The GEOELECTRICAL methods for geothermal exploration

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Goals to be achieved by Geophysics

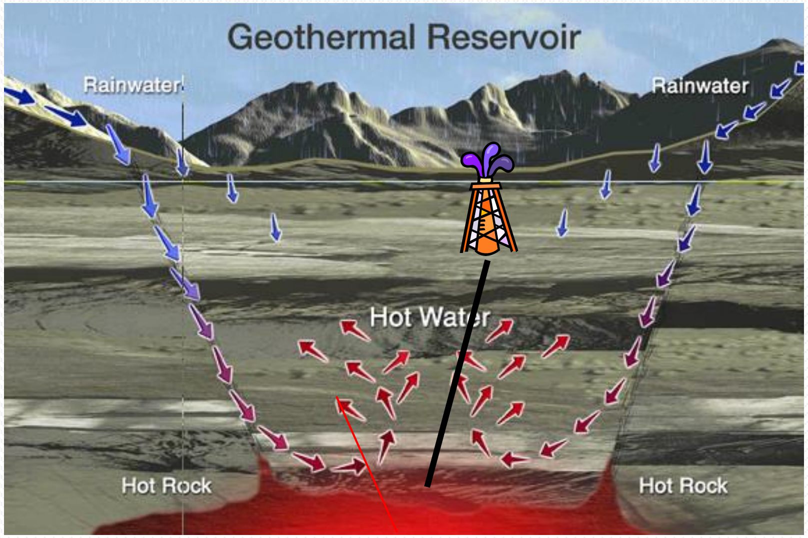
1. before and during production

- Improve methods of identifying prospective reservoirs without drilling
- Define boundaries (lateral and vertical)
- Improve methods to identify drilling targets

Main permeability is driven

by fracture and faults.

>30% of wells not economic



Goals to be achieved by Geophysics

2: during and after production

- Continuously characterize the reservoir during energy extraction
- Follow the effect of production and fluid re-distribution, including the formation of steam or gas cap
- Characterize the rock fabric to define fluid flow paths within reservoir
- Track injected fluids
- Characterize formations during deep drilling and stimulation in order to predict reservoir performance/lifetime (effectiveness and sustainability)

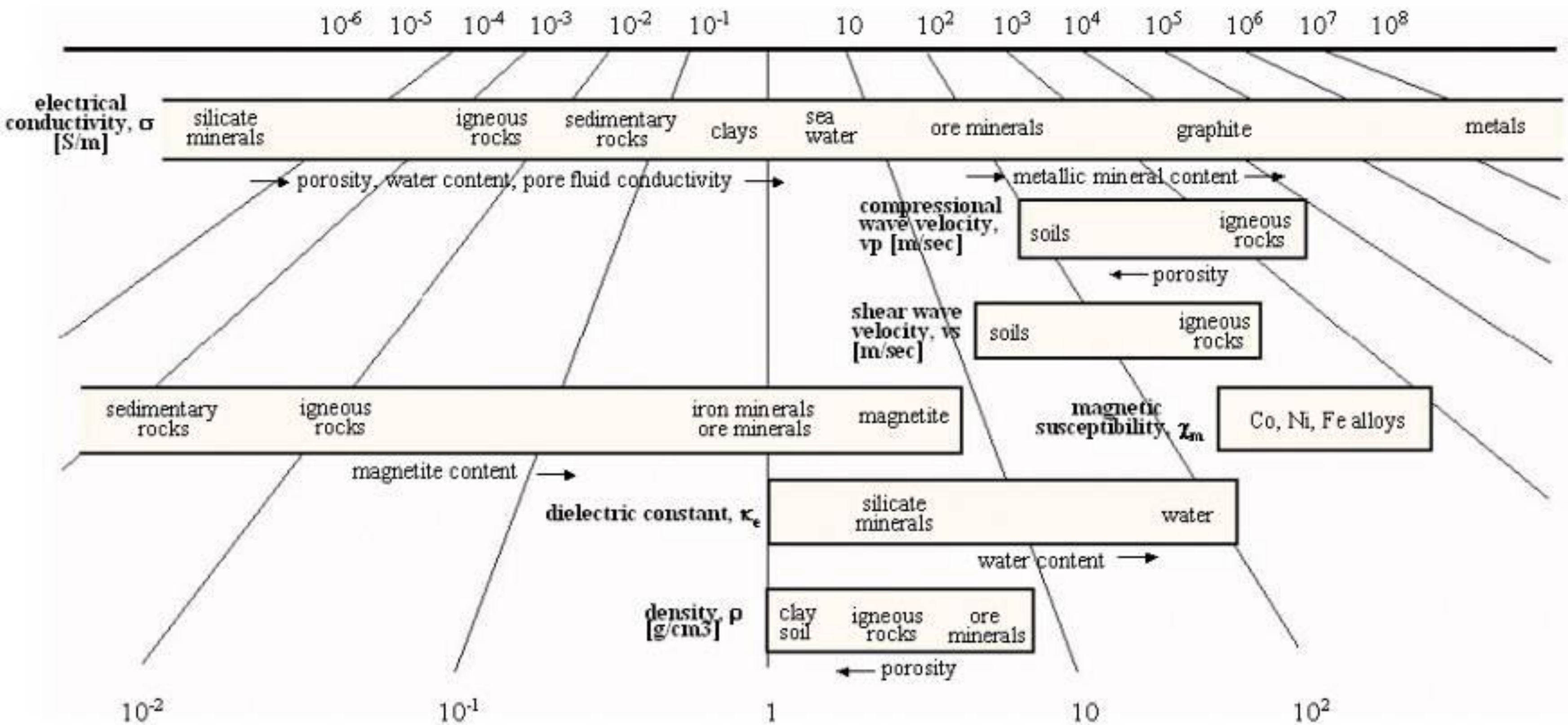
Geophysical exploration

A geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface.

Changing physical parameters:

- temperature (thermal survey)
- electrical conductivity (electrical and electromagnetic survey)
- elastic properties influencing the propagation velocity of elastic waves (seismic survey)
- density (gravity survey)
- magnetic susceptibility (magnetic survey).

The range of values for the lithologies that can be measured with the methods of applied geophysics is very variable.



Geophysical exploration

It is not wise to define a particular sequence of geophysical surveys as being applicable to all potential reservoirs

	Density	Magnetic susceptibiity	Electrical resistivity	Dielectric permittivity	Seismic velocity
Porosity	Strong	None	Strong	Moderate	Moderate
Permeability	None	None	Weak	Weak	Weak
Water content	Moderate	None	Strong	Strong	Moderate
Water quality	None	None	Strong	None	None
Clay content	Weak	None	Strong	Weak	Moderate
Magnetic mineral content	Moderate	Strong	Weak	None	None
Metallic mineral content	Strong	None	Strong	None	Moderate
Mechanical properties	Moderate	None	Moderate	Weak	Strong
Subsurface structure	Moderate	Moderate	Moderate	Strong	Strong

Strong	Moderate	Weak	None

Degree of relationship

Geophysical exploration

It is not wise to define a particular sequence of geophysical surveys as being applicable to all potential reservoirs.

Any exploration plan should be tailored to the project

NO STANDARD

To some extent the choice of method depends also upon accessibility.

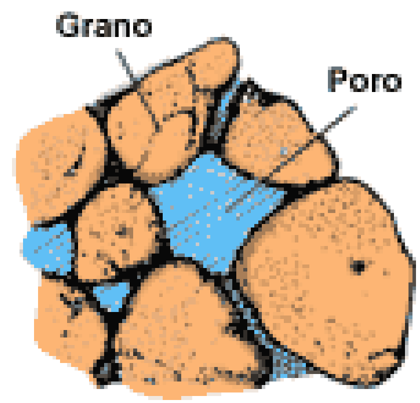
After detailed geophysical surveys we should have a convincing set of data to say there is evidence for heat and for permeability

Why resistivity?

Electric and electromagnetic methods provide the electrical resistivity ρ or its reciprocal electrical conductivity σ of the subsurface.

Resistivity depends on both host rocks and pore fluid properties

Rocks	Temperature & Pressure
	Rock mineral association - Lithology, Clays (Surface conduction)
	Microstructural properties (e.g., permeability, porosity)
Fluids	Amount – saturation, fluid content
	Nature (liquid or vapor phase, other liquids and gases)
	Geochemisty of the fluid - Salinity



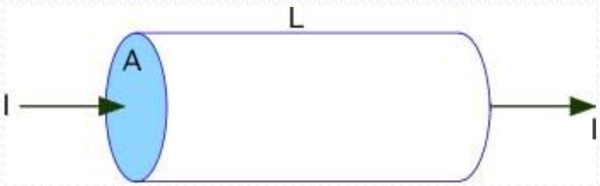
Electrical resistance = the resistance of a medium to electrical current transmission
Ohm Law

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

Where V= potential difference (volts) and I= current flow (ampere)
R is adimensional.

Current density : $J = \frac{\mathrm{I}}{A}$

Resistance = $R \propto \frac{\mathrm{L}}{A} = \frac{\rho L}{A}$



Resistivity, which is the resistance of a unit volume, has unit ohm-m
The conductivity is $\sigma = 1/\rho$

and has unit Siemens/m

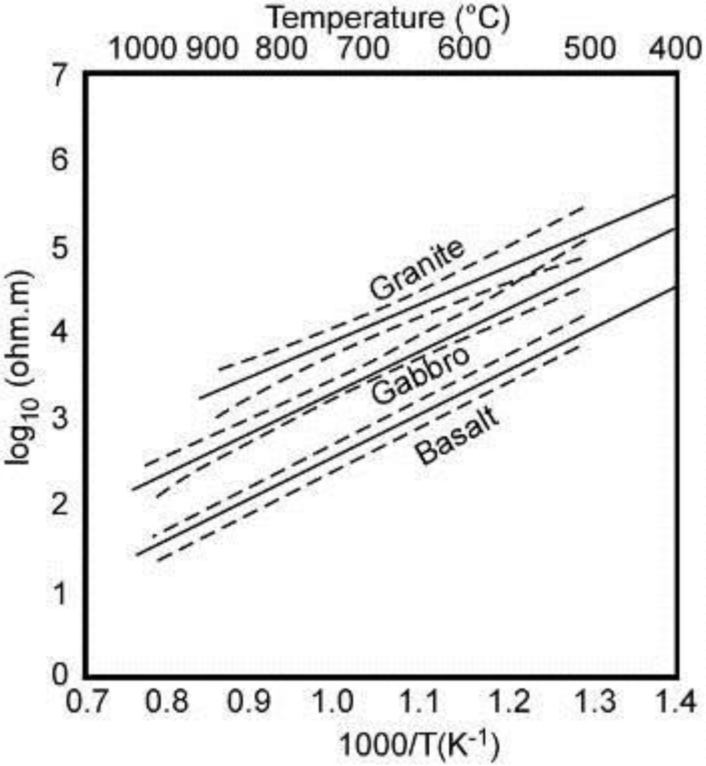
Electrical current may propagate thanks to the mobility of free charge carriers that allows current **conduction**

Main propagation mechanisms are:

Electronic ($<10^{-8}\ \Omega m$)	electrons	metals (magnetite, hematite) , graphite
Semi-conduction $10^{-5} \div 10^{-3}\ \Omega m$	electrons and ions	Solfurs
Electrolitic	ions	brines, salty water, melts

Why resistivity?

Temperature and Pressure



From Karya and Shankland, 1983

At normal temperature at the earth surface, silicate minerals have very high resistivity.

The higher the temperature, the lower the resistivity.

Approaching the melting point of a rock the resistivity becomes low enough to become comparable with resistivities in water-saturated rocks

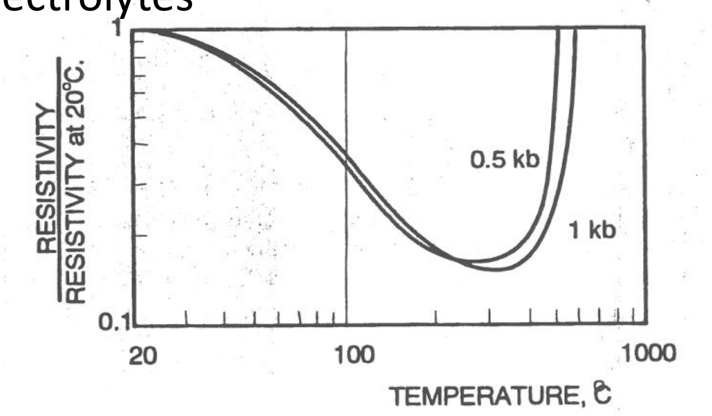
Why resistivity?

Temperature and Pressure

When rocks contain fluids, electrical conduction takes place mainly by passage of current through the fluid in the pores, since almost all rock-forming minerals are almost insulators at low-medium temperatures.

The conductivities of both the electrolytes and the rock matrix are temperature dependent in a manner that causes a large reduction of the bulk resistivity with increasing temperature.

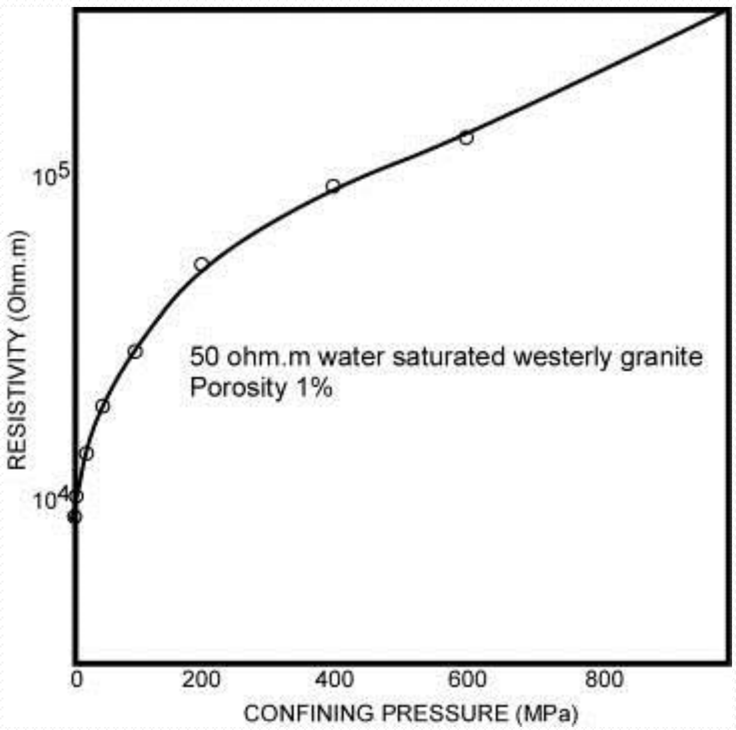
The maximum enhancement in conductivity is approximately sevenfold between 350°C and 20°C for most electrolytes

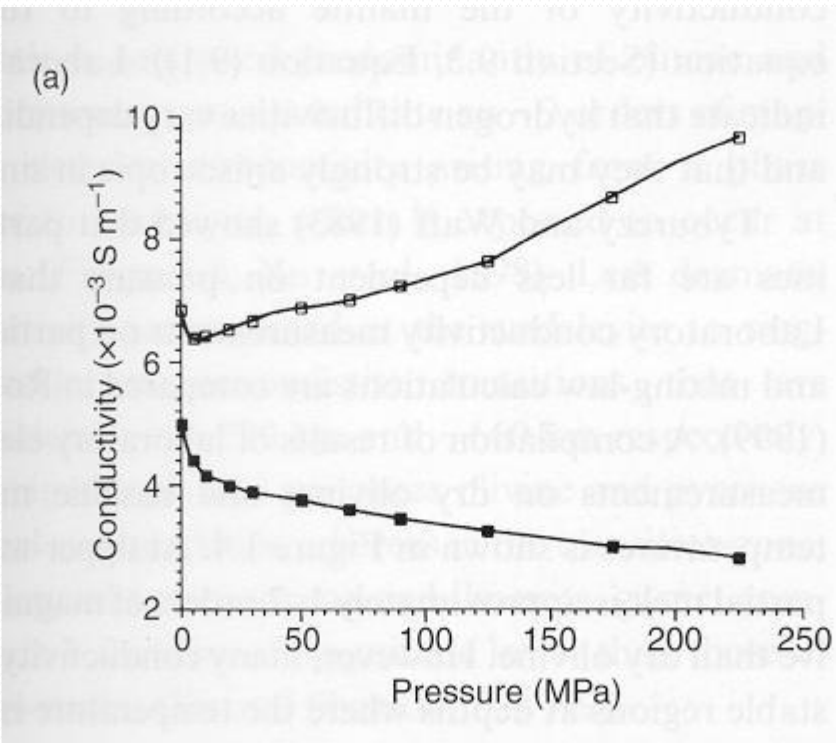


From Keller

Why resistivity?

Temperature and Pressure

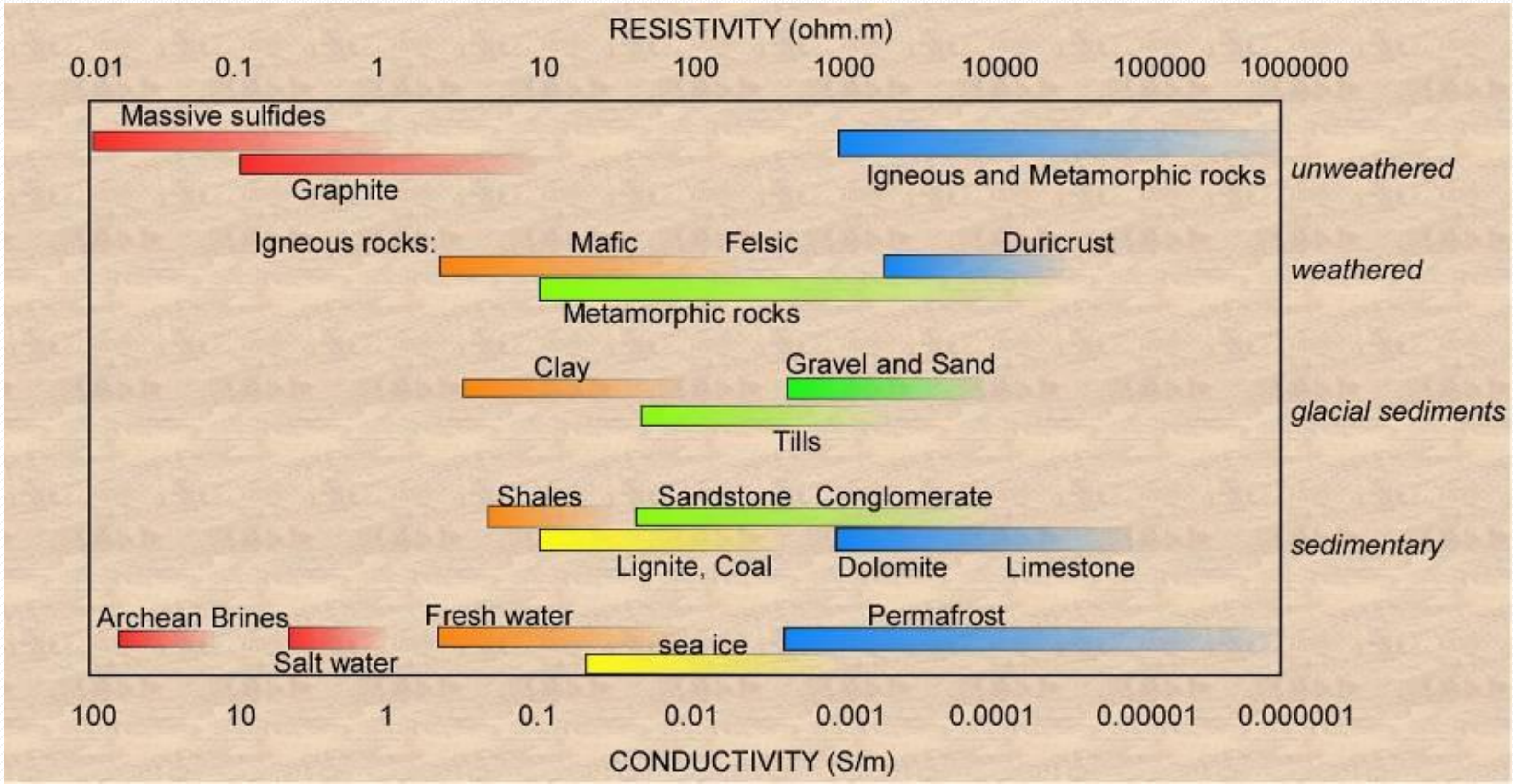




Pressure influence resistivity mainly in connection to fluids and, to a lesser extent, to reconnection of solid phases.

Why resistivity?

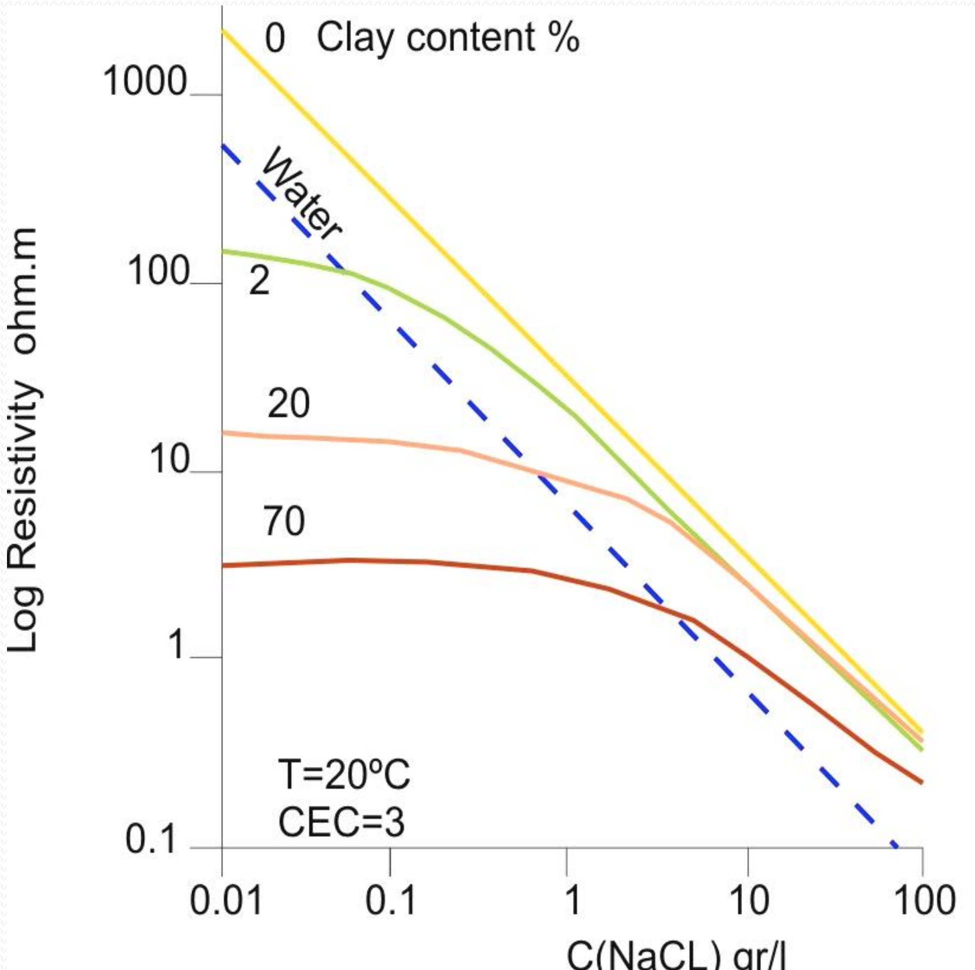
Lithology



Why resistivity?

