Hydrogeologie

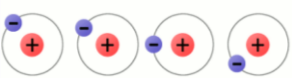
Resistivity Methods

Jakob Wilk
Institute of Earth and Environmental Sciences

Introduction

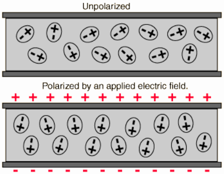
Basic Idea

- Measure electrical conductivities or resistivities using artificial fields.



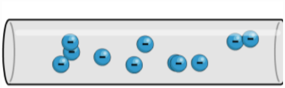
Electric

current transport



Dielectric

current transport



Electrolytic

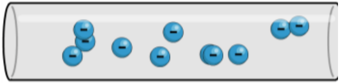
current transport

Introduction

Main Fields of Application

- Delimiting lithologic units and fault zones
- Determining depth and properties of aquifers
- Monitoring the impermeability of dams
- Exploration and monitoring of residual waste sites
- Monitoring the spread of pollutants
- Detecting potential slip surfaces (e. g., clay layers) in landslide-prone slopes

Mostly:



Introduction

Electric Field and Potential

- An electric field $\vec{E}$ exerts a force

$$\vec{F} \;=\; q\,\vec{E}$$

  on a charge q.
- In absence of time-dependent magnetic fields, the electric field can be represented by the gradient of the electric potential U:

$$\vec{E}(\vec{x}) \;=\; -\,\nabla U(\vec{x}) \;=\; -\begin{pmatrix} \frac{\partial}{\partial x_1} U(\vec{x}) \\ \frac{\partial}{\partial x_2} U(\vec{x}) \\ \frac{\partial}{\partial x_3} U(\vec{x}) \end{pmatrix}$$

$$\Downarrow$$

$$\vec{F}(\vec{x}) \;=\; -\,q\,\nabla U(\vec{x})$$

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$$\Downarrow$$

$$\vec{F}(\vec{x}) = -q\,\nabla U(\vec{x})$$

Introduction

Ohm‘s Law

Force on free electrons in a conductor

$\Downarrow$

Drift of electrons in direction of the force, velocity proportional to the force

$\Downarrow$

Current density (charge density $\times$ drift velocity)

$$\vec{j}(\vec{x}) \; = \; -\sigma \nabla U(\vec{x})$$

- Named after Georg Simon Ohm, 1789–1854.
- The constant of proportionality σ is a property of the material and is denoted electrical conductivity.

Introduction

Conductivity and Resistivity

Conductivity σ

$$[\sigma] = \frac{1}{\Omega\mathrm{m}} = \frac{\mathrm{S}}{\mathrm{m}},\ \Omega = \mathrm{Ohm} = \frac{\mathrm{V}}{\mathrm{A}},\ \mathrm{S} = \mathrm{Siemens} = \frac{\mathrm{A}}{\mathrm{V}}$$

Resistivity $\rho = \frac{1}{\sigma}$

$$[\rho] = \Omega\mathrm{m}$$

Conductance and resistance refer to objects and not to materials and are measured in S and Ω, respectively.

(Semi)Conductors	ρ [Ωm]
copper	1.7×10^{-8}
iron	10^{-7}
silicium	2300

Nonconductors	ρ [Ωm]
porcelain	10^{12}
rubber	10^{13}
silica glass	7.5×10^{17}

Introduction

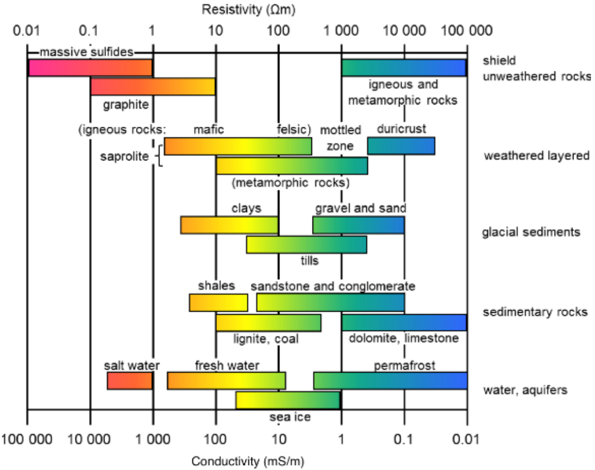
Conductivity / Resistivity of Rocks and Soils

- Rock forming minerals have very low conductivities.
- Many ores have considerably higher conductivities.
- The conductivity of pure water is rather low, but strongly increases by solving salts.

Solution	ρ [Ωm]
distilled water	10000
ocean water	0.5
10 % copper sulfate	0.3
10 % sodium chlorite	0.08
10 % sulfuric acid	0.025
10 % hydrochloric acid	0.015

Introduction

Conductivity / Resistivity of Rocks and Soils



Source: Telford 1990 Applied Geophysics

Rock	% H_2O	P [Ohm m]
Siltstone	0.54	$1.5*10^4$
	0.38	$5.6*10^8$
Coarse grain SS	0.39	$9.6*10^5$
	0.18	10^8
Medium grain SS	1.0	$4.3*10^3$
	0.1	$1.4*10^3$
Dolomite	1.3	$6*10^3$
	0.96	$8*10^3$
Granite	0.31	$4.4*10^3$
	0.19	$1.8*10^6$
Basalt	0.95	$4*10^4$
	0	$1.3*10^8$
Graywacke SS	1.16	$4.7*10^3$
	0.45	$5.8*10^4$
Peridotite	0.1	$3*10^3$
	0	$1.8*10^7$

Introduction

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Conductivity / Resistivity of Rocks and Soils

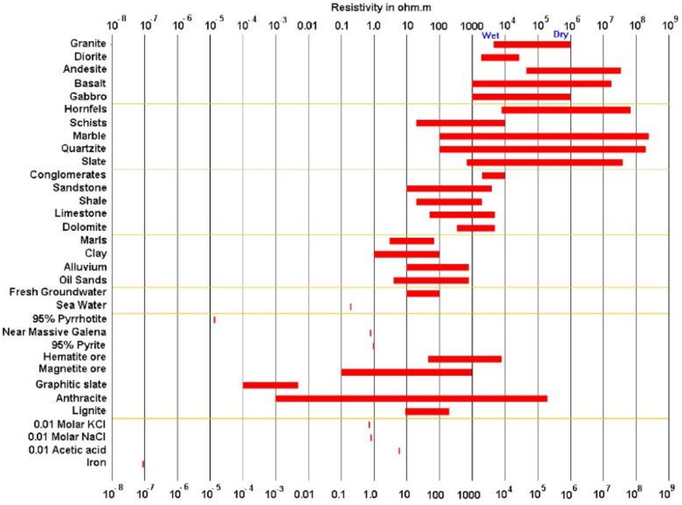
Material	ρ [Ωm]
halite	$10^5 - 10^7$
dry sand	10^5
water satur. sand	$1000 - 10000$
quartzite	$3000 - 10^5$
ice	$1000 - 10^5$
granite	$300 - 30000$
sandy soils	$150 - 7000$
loamy soils	$50 - 9000$
clayey soils	$20 - 4000$

Material	ρ [Ωm]
limestone	$100 - 7000$
marsh	$30 - 700$
glacial moraine	$10 - 300$
clay shale	$10 - 1000$
marl	$5 - 200$
loam	$3 - 300$
dry clay	$30 - 1000$
wet clay	$1 - 30$
silt	$10 - 1000$

