Geophysics of Exploration for Water

References and suggested literature

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Geoelectrical methods

edited by Peter Vass

A short review of electricity

Due to the subatomic properties of matter (material substance), two types of *electric charge*s exist in nature: *positive* and *negative* charges.

The electric charge is often denoted by Q, and its unit in SI is coulomb (C).
In engineering practice, the use of ampere-hour as a unit of electric charge is also common (Ah).
An electric charge produces an electric field around itself.
The charges are able to exert influences on each other by their electric fields.
The force which appears between the charges is called Coulomb force or electric force.
Charges with identical signs repel each other, while charges with different signs attract each other.

A short review of electricity

In consequence of the superposition principle, the electric field of an investigated volume is the resultant of the individual electric fields coming from the individual electric charges (found within that volume).

The electric field is able to interact with the charged particles, it has energy but no mass.

Mathematically, it can be described by a vector field.

Electric field is often denoted by $\vec{E}$, and its unit is volt per meter (V/m)

In the macroscopic point of view, objects are generally neutral, because the positive and negative charge carriers are located randomly and in equal amounts inside them.
A neutral object has no resultant electric force, therefore it does not show any electric behaviour.

A short review of electricity

In order to produce the excess of positive or negative charges in some part of an object, energy must be transferred to the object.

The charge separation can take place by either natural or man-made processes, so we can speak about natural and artificial (or man-made) electricity.

A special case of electricity is the electrostatics.
An electrostatic field occurs when the charge carriers in an electrically charged volume are fixed (do not change their position).
This is the only case when electric field may exist without magnetic field.
If the charge carriers are not static (they are moving), a magnetic field associates with the electric field.

A short review of electricity

The spatial and temporal energy distribution of an electric field is characterized by the so-called electric potential.
Electric potential is a scalar field which is often denoted by U, and its unit is volt (V).

Voltage is the electric potential difference between two points of an electric field.
So, the voltage is defined between two different points of an electric field.
It is often denoted by U, and its unit is the same as that of electric potential (V).

If there is no electric potential difference between two points, there is no voltage either.

A short review of electricity

A directional flow of charge carriers between two points of a medium is called *electric current*.

The *electric current (intensity)*, which characterizes the magnitude of an electric current, is commonly denoted by I, and its unit is ampere (A).

When the current intensity does not change in time, the current is called *direct current* (DC) or stationary current.

Two conditions have to be fulfilled in order that electric current can flow between two points of a material:

- the material should be an *electrical conductor* (a material through which charge carriers are able to flow)
- electric potential difference (electric voltage) should be exist between the two points of a conductive material.

A short review of electricity

In the case of non-conductive materials (dielectrics or insulators) the charge carriers are not able to move from one point to another by the effect of potential difference.

There is a relation between electric current (I) and voltage (U) which is given by *Ohm's law*.
Ohm established that the current flowing through a conductor is directly proportional to the voltage.

The constant of proportionality is called *resistance*, and it is usually denoted by R. The unit of resistance is ohm (Ω).
The formula of Ohm's law can be described as follows:

$$I = \frac{U}{R}$$

The reciprocal of the resistance is called *conductance*, and it is often denoted by C. Its unit is siemens (S).

Resistivity

One of the most important physical properties of rocks is the electrical resistivity. It is a material constant.

Electrical resistivity (or simply resistivity) is the ability of a material to resist the flow of electric current through itself.

It is commonly denoted by ρ, and its unit is ohmmeter (Ωm).

The reciprocal of electrical resistivity is called *electrical conductivity* (or simply conductivity).

It gives the ability of a material to pass the flow of electric current through itself.

It is often denoted by σ, and its unit is siemens per meter (S/m).

Electrical conduction in rocks

Two types of electrical conduction may be occurred in rocks:
- metallic conduction
- and electrolytic conduction.

The main properties of ***metallic conduction***:
- electrons as charge carriers flow through a solid material,
- there is no transfer of matter during the conduction,
- the resistivity increases with increasing temperature.

In the case of rocks, the metallic conduction is not typical. Only the higher content of some metallic minerals or graphite may cause metallic conduction in some rocks.

Electrical conduction in rocks

The main properties of electrolytic conduction:

- ions as charge carriers flow through a solvent,
- the conduction entails transfer of matter,
- the resistivity decreases with increasing temperature.

In the case of rocks the electrolytic conduction may be significant when the rock contains water and dissolved ions in the pore space.