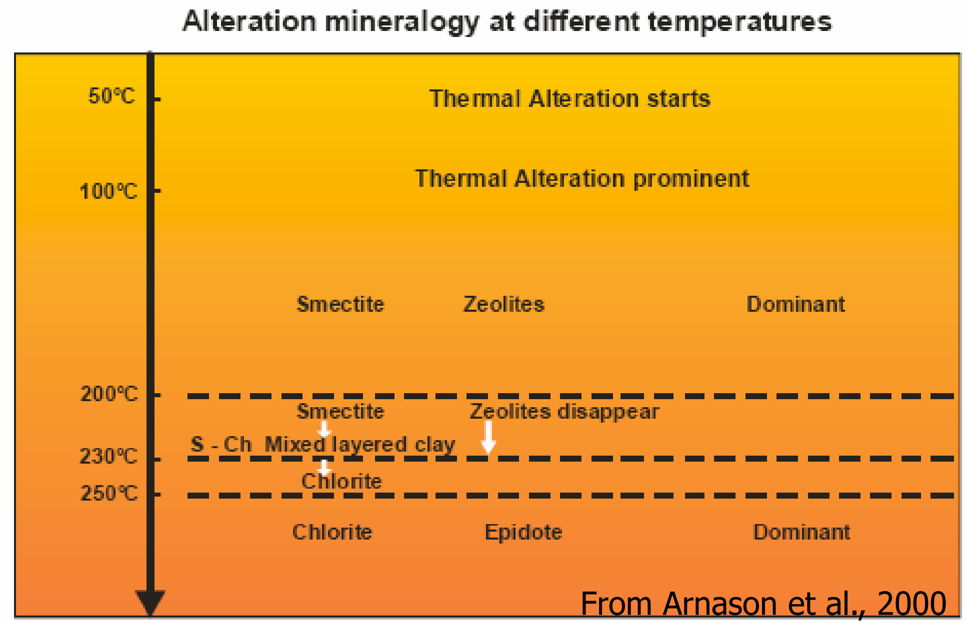
Clay minerals

Resistivity is strongly affected by the presence of clays. In this case there is an electrolyte conductivity dominance



Why resistivity?

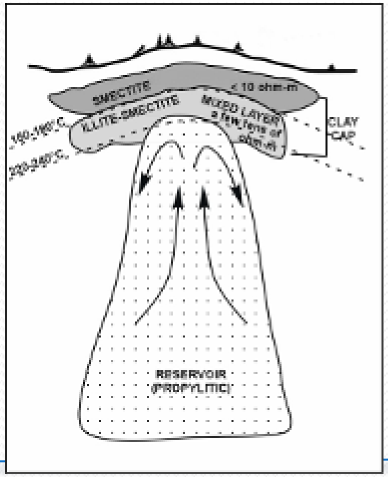
Clay minerals and surface conduction



From Arnason et al., 2000

Clays not only decrease the resistivity by themselves, but also increase the surface effect (frequency-dependent IP)

The resulting resistivity is also related to the presence of clay minerals, and can be reduced considerably when the clay minerals are broadly distributed.



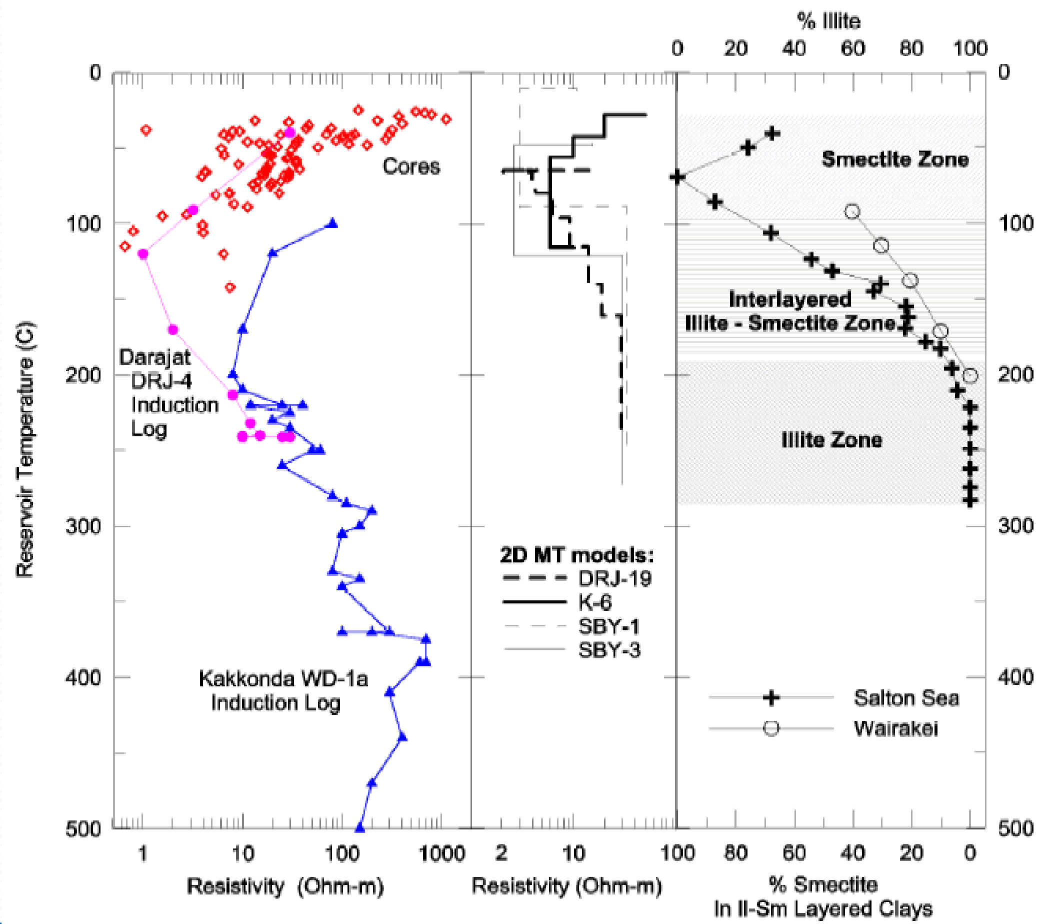
From Pellerin et al., 1996

Why resistivity?

Clay minerals and surface conduction

The effect of clay over the resistivity is important in geothermal areas since clayey alteration minerals are very frequent, particularly in volcanic rocks.

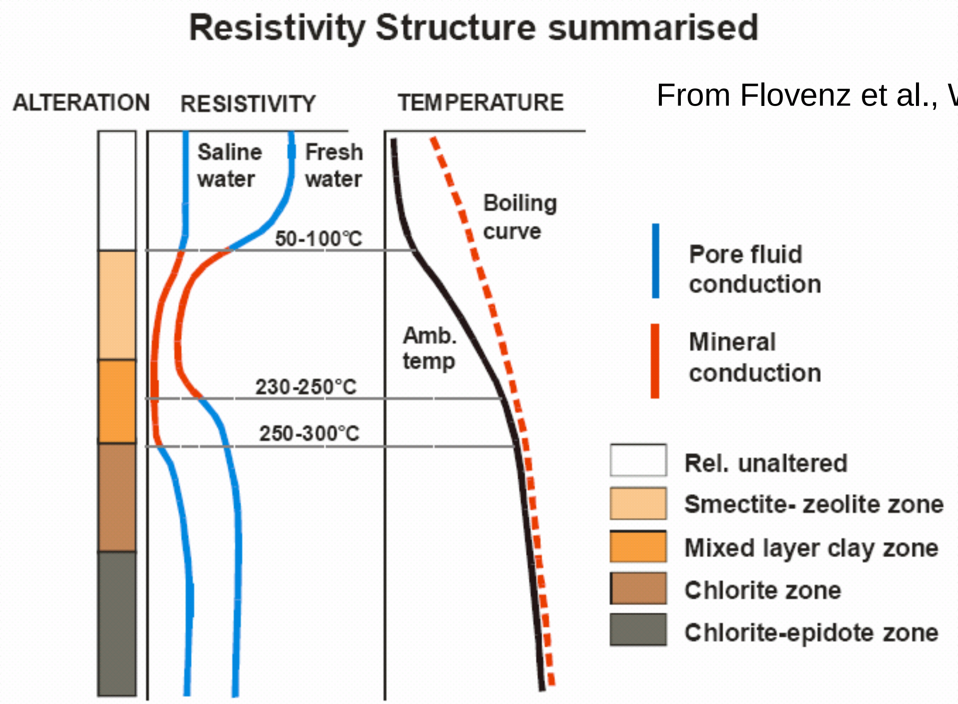
Comparison of the resistivity structure with geological data in volcanic geothermal fields has shown a good correlation with alteration mineralogy.



Why resistivity?

Clay minerals and surface conduction

Resistivity should be always considered with care. Experience has shown that the apparent one-to-one correlation between low resistivity and the presence of fluids is not correct, since alteration minerals produce comparable, and often higher reduction of resistivity with respect to fluid flow.



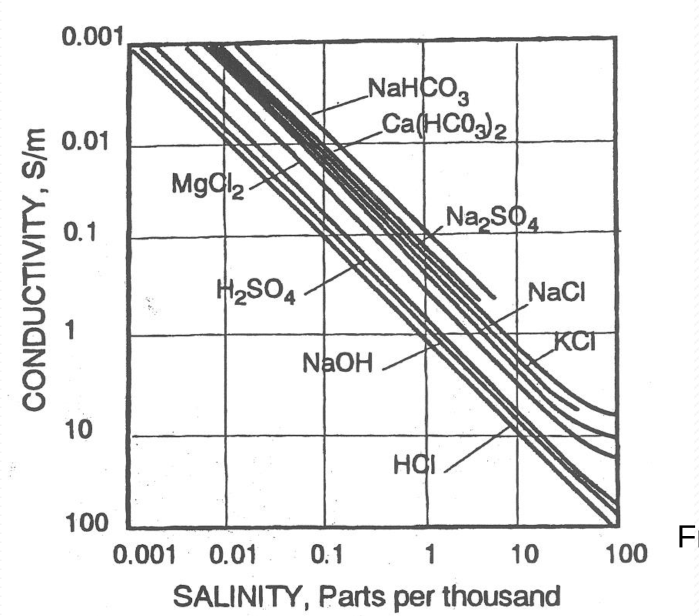
From Flovenz et al., WGC2005

Moreover, although the hydrothermal systems in volcanic rocks have an associated low-resistivity signature, the converse is not true.

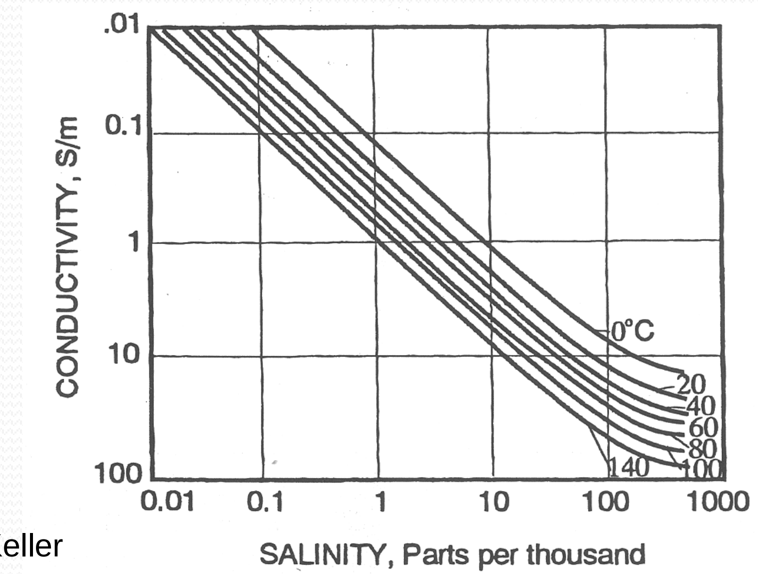
Why resistivity?

Salinity

Geothermal waters have high concentrations of dissolved salts which provide conducting electrolytes within a rock matrix



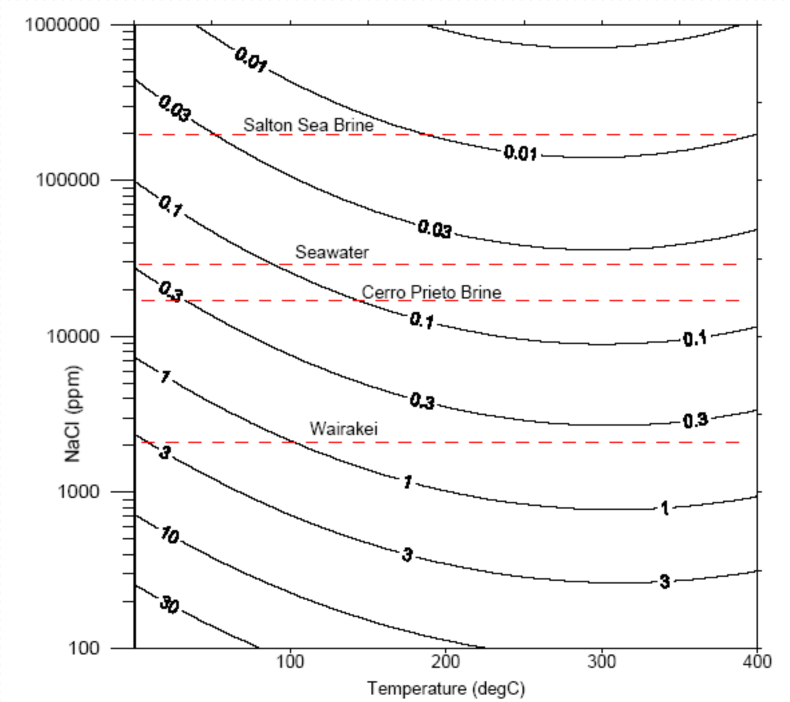
From Keller



As a result, it is not unusual to see an increase in conductivity by an order of magnitude or more in a geothermal reservoir compared with rocks at normal temperatures removed from the reservoir.

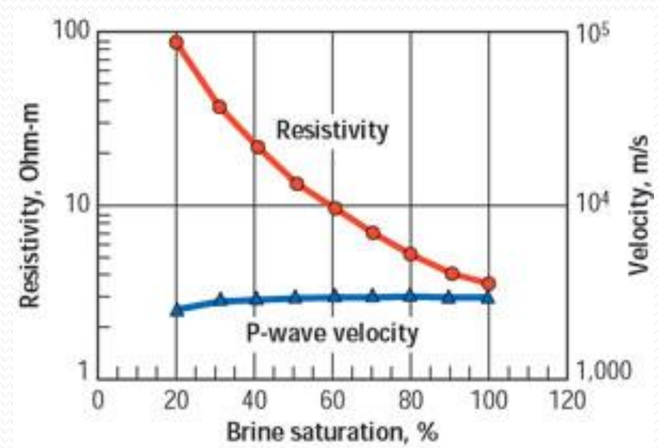
Why resistivity?

Salinity



Variation of resistivity (in ohm-m) of NaCl solutions. The salinity of several known geothermal field is also shown.

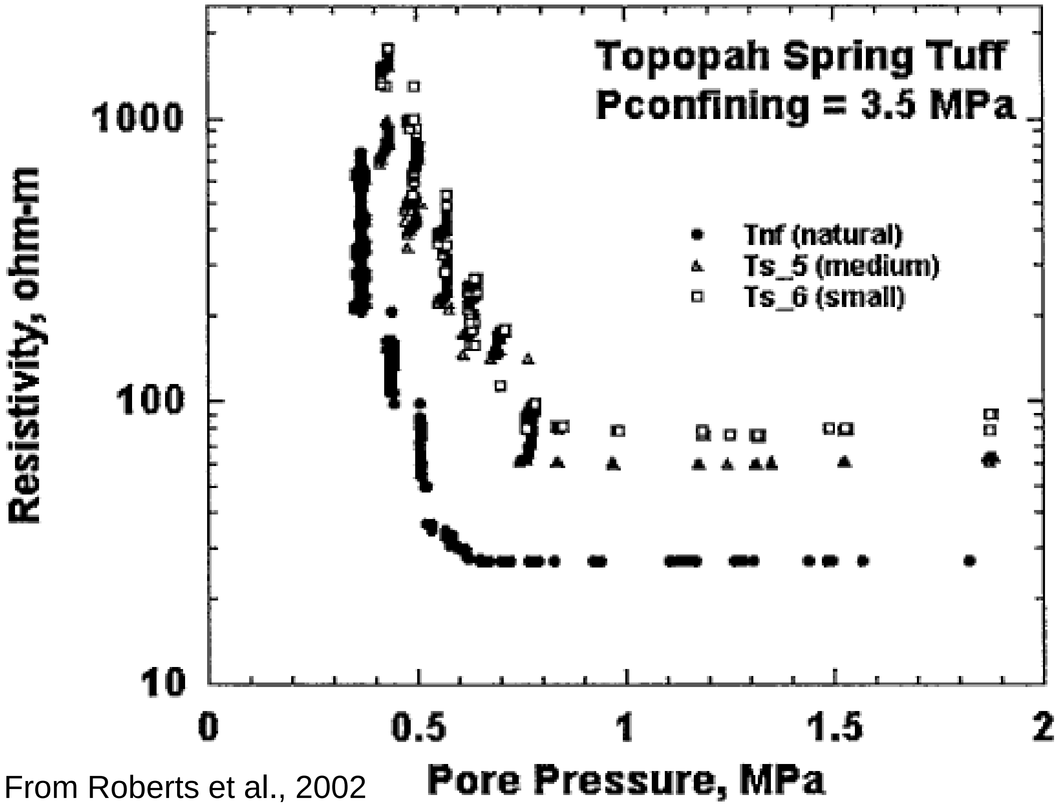
From Ussher et al., WGC2000.



From Wright, Ziolkowski & Hobbs TLE 9/02; after Wilt & Alumbaugh, 1998

Why resistivity?

Fluid phase



From Roberts et al., 2002

Why resistivity?

Hydraulic properties

In most rocks there is an empirical relationship, established by *Archie (1942)*, between the ratio of the bulk rock resistivity, ρ_b, to the pore fluid resistivity, ρ_f, called the formation factor, F, and the volume fraction porosity, ϕ. The relationship, now called Archie's law, is:

$$\frac{\rho_b}{\rho_f} = F = a\phi^{-m}$$

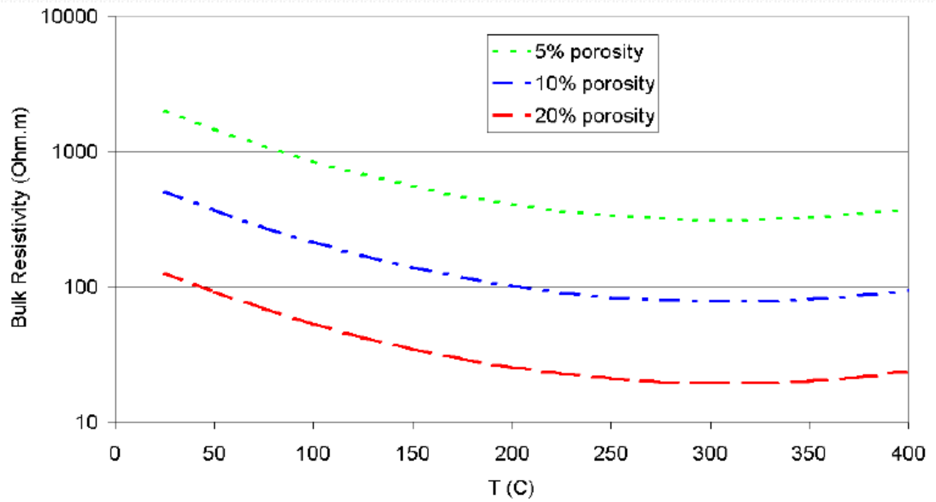
a, m empirical parameters.

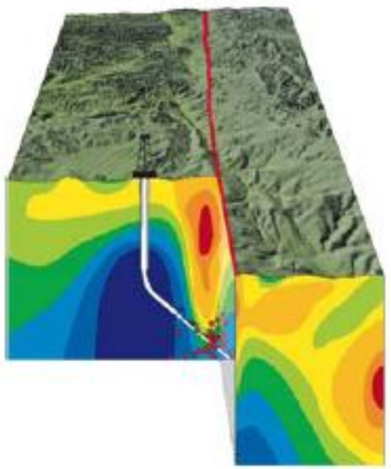
The equation apply when clays are not present

Why resistivity?

Hydraulic properties

$$\frac{\rho_b}{\rho_f} = F = a\phi^{-m}$$





Bulk resistivity versus temperature for rocks saturated with 1000 ppm NaCl solutions, using Archie's law.

From Ussher et al., WGC2000.

Why resistivity?

Hydraulic properties

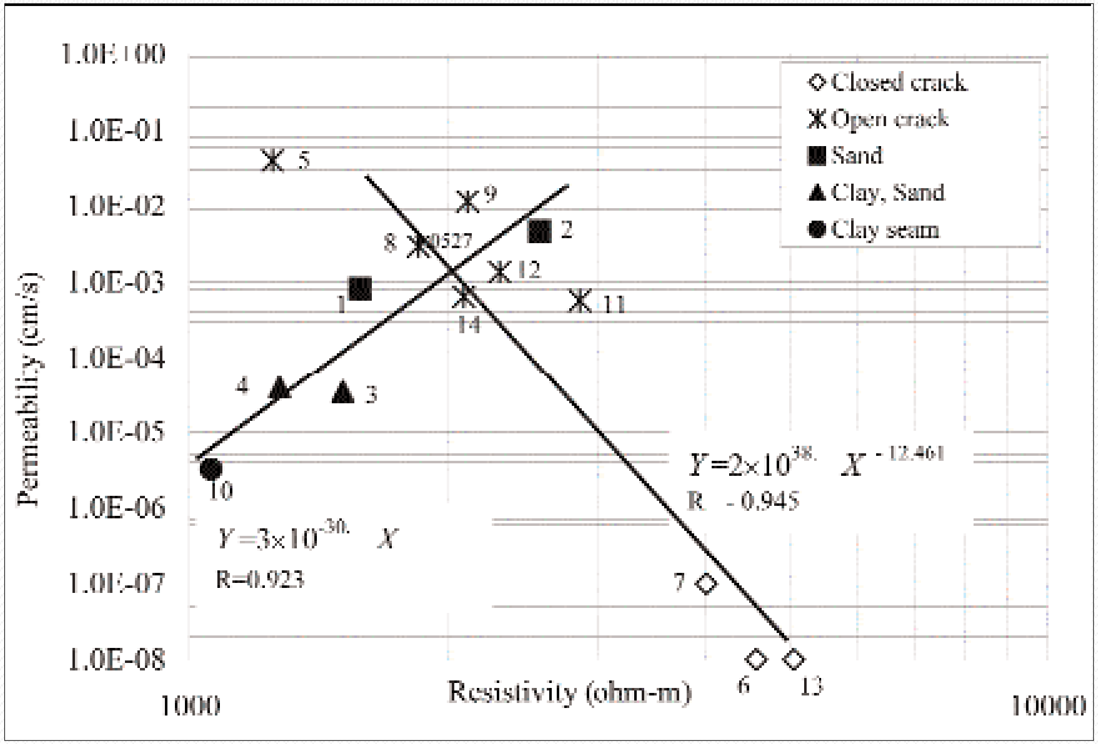
$$\frac{\rho_b}{\rho_f} = F = a\phi^{-m}$$

When clays are present, Archie's law modifies to a general law

$$\rho = f(a, \rho_w, \phi, m, \rho_{clay})$$

Why resistivity?

Hydraulic properties



Relationship between resistivity and permeability measured in three boreholes in Mt. Tsukuba in Ibaraki Prefecture, central Japan (*Sudo et al., 2004*).

Some empirical equations relating resistivity and permeability (or other hydraulic parameters) were obtained on the electrical logging and in-situ permeability data from boreholes.

They are site-specific and requires wells

Why resistivity?

Hydraulic properties

Frequency dependent complex property

$$\sigma^* = \frac{1}{\rho^*} = i\omega\varepsilon^*$$

$$\sigma_{eff}(\omega) = \sigma'(\omega) + i\sigma''(\omega)$$

-Real component σ’ ohmic conduction (energy loose) measured with EM and DC methods

-Imaginary component σ” polarization (energy storage) measured with IP, SP methods

Complex conductiviy σ*

real part σ'

Pore-volume conductivity(electrolite)

Petrophysics

Porosity Φ

Formation factor F

Pore –surface conductivity (CEC)

Surface area (S_s)

Grain size

Clay content

imaginary part σ"

Pore –surface conductivity (CEC)

Surface area (S_s)

Grain size

Clay content

Kozeny-Carman

Hydraulic conductibity K/ permeability k $k = \frac{\phi \ r^2}{aT}$

Why resistivity?

