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اسم المادة بالعربي: الجيوفيزياء الجهدية - الطرق الكهربائية

اسم المادة بالإنكليزي: Potential Geophysics- Electrical Methods

عنوان المحاضرة: Electrical Resistivity Tomography (ERT)

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# **Electrical Resistivity Tomography (ERT)**

The Resistivity technique is a useful method for characterizing the sub-surface materials in terms of their electrical properties. Variations in electrical resistivity (or conductivity) typically correlate with variations in lithology, water saturation, fluid conductivity, porosity and permeability, which may be used to map stratigraphic units, geological structure, sinkholes, fractures and groundwater.

The acquisition of resistivity data involves the injection of current into the ground via a pair of electrodes and then the resulting potential field is measured by a corresponding pair of potential electrodes. The field set-up requires the deployment of an array of regularly spaced electrodes, which are connected to a central control unit via multi-core cables. Resistivity data are then recorded via complex combinations of current and potential electrode pairs to build up a pseudo cross-section of apparent resistivity beneath the survey line. The depth of investigation depends on the electrode separation and geometry, with greater electrode separations yielding bulk resistivity measurements from greater depths.





The recorded data are transferred to a PC for processing. In order to derive a crosssectional model of true ground resistivity, the measured data are subject to a finitedifference inversion process via RES2DINV (ver 5.1) software.

Data processing is based on an iterative routine involving determination of a twodimensional (2D) simulated model of the subsurface, which is then compared to the observed data and revised. Convergence between theoretical and observed data is achieved by non-linear least squares optimization. The extent to which the observed and calculated theoretical models agree is an indication of the validity of the true resistivity model (indicated by the final root-mean-squared (RMS) error).

The true resistivity models are presented as color contour sections revealing spatial variation in subsurface resistivity. The 2D method of presenting resistivity data is limited where highly irregular or complex geological features are present and a 3D survey maybe required. Geological materials have characteristic resistivity values that enable identification of boundaries between distinct lithologies on resistivity cross-sections. At some sites, however, there are overlaps between the ranges of possible resistivity values for the targeted materials which therefore necessitate use of other geophysical surveys and/or drilling to confirm the nature of identified features.

Constraints: Readings can be affected by poor electrical contact at the surface. An increased electrode array length is required to locate increased depths of interest therefore the site layout must permit long arrays. Resolution of target features decreases with increased depth of burial.



As part of a hydrological study, a series of resistivity tomography profile lines were acquired to map variations within the overburden thickness. The example section above displays an extensive erosional channel feature together with more subtle overburden thickness variations.



The figure above shows a 3D resistivity survey which carried out to map the lateral and vertical extent of buried foundations in engineering site application. The grey zones represent noisy data due to buried services and the high resistivity values (red) reflect the foundation material. The resistivity suggests that the foundations extend to a maximum depth of 2m.

#### **Electrical Self Potential (SP) Surveys**

SP surveys were at one time popular in mineral exploration because of their low cost and simplicity. They are now little used because some near-surface ore bodies that are readily detected by other electrical methods produce no SP anomaly.

### **Origins of natural potentials**

Natural potentials of as much as 1.8 V have been observed where Alunite (Alunite is a hydroxylated aluminium potassium sulfate mineral, formula KAl<sub>3</sub>(SO<sub>4</sub>)<sub>2</sub>(OH)<sub>6</sub>), weathers to sulphuric acid, but the negative anomalies produced by sulphide ore bodies and graphite are generally less than 500 mV. The conductor should extend from the zone of oxidation near the surface to the reducing environment below the water table, thus providing a low-resistance path for oxidation–reduction currents (see the following figure).

From the following figure Sources of SP effects. The sulphide mass straddling the water table concentrates the flow of oxidation–reduction currents, producing a negative anomaly at the surface. The downslope flow of groundwater after rain produces a temporary SP, in this case inversely correlated with topography.



sometimes SP surveys are useful in hydrogeology but can make mineral exploration surveys inadvisable for up to a week after heavy rain.