Source: Beblo (Ed.), Umweltgeophysik

Introduction

Conductivity / Resistivity of Rocks and Soils



Source: Loke, Tutorial: 2-D and 3-D electrical imaging surveys

Introduction

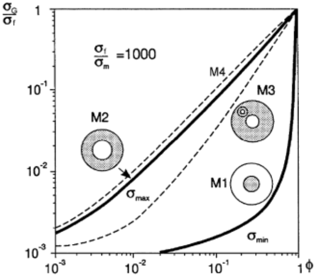
Conductivity / Resistivity of Rocks and Soils

Thus, the total conductivity of a rock or a soil strongly depends on

- porosity
- water saturation
- connectivity of the pore space
- pureness of the contained water (in return depends on the properties of the rock/soil)

$$\sigma_G = a\, \varphi^n\, S^m\, \sigma_F$$

with:
material conductivity (σG),
material properties (a, n, m),
porosity (ϕ),
conductivity of formation water (σ_F)
and pores actually containing water (S)



Hashin and Shtrikman (1962)

Introduction

Conductivity / Resistivity of Rocks and Soils

Thus, the total conductivity of a rock or a soil strongly depends on

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Question

Which are the main dependencies of the hydraulic conductivity of an aquifer?

Introduction

Conductivity / Resistivity of Rocks and Soils

Thus, the total conductivity of a rock or a soil strongly depends on

- porosity
- water saturation
- connectivity of the pore space
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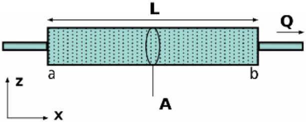
Question

Which are the main dependencies of the hydraulic conductivity of an aquifer?

$$Q = \frac{kA}{\mu L} \Delta p$$



Dynamic viscosity (μ), Permeability (κ) and Pressure drop (Δp)

ER – Basic Terms

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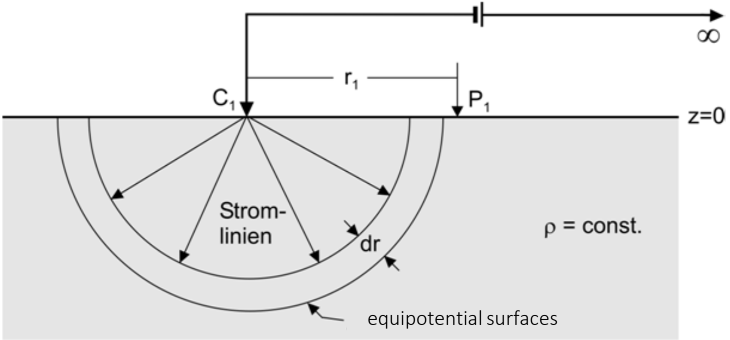
The Principle of Subsurface Resistivity Measurement

1. Two current electrodes A und B are plugged into the ground, and a voltage is applied, generating a current I from A to B.
2. Two potential electrodes M und N are plugged into the ground, and the voltage U between both is measured.



(from script Electromagnetic Methods in Geophysics H.Brasse SS2011)

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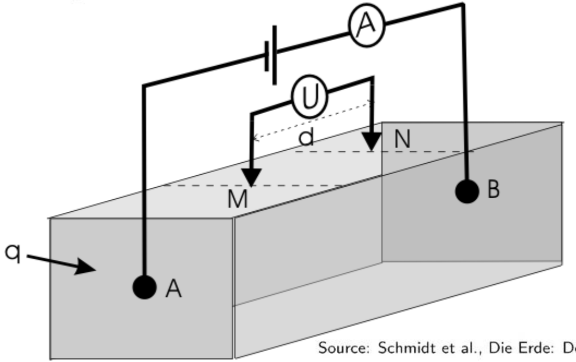
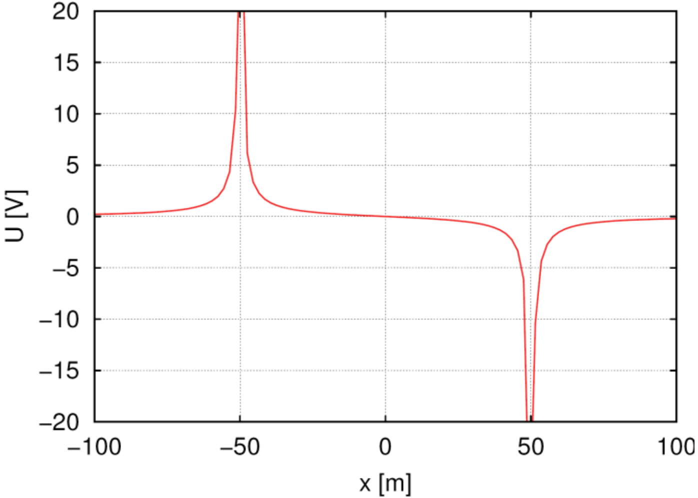


Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

The Potential between the Electrodes



$\rho = 1000\,\Omega\mathrm{m},\ I = 100\,\mathrm{mA},\ \mathrm{offset} = 100\,\mathrm{m}$

Basics

Solutions of the Potential Equation in a Homogeneous Medium

Potential of a point source at the origin feeding a current I:

$$U(\vec{x}) = \frac{\rho I}{4\pi\,|\vec{x}|}$$

Potential of a point source at the point $\vec{x}_A$ if the current is distributed in a half space only:

$$U(\vec{x}) = \frac{\rho I}{2\pi\,|\vec{x} - \vec{x}_A|}$$

Feeding in a current I at $\vec{x}_A$ and extracting I at $\vec{x}_B$:

$$\begin{aligned} U(\vec{x}) &= \frac{\rho I}{2\pi\,|\vec{x} - \vec{x}_A|} - \frac{\rho I}{2\pi\,|\vec{x} - \vec{x}_B|} \\ &= \frac{\rho I}{2\pi}\left(\frac{1}{|\vec{x} - \vec{x}_A|} - \frac{1}{|\vec{x} - \vec{x}_B|}\right) \end{aligned}$$

Arbitrary Electrode Configuration in a Homogeneous Half-Space

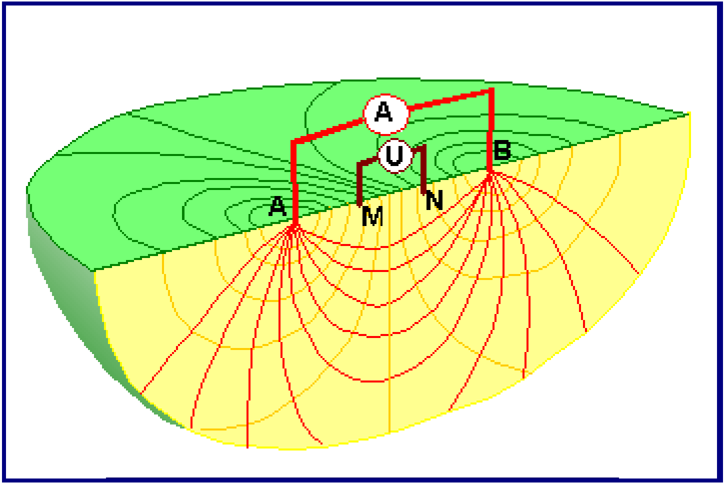
- Voltage between M and N is the difference of the potentials at $\vec{x}_M$ and $\vec{x}_N$:

$$
\begin{aligned}
U &= U(\vec{x}_M) - U(\vec{x}_N) \\
&= \frac{\rho I}{2\pi}\left(\frac{1}{|\vec{x}_M - \vec{x}_A|} - \frac{1}{|\vec{x}_M - \vec{x}_B|} - \frac{1}{|\vec{x}_N - \vec{x}_A|} + \frac{1}{|\vec{x}_N - \vec{x}_B|}\right) \\
&= \frac{\rho I}{2\pi}\left(\frac{1}{r_{MA}} - \frac{1}{r_{MB}} - \frac{1}{r_{NA}} + \frac{1}{r_{NB}}\right)
\end{aligned}
$$

  where $r_{\ldots}$ are the distances between the respective electrodes.
- Mostly, all electrodes are placed on a straight line.

