COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

RECORD NO. 1967/119

ELECTRICAL PROSPECTING TECHNIQUES

by

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Text of a paper delivered to the Second Australian Institute of Physics Summer School, Canberra, January 1967

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In this paper I shall consider the subject of geophysics in a very restricted domain.viz. the application of physical measurements to the study of near-surface problems.

Firstly, a few general comments concerning the geophysical methods used in investigating such shallow features of the earth's crust. Parasnis (1962) in his book 'Principles of Applied Geophysics' divides the geophysical methods into four broad categories. On the one hand are the static methods in which the distortion of a static physical field is detected and measured accurately in order to delineate the features producing them. The static field may be a natural field like the geomagnetic, the gravitational, or the thermal gradient field or it may be an artificially applied field like an electric potential gradient.

On the other hand we have the dynamic methods in which signals are sent into the ground, the returning signals are detected, and their strengths and times of arrival are measured at suitable points. In the dynamic methods the dimension of time always appears in the appropriate field equations either directly as the time of wave arrival (as in the seismic method) or indirectly as the frequency or phase difference (as in the electromagnetic method).

There is a class of methods which lie in between the two just mentioned. These are called relaxation methods and their feature is that the dimension of time appears in them as the time needed for a disturbed medium to return to its normal state. This class includes the overvoltage or induced polarisation methods.

Finally, there are what we may call integrated effect methods in which the detected signals are statistical averages over a given area or within a given volume. The methods using radioactivity fall in this class.

I take it that you will hear quite a deal concerning seismic, gravity, and magnetic methods before this Conference is finished so I intend to concentrate upon the electrical properties of the subsurface (particularly as applied to the search for economic mineralisation), which can be explored either electrically or electromagnetically. The purely electrical methods which I will discuss include self-potential, earth resistivity, and induced polarisation.

The self potential method is based upon measuring the natural potential differences which generally exist between any two points on the ground and in particular in the vicinity of sulphide-ores. Here I am not considering telluric currents but the constant and unidirectional potentials due to electrochemical actions in the surface rocks or in bodies embedded in them.

There is considerable speculation concerning the electrochemical mechanism producing self-potentials. The normal potentials observed over clays, marls, and other sediments can be explained by such well-known phenomena as ionic layers, electrofiltration, pH differences, and electro-osmosis (e.g. water flowing over the sand on a sea-beach sets up electrical potentials due to electrofiltration). However, the large potentials (sometimes up to several hundred millivolts) observed over sulphide ores and graphite are more difficult to explain. Most theories have attributed the sulphide potentials to the oxidation of parts of the ore above the water table but such an explanation cannot fit graphite, which does not normally undergo significant oxidation.

Since we are concerned with an electronic conductor (the ore) in contact with an ionic conductor (electrolytes in the country rock) there must be an exchange of electrons and ions at their boundary. From the directions of current and ion flow implied by a negative centre over the sulphide body it is evident that electrons are being supplied to the upper end of the orebody whereas an oxidation of this end will require a liberation of electrons. The latest theory, by Sato and Mooney (1960), proposes that the orebody merely serves to transport the electrons from the reducing agents at depth to the oxidising ones at the top without itself directly participating in the electrochemical action. However, the problem is by no means solved because large potentials exist even when the ore is totally submerged under the water table.

The measurement of self-potentials can be made by means of a millivoltmeter with a sufficiently high input impedance and using two non-polarising electrodes (such as a copper coil inside a porous pot filled with a saturated solution of copper sulphate). Ordinary metal stakes will not do since electrochemical action at their contact with the ground tends to obscure the natural potentials.

In the earth resistivity method a direct, commutated or low frequency alternating current is introduced into the ground by means of two electrodes (usually iron spikes) connected to the terminals of a portable source of e.m.f. The resulting potential distribution on the ground mapped by means of two probes (usually non-polarising electrodes) is capable of yielding the distribution of electric resistivity below the surface.

In the Wenner arrangement there is a constant distance, a, between electrodes and on the assumption of a homogeneous earth, the apparent resistivity ρ is given by:

$$\rho = 2\pi aR$$

where $R = \Delta V/I$

The earth is far from being homogeneous, of course, and various techniques are used to analyse the resistivities of the uppermost layers. With an expanding Wenner type electrode configuration Gish and Rooney were able to give the simple rule that the depth at which a discontinuity occurs is equal to the electrode separation corresponding to the turning point on the resistivity-electrode separation curve (Edge and Laby, 1931). However, other electrode configurations (e.g. The Schlumberger arrangement) can be used for particular investigations such as logging boreholes.