Movements of steam or hot water can explain most of the SPs associated with geothermal systems, but small (<10 mV) voltages, which may be positive or negative, are produced directly by temperature differences. Geothermal SP anomalies tend to be broad (perhaps several kilometres across) and have amplitudes of less than 100 mV, so very high accuracies are needed.

Small alternating currents are induced in the Earth by variations in the ionospheric component of the magnetic field and by thunderstorms. Only the long-period components of the associated voltages, seldom amounting to more than 5 mV, are detected by the DC voltmeters used in SP surveys. If, as is very occasionally the case, such voltages are significant, the survey should be repeated at different times of the day so that results can be averaged.

#### SP surveys

Voltmeters used for SP work must have millivolt sensitivity and very high impedance so that the currents drawn from the ground are negligible. A pair of Copper/ copper-sulphate 'pot' electrodes are almost universal is used; see the following figure, and linked to the meter by lengths of insulated copper wire.



An SP survey can be carried out by using two electrodes separated by a small constant distance, commonly 5 or 10 m, to measure average field gradients. The method is useful if cable is limited, but errors tend to accumulate and coverage is slow because the voltmeter and both electrodes must be moved for each reading. More commonly, voltages are measured in relation to a fixed base. One electrode and the meter remain at this point and only the second electrode is moved. Sub- bases must be established if the cable is about to run out or if distances become toogreat for easy communication. Voltages measured from a base and a sub-base can be related provided that the potential difference between the two bases is accurately known.

The following figure shows how a secondary base can be established. The end of the cable has almost been reached at field point B, but it is still possible to obtain a reading at the next point, C, using the original base at A. After differences have been measured between A and both B and C, the field electrode is left at C and the base electrode is moved to B. The potential difference between A and B is thus estimated both by direct measurement and by subtracting the B to C voltage from the directly measured A to C voltage. The average difference can be added to values obtained with the base at B to obtain values relative to A.



The figure above shows how to move a base station in an SP survey. The value at the new base (B) relative to A is measured directly and also indirectly by measurements of the voltage at the field point C relative to both bases. The two estimates of the voltage difference between A and B are then averaged.

#### **Constraints**

If two estimates of a base/sub-base difference disagree by more than one or twomill volts, work should be stopped until the reason has been determined. Usually it will be found that copper sulphate solution has either leaked away or become undersaturated. Electrodes should be checked every two to three hours by placing themon the ground a few inches apart. The voltage difference should not exceed 1 or 2mV. Accumulation of errors in large surveys can be minimized by working in closed and interconnecting loops around each of which the voltages should sum to zero.

# **Induced Polarization (IP) Method**

Conrad Schlumberger (Dobrin 1960) probably was first to report the induced polarization phenomenon, which he called "provoked polarization." While making conventional resistivity measurements, he noted that the potential difference, measured between the potential electrodes, often did not drop instantaneously to zero when the current was turned off. Instead, the potential difference dropped sharply at first, then gradually decayed to zero after a given interval of time. Certain layers in the ground can become electrically polarized, forming a battery when energized with an electric current. Upon turning off the polarizing current, the ground gradually discharges and returns to equilibrium.

The study of the decaying potential difference as a function of time is now knownas the study of induced polarization (IP) in the time domain (see the figure below).



In this method the geophysicist looks for portions of the earth where current flowis maintained for a short time after the applied current is terminated. Another technique is to study the effect of alternating currents on the measured value of resistivity, which is called IP in the "frequency domain" (see the previous figure - b). In this method the geophysicist tries to locate portions of the earth where resistivity decreases as the frequency of applied current is increased. The induced electrical polarization method is widely used in exploration for ore bodies, principally of disseminated sulfides. Use of IP in geotechnical and engineering applications has been limited, and has been used mainly for groundwater exploration. Groundwater IP studies generally have been made with time-domain IP.