Fluid flow

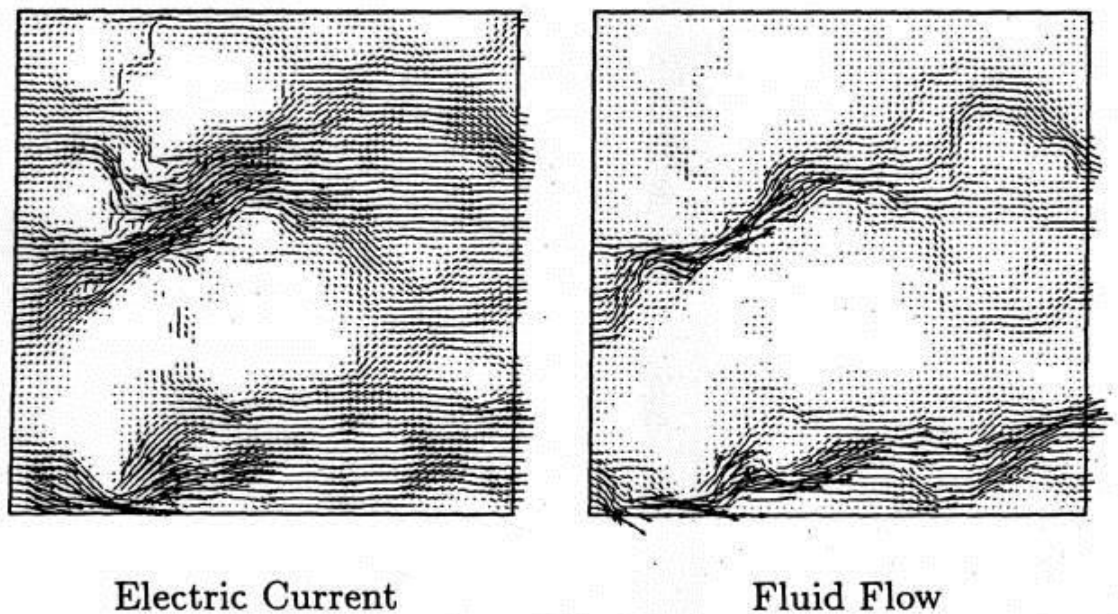


Fig. 5. Electric current and volume flow rate fields for the same fracture as Figure 4. The surface separation is $d_m = 1\sigma$. The magnitude and direction of the local electric current and volume flow rate are represented by small vectors. For comparison, the longest volume flow rate and electric current vectors were scaled to have the same length. Contact areas are shown as blank patches.

Lab measurements have shown that hydraulic and electric flow follow the same paths, but currents are more diffusive

EM Geophysical methods

natural-source induction methods

(magnetotellurics, audiomagnetotellurics and self-potential)

controlled-source induction methods

(TDM, CSMT, VLF)

direct current methods

(VES, electric tomography)

Their objective is the mapping of electrical structures at depths that are meaningful in terms of geothermal exploration.

These depths must be several kilometres at least when looking for the anomaly in conductivity associated with reservoir rocks, and several tens of kilometres when seeking the thermally excited conductive zone associated with the source of a geothermal system.

EM Geophysical methods

Inductive methods usually provide information on conductivity-thickness products of conductive layers, whereas they usually provide only thickness information on resistive layers.

On the contrary, resistivity techniques usually provide information on resistivity-thickness products for resistive layers and conductivity-thickness products for conductive layers.

For this reason, inductive methods are the most suitable for geothermal exploration, since the target is conductive.

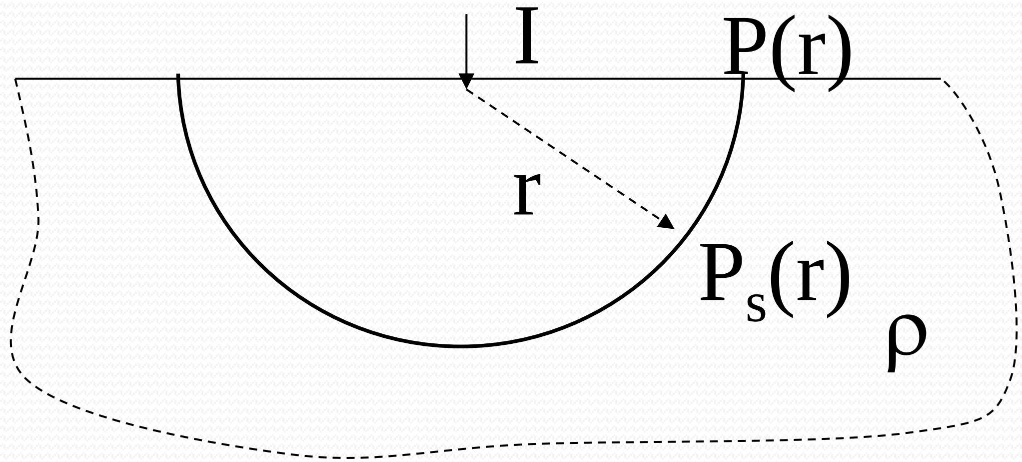
ELECTRICAL (DC) METHODS

The direct current methods achieve control of the depth of the penetration by regulating the geometry of the array of equipment used.

Two principal variations of the direct current method have found use in geothermal exploration, though there has been some controversy in the literature over the relative merits of these techniques.

ELECTRICAL (DC) METHODS

For a point source in a homogeneous body



Ohm's law is applied

$$V = RI = \rho \frac{l}{s} I$$

where

$$l = r$$

$$s = \frac{4\pi r^2}{2}$$

$$V_{P_s(r)} = V_{P(r)} = \rho \frac{r}{\frac{4\pi r^2}{2}} I$$

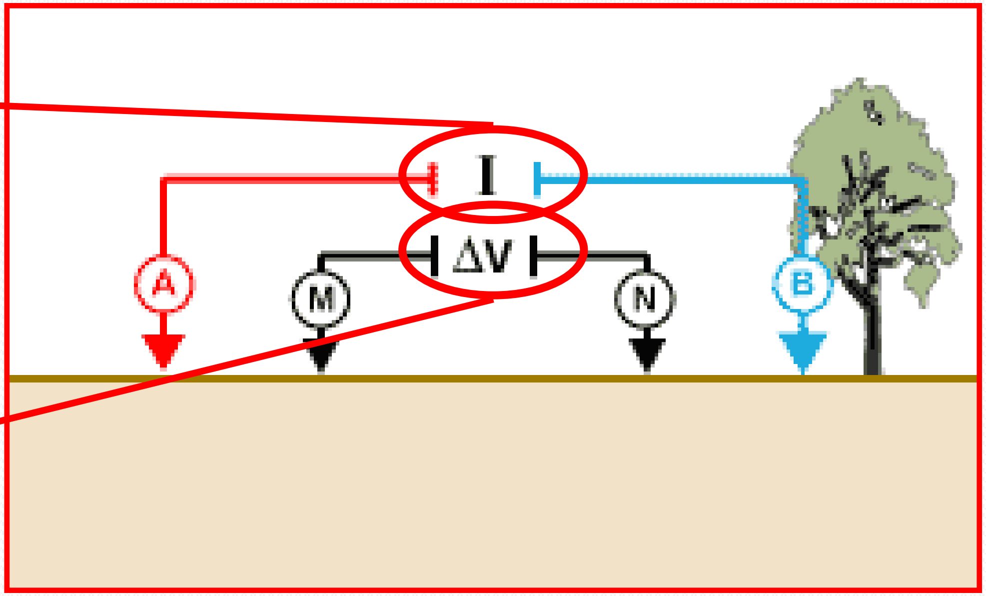
$$\rho = 2\pi r \frac{V_{P(r)}}{I} = k \frac{V_{P(r)}}{I}$$

ELECTRICAL (DC) METHODS

In practice current is injected through a couple of electrodes (usually named A and B) and the voltage difference is measured between two other electrodes (usually named M and N)

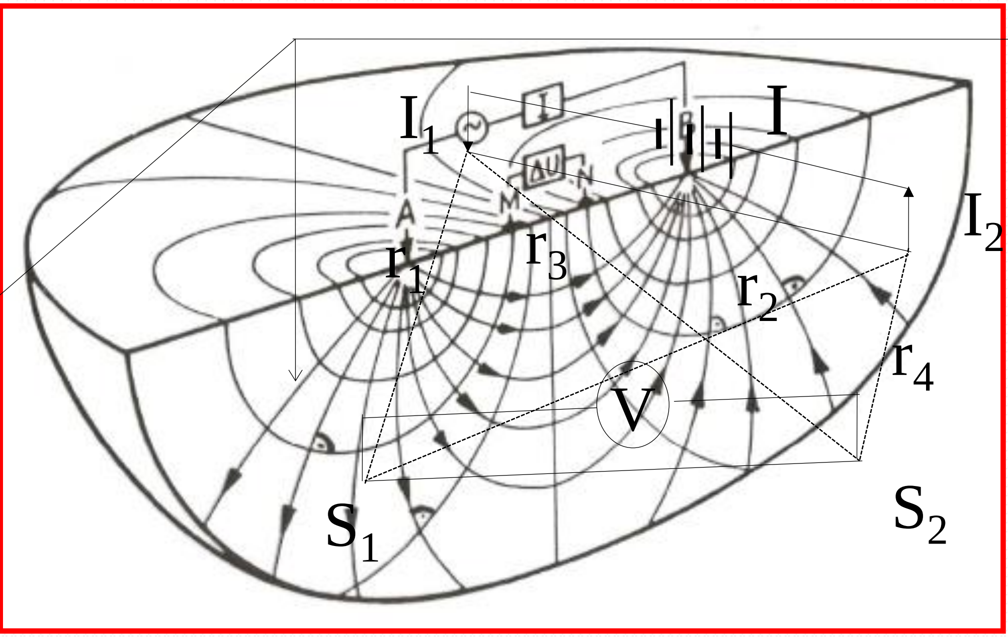
Injected current

Resulting voltage difference



ELECTRICAL (DC) METHODS

For a measuring quadripole in a homogeneous body



$$V_{S1} = \frac{\rho I}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2}\right]$$

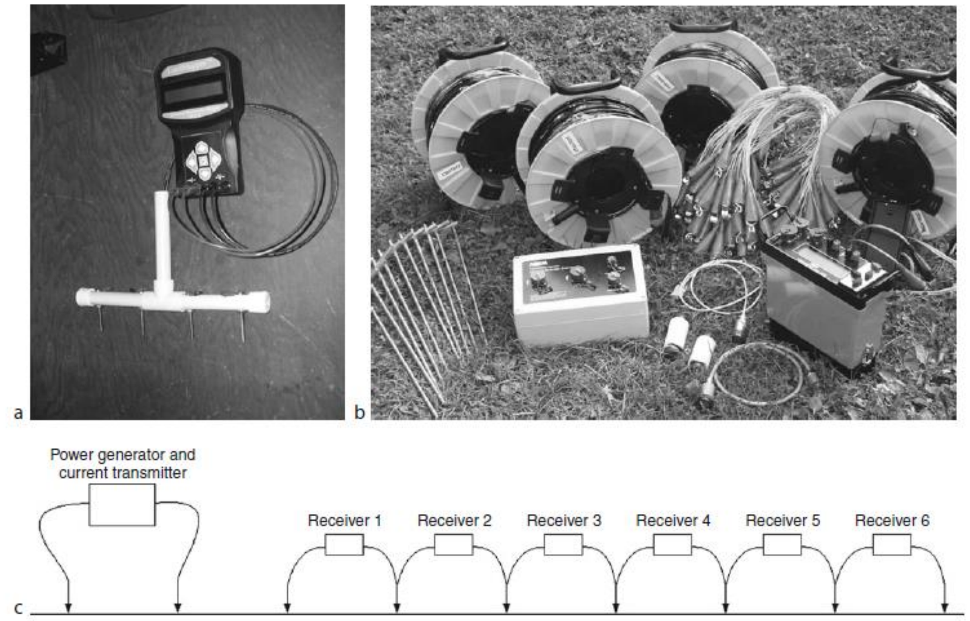
$$V_{S2} = \frac{\rho I}{2\pi}\left[\frac{1}{r_3} - \frac{1}{r_4}\right]$$

$$V_{S1-S2} = \frac{\rho I}{2\pi}\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right]$$

$$\rho = \frac{2\pi}{\left[\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right]}\frac{\Delta V}{I} = k\frac{\Delta V}{I}$$

The basic parts of a resistivity measurement system include a source of electrical current, a voltage measuring system, and the cables to connect these components to the electrodes. A typical system (with associated cables and electrodes) for environmental and engineering surveys that uses an internal battery usually weigh between 10 and 50 kg. The current source and voltage measuring circuitry are integrated into a single unit (the resistivity meter), and the investigayion depth is about 200 m.

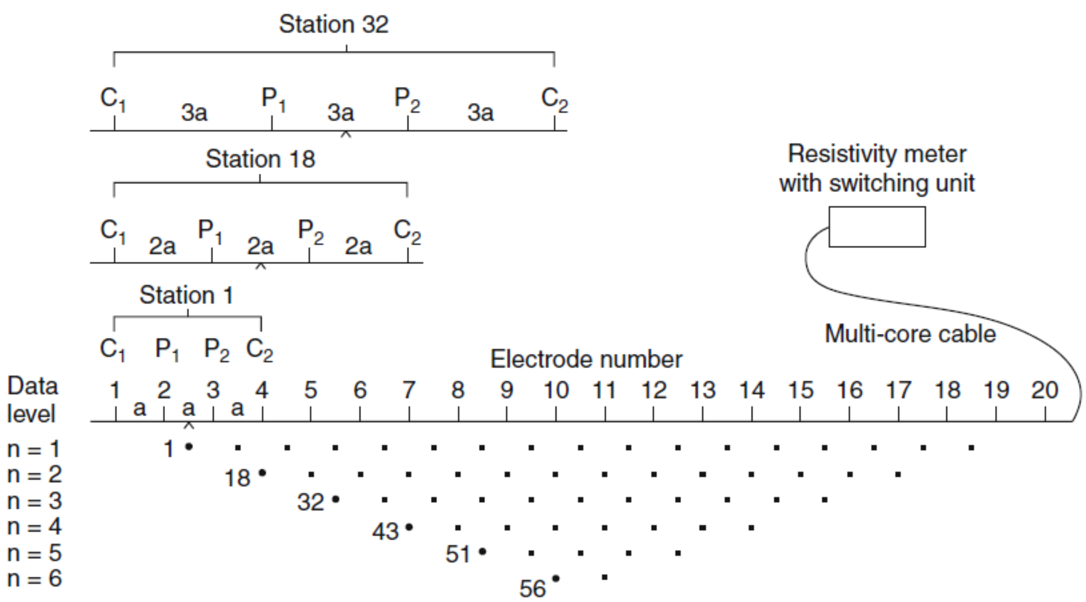
For deeper surveys where currents of up to 10 A are used, a petrol/diesel engine– powered electric generator is usually used. Such systems can weigh several hundred kilograms.



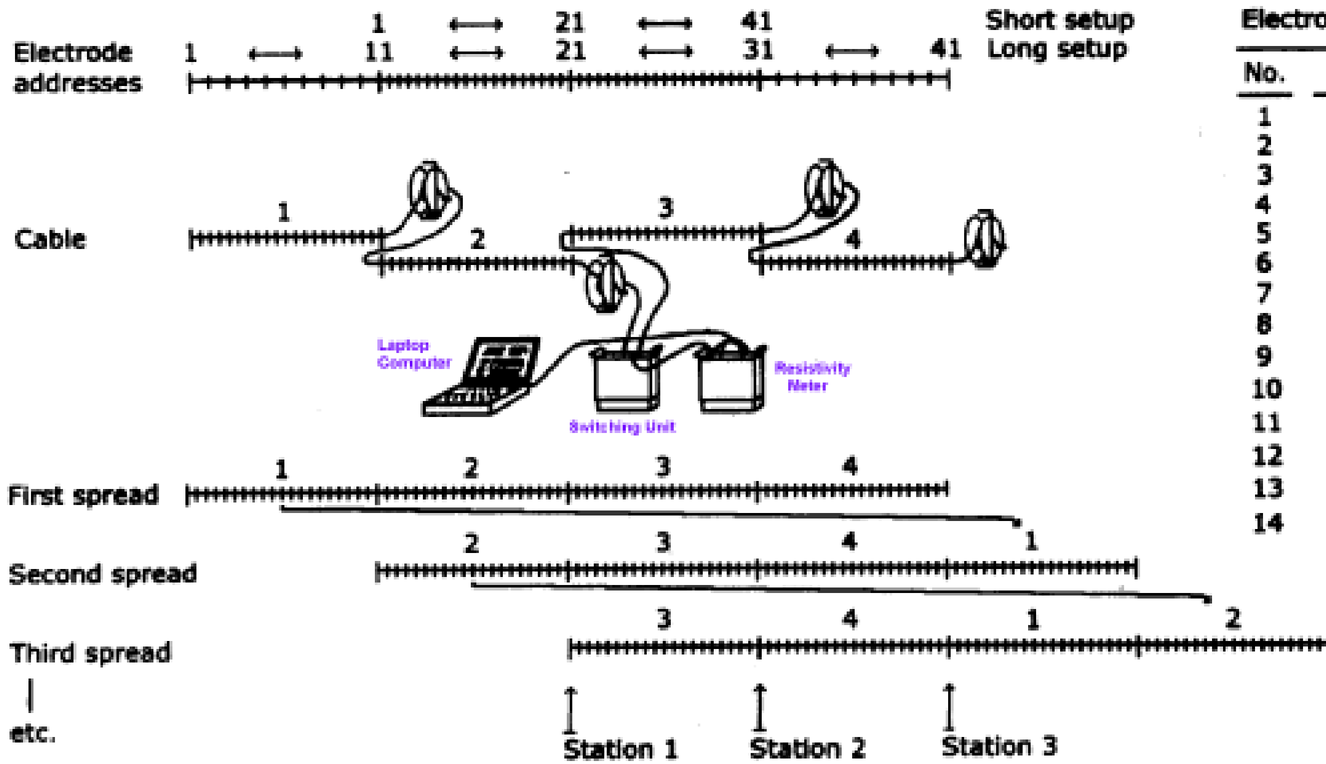
Instrumentation, Electrical Resistivity, Figure 2 Different classes of resistivity instruments. **(a)** A lightweight portable system (courtesy of Landviser LLC). The distance between the electrodes in the above picture is 5 cm. **(b)** A typical system used for shallow environmental and engineering surveys (courtesy of Torleif Dahlin and Abem Instruments AB.), and **(c)** a schematic diagram of a system for deep surveys.

Before early 1990s, the electrical resistivity method was mainly used in resistivity sounding, profiling, and mapping surveys and quantitative interpretation was mainly confined to 1-D (one-dimensional) structure of the subsurface consisting of horizontal layers.

The development of multielectrode and multichannel systems over the past 20 years has sparked a revolution in resistivity surveying. The advent of 2-D and 3-D (three-dimensional) resistivity tomography has opened up whole new application areas to electrical methods.
The multielectrode systems made it practical to carry out 2-D imaging surveys that give a more accurate picture of the subsurface in a routine manner.



Instrumentation, Electrical Resistivity, Figure 4 Schematic diagram of a multielectrode system used for a 2-D electrical survey and an example sequence of measurements used to build up a pseudosection using the Wenner array.

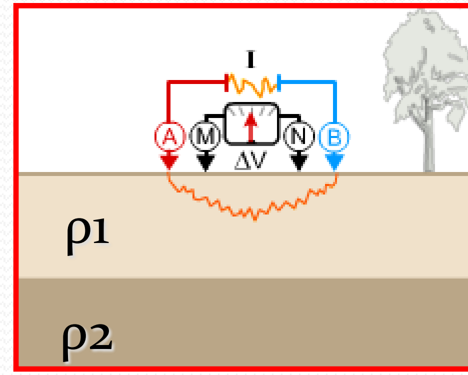


Electrode spacings		
No.	A	B
1	120	48
2	110	44
3	100	40
4	90	36
5	80	32
6	70	28
7	60	24
8	50	20
9	40	16
10	30	12
11	20	8
12	15	6
13	10	4
14	5	2

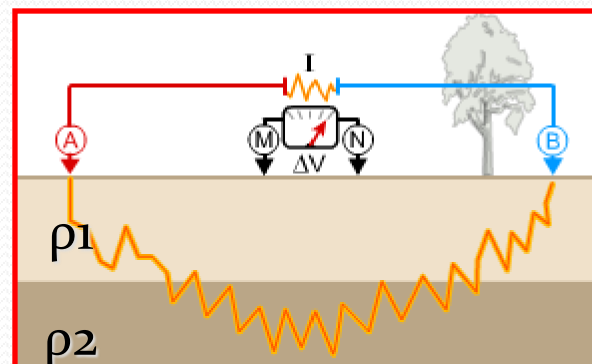
Figure 2.3. Sketch outline of the ABEM Lund Imaging System. Each mark on the cables indicates an electrode position (Dahlin 1996). The cables are placed along a single line (the sideways shift in the figure is only for clarity). This figure also shows the principle of moving cables when using the roll-along technique. The total layout length depends on the spacing between the nodes, but is usually between 160 meters and 800 meters.

ELECTRICAL (DC) METHODS

Short electrode distance (AB): the current is essentially confined to the shallow layer (resistivity ρ1) and the apparent resistivity value is related only to ρ1.



For increasing AB distance, a progressively larger current portion flows in the deeper layer with resistivity ρ2 and the apparent resistivity is more and more influenced by ρ2.

