrical prospection, a contribution better than the attempts prior to 1912, which, do not forget, were already due in part to the initiative of the Swedish.

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[illegible] account of the results of the [illegible] investigation made in Sweden up to 1923, then we describe the [illegible] list of mineral deposits in the field, in collaboration with Mr. [illegible], at the initiative of the Society "Svenska Diamantbergborrnings Aktiebolaget". The figures represent [illegible] in the following regions: Västra Ammeberg [illegible] at Norberg (iron ore with magnetite); [illegible] Gruvor (iron ore with magnetite); Orkla Grubber, at Lökken, Norway (mine of cupriferous pyrite); [illegible], at Lökken. The authors used contacts either pointed, linear, or in the mineral. The figures show some very notable deformations of the equipotentials; the precise interpretation of these perturbations is not given.

The Swedish investigations do not seem to be interested in the numbering of the curves, that is to say, in measuring relative to the drops of potential. They have produced in the laboratory certain phenomena observed in the field, but operating not on an artificial soil of great dimensions, but merely on a plane conductor (wet blotting-paper).

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