Basics

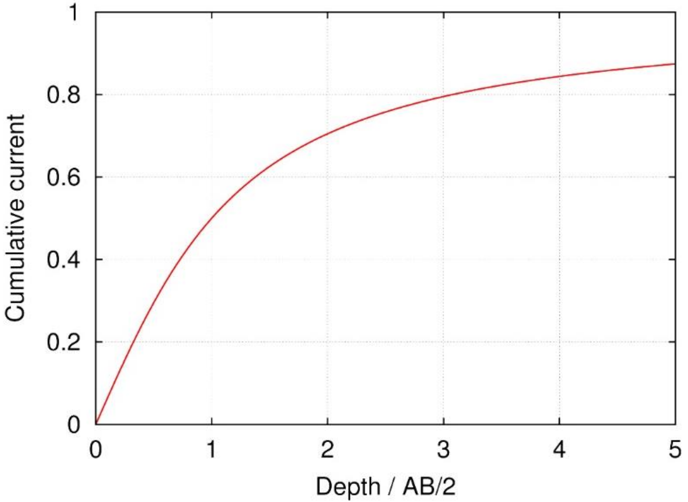
Dipole Field in a Homogeneous Half-Space



Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

Basics

Penetration Depth of the Current



ER – Measuring Principle

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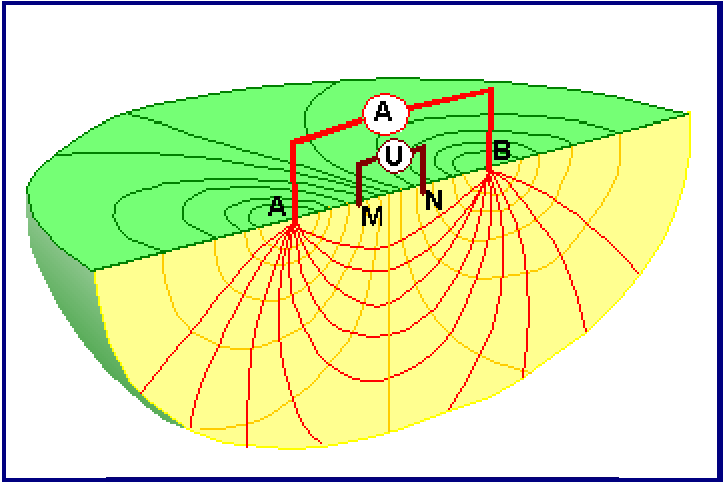
Measuring Principle

Dipole Field in a Homogeneous Half-Space



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Measuring Principle

Arbitrary Electrode Configuration in a Homogeneous Half-Space

- Voltage between M and N is the difference of the potentials at $\vec{x}_M$ and $\vec{x}_N$:

$$\begin{aligned} U &= U(\vec{x}_M) - U(\vec{x}_N) \\ &= \frac{\rho I}{2\pi}\left(\frac{1}{|\vec{x}_M - \vec{x}_A|} - \frac{1}{|\vec{x}_M - \vec{x}_B|} - \frac{1}{|\vec{x}_N - \vec{x}_A|} + \frac{1}{|\vec{x}_N - \vec{x}_B|}\right) \\ &= \frac{\rho I}{2\pi}\left(\frac{1}{r_{MA}} - \frac{1}{r_{MB}} - \frac{1}{r_{NA}} + \frac{1}{r_{NB}}\right) \end{aligned}$$

  where $r_{\dots}$ are the distances between the respective electrodes.
- Mostly, all electrodes are placed on a straight line.

Measuring Principle

Arbitrary Electrode Configuration in a Homogeneous Half-Space

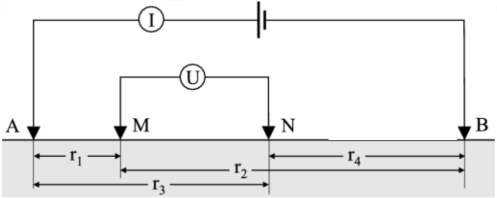
The resistivity of a homogeneous half-space can be determined according to

$$\rho = K \frac{U}{I}$$

with the geometric factor

$$K = \frac{2\pi}{\frac{1}{r_{MA}} - \frac{1}{r_{MB}} - \frac{1}{r_{NA}} + \frac{1}{r_{NB}}}$$

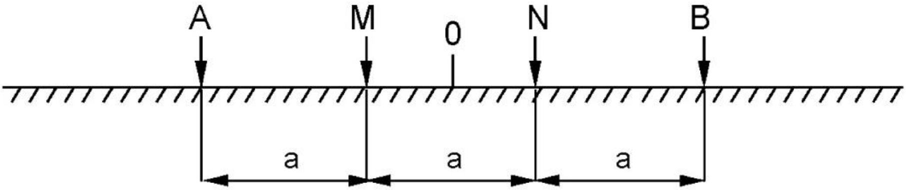
of the selected electrode configuration.



(from script Electromagnetic Methods in Geophysics H.Brasse SS2011)

Measuring Principle

The Wenner (α) Configuration



Source: Wikipedia

$$K = 2\pi a$$

Widely used for horizontal profiling (a fixed)

Measuring Principle

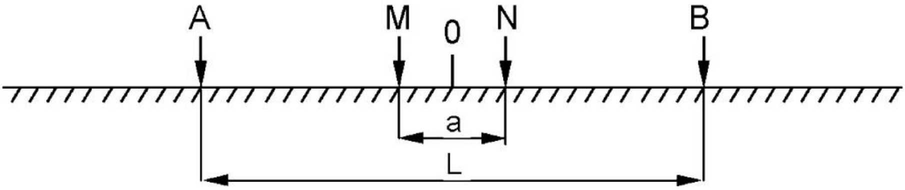
Variants of the Wenner Configuration

Configuration	Electrode sequence	Geometric factor
Wenner α	A-M-N-B	$K = 2\pi a$
Wenner β	A-B-M-N	$K = 6\pi a$
Wenner γ	A-M-B-N	$K = 3\pi a$

Wenner α is the standard configuration (Wenner without further specification).