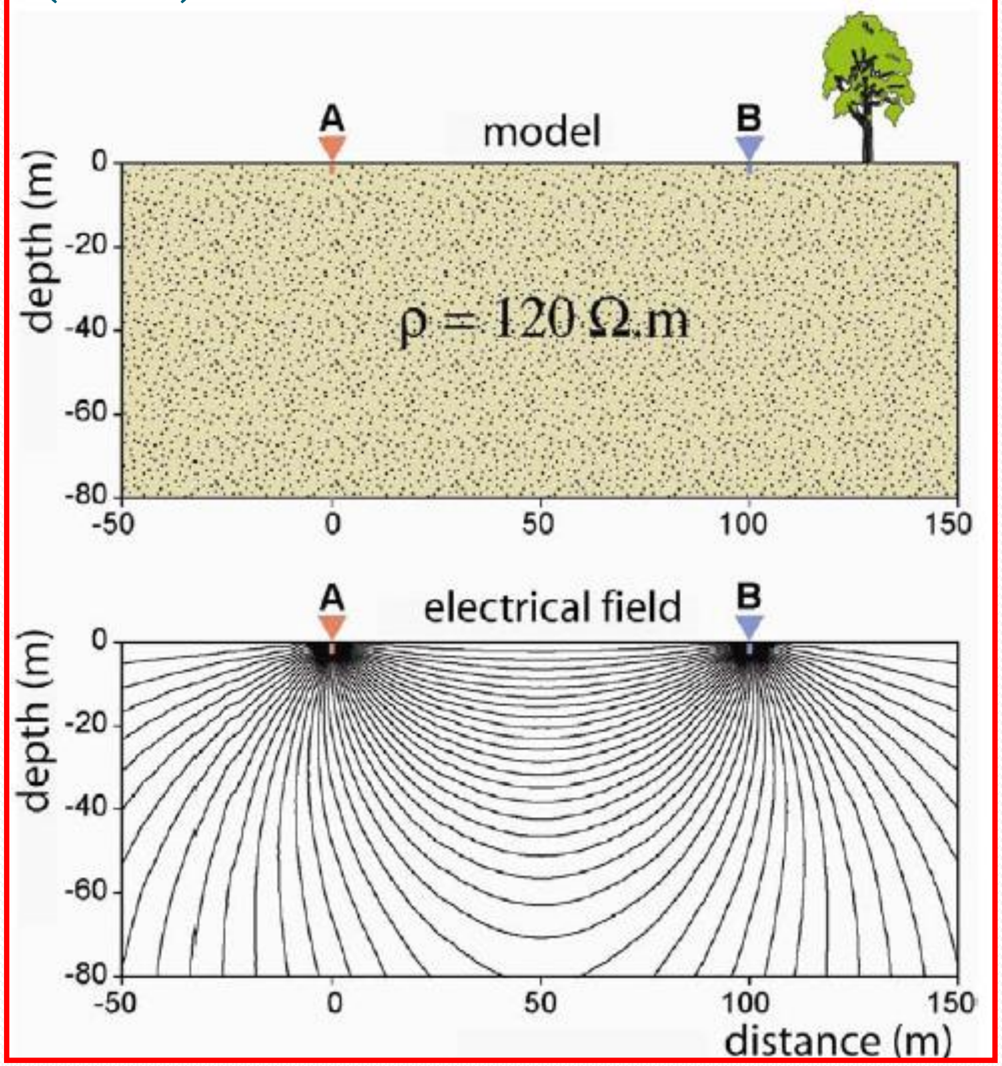


ELECTRICAL (DC) METHODS

As a rule of thumb, the investigation depth is in the range :

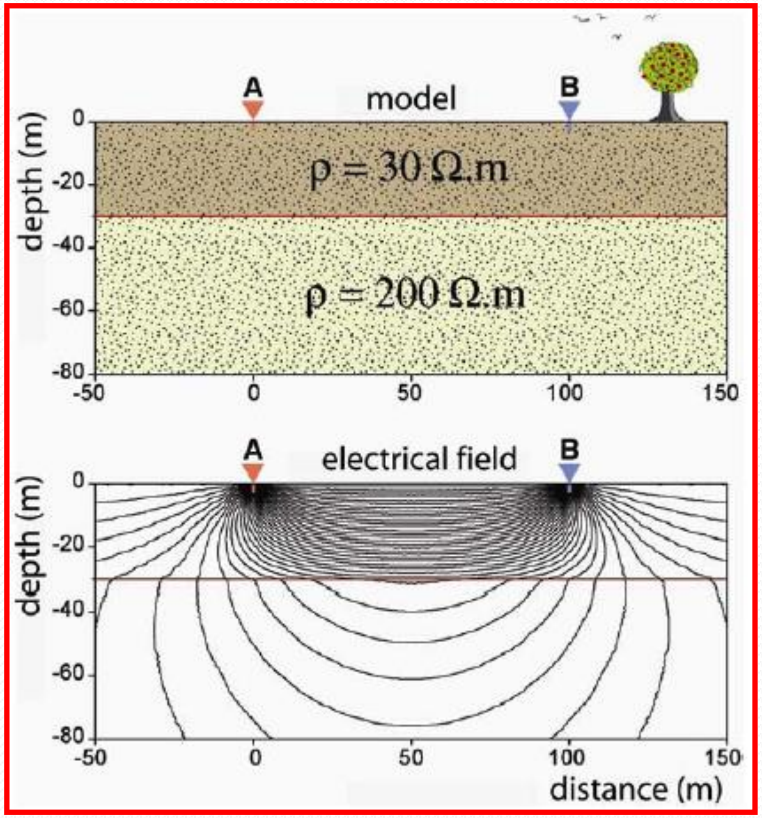
AB/4 – AB/8

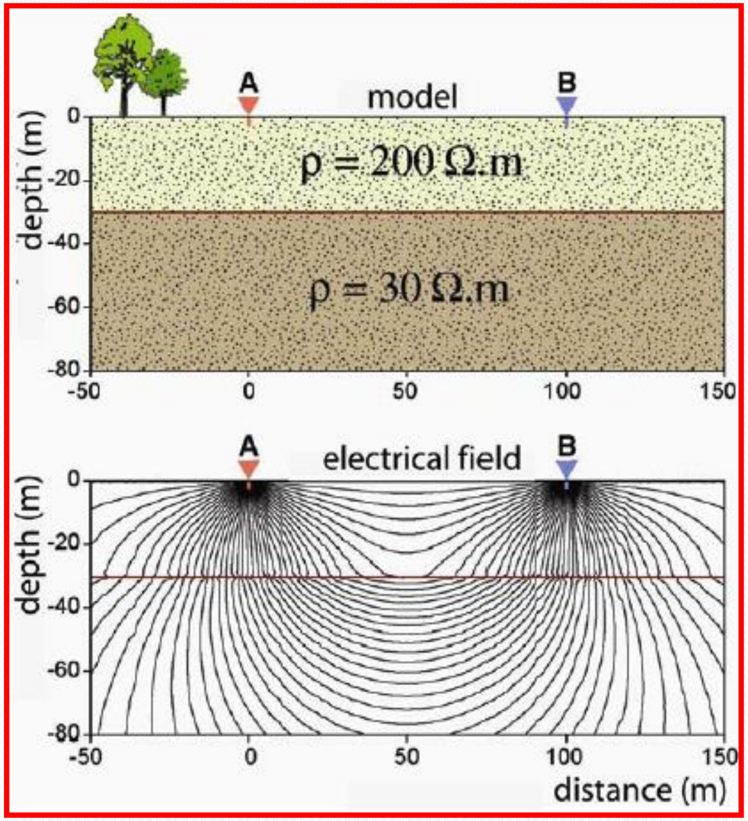
This determines long arrays, and difficult layout to reach large investigation depths.



ELECTRICAL (DC) METHODS

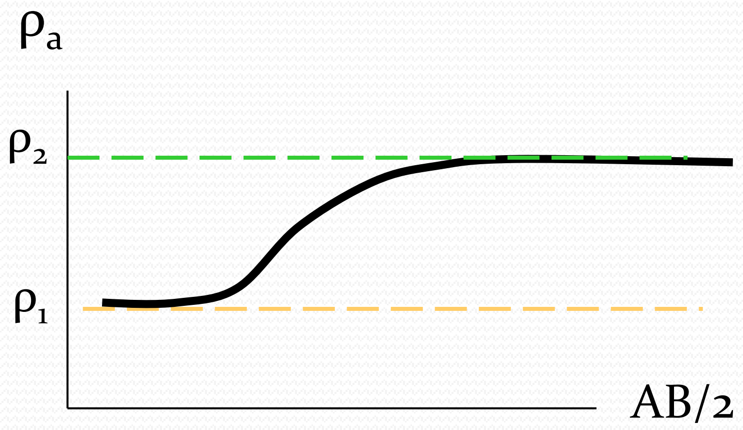
In a stratified terrain:

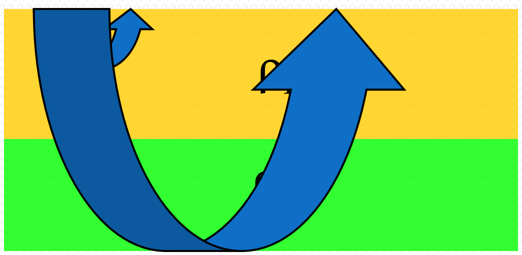




- Current line dendity is higher in conductive layers.
- Shallow resistive layers limit current propagation at depth.

ELECTRICAL (DC) METHODS





Data are represented as an “apparent resistivity”, defined as the resistivity of the homogeneous earth which would produce the measured response at a certain distance between transmitter electrodes

ELECTRICAL (DC) METHODS

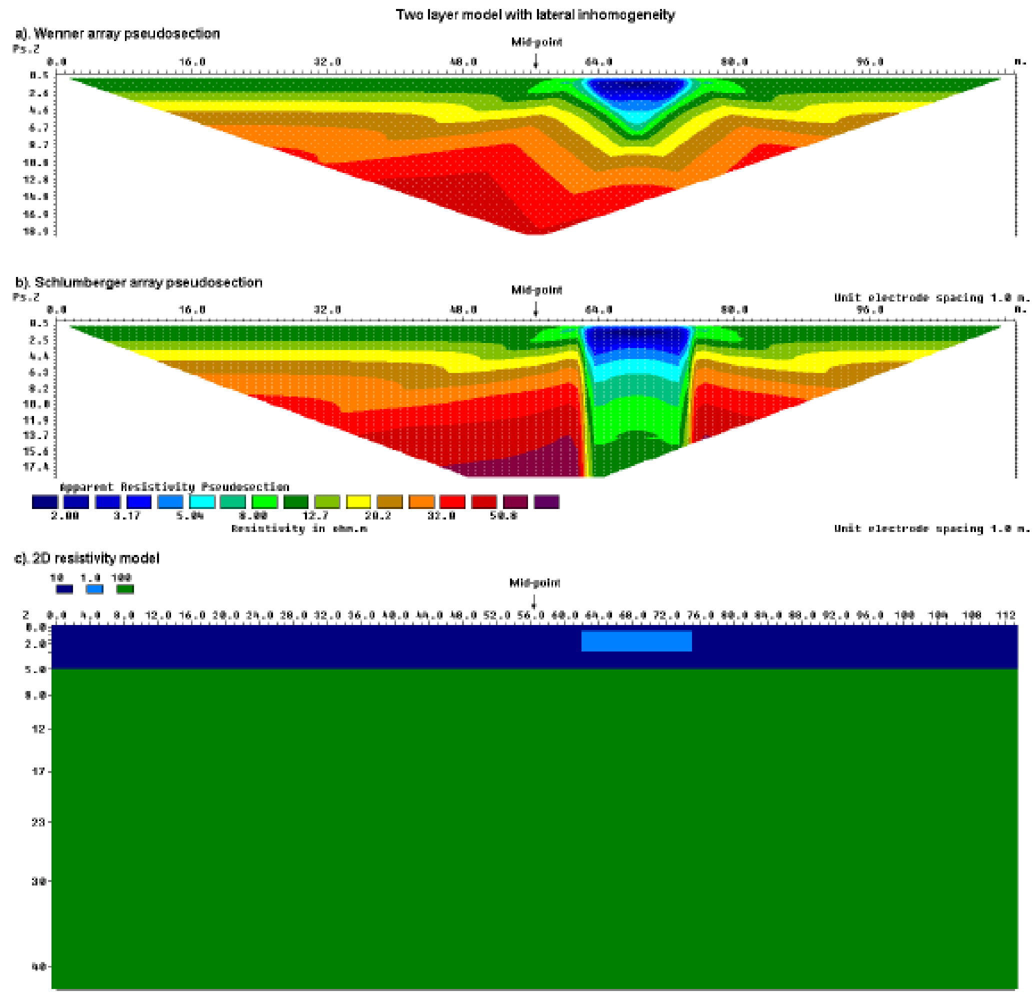
The resulting image is a pseudosection apparent resistivity versus depth.

The horizontal location of the point is placed at the mid-point of the set of electrodes used to make that measurement. The vertical location of the plotting point is placed at a distance that is proportional to the separation between the electrodes.

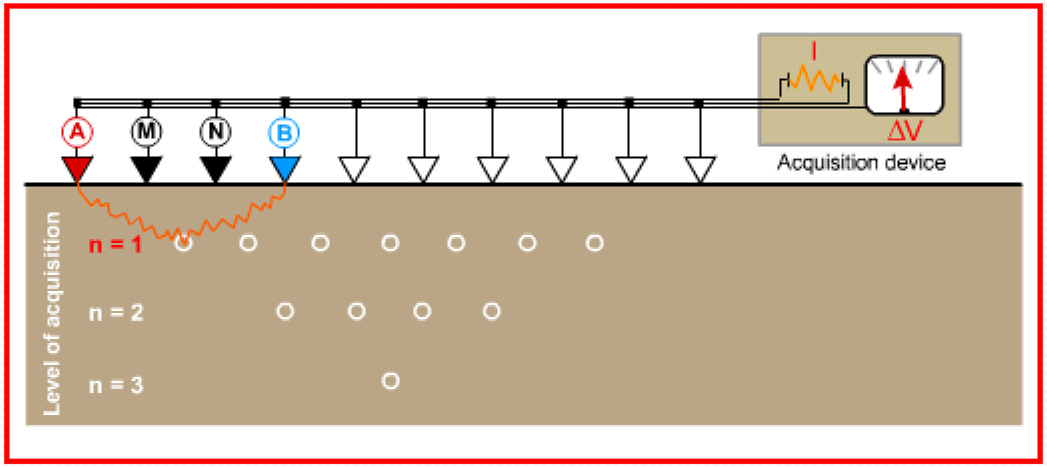
The pseudosection gives a very approximate picture of the true subsurface resistivity distribution.

ELECTRICAL (DC) METHODS

However the pseudosection gives a distorted picture of the subsurface because the shapes of the contours depend on the type of array used as well as the true subsurface resistivity

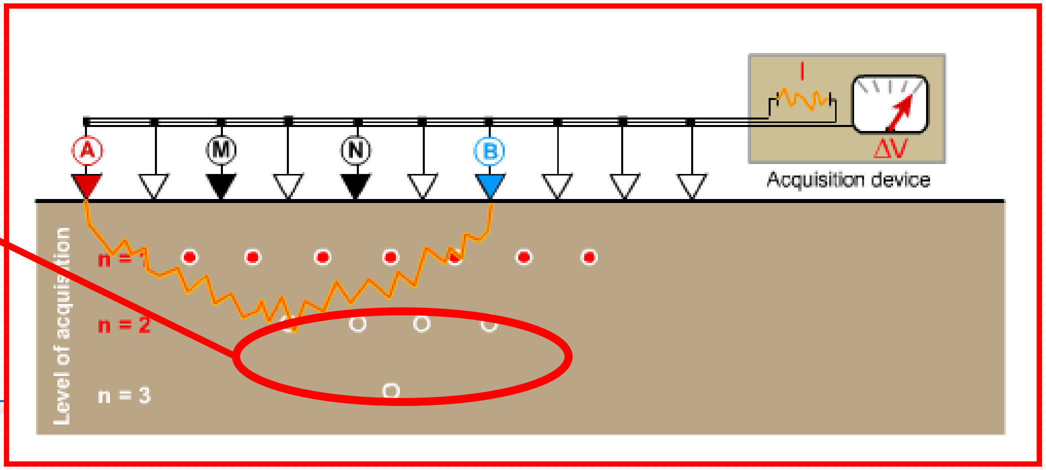


ELECTRICAL (DC) METHODS



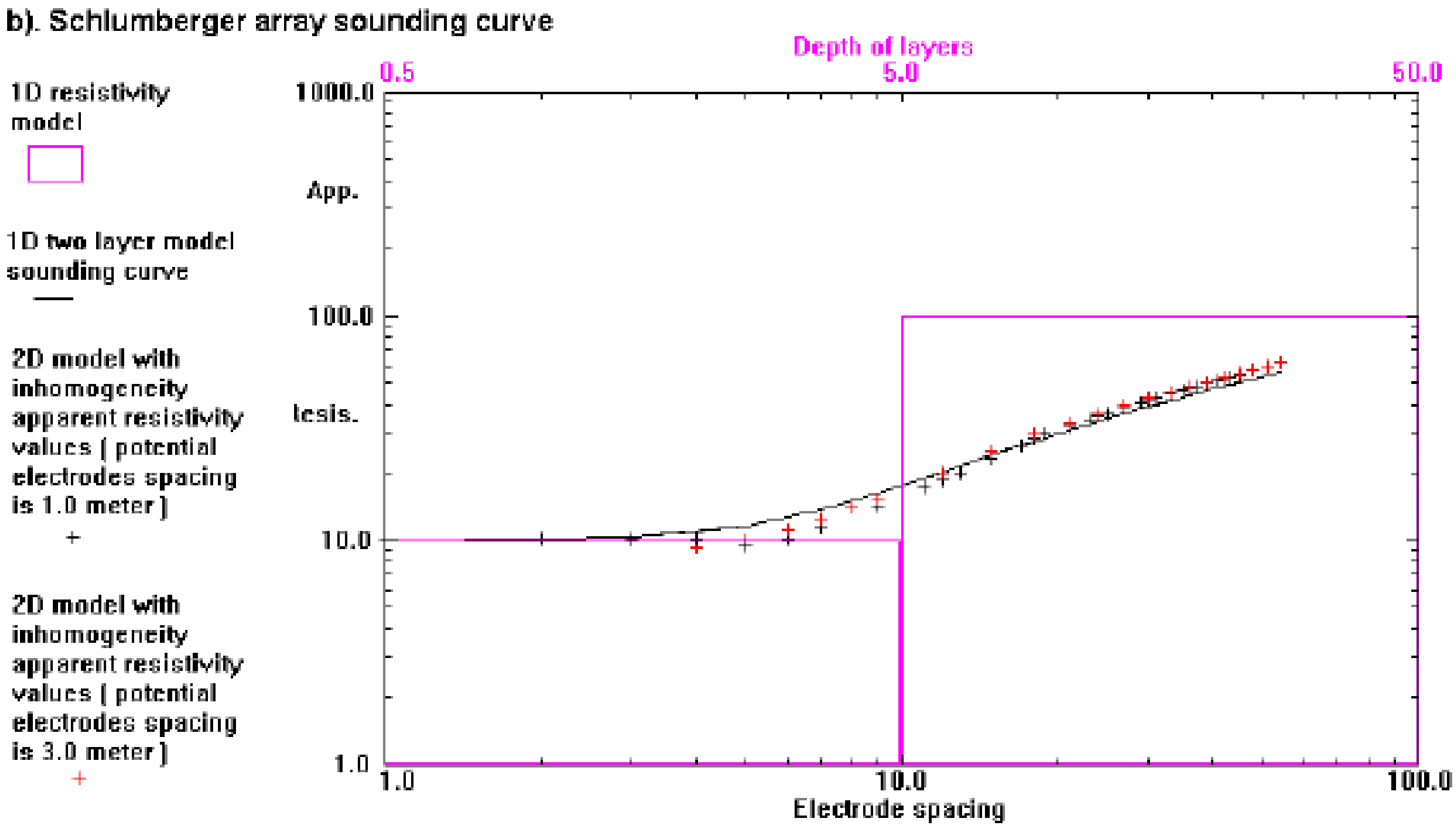
The number of measurements decreases for increasing electrode distance.

The maximum investigation depth is at the center of the profile.

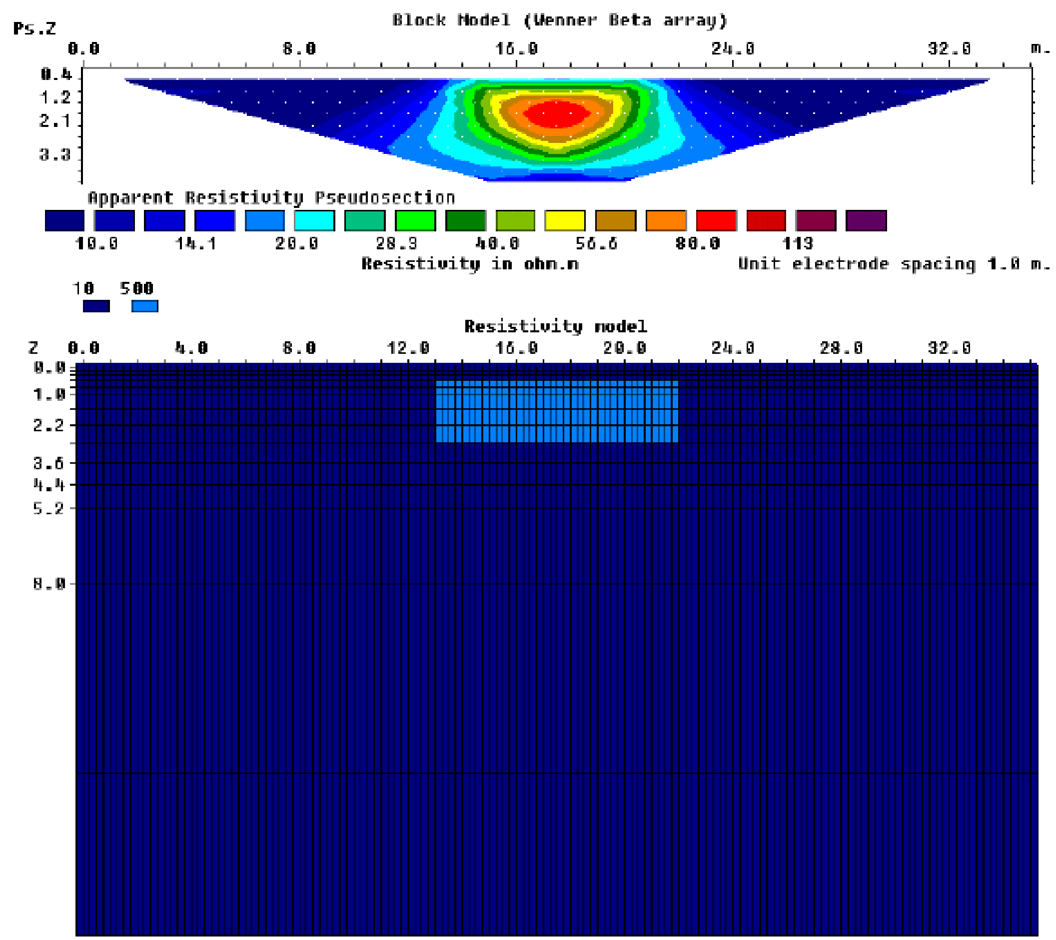


ELECTRICAL (DC) METHODS

Data are then modelled using available software. Modelling can be performed in 1D (resistivity sounding method), 2D and 3D mode, both in forward and inverse mode.



An example of 2D forward modelling



In inversion, the first step is to erase bad data point (noise) either manually or automatically.

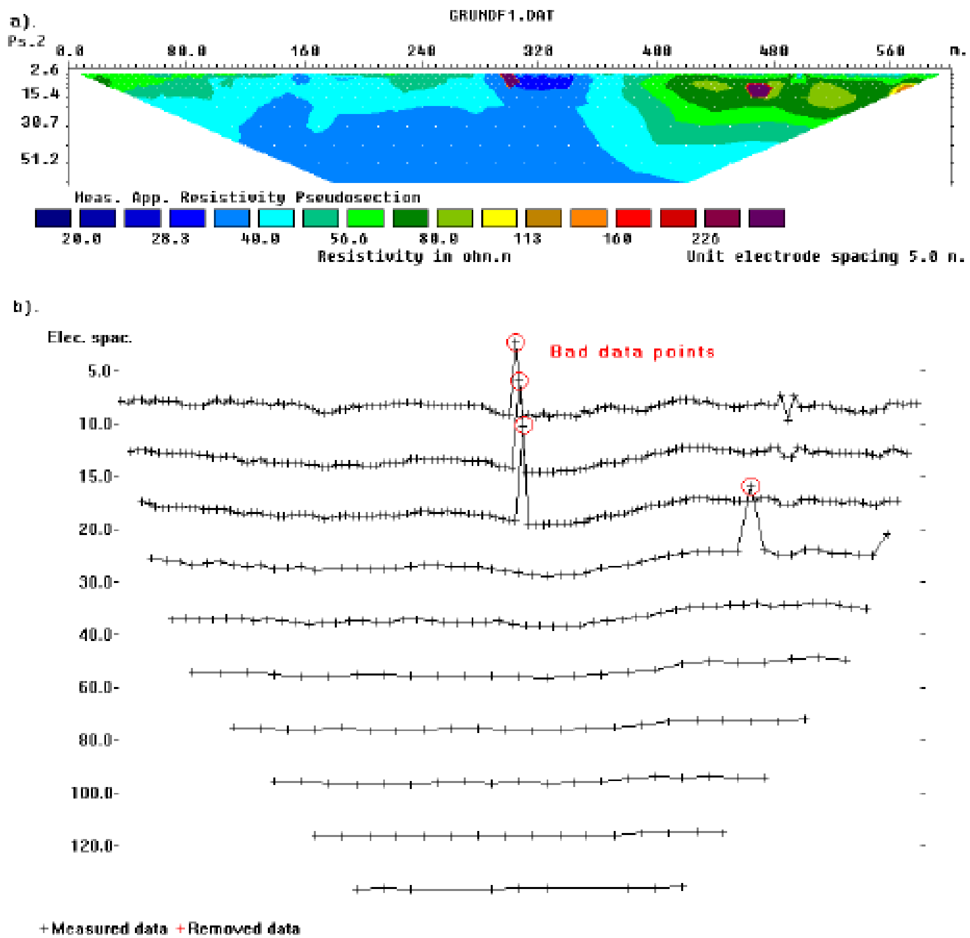
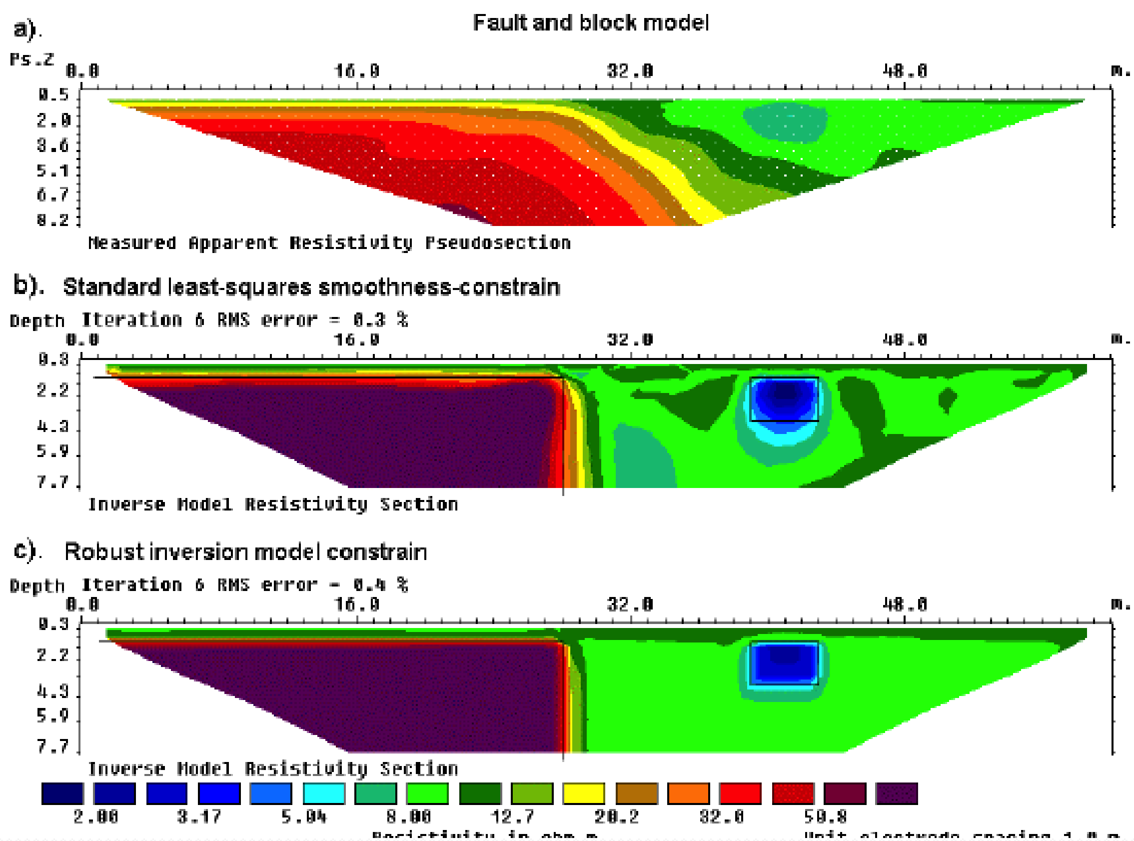


Figure 4.1. An example of a field data set with a few bad data points. The most obvious bad datum points are located below the 300 meters and 470 meters marks. The apparent resistivity data in (a) pseudosection form and in (b) profile form.