Resistivity of rocks

From the perspective of conductivity, minerals can be classified into three groups:

- conductors,
- semiconductors,
- and dielectrics (or insulators)

Conductors are characterized by very low resistivity (n x 10^{-8} Ωm). In nature, only the native metals (copper, gold, silver, platinum etc.) and graphite belong to the group of conductors.
Since the rates of their occurrence in nature is low, their influence on the resistivity of rocks is generally not significant .

Semiconductors are characterized by much higher resistivity than that of conductors (n x 10^{-6} – n x 100 Ωm).
Among the minerals, metal oxides, sulphides and tellurides belong to the group of semiconductors.

Resistivity of rocks

Dielectrics are characterized by very high resistivity (> 10^3 Ωm). The common rock-forming minerals (quartz, feldspars, micas, pyroxenes, amphiboles, olivine, calcite etc.) and most of the other minerals behave as dielectrics in electric fields.
They do not participate in electrical conduction.

The resistivity of rocks varies in a wide range.
The most important factors influencing the resistivity of rocks are the following:

- mineral composition,
- porosity,
- type of fluid filling the pore space,
- clay volume fraction.

Resistivity of rocks

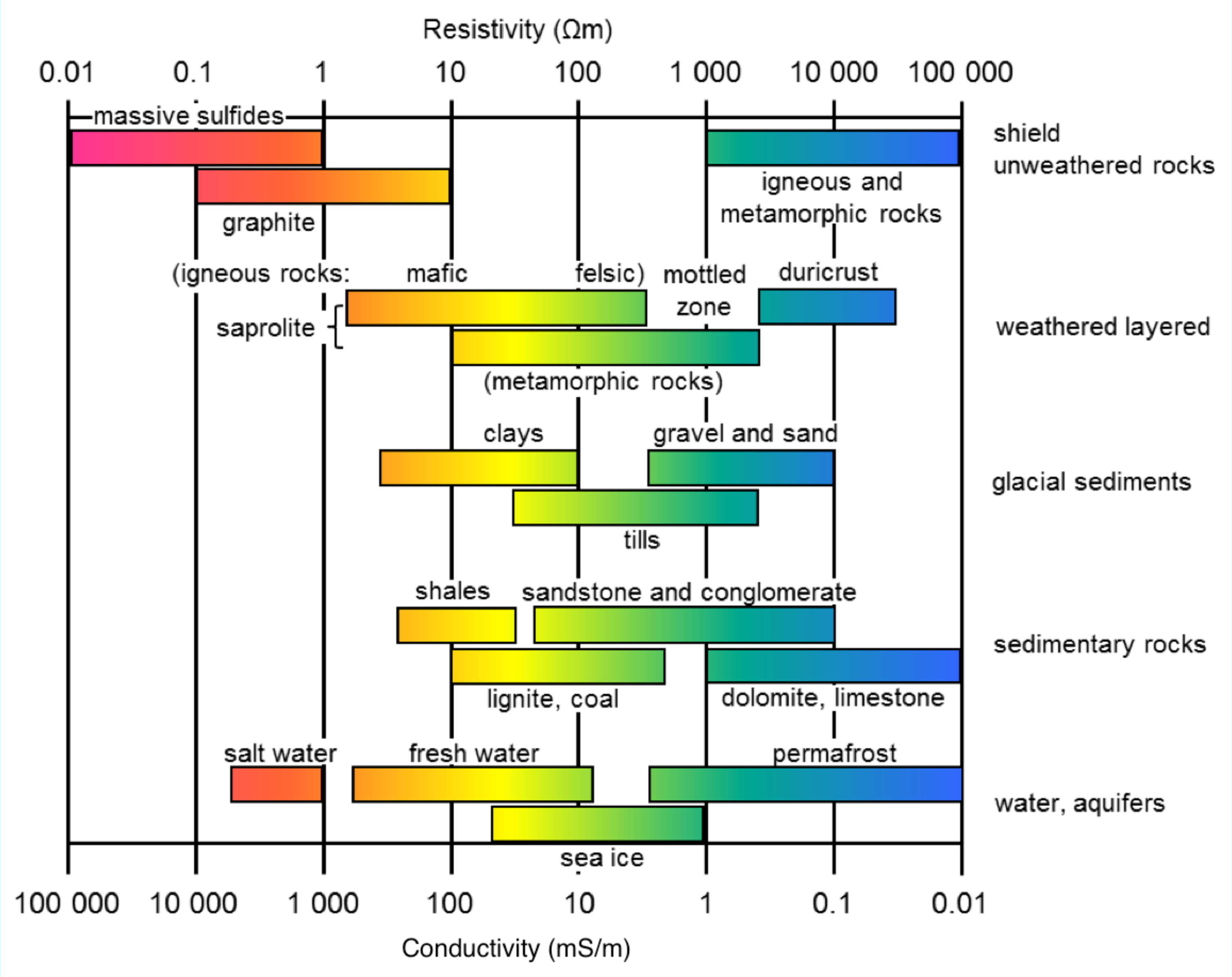
There is no unambiguous correlation between the resistivity and the type of rock because several factors collectively determine the resistivity of a rock.