# **General Theory of the IP Effect**

The origin of induced electrical polarization is complex and is not well understood. This is primarily because several physio-chemical phenomena and conditions are likely responsible for its occurrence. Only a fairly simple discussion will be given here. According to Seigel (1970), when a metal electrode is immersed in a solution of ions of a certain concentration and valence, a potential difference is established between the metal and the solution sides of the interface. This difference in potential is an explicit function of the ion concentration, valence, etc. When an external voltage is applied across the interface, a current is caused to flow, and the potential drop across the interface changes from its initial value. The change in interface voltage is called the "overvoltage" or "polarization" potential of the electrode. Overvoltages are due to an accumulation of ions on the electrolyte side of the interface waiting to be disged. The time constant of buildup and decay is typically several tenths of a second.

Overvoltage is therefore established whenever current is caused to low across an interface<sub>2021-02-21</sub> 12:09:21 between ionic and electronic conduction. In normal rocks, the current

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that flows under the action of an applied emf does so by ionic conduction in the electrolyte in the pores of the rock. There are, however, certain minerals that have a measure of electronic conduction (almost all the metallic sulfides (except sphalerite) such as pyrite, graphite, some coals, magnetite, pyrolusite, native metals, some arsenides, and other minerals with a metallic lustre). The figure below represents a simplified representation of how over voltages are formed on an electronic conducting particle in an electrolyte under the influence of current flow.



Overvoltage on a metallic particle in electrolyte. (Seigel 1970; Geological Survey of Canada)

The most important sources of nonmetallic IP in rocks are certain types of clay minerals (Vacquier 1957, Seigel 1970). These effects are believed to be related to electrodialysis of the clay particles. This is only one type of phenomenon that can cause "ion-sorting" or "membrane effects." For example, the figure below shows a cation-selective membrane zone in which the mobility of the cation is increased relative to that of the anion, causing ionic concentration gradients and therefore polarization.



Nonmetallic induced polarization agent. (Seigel 1970; Geological Survey of Canada)

A second group of phenomena includes electro kinetic effects that produce voltage gradients through the `streaming potential' phenomenon. These voltage gradients will have the same external appearance as polarization effects due to separation of ge. Electrokinetic effects seen less important than membrane effects in the overallpol response to all geophysical methods in mineral exploration.<sup>2021-02-21</sup> 12:26:00 being the only ones responsive to low-grade disseminated mineral ization. There are two main mechanisms of rock polarization and three main ways in which polarization effects can be measured. In theory the results obtained by the different techniques are equivalent but there are practical differences. These ways of measuring polarization effects are :

### 1- Membrane polarization:

The surfaces of clays and some other platy or fibrous minerals are negatively charged and cause *membrane polarization* in rocks with small pore spaces. Positive ions in the formation waters in such rocks congregate near the pore walls, forming an *electrical double layer*. If an electric field is applied, the positive ion

clouds are distorted and negative ions move into them and are trapped, producing concentration gradients that impede current flow. When the applied field is removed, a reverse current flows to restore the original equilibrium.

# 2- Electrode polarization:

This *electrode polarization* occurs not merely at artificial electrodes but wherever grains of electronically conducting minerals are in contact with the groundwater. The degree of polarization is determined by the surface area, rather than the volume, of the conductor present, and polarization methods are thus exceptionally well suited to exploration for disseminated *porphyry* ores. Strong anomalies are also usually produced by massive sulphide mineralization, because of surrounding disseminated haloes. Although, for equivalent areas of active surface, electrode polarization is the stronger mechanism, clays are much more abundant than sulphides and most observed IP effects are due to membrane polarization.

#### **3-The square wave in chargeable ground:**

When a steady current flowing in the ground is suddenly terminated, the voltage  $V_{o}$  between any two grounded electrodes drops abruptly to a small *polarization voltage*  $V_{p}$  and then declines asymptotically to zero.