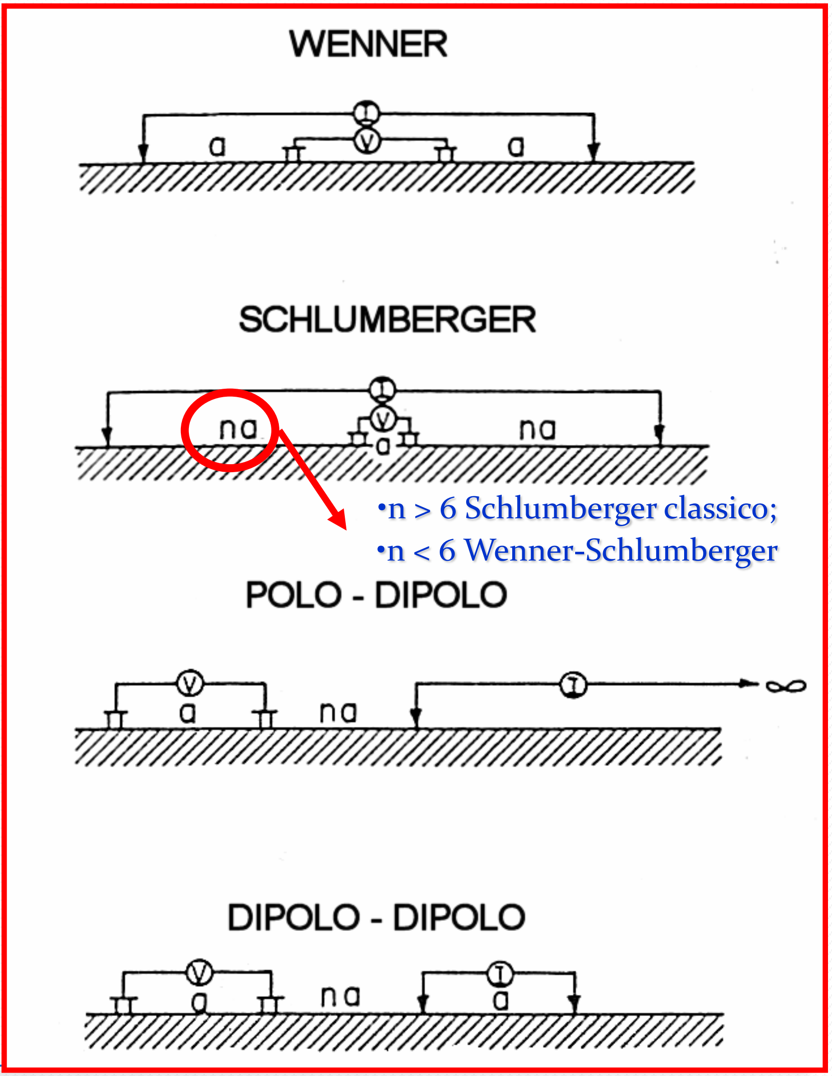
After choosing the parametr setting, the inversion provides the “true” distribution of resistivity with depth, i.e., the distriution of the best fit of experimental data with a resistivity distribution model.



Pseudosection is also produced (top), for comparison with the experimental one

ELECTRICAL (DC) METHODS

Various kinds of measuring quadripole exists (standard quadripoles)



They differ for:

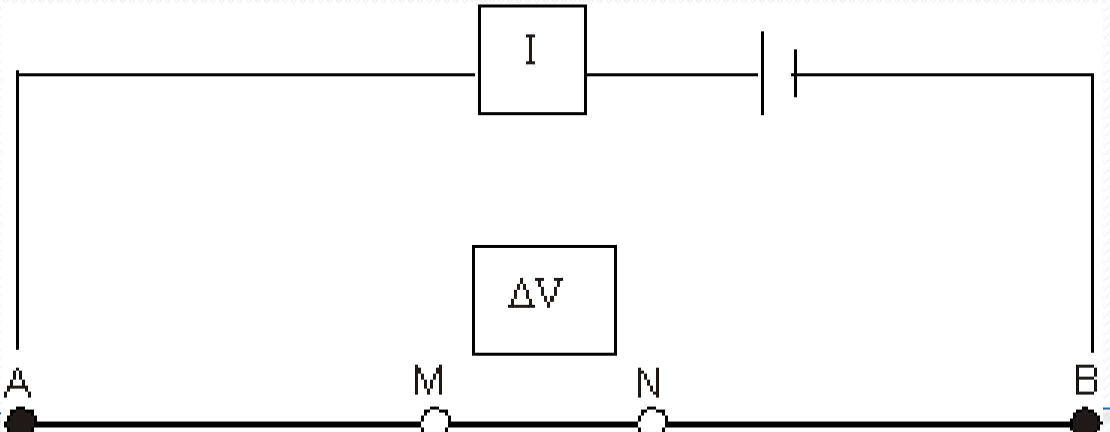
- investigation depth;
- Sensitivity to different subsurface resistivity distributions;
- signal strength at the recoring electrodes.

ELECTRICAL (DC) METHODS

- Schlumberger

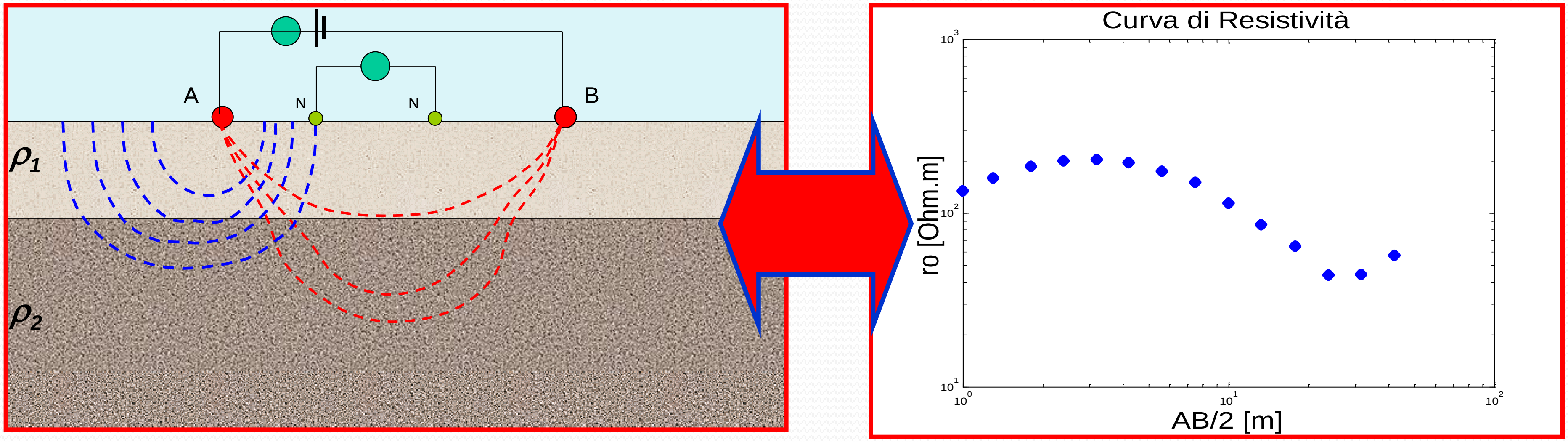
The best tested of the techniques is the **Schlumberger** array, where the electrodes are placed along a common line and separated by a distance, which is used to control the depth of penetration.

The outer two electrodes drive current into the ground, while the inner two, located at the midpoint between the outer two, are used to detect the electric field caused by that current.
The outer two electrodes, AB, are separated by progressively greater distances as a sounding survey is carried out, so that information from progressively greater depths is obtained.

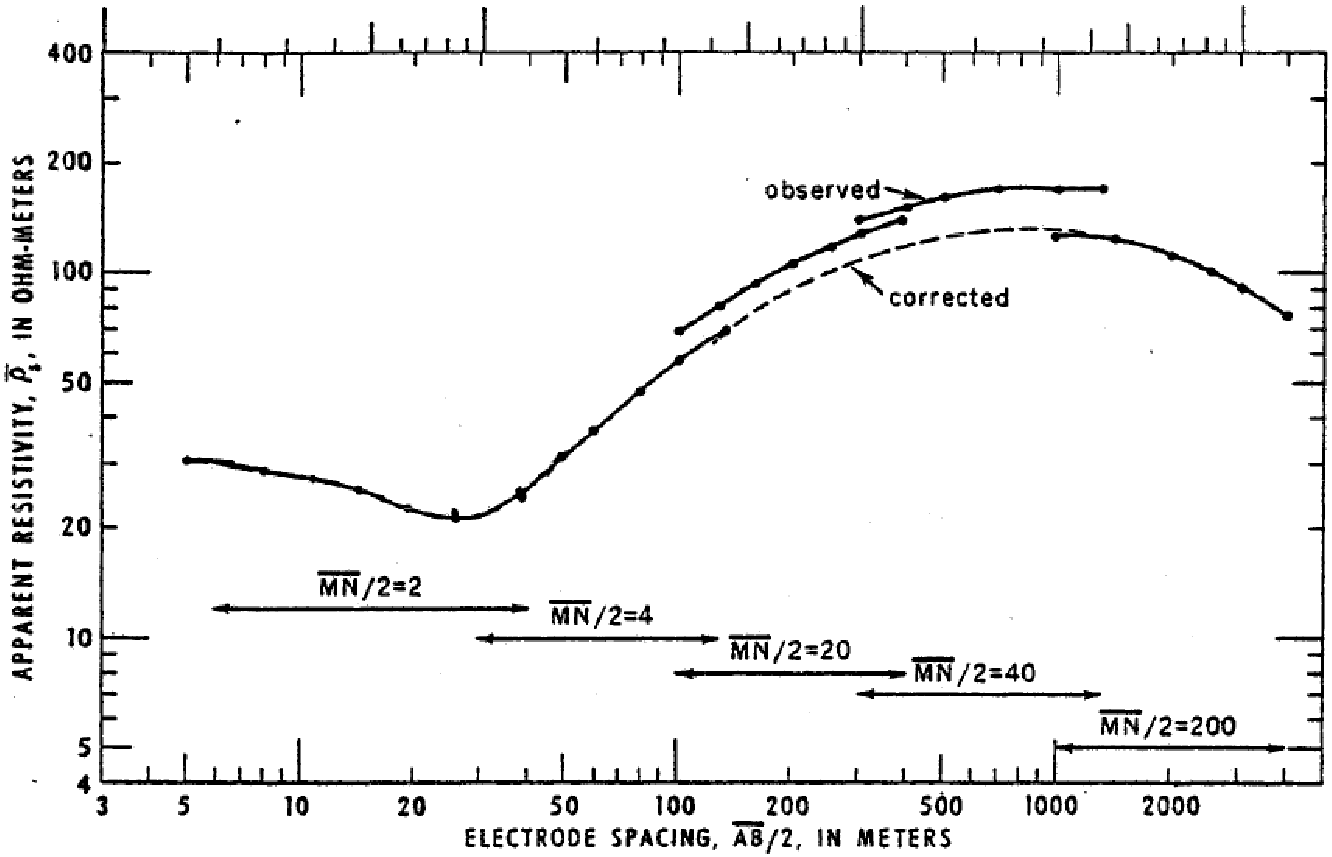


ELECTRICAL (DC) METHODS

The result is a bilogaritmic plot of apparent resistivity versus AB/2 :



ELECTRICAL (DC) METHODS



Usually MN electrodes (receivers) are left fixed. However for increasing investigation depths AB may become too large for detecting a proper signal, and MN must be anlarged (keeping fixed the center). Curves are superposed in the same plot.

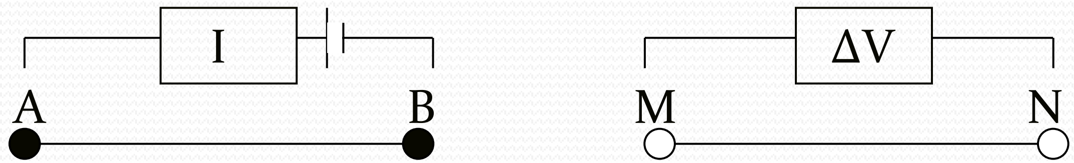
ELECTRICAL (DC) METHODS

- Wenner

Also with the **Wenner** array electrodes are placed along a common line and separated by a distance, which is used to control the depth of penetration.

A couple of electrodes drive current into the ground, while the other couple is used to detect the electric field caused by the transmitted current.
The two couples of electrodes are separated by progressively greater distances as a sounding survey is carried out, so that information from progressively greater depths is obtained.

This method is particularly influenced by vertical structures

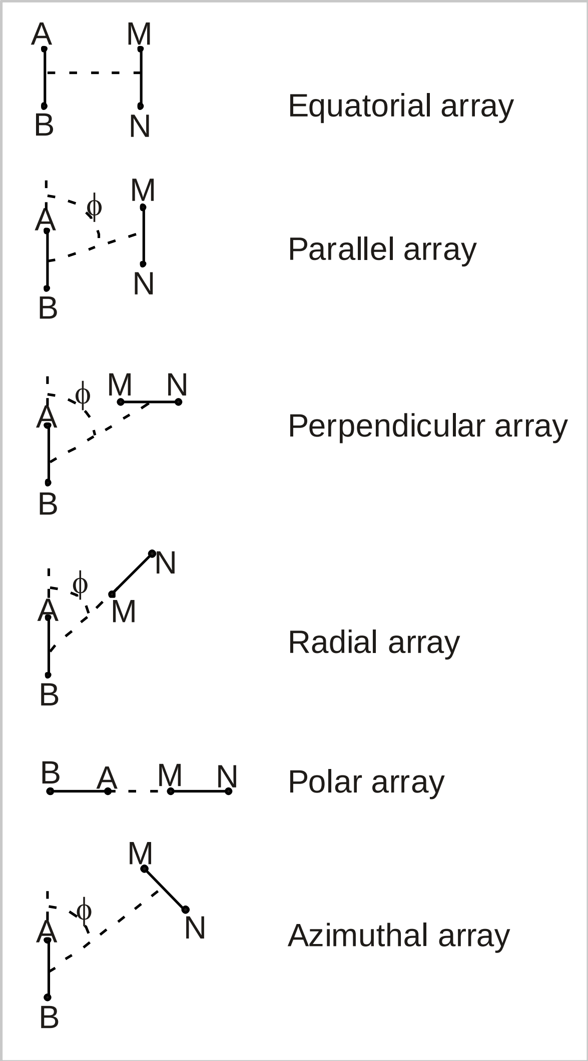


ELECTRICAL (DC) METHODS

In a survey of a geothermal area, the spacing between electrodes will be increased incrementally from distances of a few metres or tens of metres to distances of several kilometres or more.

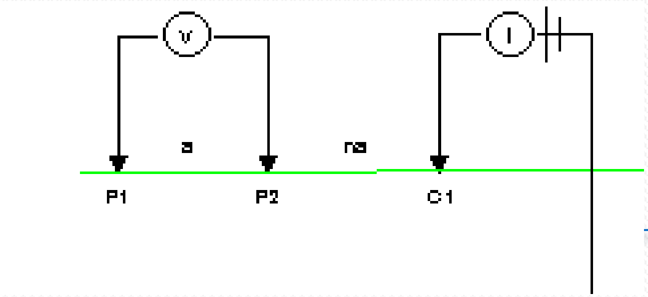
The Schlumberger method has several limitations, including the relatively slow progress with which work can be carried forward in deep sounding, and the fact that in areas of geothermal activity the lateral dimensions of the areas of anomalous resistivity may be considerably smaller than the total spread required between electrodes.

In order to detect the presence of lateral discontinuities in resistivity, the **bipole–dipole** and **dipole–dipole** techniques have come into use.



In the **dipole–dipole** technique, four electrodes arrayed along a common line are used, but in this case the outer two electrodes at one end of the line provide current to the ground while the outer two electrodes at the other end of the line are used to measure the voltage caused by that current.

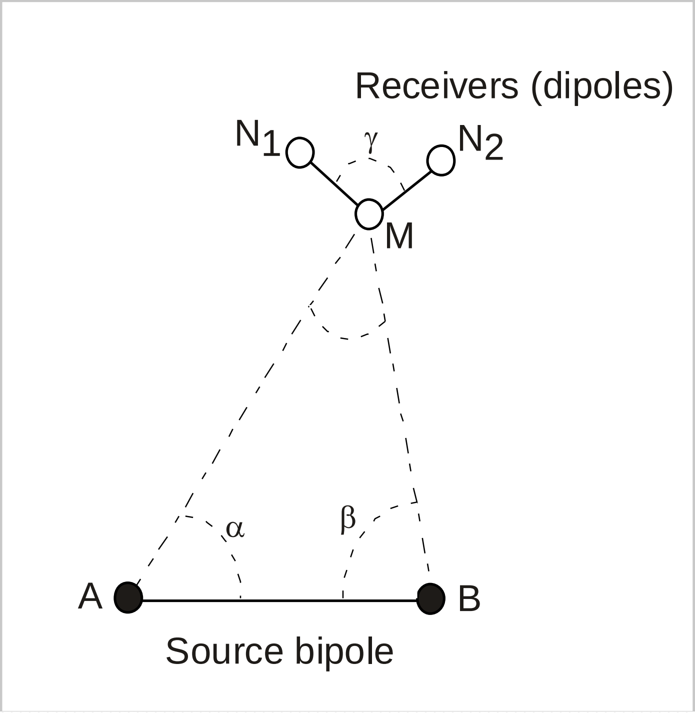
In a survey, the receiving electrodes and transmitting electrodes are separated progressively by increments equal to the separation between one of the pairs, in the direction along which they are placed.



The separation between the two dipoles can be increased from one dipole length to as much as 10 dipole lengths.
When this has been done the current dipole is advanced by one dipole length along the traverse and the procedure repeated.
The process is continued with the entire system moving along a profile.

The dipole–dipole method has the advantage of portraying the effects of lateral changes in resistivity clearly, but suffers from the disadvantage of being a cumbersome method to apply in the field.

In the **bipole–dipole** mapping method, current is driven into the earth with a fixed pair of electrodes at a source bipole.



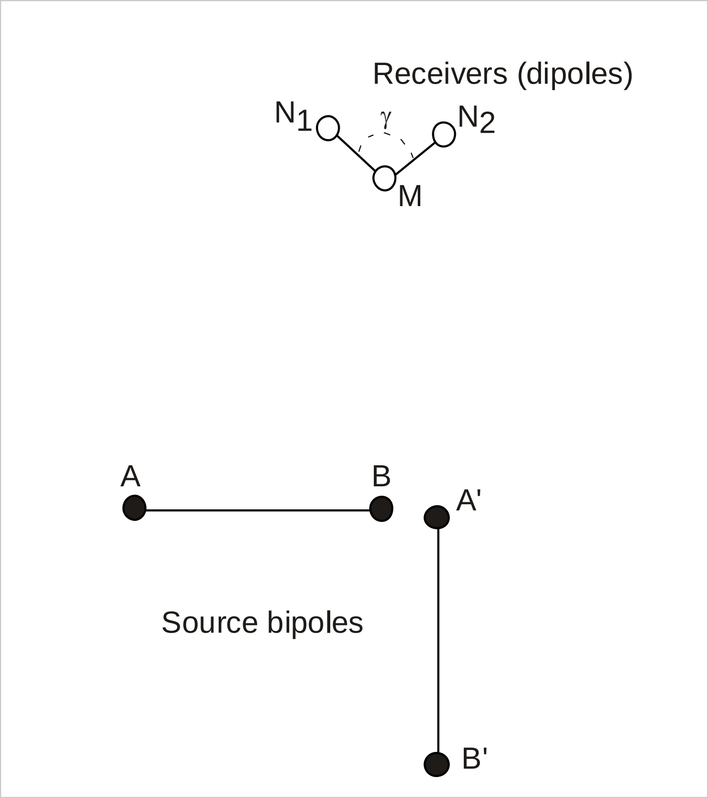
The behaviour of the current field over the surface of the earth is then surveyed by making voltage measurements with orthogonal pairs of electrodes (dipoles)
at many locations around the source.

Values for apparent resistivity are computed and contoured.

In some cases a simple relationship exists between contours of apparent resistivity and the subsurface electrical structure, but in many cases the relationship between the contoured apparent resistivities and the subsurface structure is difficult to determine.

An important modification of the bipole–dipole method, which has been used in more recent surveys to improve the meaningfulness of the results, is the use of two orthogonal bipole sources.

The two sources are energised separately, and at a receiver site two electric fields are determined, one for each source.



By combining these two electric fields in various proportions, apparent resistivity is computed as a function of the direction of current flow at the receiver station.

The result is an ellipse of apparent resistivity drawn as a function of the direction of current flow. These ellipses provide considerably more insight into the nature of the subsurface than do the single values of apparent resistivity obtained with the single-source bipole–dipole method.

ELECTRICAL (DC) METHODS

Why so many different layouts?

Specific features for the different layout:

- Investigation depth
- Sensitivity to vertical or horizontal structures
- Horizontal coverage of data
- Signal strength (voltage)

ELECTRICAL (DC) METHODS

Why so many different layouts?