The resistivity may vary in a wide range even for a given rock type.
In addition, the typical resistivity ranges of different rock types partially overlap each other.

Thus, only a range or an order of magnitude of resistivity can be given to the rocks.

It means that we cannot identify the type of rock on the basis of a measured value of resistivity.

Resistivity of rocks



http://gpg.geosci.xyz/content/physical_properties/physical_properties_conductivity.html

Resistivity of rocks

Since most of the minerals are considered dielectrics (insulators), the conductance of (dry) solid rock framework is usually negligible.
Its resistivity generally varies in the range of 10^3 to 10^8 Ωm.

But the accumulation of metal bearing minerals (e.g. ores) with lower resistivity may cause significant decrease in resistivity of rocks.
In order that the metal content can observably decrease the resistivity of a rock, *at least 5-10% metal concentration* is necessary.
So, the metallic conduction plays considerable role only for the metal ores.

Resistivity of rocks

The electrolytic conduction in rocks occurs more frequently in nature than metallic conduction.

This type of conduction is due to the *water content* of rocks.

The resistivity of water is usually a few ohm meter, but it strongly depends on the quality and quantity of salts dissolved in the water as a solvent.

Increasing salinity decreases the resistivity of water and the resistivity of water bearing rocks, too.

Because of the high mobility of sodium and chloride ions in water, they have a significant effect on the resistivity of water.

The resistivity values of some types of natural water:

rain-water	300 – 1000 Ωm
river	20 – 120 Ωm
karst water	15 – 20 Ωm
sea-water	0.6 Ωm
formation water	0.2 – 20 Ωm

The salinity of water in rocks is generally increases with depth.

Resistivity of rocks

The effect of ***porosity*** on the resistivity of rocks depends on the fluid content of the pore space.

The dry pore space, that is the air-filled porosity, increases the resistivity of rocks.

On the contrary, the water-filled porosity decreases the resistivity of a porous rock.

dry sand	$10^2 – 10^5\ \Omega$m
water-filled sand	$20 – 10^3\ \Omega$m
dry gravel	$10^2 – 10^6\ \Omega$m
water filled gravel	$50 – 10^3\ \Omega$m

In the case of water saturated rocks increasing porosity decreases the resistivity of rocks

The increase of ***temperature*** also decreases the resistivity of water bearing rocks (because of increasing ionic mobility with temperature).

The effect of temperature on the resistivity of rocks is significant mainly in the range of 20°C – 300°C. (this factor must be taken into account in thermal water exploration.)

Resistivity of rocks

There is a special effect of ***clay minerals*** on the resistivity of rocks.
Clay minerals in rocks can be considered relatively good electrical conductors because of their water content and the cations weakly connected to their surface.
Sediments and sedimentary rocks with high content of clay minerals (e.g. clay, silt, claystone, shale) are usually characterized by low resistivity values (typically n x Ωm).
These rocks are made up of very fine grains, and contain a lot of bound water (generally 30 - 35 %) among their solid constituents.
In the case of clastic sediments and weathered igneous rocks, the increase of **clay volume fraction** significantly decreases the resistivity.

Geoelectric methods

The horizontal and vertical variations of electrical properties of the sub-surface can be explored by geoelectric and electromagnetic methods.

The most simple geoelectric method called **self-potential (SP) method** is based on measuring the effects of local electric fields generated by natural processes under the surface.

Self-potential may occur due to different effects such as electro-filtration, concentration difference (diffusion), contact potential and mineral potentials.

In the course of SP surveys, the investigation depth cannot be controlled, so we can determine only the horizontal distribution of natural electric potential in the near subsurface.