A lot of controversial material has been written concerning the induced polarisation (IP) method but it is believed that the predominant cause of IP effects in geological materials is due to the polarising of metallic minerals in the rocks. When minerals block the pore passages of a rock and an electric current is passed through the rock an electrochemical barrier is set up and must be overcome by the current flowing through the interface between the metallic minerals and the solution in the pore passage. The interface is said to be 'polarised' and the extra voltage necessary to drive the current across the barrier is called the 'overvoltage'.

When the inducing current is interrupted the overvoltage decays with time and the polarisation can be detected by observing this decay. The impedance of a polarised zone decreases with increasing frequency of the inducing current and the variation of impedance with frequency is therefore another method of detecting polarisation. The two methods of measurements are known respectively as time domain and frequency domain.

In the time domain measurements or 'pulse' type systems, a current is applied to the ground for a fixed period, usually several seconds, and then switched off. At the beginning of the 'off' period, or preferably at a fixed time later, the ground voltage is measured and compared with the 'on' voltage, the result being expressed in terms of millivolts per volt. Another practice is to integrate the off period voltage in terms of millivolt-seconds per volt.

The overvoltage effects resemble ordinary dielectric behaviour but there are important differences. The relaxation is not a simple exponential one but rather a hyperbolic one in many cases. Also the decay constant in IP, about a fraction of a second, is 3 to 4 orders of magnitude greater than the RC constant of the ground.

In the BMR we use measurements in the frequency domain. Here a current is applied to the ground successively at two frequencies and the resulting change in resistivity is noted. As the current is kept constant for all measurements at one field set-up this reduces to a measurement of the change in received voltage. This is called the frequency effect and is expressed as a percentage, viz:

$$F.E. = \frac{\rho dc - \rho ac}{\rho ac} \times 100\%$$

where ρac, ρdc, are the higher and lower frequency measurement of resistivity respectively. As the magnitude of this measurement is influenced by the resistivity of the ground it is usually normalised by dividing the F.E. by the resistivity ; this result is called the Metal Factor, viz:

$$M.F. = \frac{F.E. \times 2}{\rho dc} \times 10^3$$

where ρ = resistivity $= \frac{V\,l}{2I \times 10^3}\, n\,(n^2 - 1)$ ohm-metres

for a dipole-dipole set-up where:

V = receiver millivolts

l = dipole length

I = transmitter current

n = dipole separation transmitter to receiver

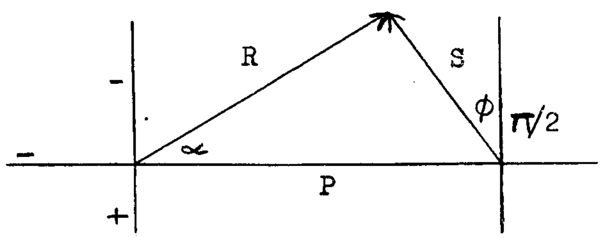
For most field work the dipole-dipole electrode geometry is used. Pole-dipole geometry is sometimes used to provide a larger signal but this is not as versatile, as the second transmitting electrode must be effectively at infinity. Electromagnetic coupling can be especially troublesome in areas of low ground resistivity. Electromagnetic pick-up increases with frequency while IP effects decrease with increase of frequency; hence the presence of a real IP effect usually can be tested by using a different step frequency.

Typical values for frequency are 3 c/s and 0.3 c/s. A square waveform (switched d.c.) is used as it is easier than a sine wave to generate for the larger currents used. Spontaneous potential bucking is required at very low frequencies (e.g. 0.05 c/s)

Polarisation does not occur in electrolytic conductors (e.g. saline waters); hence this represents a major break-through in exploration especially in Australia where saline water is fairly prevalent. However, graphite produces polarisation effects whereas clay produces membrane polarisation effects so that the method has by no means solved all the problems of exploration.

Now we shall consider some of the electromagnetic methods in use. If an electromagnetic field is produced on the surface of the ground, currents will flow in subsurface conductors in accordance with the laws of electromagnetic induction. These currents give rise to secondary electromagnetic fields which distort the primary field at any point on the surface. In general, the resultant field, which may be picked up by a suitable search coil, will differ from the primary field in intensity, phase, and direction and reveal the presence of the conductors.