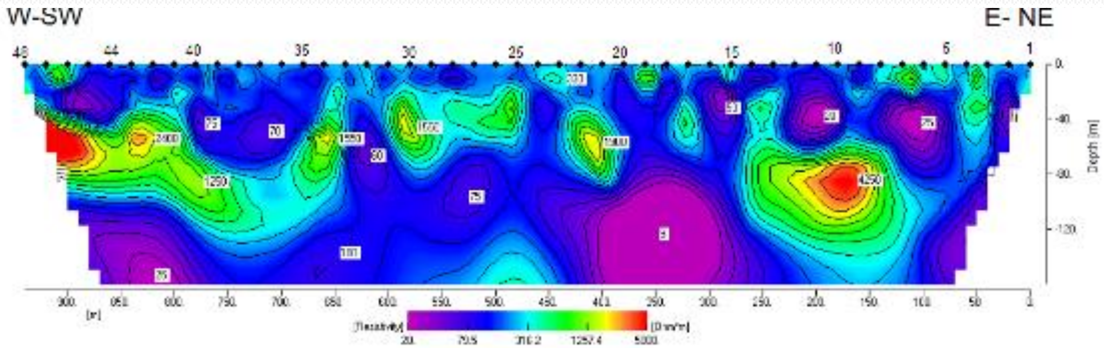
1) The “investigated volume” have different shapes, and the different layouts have different resolving power;

2) A different “investigation density” as a function of depth, within the target volume

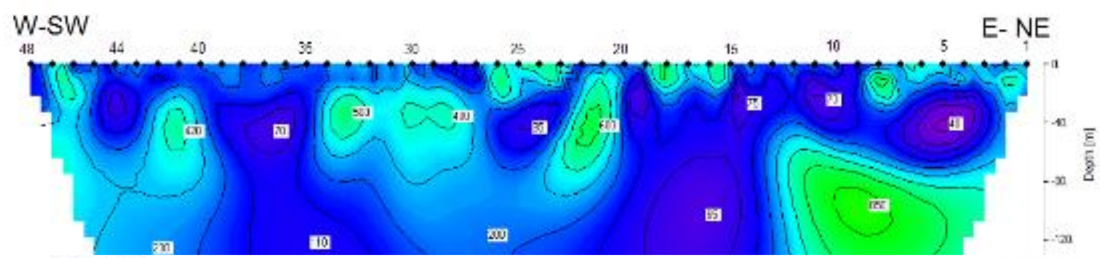
Depending on the application, the choice of the best layout has a main importance

ELECTRICAL (DC) METHODS

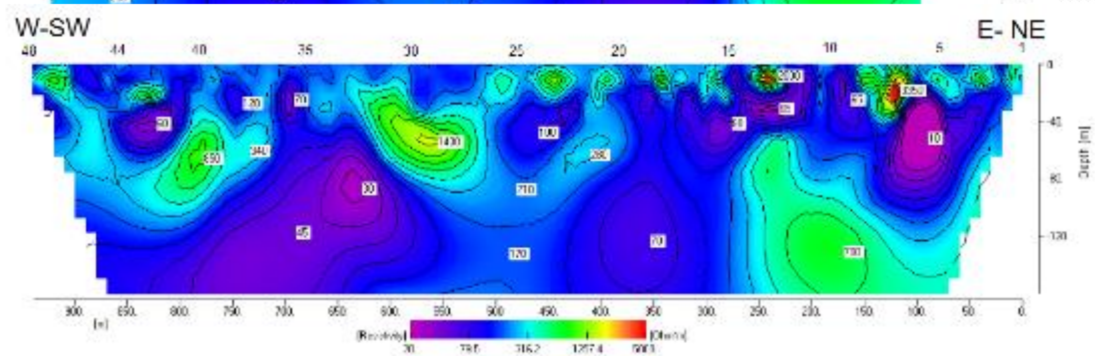
dipole-dipole



Wenner



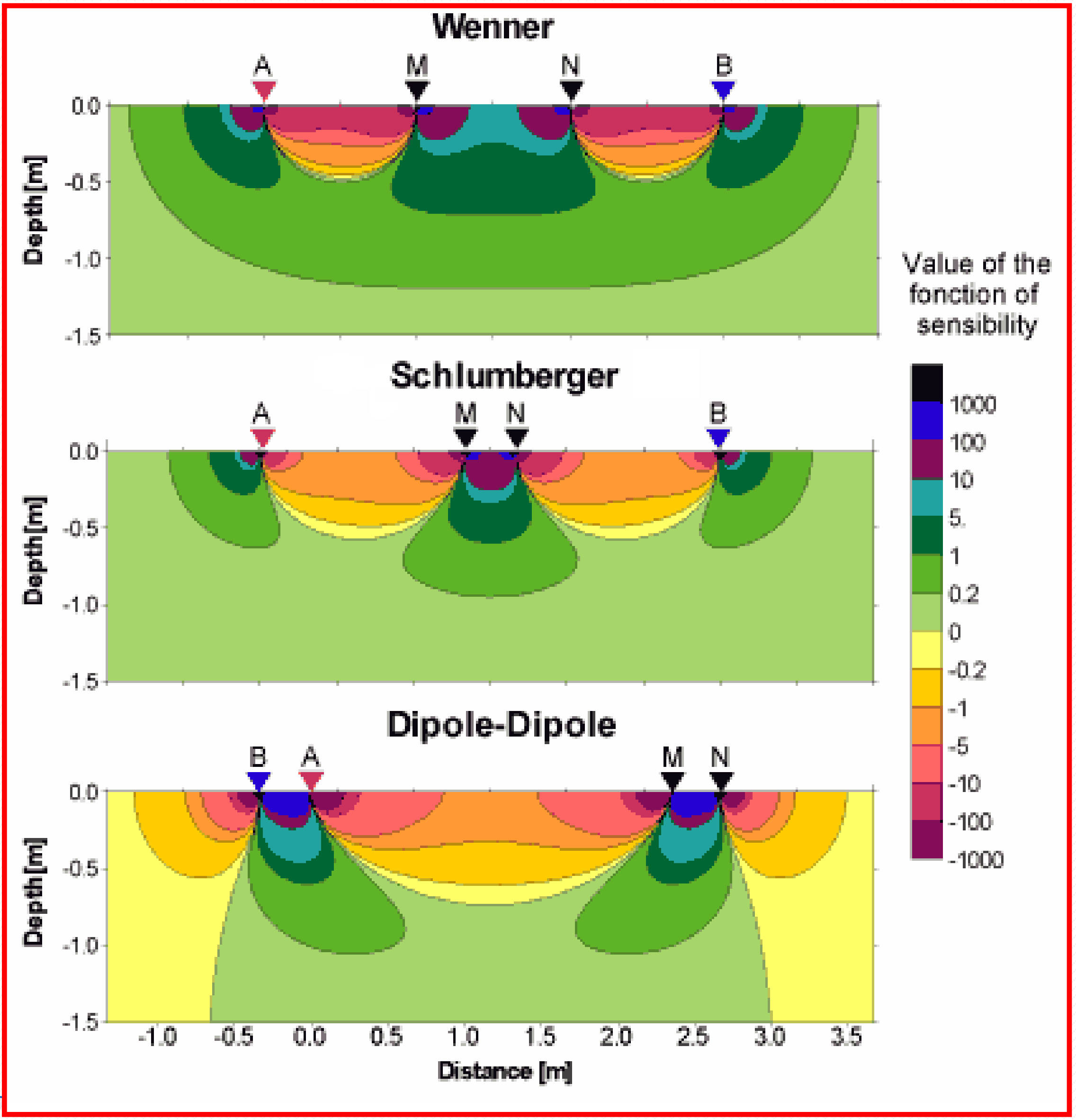
Schlumberger



ELECTRICAL (DC) METHODS

Sensitivity of standard quadripoles :

Sensitivity derives from the array voltage variation measured for varying resistivity in a certain subsurface volume

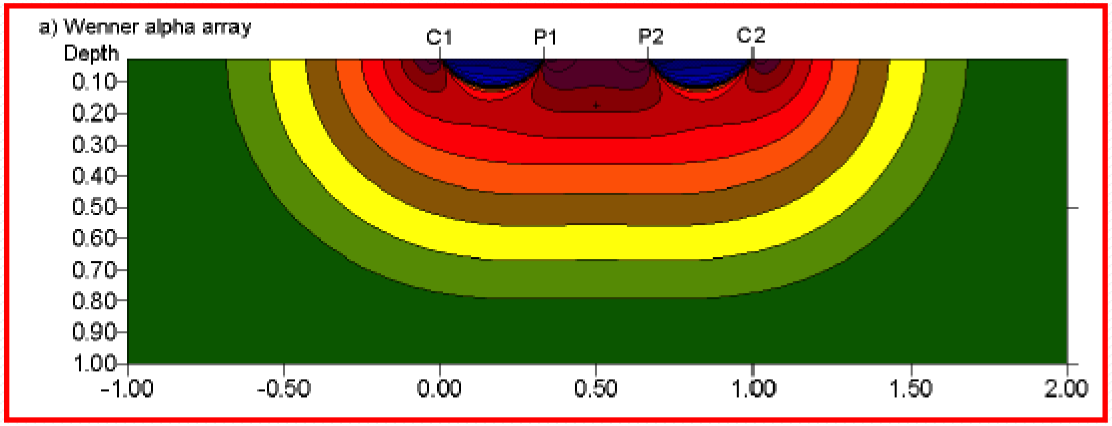


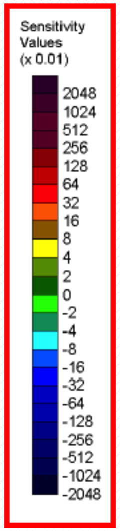
ELECTRICAL (DC) METHODS

• Wenner

It is a robust array, very used in the first attempts of tomography surveys :

- much more sensible to vertical variations of resistivity with respect to horizontal ones
- average investigation depth
- strong signal strenth (voltage difference) useful in noisy areas
- reduced horizontal coverage for increasing depth

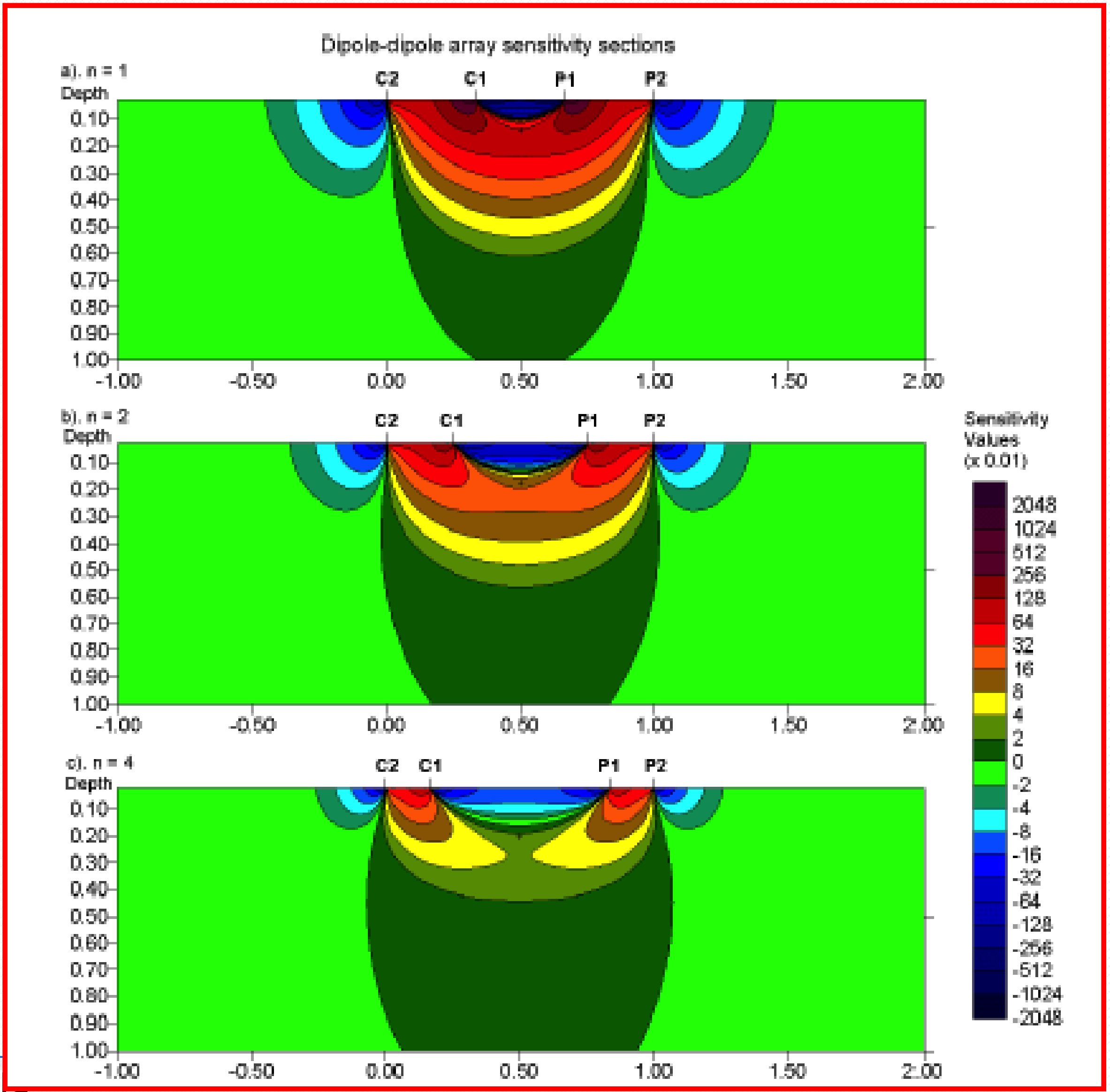




ELECTRICAL (DC) METHODS

- Dipole Dipole

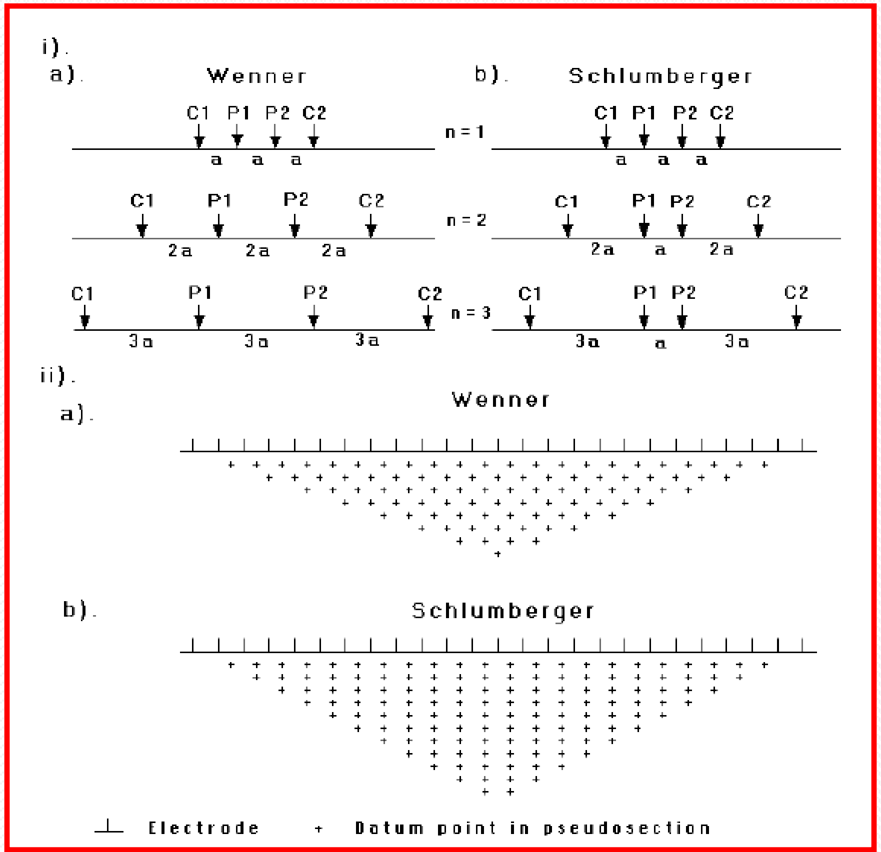
Sensitivity is particularly high around the current and voltage electrodes



ELECTRICAL (DC) METHODS

- Wenner-Schlumberger

This mixed array is relatively new and recently very used in tomography

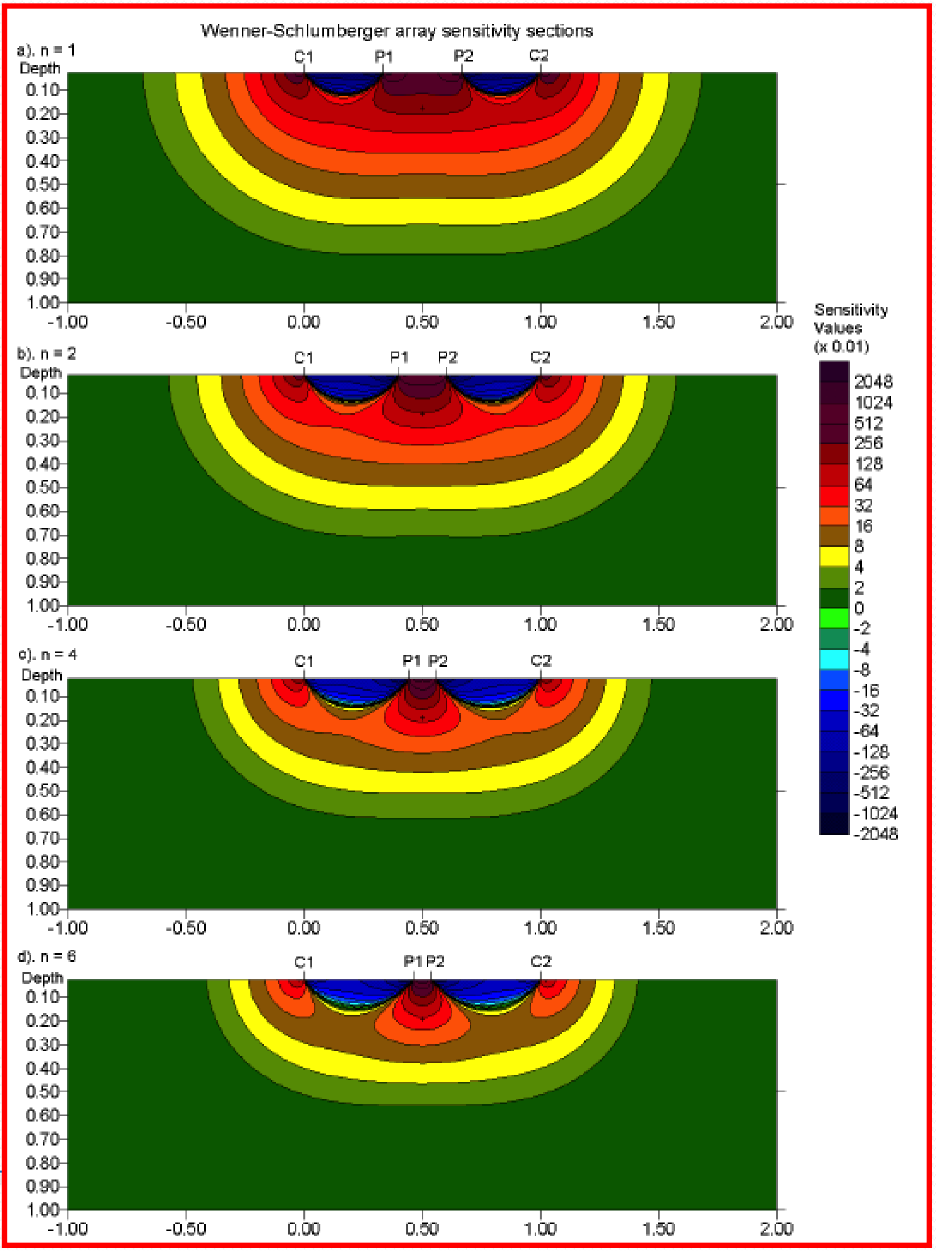


- moderately sensible to both vertical and horizontal resistivity variations
- investigation depth is higher than with just wenner array (n>3).
- good horizontal coverage
- Intermediate signal strength with respect to wenner and schlumberger

ELECTRICAL (DC) METHODS

- Wenner-Schlumberger

It can be applied in various contexts thanks to its flexibility and intermediate features



Array advantages and disadvantages

Array	Advantages	Disadvantages
Wenner	1. Easy to calculate ρ_a in the field 2. Less demand on instrument sensivity	1. All electrodes moved each sounding 2. Sensitive to local shallow variations 3. Long cables for large depths
Schlumberger	1. Fewer electrodes to move each sounding 2. Needs shorter potential cables	1. Can be confusing in the field 2. Requires more sensitive equipment 3. Long Current cables
Dipole-Dipole	1. Cables can be shorter for deep soundings	1. Requires large current 2. Requires sensitive instruments

Induced polarization

Induced polarization (or IP) is a secondary measurement that can be made at the same time as DC resistivity if the correct equipment is included. IP have been known for a long time, but sparsely used, mainly confined to mineral (ore) exploration.

IP measurements respond to variations in the capacity for subsurface materials to retain electric charge. This physical property is referred to as **chargeability**. The principal materials that exhibit this property are clays, graphite, and sulphide minerals. However, small changes in chargeability can be detected when groundwater is contaminated with salt, hydrocarbons, or other materials.

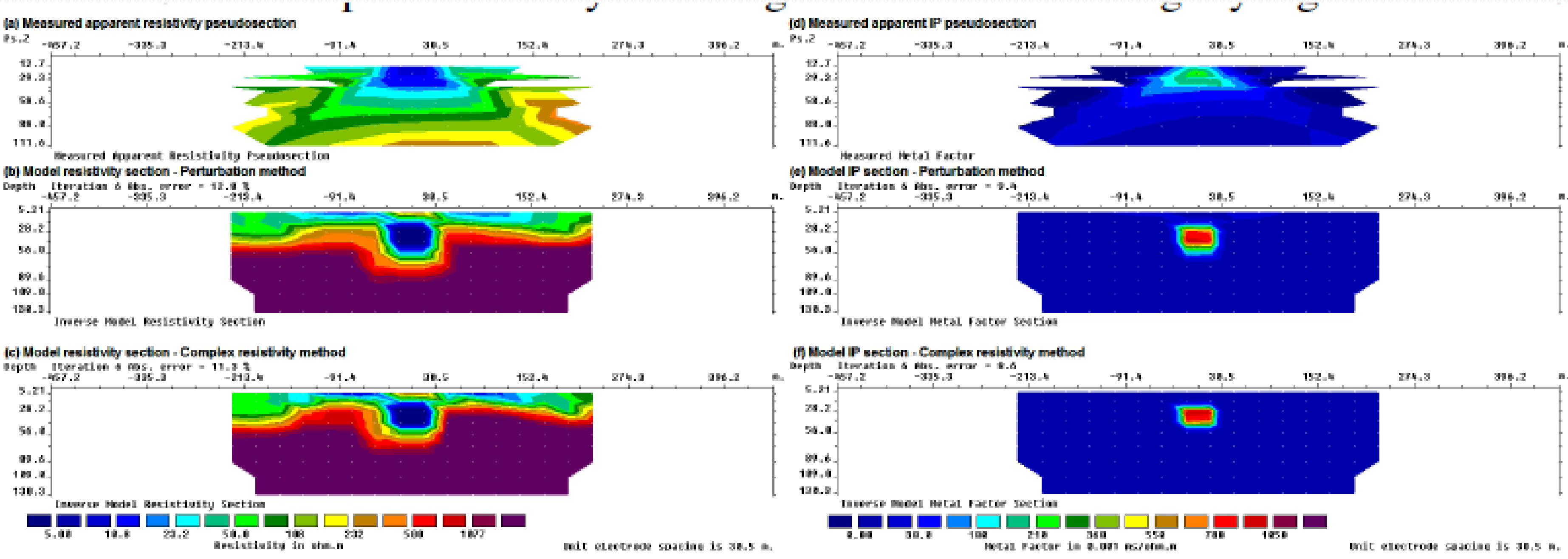
Induced polarization

With modern equipment, acquisition and modelling of IP data has been made quick, and IP data are now used to hellp in ERT data interpretation, since it is possible to distinguish the effects due to clays, since the chargeability of clays (in the 10 to 50 mV/V range) is much smaller that that due to conductive minerals.

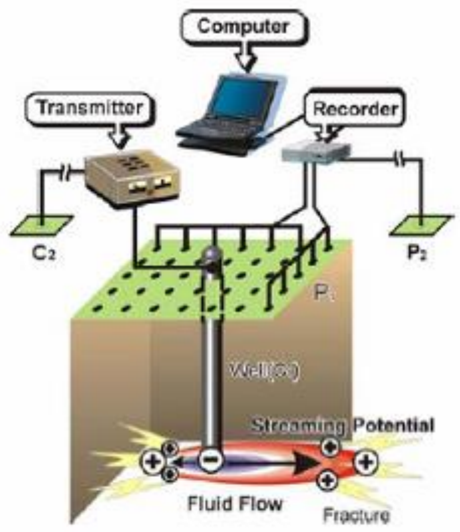
The IP effect is caused by two main mechanisms, the membrane polarization and the electrode polarization effects. The membrane polarization effect is largely caused by clay minerals present in the rock or sediment.

IP measurements are made in the time-domain or frequency domain.

Induced polarization



Self-potential method



Only the naturally existing voltage gradients in the earth are measured

Causes of these natural voltages:
• oxidation or reduction of various minerals by reaction with groundwater
• generation of Nernst voltages where there are concentration differences between the waters residing in various rock units
• streaming potentials, occurring when fresh waters are forced to move through a fine pore structure, stripping ions from the walls of the pores

In geothermal areas, very large self-potential anomalies have been observed, and these are apparently caused by a combination of thermoelectric effects and streaming potentials

Self-potential method

To avoid spurious contribution to the voltage by chemical reaction, *non-polarizing electrodes* are used, which consist of a metal electrode in contact with a stable electrolyte, with the whole being contained in a semi-permeable container serving as salt bridge between the metal electrode and the dirty electrolyte present in the pores of the soil or rock with which it makes contact the two electrode potential will be equal and cancel.