Geoelectrical methods

The other group of geoelectrical methods uses direct current (DC) for determining the variations of resistivity occurring under the surface.

The so-called **vertical electrical sounding (VES)** method helps us to discover the vertical variations in the resistivity of rocks.

The penetration depth of the current coming from a man-made, external source can be controlled by the arrangement of current electrodes.

For a simple, horizontally layered structure, the shape of the sounding curve reflects the resistivity variations with depth

The other version of geoelectrical methods is the **electrical profiling (EP).**

It is used for investigating the horizontal variations in the resistivity of rocks.

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Self-potential method

In nature, local electric fields may come into being by physical chemistry and electrokinetic processes.
These processes take place in some types of rock formations, and along the contacts of two subsurface media with different chemical or physical properties.

In the case of self-potential (SP) surveys, the lateral variations of electric potential are measured between a pair of metal electrodes.
The electrodes are used to make a contact between the subsurface and the surface part of the circuit used for measuring the electric potential.

Self-potential method

If we measure the SP values over an area, we can produce the electrical potential map of the area.

- By the evaluation of the potential map, we can find and delimit anomalies which indicate the presence of some subsurface structures (e.g. ore bodies),
- subsurface flow of water
- or special formations causing the change in the potential field.

Self-potential method

Several processes may cause a self-potential (also known as spontaneous potential) field in the subsurface but some of them have not been understood completely yet.
The most important processes causing self-potential are the following:

- electrofiltration,
- ionic diffusion (between solutions with different concentrations),
- processes taking place along the contact of rocks with different chemical or physical properties,
- and mineralization.

It may occur that more than one process participate in generating the self-potential field at the same time and location.
In such a case, the measured potential field is the resultant of the potential components produced by the different processes.

Self-potential method

Electrofiltration or **streaming potential**

It is generated by the subsurface flow of water through porous rocks.

This effect probably occurs due to electrokinetic coupling between ions dissolved in water and the pore walls of rocks.

The magnitude of electrofiltration potential ranges from a few millivolts to a few hundred millivolts (n x mV – n x 100 mV).

This potential is always associated with the flow of subsurface water.

It is often observed:

- over zones of water leakage through fissures in the rock floor of reservoirs,
- in the vicinity of water wells during pumping,
- over areas with significant changes in elevation (subsurface water flows along the slopes downwards),
- and in geothermal areas.

Self-potential method

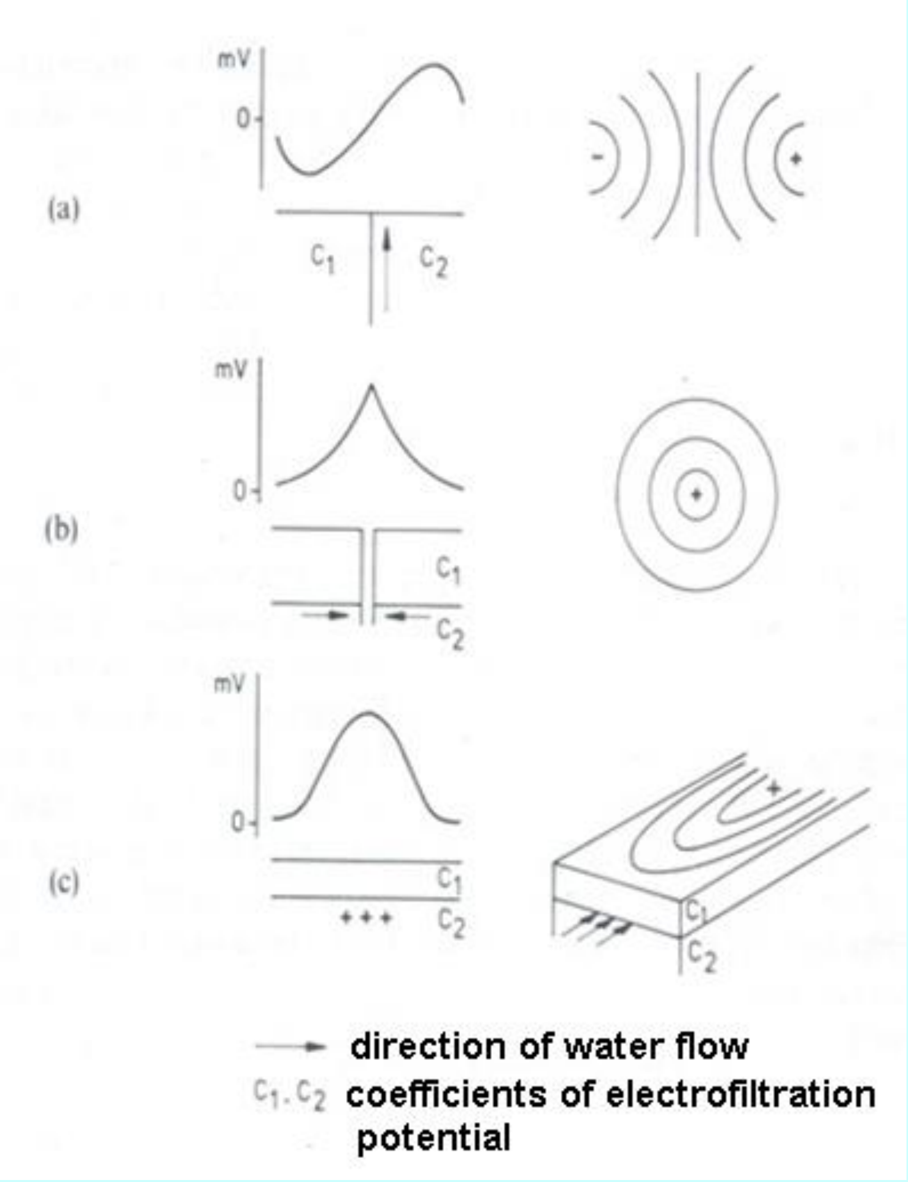
Idealized electrofitration potential profiles and maps for some models of subsurface water flow.