Measuring Principle

The Schlumberger Configuration



Source: Wikipedia

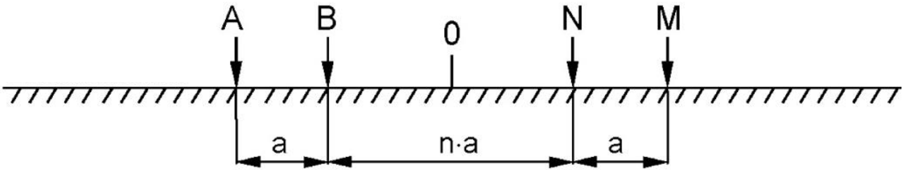
$$K = \frac{\pi\left(L^2 - a^2\right)}{4a} \approx \frac{\pi L^2}{4a} \quad \text{für } L \gg a$$

Widely used for vertical sounding (a fixed, L variable)

Caution: Sometimes L is used for AB/2 instead of the total offset AB.

Measuring Principle

The Dipole-Dipole Configuration



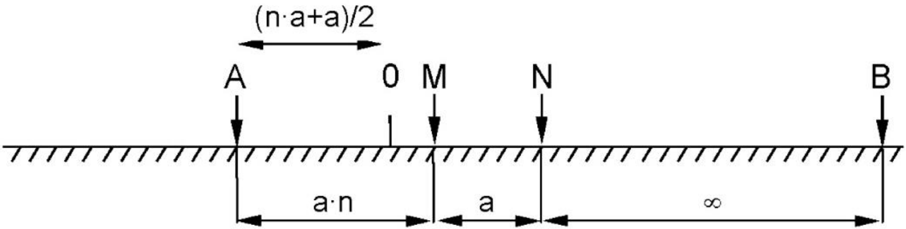
Source: Wikipedia

$$K = \pi n(n+1)(n+2)\,a$$

Particularly suitable for profiling of small-scale structures, but a requires high power input.

Measuring Principle

The Pole-Dipole Configuration



Source: Wikipedia

$$K = 2\pi \, n(n+1) \, a$$

Particularly suitable for investigating horizontal contrasts.

Measuring Principle

Surveys

Source: http://www.gfinstruments.cz

Source: http://www.lgm.de

Measuring Principle

Types of Resistivity Measurements

Results obtained for large offsets AB are more sensitive to the resistivities at greater depth than results obtained for small offsets.

Vertical sounding: same location, but different offsets

Horizontal profiling: constant electrode configuration used at different positions

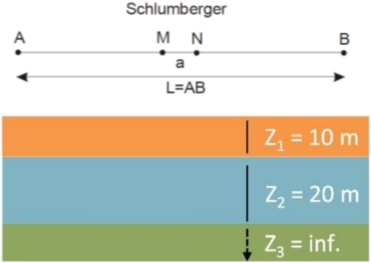
Resistivity tomography: variable location and variable electrode spacing

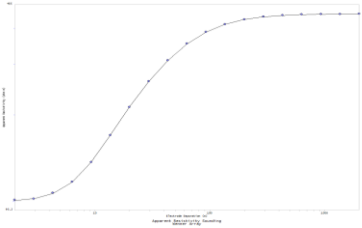
$\Downarrow$

Various types of electrode configurations more or less suitable for different purposes

Measuring Principle

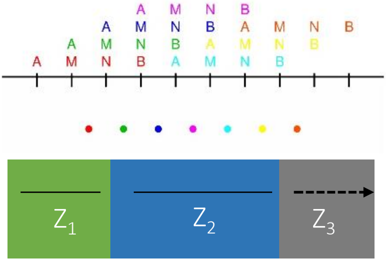
Surveys – Vertical Sounding

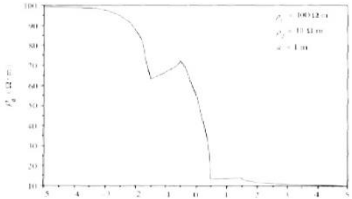




Measuring Principle

Surveys – Horizontal Profiling/Constant Separation Traversing (CST)

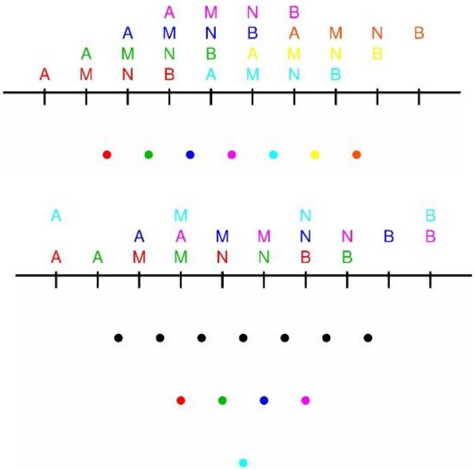


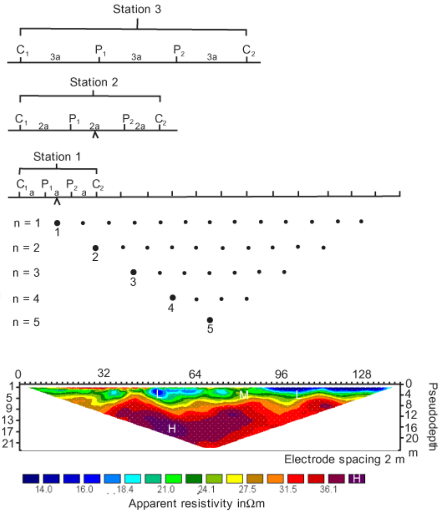


Source: Teaching material A. Henk

Measuring Principle

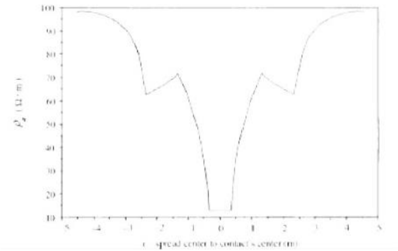
Surveys – Resistivity Tomography (ERT)

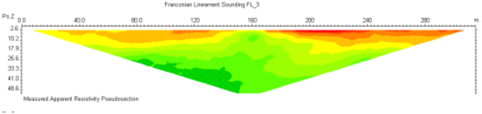




Measuring Principle

Surveys – ERT vs. Horizontal Profiling (CST)





1D profile and 2d inversion of Wenner line over the Franconian line (Source: H.Brasse 2003)

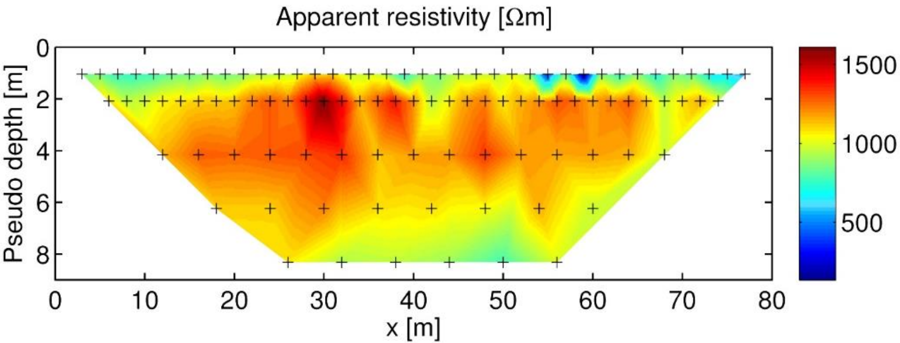
Measuring Principle

Surveys – Resistivity Tomography (ERT)

- Several (up to some hundred) electrodes are plugged into the ground, either on a profile line or distributed in two dimensions.
- A programmable channel selector replays a defined sequence of usage of the electrodes as current or potential electrode pairs.
- The method is also called electric tomography, in particular if the electrodes are distributed in two dimensions.