Two different field procedures can be used in mapping SP

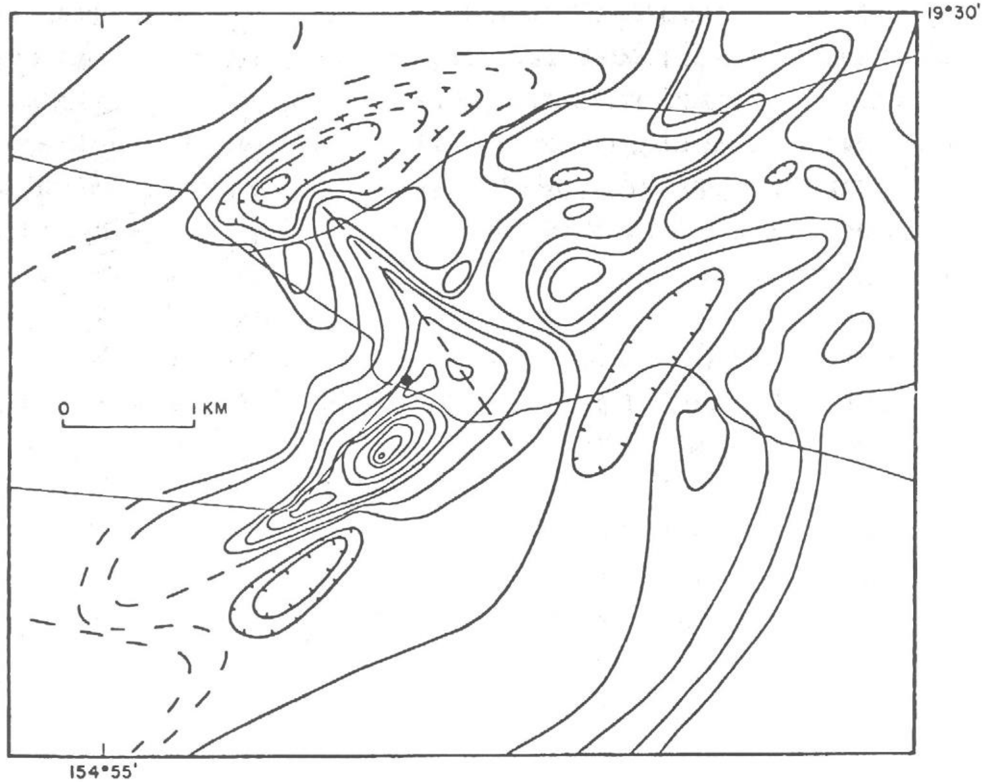
The *single reference* method

One non-polarizing electrode is held fixed at a reference point while the other electrode is moved about over the survey area to determine the distribution of potential over the region

Only areas of few hundred meters square because large separation between electrodes induces telluric electric voltages to the SP

The *leap-frog* method

The two electrodes are moved along a closed survey path. After each measurement, the trailing electrode is moved ahead of the leading electrode for the next measurement. The incremental voltages observed along the loop are successively added and subtracted to arrive to a potential map with respect to the starting point of the loop. The net voltage when the loop closes should be zero; any residual voltage reflects survey errors and can be distributed around the loop.



Contour interval is 100 mV. Areas of low voltage are indicated by interior ticks on the contour.
The filled circle indicates the location of a successful geothermal wildcat well.

An example of
Self-Potential data acquired
at Hatchobaru geothermal
field, Japan (from Ushijima
et al, WGC2000)

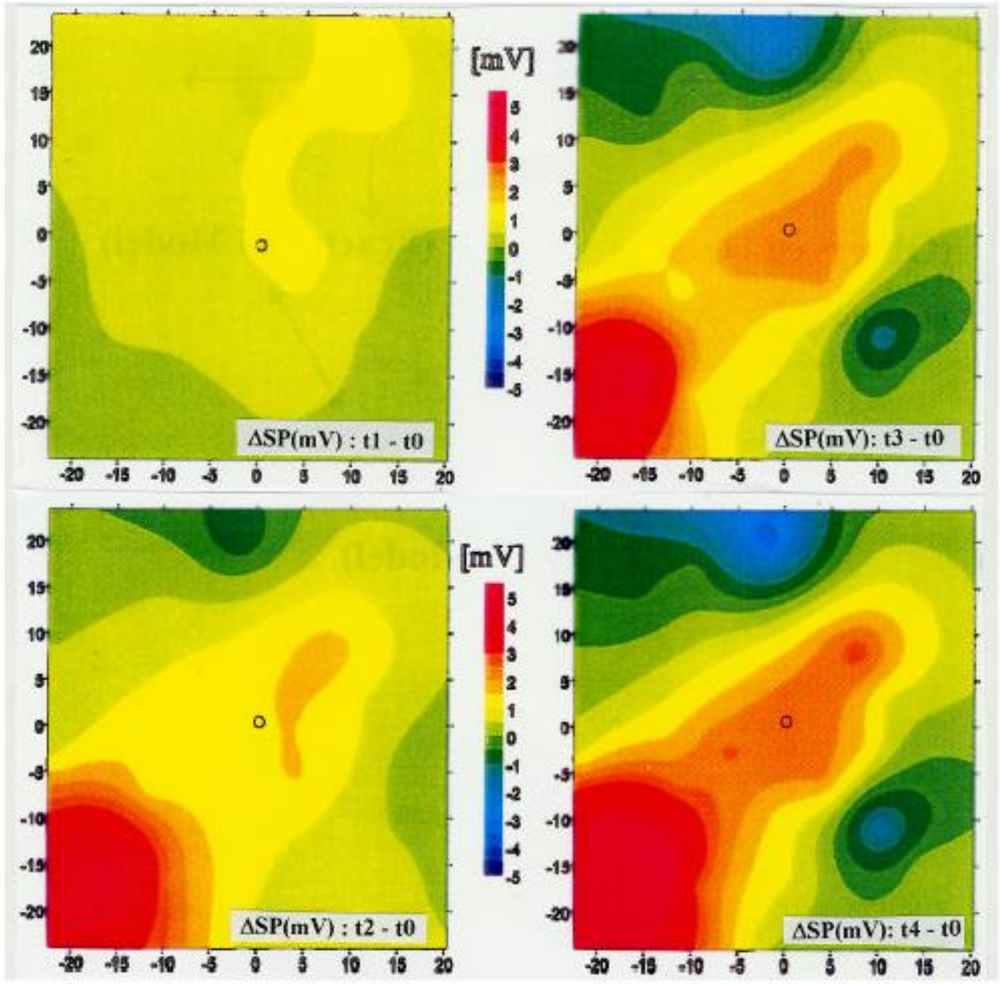


Figure 6. Residual SP variation with a function of time observed during water injection into H-28 exploratory borehole in Hatchobaru geothermal area.

An example of Self-Potential data acquired at Pohuthu geothermal field,
New Zealand
(from Nishi et al, WGC2000)

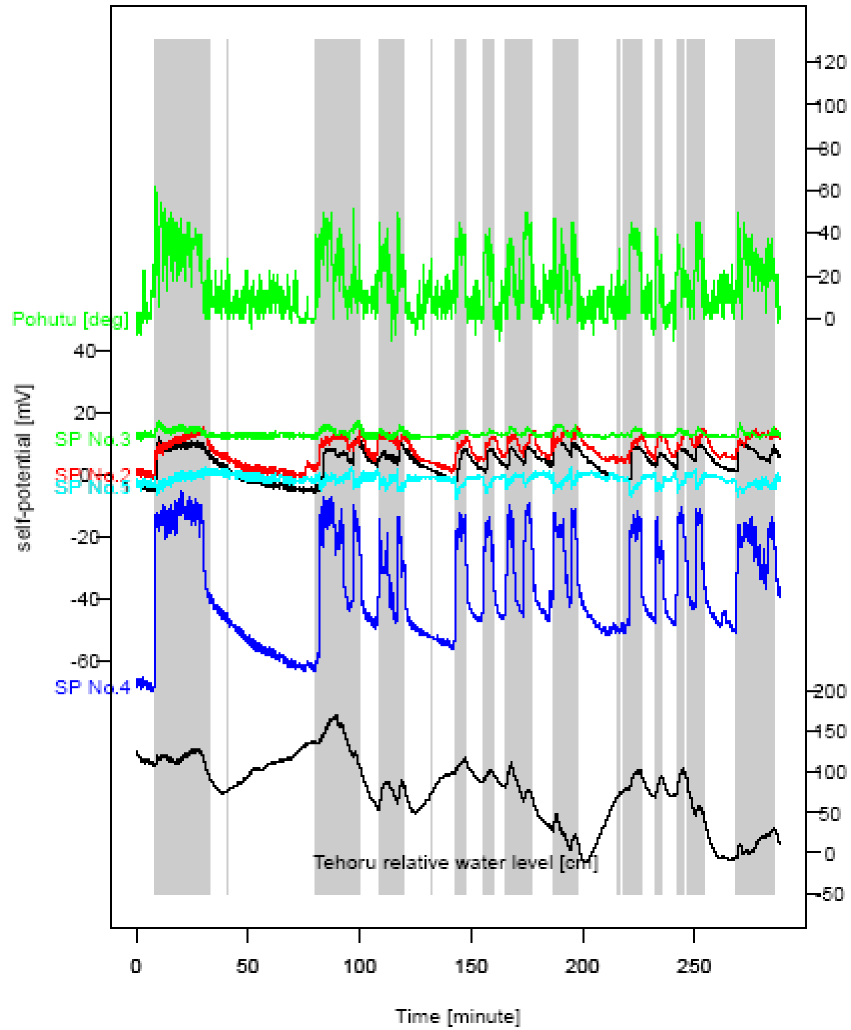


Figure 3 Temporal variations of geyser activity of Pohutu (upper), self-potential (SP) (middle) and the water level of Te Horu (lower).

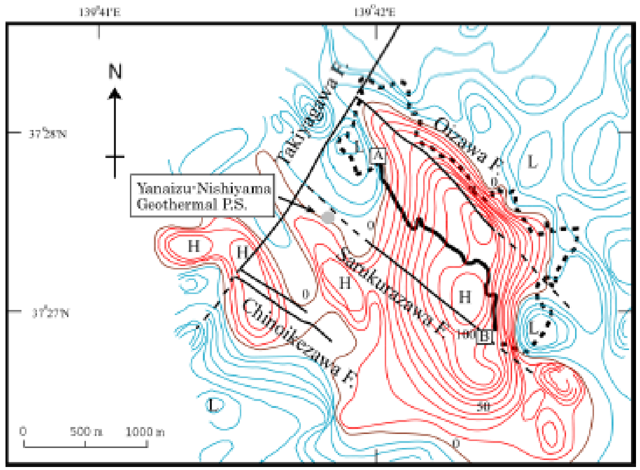


Fig. 1 Fault system and SP distribution at the 1982-83 survey in the yanaizu-Nishiyama area

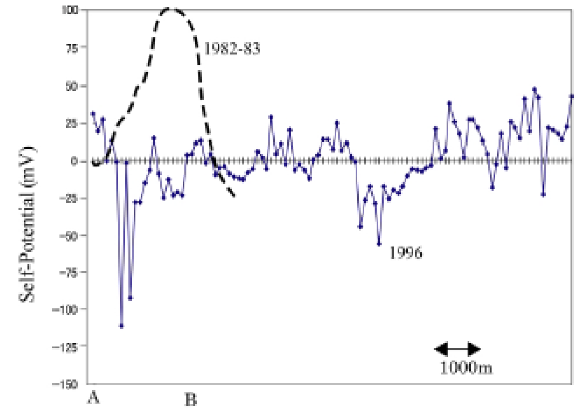


Fig. 2 SP profile along the survey line shown in Fig. 1. The survey was carried out in 1996 at 1.5 years after the commencement of the production. The dashed line shows the SP profile in 1982-83, 12 years before the power plant start-up.

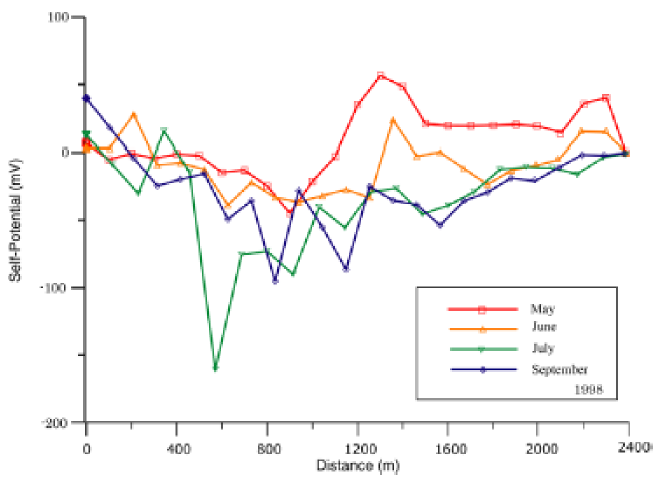


Fig. 3. SP profiles at the repeat surveys from May to September, 1998.

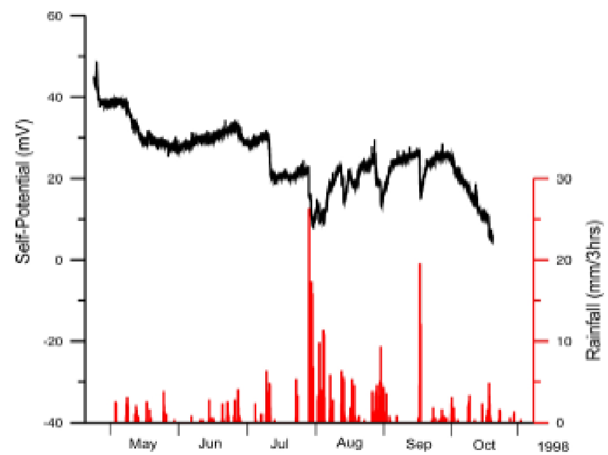


Fig. 4. The continuous SP record and the rainfall in 1998.

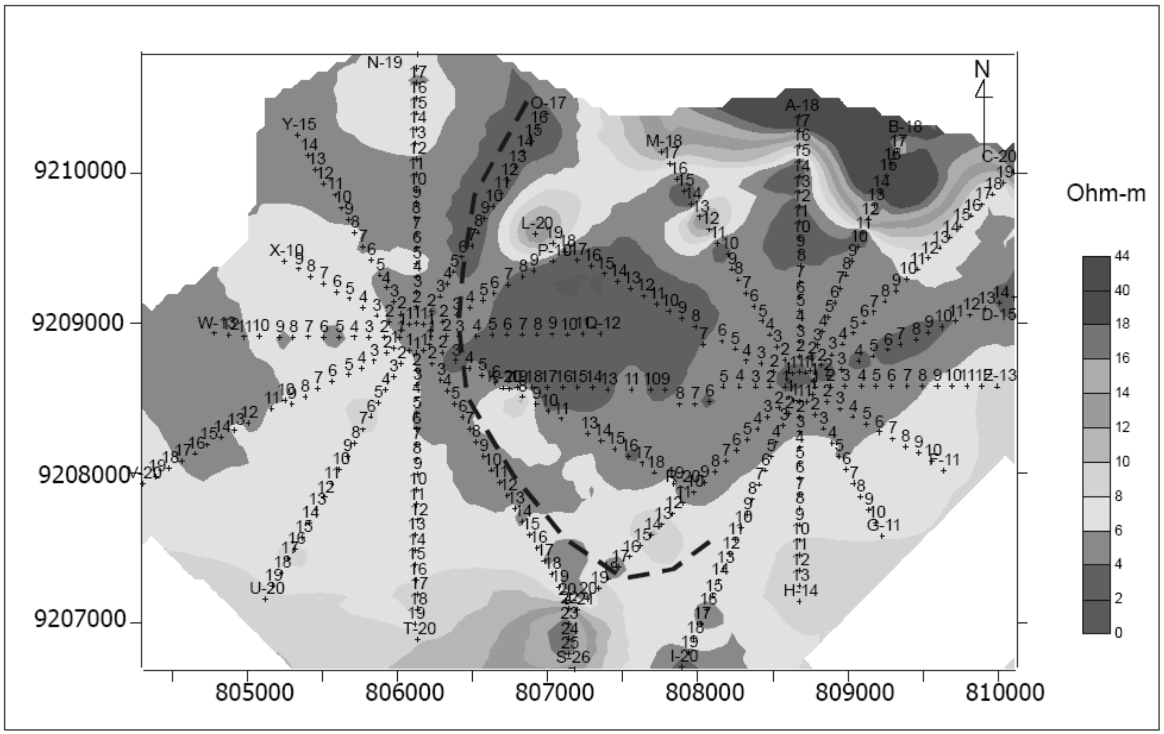
An example of Self-Potential data acquired at Yanaizu-Nishiyama geothermal field, Japan (from Tosha et al, WGC2000)

Mise-a-la-masse method

It is used when a prospect hole penetrates a highly conductive zone. A current electrode, lately the casing pipe itself, is embedded in the conductive zone and energized with direct current, the other electrode being a large distance away on surface.

This method is now used to monitor fluid flow behaviour during reinjection and during hydraulic fracturing operations in hot dry rocks.

Mise-a-la-masse method



Cross-hole resistivity survey

When many wells are logged, the EM tomography method may define the distribution of resistivity around the borehole and the whole area interested by drilling

A transmitter is located in one hole while a receiver is drawn up in another. The attenuation of the signal depends on the resistivity structure.

Attenuation will be greater if the field senses a region of low resistivity, and lower if a region of high resistivity is seen.

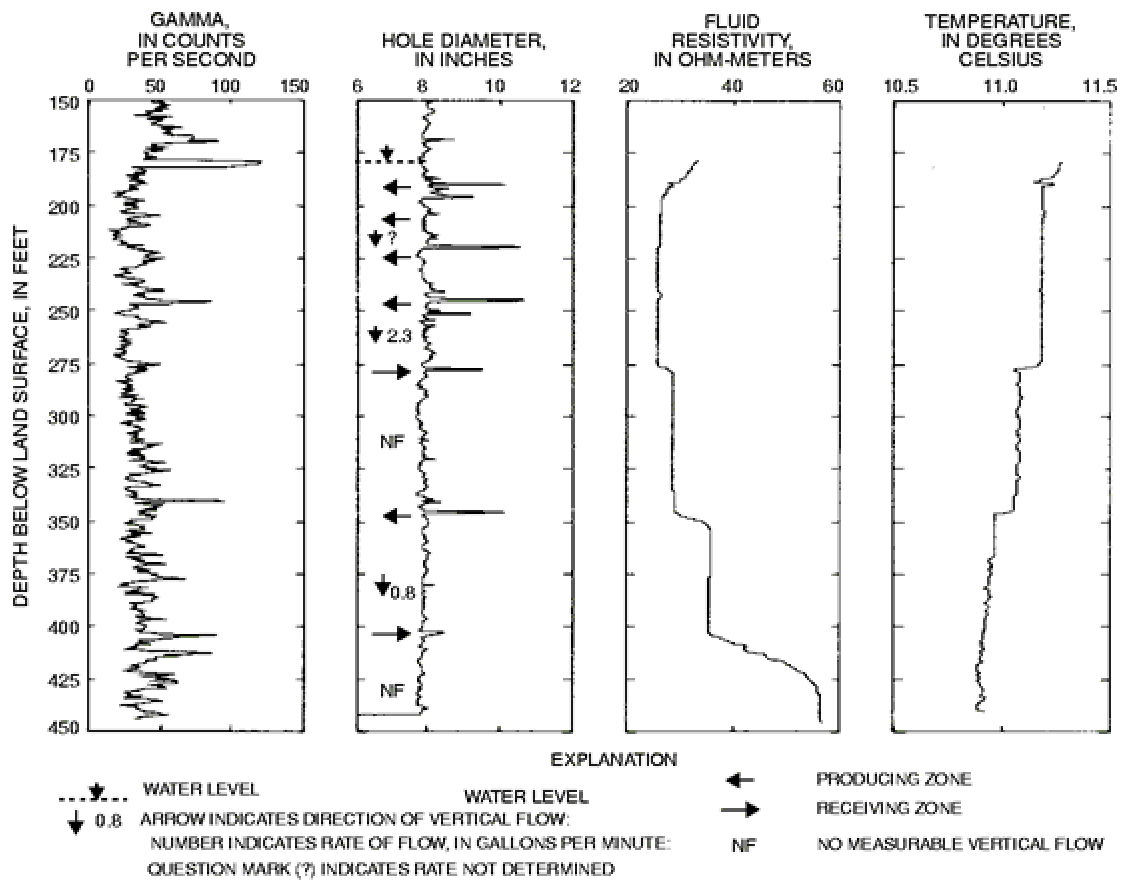
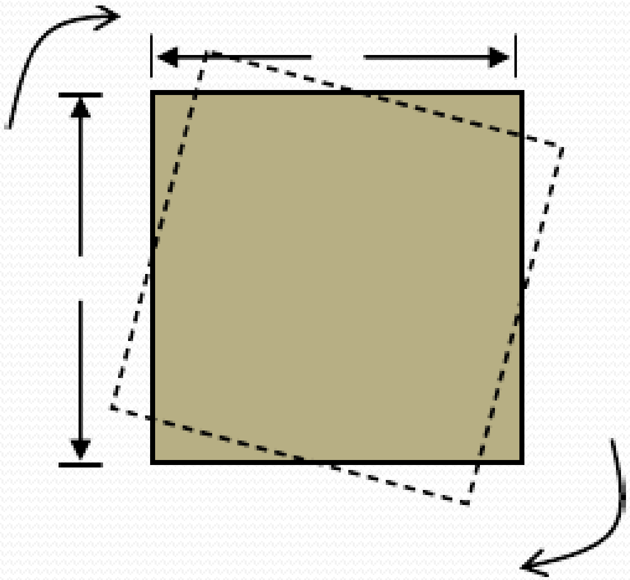


Figure 5. Typical suite of geophysical logs. Caliper log shows water-producing, vertical borehole flow, and water-receiving zones (from Williams and Conger, 1990, fig. 3).

Azimuthal sounding

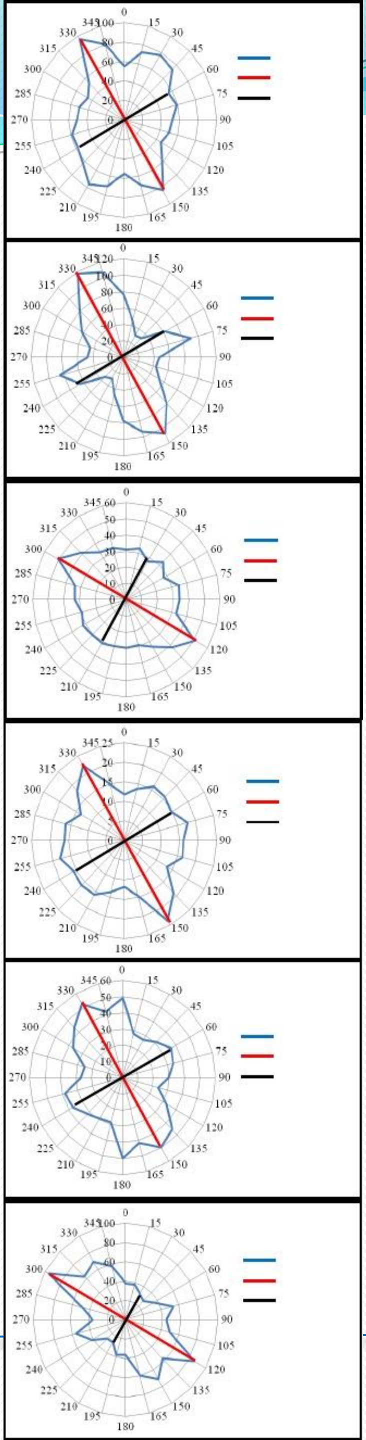


Azimuthal resistivity sounding method has been used to detect vertical fractures in geothermal manifestations areas. The method consist on rotating the Ab and MN array and measure the variation of resistivity parameters with direction.

Azimuthal sounding

Application of azimuthal resistivity sounding method in Gunung Lamongan (East Java). Anisotropy coefficient is proportional to the dimensions of the fracture. The results of field measurements and data processing, pattern of cracks in the geothermal manifestations was N10ºE to N60ºE.