a.) water flow along a vertical boundary of rocks

b.) water flow produced by a water well

c.) water flow along horizontal boundary of layers

The coefficient of electrofiltration potential is a quantity which is typical of the medium and it is proportional to the magnitude of electrofiltration potential.



Self-potential method

Liquid-junction, or diffusion potential
It occurs when aqueous solutions with different concentrations meet in porous rocks.
By the effect of the difference in concentration, the ions begin to diffuse from the place with higher concentration to the place with lower concentration (diffusion).
But the mobility of anions and cations are not equal, so the balance of positive and negative charges will stop in the solutions in some time. Actually a charge separation will occur.
This charge separation is the source of diffusion potential whose magnitude is about n x 10 mV.

Nernst potential is a special potential, which occurs when two identical metal electrodes are immersed in a solution with locally different concentrations.
Since a self-potential measurement is implemented by two metal electrodes coupled with the ground at different points, the measured potential always includes the effect of Nernst potential.

Self-potential method

The combination of diffusion potential and Nernst potential is called **electrochemical**, or **static self-potential**.
The electrochemical potential is directly dependent on the concentration difference and the temperature.
So, this potential may be observed

- in geothermal area
- and in the vicinity of subsurface water contaminations causing an increase in ionic concentration.

Contact potential

It occurs due to processes taking place along contact of two rocks with different physical or chemical properties (e.g. at the contact of frozen soil and water filled soil, or at the contact of rocks with different mineral composition).

Mineralization potential

It can be observed over deposits of some metallic minerals (e.g. pyrite, chalcopyrite, magnetite or graphite). The magnitude of this potential ranges from 100 – 1000 mV.

Self-potential method

The field equipment used for SP measurements is simple and not expensive.
It is made up of