The relation between the primary (P), the secondary (S), and the resultant (R) fields is as follows:



where P = $H_o \sin wt$ of frequency $w/2\pi$ say, acts on a coil (or a conductor). The secondary e.m.f., then, lags $\pi/2$ behind the primary field. If X and L are the resistance and self inductance of the coil, the current in the coil and the secondary magnetic field produced by it lag $\pi/2 + \phi$ behind the primary field, where $\phi = \arctan(WL/X)$, the lag $\pi/2$ being caused by the fundamental law of induction and ϕ by the properties of the secondary circuit.

Thus a very good conductor produces a secondary field almost opposite in phase to the primary field ($X \to 0$, $\phi \to \pi/2$) while a poor conductor produces a field that lags 90° behind the primary one ($X \to \infty$, $\phi \to 0$) the component of S in phase with P (the real component) is $-S \sin \phi$; the component lagging 90° behind P (out-of-phase or imaginary component) is $+S \cos \phi$. Thus a good conductor produces a large real but a small imaginary component while a poor conductor produces a relatively large imaginary but a small real component.

The resultant field is actually elliptically polarised and many early electromagnetic methods were based upon determining the azimuth and the dip of the ellipse of polarisation as well as its major and minor axes, which in fact represent the amplitudes of the real and imaginary components of the resultant field. If a search coil is connected via an amplifier to a pair of headphones the plane of the ellipse will be indicated by the position of the coil in which a silence is obtained in the phones. Setting the coil normal to the plane of polarisation and measuring the maximum and minimum signals induced in it as it is turned through one complete revolution one obtains the two axes of the ellipse. This method gives the most complete information about the electromagnetic field at a point but it is cumbersome and not accurate and usually only the horizontal and vertical components of the field are measured.

One advantage of the electromagnetic methods is that they can be applied successfully even when good conductive ground connections are not possible. However, one of the serious drawbacks in the electromagnetic methods is that the secondary currents in superficial layers of good conductivity e.g. clays, graphitic shales, etc. may screen the deeper conductors partially or wholly from the primary field. The deeper conductors, which are the real objects of exploration will then produce weak or no distortions (or anomalies) in the primary field and may therefore be indetectable.

I shall now briefly describe three of the more commonly used electromagnetic methods;

In the compensator method the primary layout consists either of a long cable grounded at both ends or a large horizontal loop through which an alternating current of low frequency (say 500 c/s) is passed. The cable or the long side of the primary loop is generally placed approximately parallel to the geological strike in the area and the electromagnetic field is investigated at regular intervals along traverses perpendicular to it. At each field station a search coil is held horizontal (to measure the vertical component) or vertically (to measure the horizontal component) and the voltage induced in it is compared with a reference voltage, which is usually obtained via a 'feed' coil inductively coupled to the primary layout.

The comparison of voltages is made on a compensator, essentially an a.c. potentiometer, in which the inclusion of a reactive element enables one to determine phase differences.

However, the necessity to have a direct connection between the primary layout and the observation point becomes cumbersome. In the Turam method the primary field is produced as before and two search coils, 50 to 200 feet apart are carried along the line of measurement. For each position of the coils, the ratio of the amplitudes of and the phase difference between the voltages induced in the coils are measured on a bridge-type compensator.

The coils are usually held horizontally so as to compare the vertical components of the resultant field. The quantities measured in Turam work are V1/V2, V2/V3,....., etc. and $\alpha_2 - \alpha_1$, $\alpha_3 - \alpha_2$,.., etc, where the V's are the amplitudes and the α's the phases of the vertical electro-magnetic field at stations 1, 2, 3, ...,etc. To correct for the variation of the primary field (p) with the distance from the source the measured ratios are divided by the normal amplitude ratios p1/p2, p2/p3, etc., and the normalised or reduced ratios V1p2/V2p1, V2p3/V3p2,etc. will all be equal to unity in the absence of subsurface conductors. The normal phase differences are, of course, zero provided the ground is non-conducting. On conductive ground the phase may change appreciably within relatively short distances and, moreover, the field will be elliptically polarised so that the inclination of the ellipse becomes more and more horizontal away from the cable. In detailed and accurate work these effects must be taken into account as also must the effect due to changes in topography along the traverse.