Measuring Principle

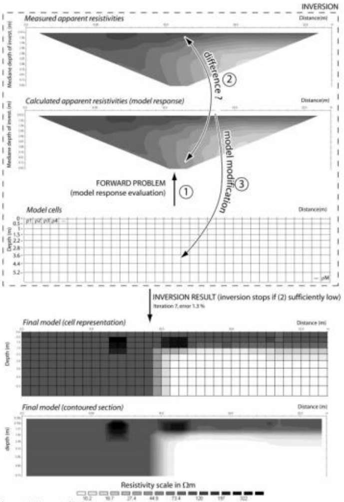
Surveys – Resistivity Tomography (ERT)



The Wenner (α) configuration is most widely used, but all other configurations are also possible.

Measuring Principle

Surveys – Resistivity Tomography (ERT)



Laurent Marescot, 2010

Electric tomography inversion

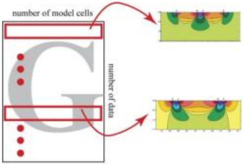
$$\Delta \mathbf{m} = \left[\mathbf{G}^{\mathrm{T}} \mathbf{G} + \mathbf{W} \right]^{-1} \mathbf{G}^{\mathrm{T}} \, \Delta \mathbf{d}$$

with:

$$\Delta \mathbf{m} = \log(\rho)$$

$$\Delta \mathbf{d} = \log(\rho_a^{meas}) - \log(\rho_a^{calc})$$

$$G_{ij} = \frac{\partial g(m)_i}{\partial m_j}$$ is the sensitivity matrix



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Surveys – Electrodes

Current and potential electrodes are technically identical. Criteria (in particular for the potential electrodes):

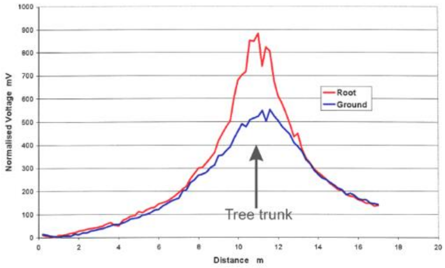
Contact resistance to the ground should be low.

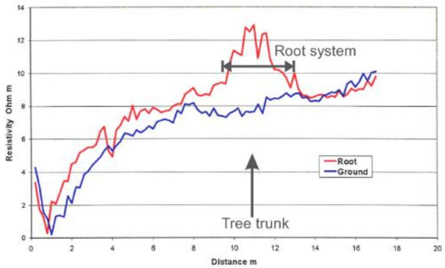
Contact voltage should be small.

- Usage of nonpolarizable electrodes, e. g., copper core in $CuSO_4$ solution in a porous clay cylinder.
- Simple steel electrodes can be used with modern central units that are able to compensate contact voltages automatically.

Measuring Principle

Surveys – Horizontal Profiling





Comparison between planting the current electrode directly into a tree trunk versus into the ground near the tree's base: left - normalized potential, right – normalized resistivity profile

Measuring Principle

Surveys – Electrodes

- Power source (constant current),
- voltmeter, and
- channel selector (for multi-electrode equipment)

are mostly combined in one unit.

Power up to about 1000 W

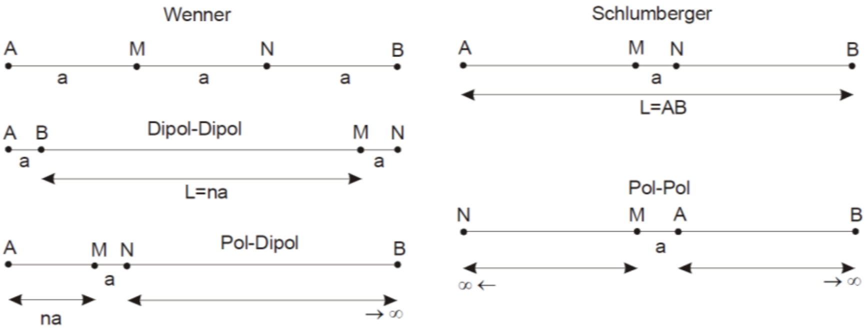
Currents mostly between 10 mA and 1 A

Voltages (between the current electrodes) up to some 1000 V

Types of current: DC, low-frequency AC or switched DC with changing polarity

Measuring Principle

Surveys



ER - Data Analysis I

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Apparent Resistivity

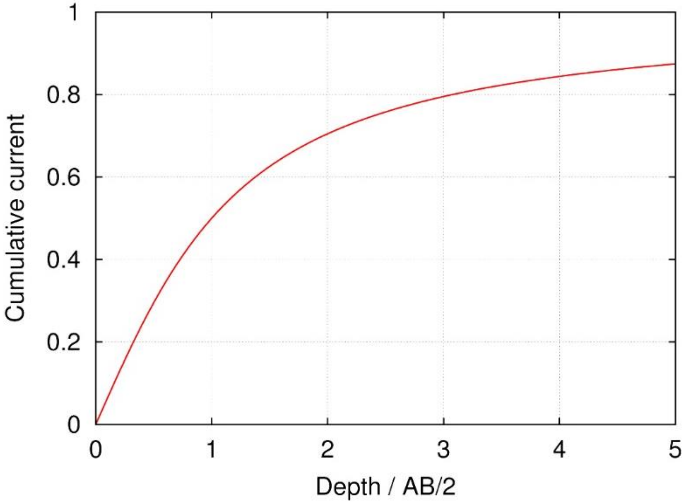
In a inhomogeneous medium,

$$\rho_a = K\frac{U}{I}$$

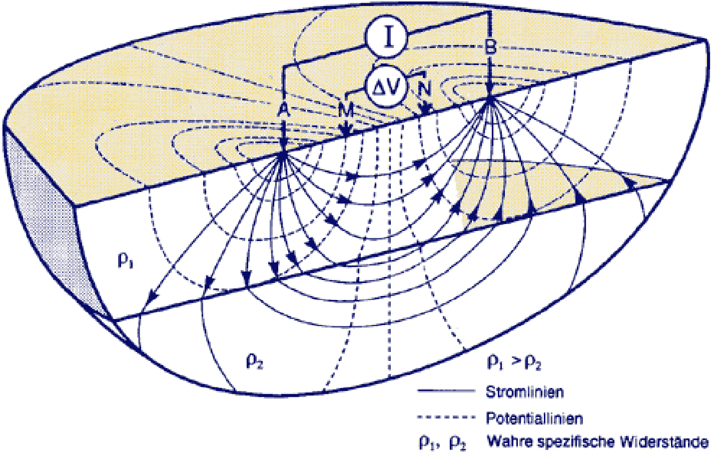
is called the apparent resistivity obtained from one measurement.

- ρ_a is the resistivity of a homogeneous medium that would yield the same result for the considered electrode configuration.
- ρ_a is not the real resistivity at any depth.
- The larger the offset is, the bigger is the contribution of deep regions to ρ_a.