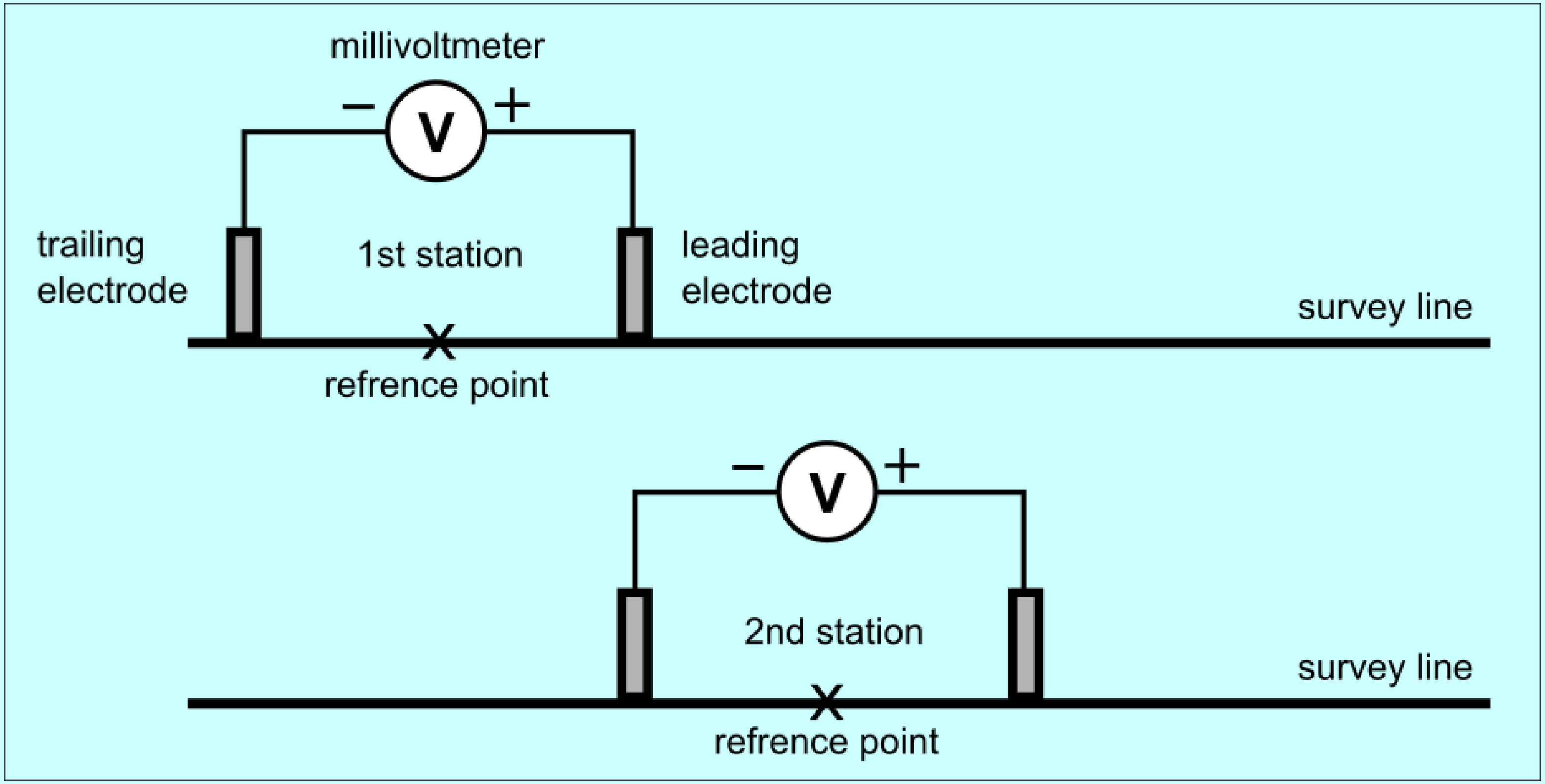
- a pair of metal electrodes (in practice, non-polarizable electrodes are used),
- a millivoltmeter with high sensitivity,
- and insulated cables for making contacts between the electrodes and the millivoltmeter.

Two different electrode configurations are used for measuring the potential field of an area:

- gradient (or dipole) configuration,
- potential (or fixed-base) configuration.

Self-potential method

This figure illustrates a gradient electrode configuration.