Thus deviations of the reduced ratio from unity and the phase difference from zero indicate anomalous sub-surface conditions. Further, the phase difference measures essentially the horizontal gradient of the phase, and the reduced ratio to a first approximation represents the function $\frac{1 - CS'}{1 + S}$ where:

S = the secondary field expressed as a fraction of the primary field at the station

S′ = its horizontal gradient

C = the constant separation between search coils.

Thus the departures of the reduced ratios from unity constitute a measure of the horizontal gradient of the amplitude of the secondary field.

In the Slingram or moving source and receiver method the receiver is kept at a fixed distance from the transmitter and the field acting on the receiver is measured in percentage of the primary field at it. Usually both coils are held either horizontally or vertically and about 200 feet apart, though the separation will vary according to the problem under investigation. Here as in most other electromagnetic methods used in the BMR, readings at each station are taken at two widely differing frequencies within the range 220 to 1760 c/s.

Corrections (e.g. on account of topography) to the real component can be easily calculated since the primary field, being an ordinary dipole field, is known everywhere. Otherwise similar considerations apply to this method as to the electromagnetic methods discussed previously.

I should perhaps say a word here about Afmag (audio frequency magnetic fields).

Natural magnetic fields of all frequencies from very low to very high ones are continually reaching any point on the earth. By far the greatest contribution to their total energy seems to come from local and distant thunderstorms. The space between the ionosphere and the earth's surface acts as a wave guide for these fields with the result that their vertical component is normally very small. Their amplitudes tend to be random.

Normally a search coil at any point will show a marked horizontal plane of polarisation for these waves and a randomly scattered azimuth of polarisation in that plane. However, in the vicinity of highly conductive bodies the plane of polarisation tilts out of the horizontal while the azimuth becomes more definite.

The tilt measurements are made for two different frequencies, one high and one low and the response ratio, low/high, provides a measure of the conductivity of the conductor. As with the other electromagnetic results, a ratio greater than one suggests a good conductor; a ratio less than one suggests a poor conductor.

Other methods using variations of the electromagnetic principles include E.M. Gun, Eltran, magneto-tellurics, etc. I do not propose to enlarge on these except to add that many of the electrical and electro-magnetic techniques have been adapted for airborne and borehole investigations.

One last topic I would like to touch upon before concluding concerns model tests. The problem of calculating theoretically the response of a conductor to an electromagnetic field is that of solving Maxwell's equations under appropriate boundary conditions, and on account of its complicated nature the treatments have so far been confined to relatively simple conductor models.

However, the response of a 'natural' conductor can be duplicated in the laboratory on a small convenient scale. Suppose that:

dimension (full-scale)/dimension (laboratory) = n

and that the frequency used in the laboratory experiement is the same as in the 'full-scale' experiment which it is supposed to represent, then it can be shown that, if μ is the magnetic permeability:

$$\left(\frac{\rho}{\mu}\right)_{f.s.} = n^2\left(\frac{\rho}{\mu}\right)_{lab.} \qquad (\rho \text{ in ohm-m})$$

or $$\rho_{f.s.} = n^2 \rho_{lab.}$$

in the case of 'non-magnetic' conductors with which we are generally concerned.

For example, suppose that in the laboratory one millimetre is chosen to represent one metre in full-scale ($n = 10^3$). A transmitter-receiver separation of 100 m will then be represented by 100 mm, a conductor depth of 50 m by 50 mm and so on for all the other lengths involved. The response of a 1-mm thick zinc plate ($\rho = 6.0 \times 10^{-8}$ ohm-m) will then be the same as that of a 1-m thick full-scale conductor, e.g. an ore vein, of resistivity $6.0 \times 10^{-8} \times 10^{6} = 0.06$ ohm-m. Many pyrite and chalcopyrite ores have resistivities of this order.

Model tests of this type are being carried out in the BMR to simulate results from the Turam and Slingram methods. The choice of model conductors is limited more or less to metal sheets and these do not show a very wide range of conductivities but as we have the scale factor, the frequency, and to some extent the magnetic permeability as additional variables at our disposal practically any conductor in full scale can be simulated electromagnetically in the laboratory.

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ILLUSTRATIONS

19 slides were used to illustrate various points in the text.