Penetration Depth of the Current

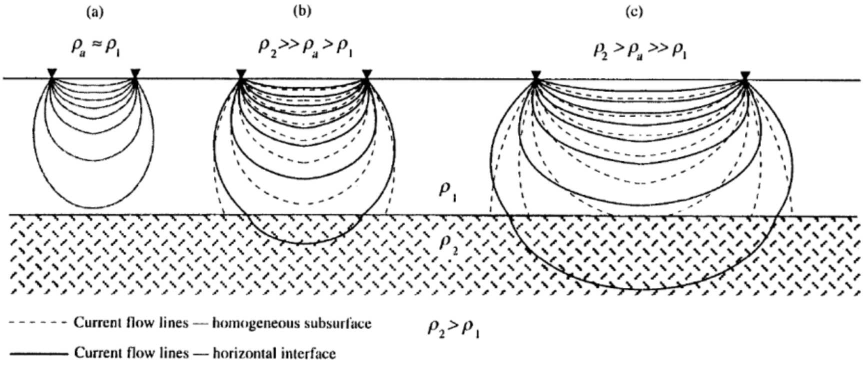


Vertical Sounding in the Two-Layer Case



Source: Knödel et al., Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten, Vol. 3

Vertical Sounding in the Two-Layer Case



apparent electric resistivity in a two layer scenario

Vertical Sounding in the Two-Layer Case

Situation: Two homogeneous regions separated by a horizontal interface.

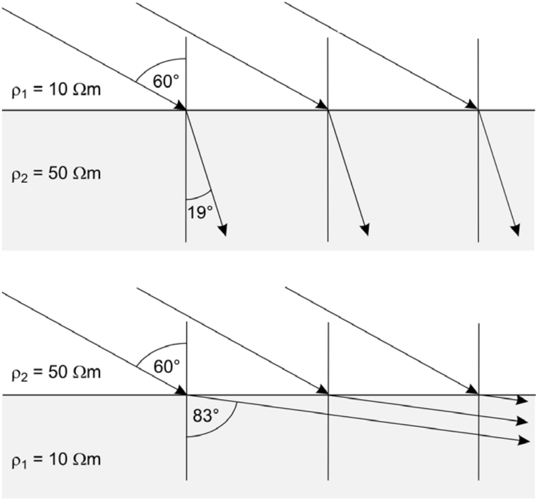
Target properties:

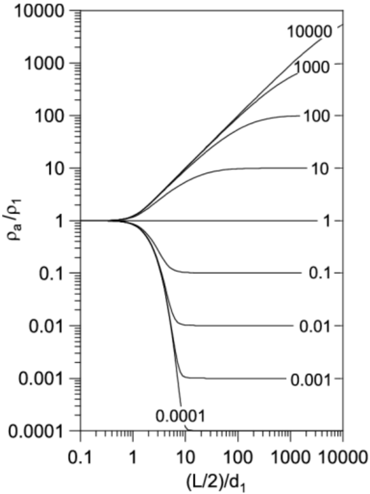
$$\begin{aligned} \rho_1 &= \text{resistivity of the upper layer} \\ \rho_2 &= \text{resistivity of the lower region} \\ d &= \text{thickness of the upper layer} \end{aligned}$$

Procedure: ρ_a is measured for several offsets AB (Wenner or Schlumberger configuration).

Data analysis can be performed graphically because $\frac{\rho_a}{\rho_1}$ only depends on $\frac{\rho_2}{\rho_1}$ and $\frac{AB/2}{d}$.

Vertical Sounding in the Two-Layer Case





Source: U.S. Environmental Protection Agency

Scaling Behaviour

Rescaling the resistivities: If $\rho(\vec{x})$ is changed by the same factor λ everywhere, ρ_a changes by the same factor λ.

Spatial scaling: Stretching the entire system (including the positions of the electrodes) horizontally and vertically by a factor λ:

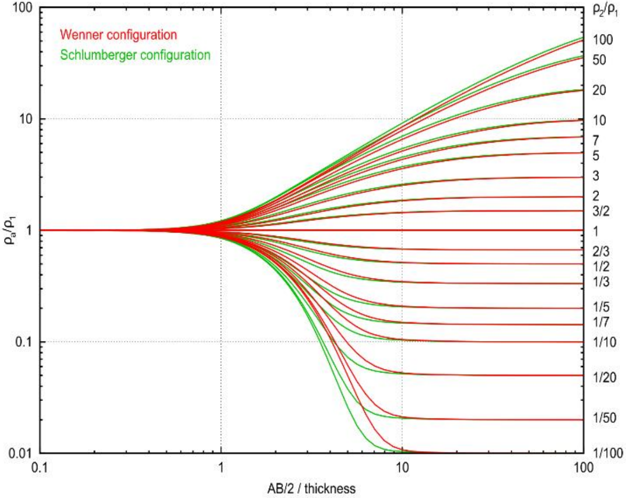
- If I is kept constant, all potentials change by the factor $\frac{1}{\lambda}$.
- K changes by the factor λ.

$$\Downarrow$$

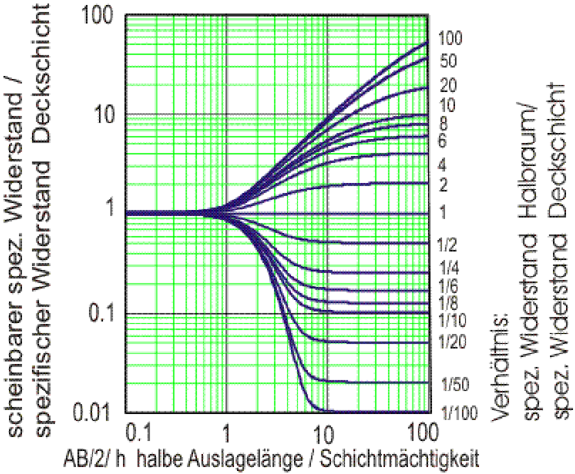
ρ_a remains the same.

Consequence for the two-layer case: For any given electrode configuration at variable offset, $\frac{\rho_a}{\rho_1}$ depends only on $\frac{\rho_2}{\rho_1}$ and $\frac{AB}{d}$ (or $\frac{AB/2}{d}$ or $\frac{a}{d}$).

Wenner and Schlumberger Configurations in the Two-Layer Case

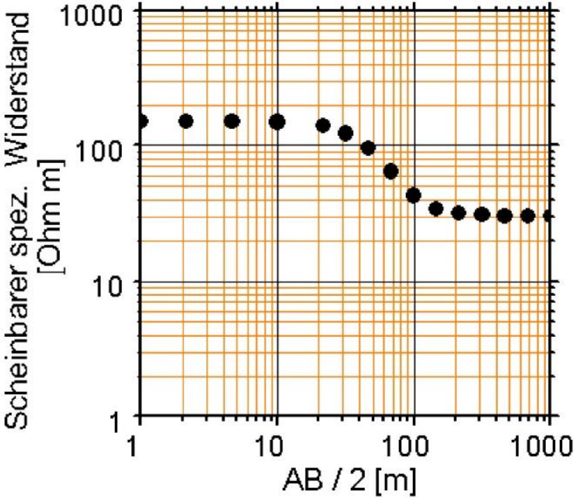


Graphical Data Analysis in the Two-Layer Case



Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

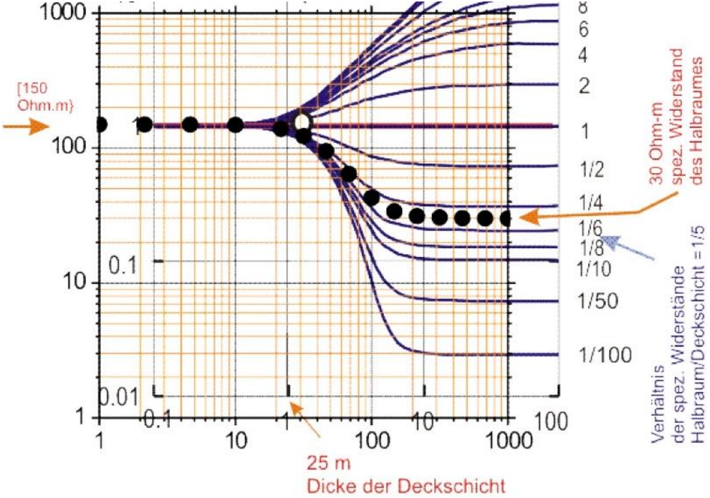
Graphical Data Analysis in the Two-Layer Case



Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

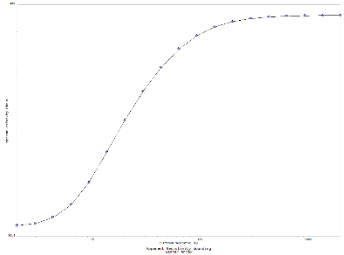
Data Analysis I

Graphical Data Analysis in the Two-Layer Case

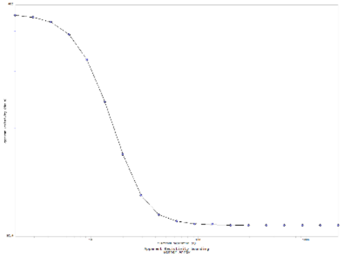


Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

Analysis in the Two-Layer Case

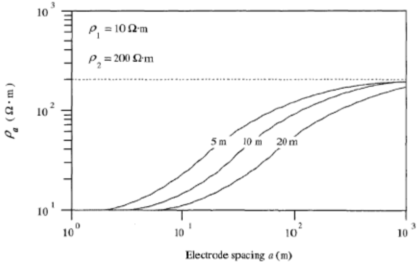


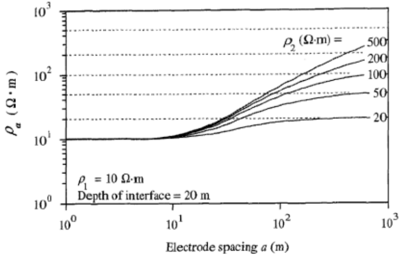
- material with greater resistivity lies below the interface