The figure above shows ground response to a square-wave signal and to a spike impulse. The ratio of  $V_o$  to  $V_p$  is seldom more than a few percent. Input voltage

waveform is for reference only. In practice its amplitude will be many times greater than the measured voltage, the exact values depending on the array being used.

Similarly, when current is applied to the ground, the measured voltage first rises rapidly and then approaches  $V_0$  symptotically (see the previous figure). Although in theory  $V_0$  is never reached, in practice the difference is not detectable after about a second.

*Chargeability* is formally defined as the polarization voltage developed across a unit cube energized by a unit current and is thus in some ways analogous to magnetic susceptibility. The *apparent chargeability* of an entire rock mass isdefined, in terms of the square wave shown in the previous figure, as the ratio of  $V_{p}$  to  $V_{o}$ . This is a pure number but in order to avoid very small values it is generally multiplied by a thousand and quoted in milli-volts per volt. The ratio of  $V_{p}$  to  $V_{o}$  cannot be measured directly since electromagnetic transients are dominant in the first tenth of a second after the original current ceases to flow. The practical definition of time-domain chargeability, which is in terms of the decay voltage at some specified delay time, is only tenuously linked to the theoretical definition. Not only do different instruments use different delays, but also it was originally essential and is still quite common to measure an area under the decay curve using integrating circuitry, rather than an instantaneous voltage. The results then depend on the length of the integration period as well as on the delay and are quoted in milliseconds.

## **4-Frequency effects:**

The previous figure also shows that if a current were to be terminated almost immediately after being introduced, a lower apparent resistivity, equal to(Vo - Vp)/I multiplied by the array geometrical factor, would be calculated. The IP

frequency effect is defined as the difference between the 'high frequency 'and 'DC' resistivities, divided by the high-frequency value. This is multiplied by 100 to give an easily handled whole number, the *percent frequency effect* (PFE). The origin of the theoretical relationship between the PFE and the chargeability could be given by:  $\mathbf{M} =$ 

# [PFE] / (100 + [PFE])

and illustrated in the previous figure.

Because of electromagnetic transients, the theoretical PFE cannot be measured and the practical value depends on the frequencies used. To cancel telluric and SP noise, 'DC' measurements are taken with current reversed at intervals of the order of a few seconds, while the 'high' frequencies are usually kept below 10 Hz to minimize electromagnetic induction.

#### **5-Metal factors:**

A PFE can be divided by the DC resistivity to give a quantity which, multiplied by 1000, 2000 or  $2000\pi$ , produces a number of convenient size known as the *metal factor*. Metal factors emphasize rock volumes that are both polarizable and conductive and which may therefore be assumed to have a significant sulphide (or graphite) content. Although this may be useful when searching for massive sulphides, low resistivity is irrelevant and can be actually misleading in exploration for disseminated deposits. As usual when factors that should be considered separately are combined, the result is confusion, not clarification.

#### **6-Phase:**

The square-wave which appears in page 53, can be resolved by Fourier analysis into sinusoidal components of different amplitudes and frequencies. The asymmetry of the voltage curve implies frequency-dependent phase shifts between the applied current and the measured voltage. In *spectral* IP surveys, these shifts are measured, in milliradians, over a range of frequencies.

# **Time-domain IP Surveys**

Large primary voltages are needed to produce measurable IP effects. Current electrodes can be plain metal stakes but non-polarizing electrodes must be used to detect the few millivolts of transient signal.

### **<u>Time-domain transmitters</u>**

A time-domain transmitter requires a power source, which may be a large motor generator or a rechargeable battery. Voltage levels are usually selectable within a range of from 100 to 500 V. Current levels, which may be controlled through a current limiter, must be recorded if apparent resistivities are to be calculated as well as IPs.