Widya Utama and Tri Martha Kusuma Putra, PROCEEDINGS, 1° ITB Geothermal Workshop 2012



ELECTRICAL (DC) METHODS

Used in areas where the geothermal circulation and related alteration take place at shallow depths (<2 km)

Long electric arrays (Schlumberger and dipole-dipole) used in the 70's and 80's for resistivity imaging

2 D and 3 D inversion softwares available "off the shelf"

Advantages : source controlled, resolution

Disadvantages :

Implementation very heavy compared with MT and TDEM

equivalences (non unique solution),

"Blackbox"software could drive very easily to erroneous interpretations

ERT, IP, self-potential methods

Used for exploration of natural manifestation or shallow low-enthalpy geothermal systems

1D, 2 D and 3 D inversion softwares available “off the shelf”

Advantages : very high resolution, possibility to distinguish clays and polarized fields

Disadvantages :

only for shallow investigation

ELECTRICAL (DC) METHODS

Example
The Cerro Prieto region was prospected with more than 400 long offset Schlumberger soundings. The geothermal area is at the center of a system of echelon faults that produce a slimming and possible rupture of the earth's crust. With the help of resistivity data, the authors obtained a 3-D resistivity image of the geothermal area and of the two principal faults that control the regional tectonics

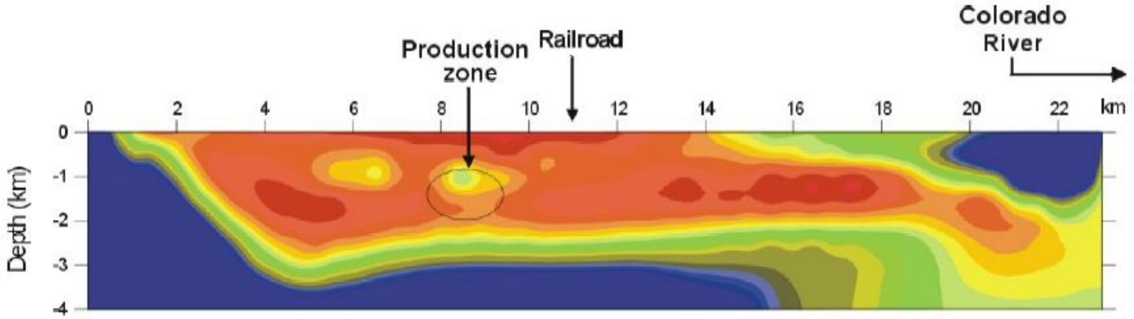
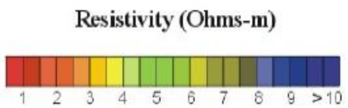


Figure 2.- Joint inversion of Dipole-dipole and Schlumberger resistivity data.



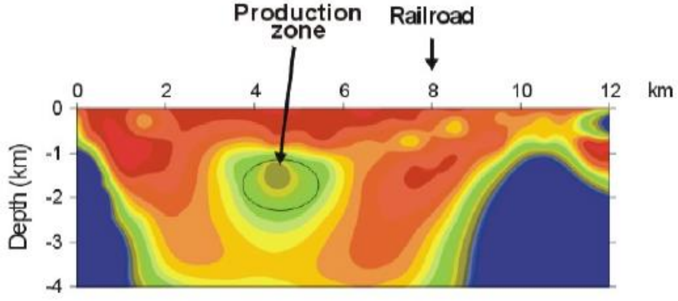


Figure 3.- Resistivity image of the Schlumberger line 6.

An example of DC data acquired at Cerro Prieto, Mexico (from Charré-Meza et al, WGC2000)

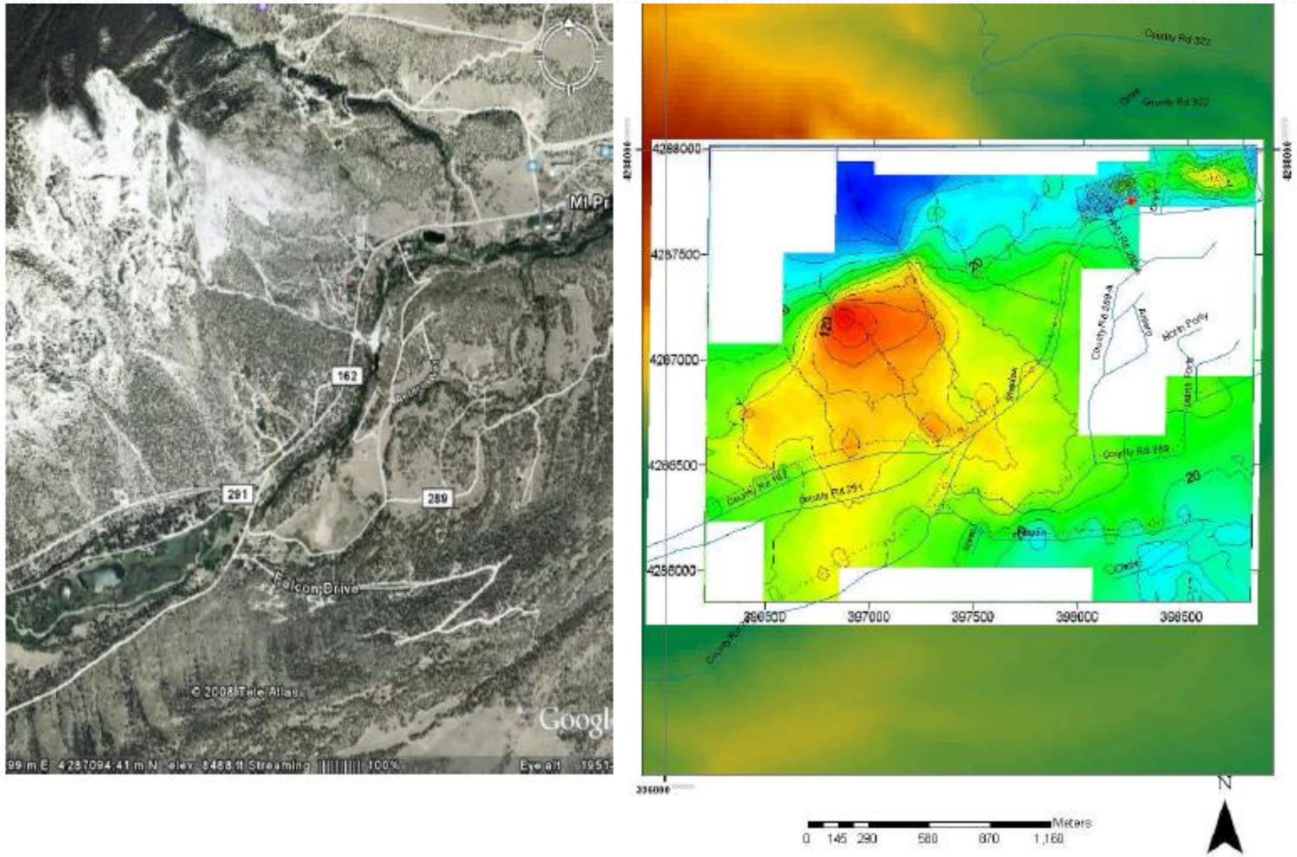
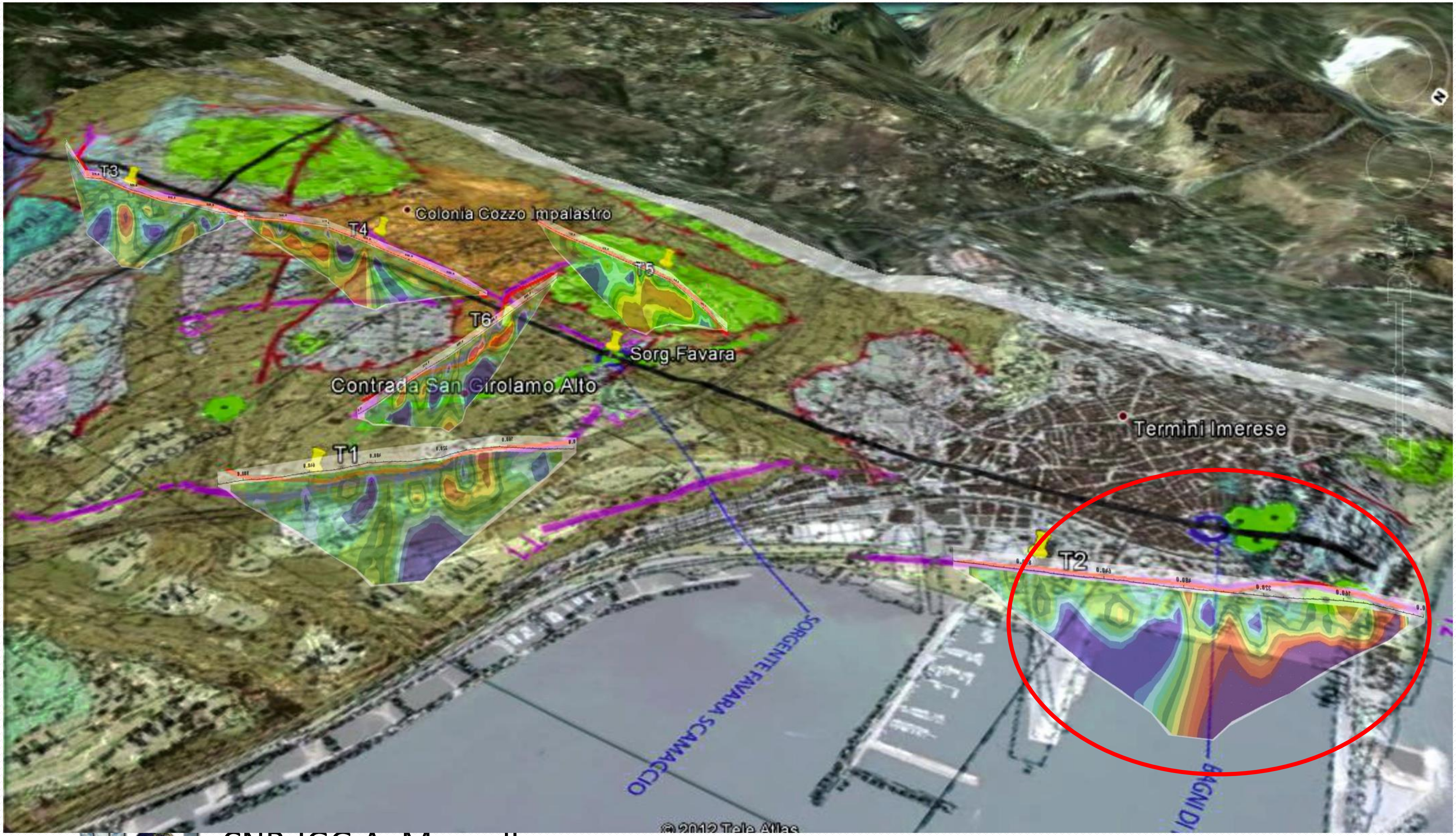


Figure II-C-2B. SP data overlaid with roads as lines in order to place anomalies in their correct surface acquisition locations. Notice how the large SP anomaly in the center correlates excellently with the Chalk Cliffs which have been hydrothermally altered from granite to kaolinite, not chalk.

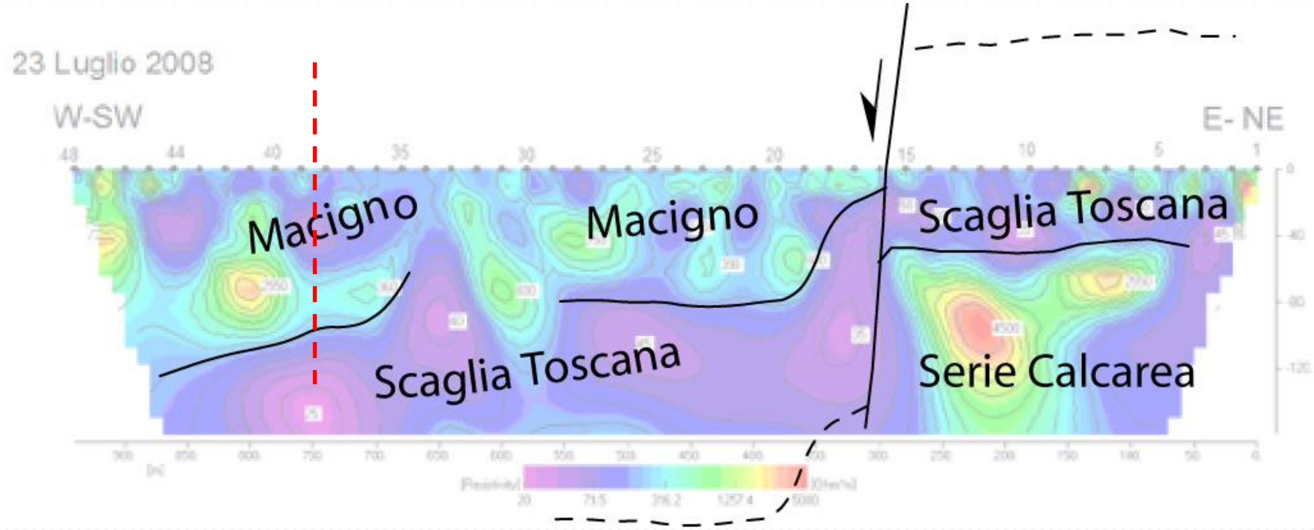
ELECTRICAL (DC) METHODS

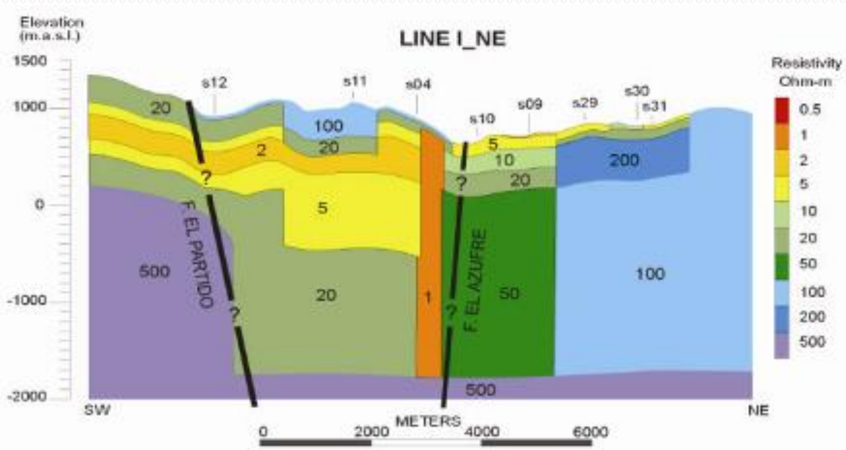


ELECTRICAL (DC) METHODS

FLUID PATHWAY

Geothermal exploration at a low enthalpy field using ERT. The low resistivity zone is coincident with a known fault.

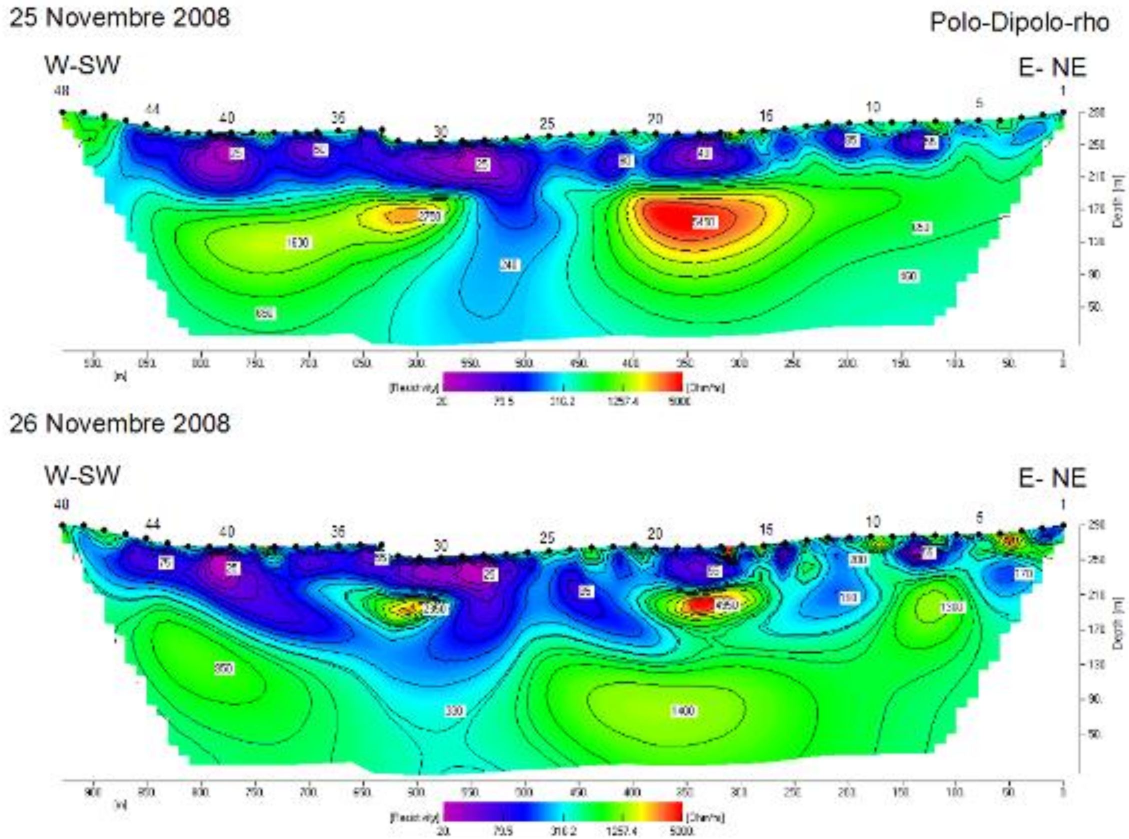




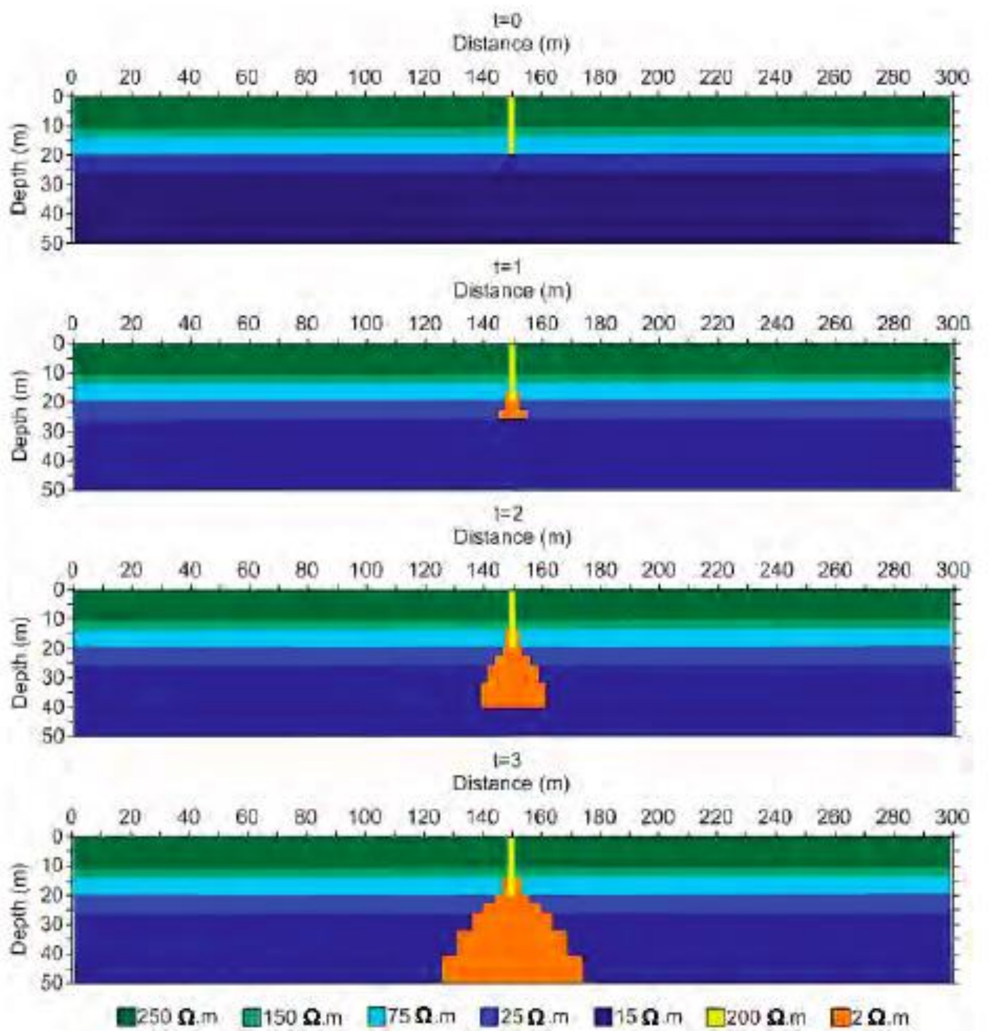
Geothermal exploration at a geothermal area of Las Tres Virginen, Mexico. The change in resistivity is coincident with known faults.

MONITORING

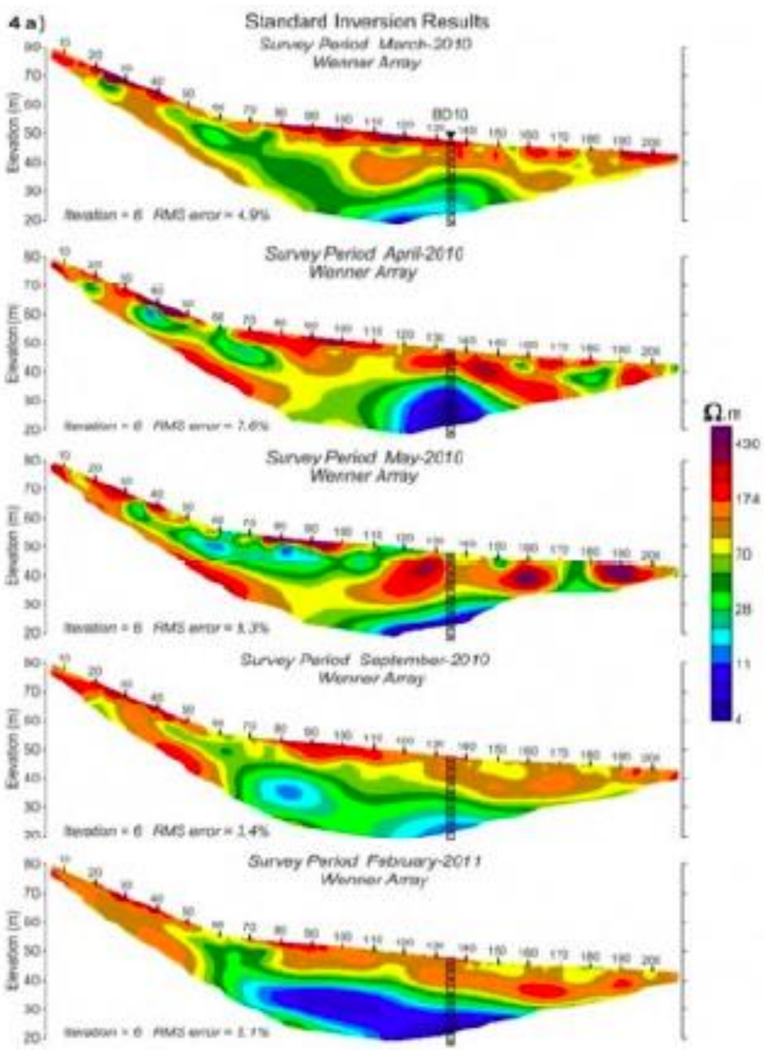
Geothermal exploration at a low enthalpy field using ERT. The low resistivity zone is coincident with a known fault where warm and saline fluids mix with surface and fresh water. An example of monitoring the effect on resistivity change when fresh water is pumped out from a well at the center of profile: the increase of salinity and temperature in the subsurface decreases the resistivity



MONITORING



Synthetic subsurface resistivity models for injection process related with different times (t = 0, 1, 2 and 3 unit; unit is equal to month for our problem).


4 a)
Standard Inversion Results
Survey Period March-2010
Wenner Array
Survey Period April-2010
Wenner Array
Survey Period May-2010
Wenner Array
Survey Period September-2010
Wenner Array
Survey Period February-2011
Wenner Array
Elevation (m)
BD10
Ω.m
430
174
70
28
11
4