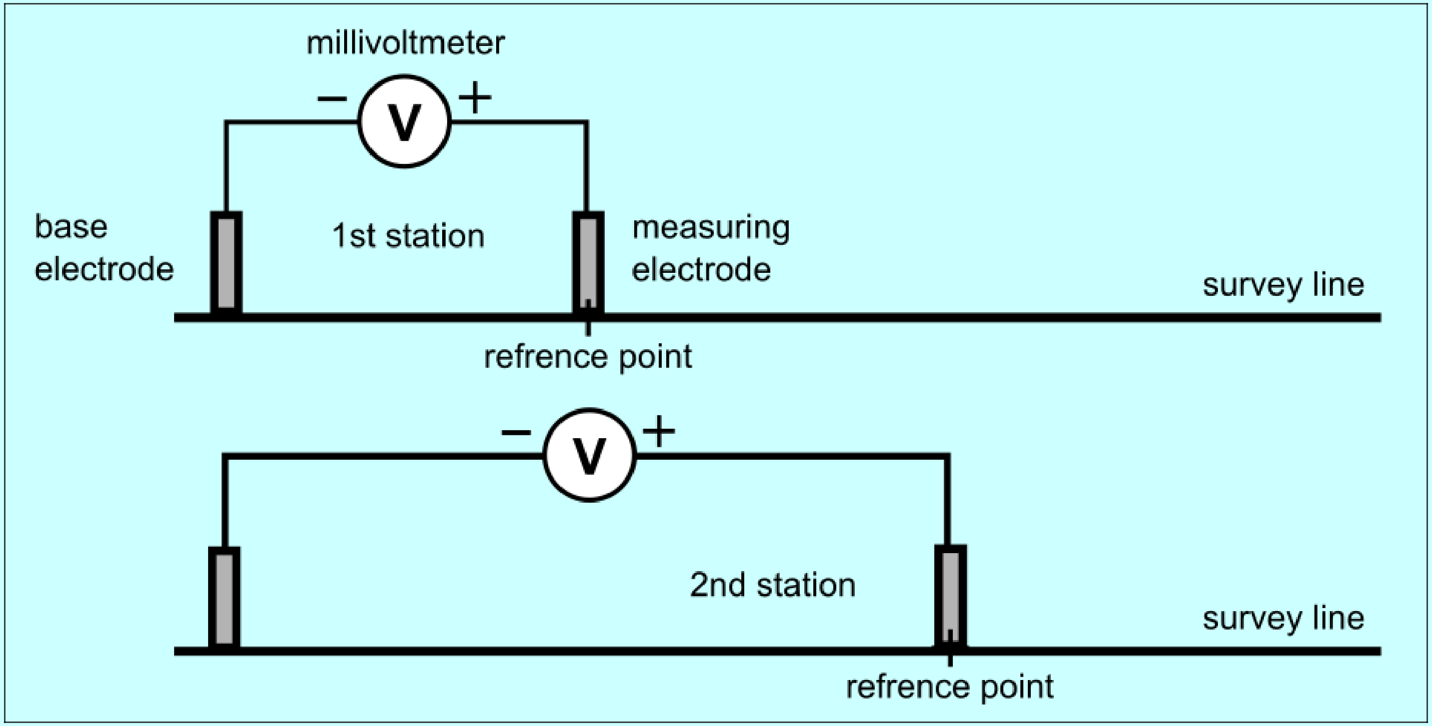


Self-potential method

During a measurement with **gradient configuration**, the space between the leading and trailing electrodes is fixed.
The negative lead of the voltmeter is connected to the trailing electrode, and the positive lead is connected to the leading electrode.
After measuring the potential at a station, the whole configuration is skipped to the next station along the survey line in the direction of leading electrode.
The reference point of a measured value is the midpoint of the distance between the electrodes.
The measured potential value in mV is referred to this point.
The length of the skip is equal to the fixed electrode space.

Self-potential method

This figure demonstrates a potential (fixed-base) electrode configuration.



Self-potential method

When a potential electrode (fix-based) configuration is applied, one of the electrodes is fixed (base electrode), while the other (measuring electrode) moves between the neighbouring stations.

The base electrode is connected to the negative lead of the voltmeter, and the measuring electrode is connected to the positive lead.

The reference point of a measured value is always the actual position of the measuring electrode.

The measured potential value in mV is referred to this point.

By using potential configuration, the SP survey is faster, but less precise.

By increasing the electrode spacing, the measured value of self-potential is getting more and more noisy due to the effect of telluric currents flowing underground.

Self-potential method

Because the raw measured data contain not only useful information about the subsurface structures and water flows but also unwanted components called noise, performing a data processing step is needed before the evaluation of results.

Data processing of measured SP data includes the hereunder main steps:

- the recognition of noise potential components,
- the separation of the noise from the measured potential,
- constructing the SP profiles and/or maps.

The most frequent factors causing noise potential are the following:

- changing soil conditions,
- changing water saturation levels in the ground,
- changing surface elevation,
- lateral resistivity variations,
- artificial noise sources (e.g. power lines, buried metal objects, grounded electrical machines etc.),
- natural telluric currents underground.

Self-potential method

As a result of SP measurement and data processing, we get an SP profile, or a contour-map showing the variations of SP with the distance.