Current direction is alternated to minimize the effects of natural voltages, and cycletimes can generally be varied from 2 to 16 seconds. One second each for energization and reading is not generally sufficient for reliable results, while cycles longer than 8 seconds unreasonably prolong the survey.

# **<u>Time-domain receivers</u>**

A time-domain receiver measures primary voltage and one or more decay voltages or integrations. It may also be possible to record the SP, so that chargeability, resistivity and SP data can be gathered together. Early *Newmont* receivers integrated from 0.45 to 1.1 seconds after current termination. The SP was first balanced out manually and the primary voltage was then *normalized* by adjusting an amplifier control until a galvanometer needle swung between defined limits. This automatically ratioed  $V_p$  to  $V_o$  for the *M* values recorded by a second needle. Experienced operators acquired a 'feel' for the shape of the decay curve from the rates of needle movement and were often able to recognize electromagnetic transients where these persisted into the period used for voltage sampling. With purely digital instruments, the diagnostic information provided by a moving needle is lost and enough cycles must be observed for statistical reduction of noise

effects. Digital systems allow more parameters to be recorded and very short integration periods, equivalent to instantaneous readings. Natural SPs are now compensated (*backed-off* or *bucked-out*) automatically rather than manually. Memory circuits store data and minimize note taking.

The receiver must be tuned to the cycle period of the transmitter so that it can lock on to the transmissions without use of a reference cable (which could carry inductive noise). Cycle times of 4, 8 or 16 seconds are now generally favoured. Changing the cycle time can produce quite large differences in apparent chargeability, even for similar delay times, and chargeabilities recorded by different instruments are only vaguely related.

#### **Decay-curve analysis**

With readings taken at several different delay times, curve analysis can be attempted. A method suggested for use with Huntec receivers assumed that each decay curve was a combination of two exponential decays, corresponding to electrode and membrane polarizations, which could be isolated mathematically. This is far too drastic a simplification and the separation, using a limited number of readings, of two exponential functions that have been added together is in any case virtually impossible in the presence of even small amounts of noise. Nonetheless, research continues into the controls on decay-curve shapes, and chargeabilities should be recorded at as many decay times as are conveniently possible in areas of interesting anomaly. In non-anomalous areas a single value generally suffices.

# IP Data

The methods used to display IP data vary with the array used. Profiles or contour maps are used for gradient arrays, while dipole–dipole data are almost always presented as pseudo-sections. In surveys with either array, the spacing between the voltage electrodes should not be very much greater than the width of the smallest target that would be of interest.

# Gradient array data

Current paths are roughly horizontal in the central areas investigated using gradient arrays, and chargeable bodies will be horizontally polarized. Profiles can be interpreted by methods analogous to those used for magnetic data, with approximate depths estimated by adopting the straight slop and Peters methods.

### **<u>Dipole-dipole data</u>**

Dipole-dipole traverses at a single n value can be used to construct profiles but multispaced results are almost always displayed as pseudo-sections, (see the next figure).



The figure above showing the Pseudo-section construction. The three different positions of the current dipole correspond to three different multiples of the basic spacing. Measured values (of IP or resistivity) are plotted at the intersections oflines sloping at 45° from the dipole centers. The plotting 'point' often doubles as a decimal point for IP values. The pant's leg anomaly shown is typical of thoseproduced by small, shallow bodies.

The relationships between the positions of highs on pseudosections and source body locations are even less simple with dipole–dipole than with Wenner arrays. In particular, the very common *pant's leg* anomaly, see the figure above is usually produced by a near-surface body with little extent in depth; every measurement

made with either the current or the voltage dipole near the body will record high chargeability. Anomaly shapes are thus very dependent on electrode positions, and the directions of apparent dip are not necessarily the directions of dip of the chargeable bodies.

Even qualitative interpretation requires considerable experience as well as familiarity with model studies. Pseudo-sections are nearly always plotted in relation to horizontal baselines, even in rugged terrain. Referencing them to topographic profiles (using construction lines similar to those of the previous figure, but at 45° to the actual ground surface) has its dangers, since it might be taken as implying much closer correlation with true sub-surface distributions of resistivity and chargeability than actually exist. However, steep and varied slopes do influence dipole–dipole results and it is better that they be displayed than ignored.

# **Negative IPs and masking**

Negative IP effects can be caused by power or telephone cables or by signal contribution sections, or by detecting lateral inhomogeneities.

Layering can also produce negative values, and can conceal deeper sources, most readily if both the surface and target layers are more conductive than the rocks in between. In these latter circumstances, the penetration achieved may be very small and total array lengths may need to be 10 or more times the desired exploration depth.

Interactions between conduction and charge in the earth are very complex, and interpreters generally need more reliable resistivity data than is provided by the dipole–dipole array, which performs poorly in defining layering. A small number of Wenner or Schlumberger expansions, carried out specifically to map resistivity, may prove invaluable. Also, any changes in surface conditions that might correlate with changes in surface conductivity should be noted. The detectability of ore is

likely to be quite different beneath bare rock ridges and under an interveningswamp.

## **Spectral Induced Polarization**

Spectral Induced Polarization (SIP) measures the variation of resistivity with frequency. The method, therefore, requires several resistivity measurements at different frequencies. These can be recorded in the frequency domain or in the time domain. In the time domain, where voltage measurements are recorded after the transmitting current has been turned off, the decaying voltage is sampled several times as it decays. Using the Fourier Transform, these data can be transformed into the frequency domain providing resistivity values at different frequencies. SIP measurements are occasionally used in mineral exploration to assist in identifying graphite and clay from sulfide mineralization. In addition, some information about the habit of the polarizable minerals could be obtained. It can also be used to map clay and, in some cases, contamination.

# **Sounding and Profiling**

The techniques of sounding and profiling, used in resistivity measurements, are also used in the IP method. IP soundings are most commonly made using the Schlumberger array, pole-dipole array, or Wenner array, and usually in the time domain. The apparent chargeability  $\eta_a$  versus the electrode spacing *a* is plotted on logarithmic coordinates. The IP sounding curve is an interpreted curve matching procedures, either graphically, using sets of IP sounding master curves, or by computer. At present, only a few two-layer master curves (for the Wenner array) have been published in the United States (Seigel, 1959; Frische and von Buttlar, 1957). Three- and four-layer curves have been published in the Soviet Union. An IP sounding curve can be of significant value in complementing a resistivity sounding curve. For example, the resistivity and IP sounding curves for the following four-layer geoelectric section are shown in the figure below:



Apparent resistivity and apparent chargeability (IP) sounding curves for a four-layer model. (Zohdy 1974)

From the figure above It is obvious that layer 3 cannot be distinguished on the four-layer resistivity curve (which resembles a two- or three-layer curve). But layer 3 is characterized by a different chargeability from the surrounding layers, and its presence is indicated clearly by the IP sounding curve.

When profiling, the pole-dipole or dipole-dipole, (see the figure below), arrays are used almost exclusively.



It can be easily employed in the field using short lengths of wire or multi-conductor cables allowing several values of the spacing multiplier (n) to be measured from one current dipole location. For one or two values of n, the IP and resistivity results are plotted as profiles. For more than two values of n, the profile method of presentation becomes confusing. A two-dimensional (usually called pseudosection) format has been developed to present the data (see the previous figure). This form of presentation helps the interpreter separate the effects of IP and resistivity variations along the line from vertical variations. The  $45^{\circ}$  angle used to plot the data is entirely arbitrary. The pseudosection plots are contoured, and the resulting anomalous patterns can be recognized as being caused by a particular source geometry and/or correlated from line to line. However, the contoured data are not meant to represent sections of the electrical parameters of the subsurface (Hallof, 1980). The pseudosection data plots are merely a convenient method for showing all of the data along one given line in one presentation.

## <u>Reference</u>

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