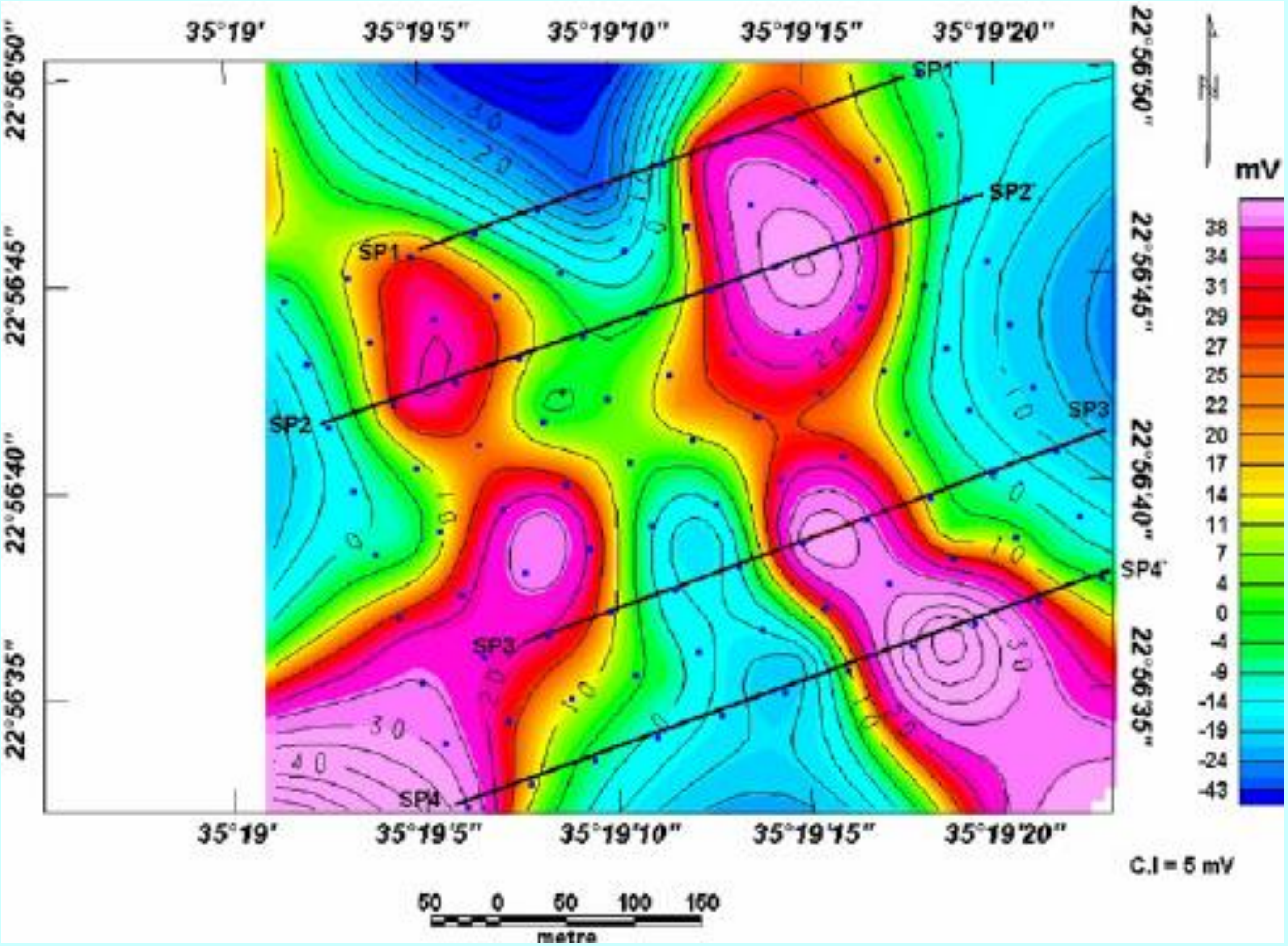
The qualitative interpretation of self-potential measurements involves:

- recognition of SP anomalies on the profiles and/or maps,
- determination of the directions belonging to the anomalies,
- determination of the areas belonging to the anomalies.
- identification of the possible causes of the anomalies,

Some important applications of SP method in water exploration and environmental problems:

- delineation of groundwater flow,
- study of geothermal fluid flow,
- seepage flow in a landslide body,
- seepage flow in reservoir floors.

Self-potential map



https://www.researchgate.net/figure/231136109_fig1_Figure-5-Self-potential-SP-map-with-measured-points-and-interpreted-profiles