- material with greater resistivity lies above the interface

Analysis in the Two-Layer Case



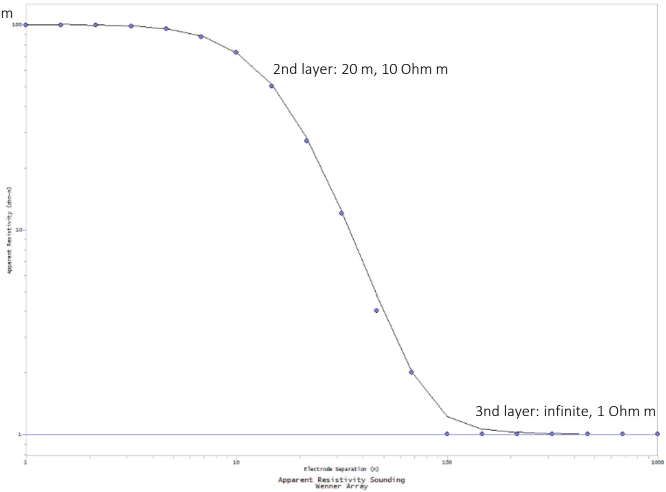


- constant resistivity
- constant depth

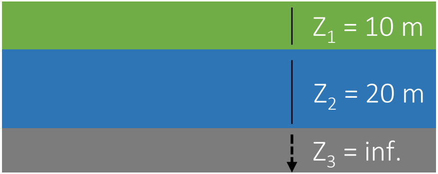
Data Analysis I

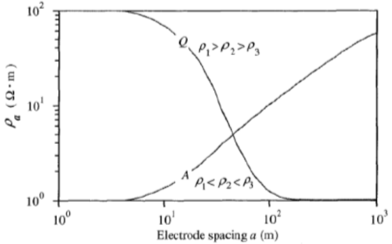
Analysis in the Two-Layer Case

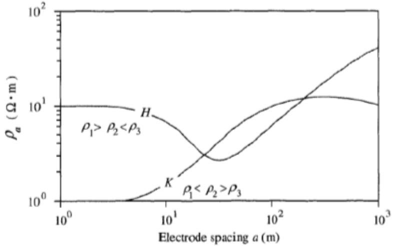
1st layer: 10 m, 100 Ohm m



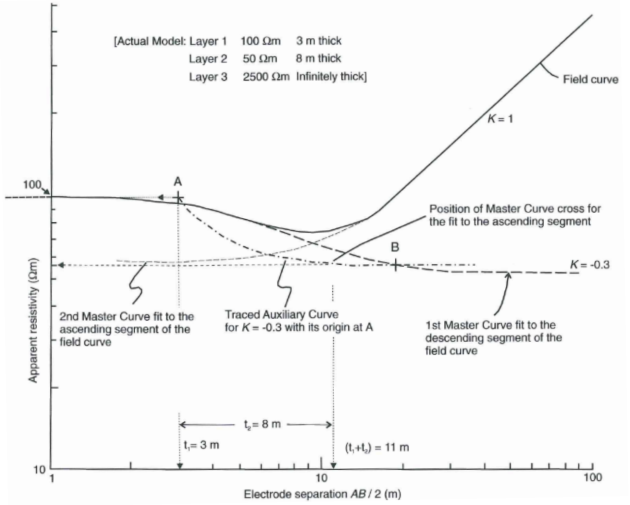
Analysis in the Three-Layer Case



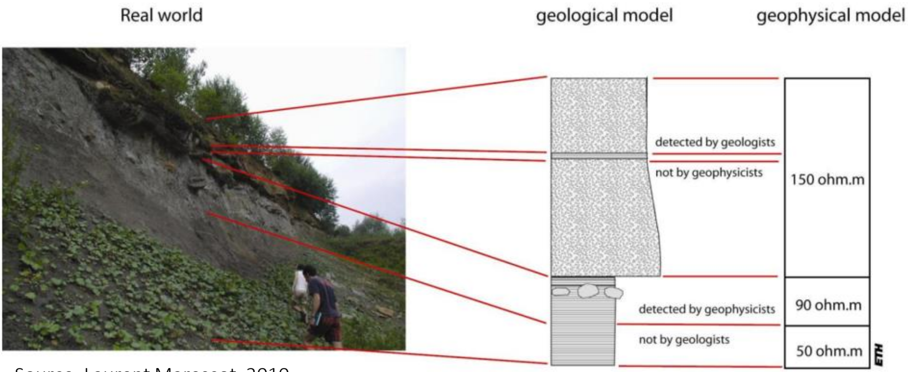




Analysis in the Three-Layer Case



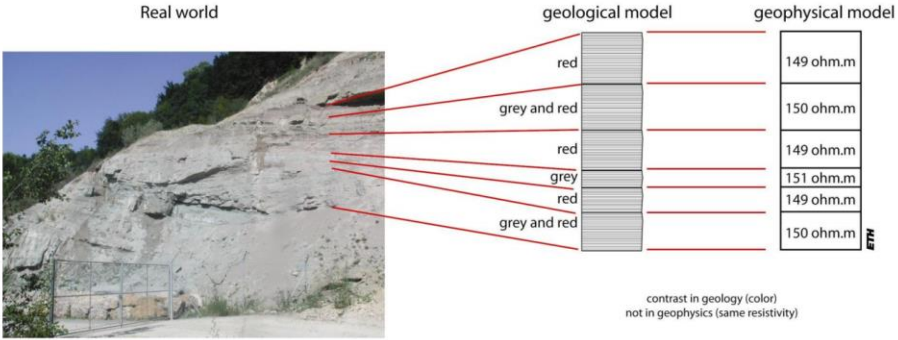
Multi-Layer Case



Source: Laurent Marescot, 2010

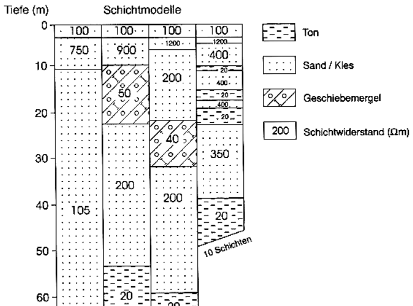
Multi-Layer Case

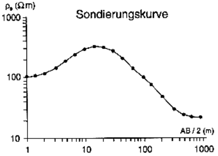
To characterize different material using geophysics, a contrast must exist (i.e. a difference in the physical properties)



Source: Laurent Marescot, 2010

Multi-Layer Case





2-Layer Case

- The result is more or less unique if a sufficient range of offsets is covered.
- The procedure can also be applied to gently dipping interfaces.
- This method has only historical and educational meaning. Practically, numerical inversion is preferred.

N-Layer Case

- Must be inverted numerically. Resistivities and thicknesses of the layers are adjusted to obtain the best fit to the measured apparent resistivities.
- The uppermost layer has a strong influence on the result.
- A deep, thin layer with a high contrast in resistivity may have a similar effect as a thicker layer with a lower contrast in resistivity.
- In the standard inversion procedure of vertical sounding, the number of layers is given, and thicknesses and resistivities are adjusted. Different numbers of layers may lead to strongly different results.

$$\Downarrow$$

Quantitative analysis often hinges on independent information, e. g., from seismics or boreholes.

ER - Data Analysis II

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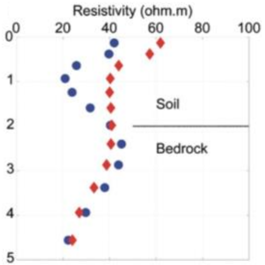
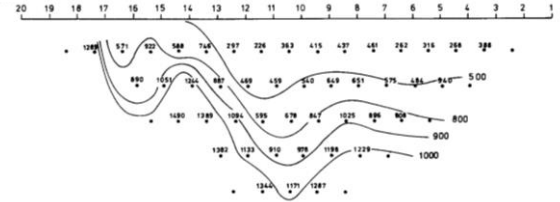
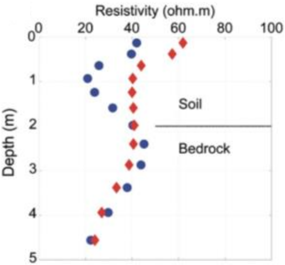
Institute of Earth and Environmental Science

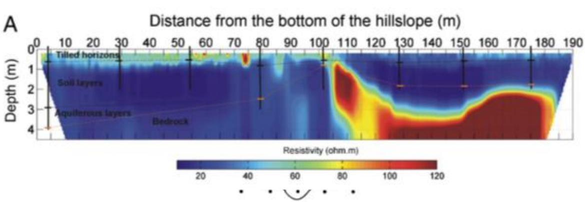
Penetration Depth of Current





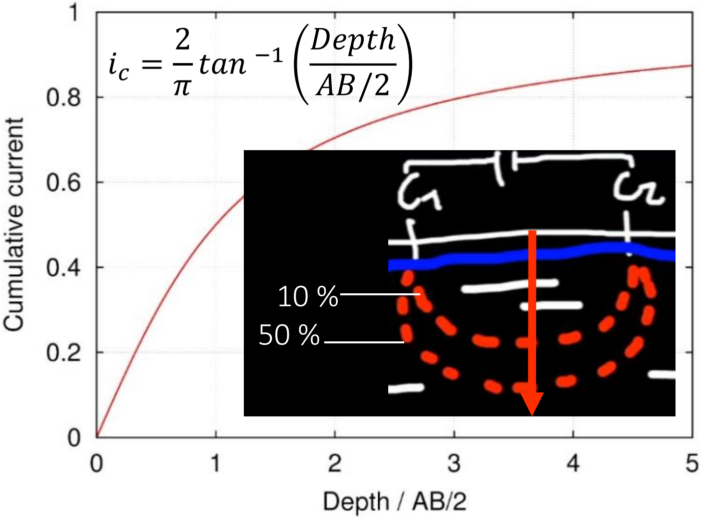
Penetration Depth of Current



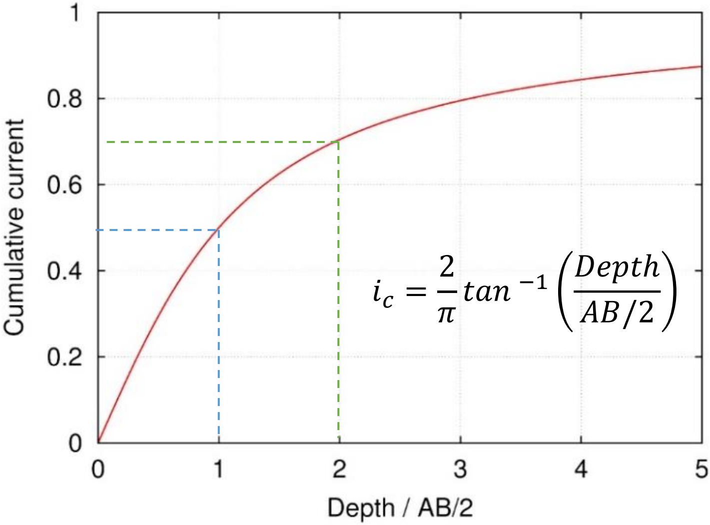


G. Coulouma et al. / Geoderma 170 (2012) 39–47

Penetration Depth of Current



Penetration Depth of Current



$$i_c = \frac{2}{\pi} tan^{-1}\left(\frac{Depth}{AB/2}\right)$$

Penetration Depth of Current

Half of the current penetrates deeper than half of the total offset (AB/2), but

- the entire current must also pass shallow regions, and
- the potential electrodes are at the surface.

$$\Downarrow$$

Typical depth of investigation is lower than AB/2.

Principle of the Sensitivity Analysis and Depth of Investigation Characteristic formula

$$\Delta\rho \sim \rho I$$

$$F(z) = \frac{2I_A}{\pi} \frac{z}{\left(r_{AM}^2 + 4z^2\right)^{1.5}}$$

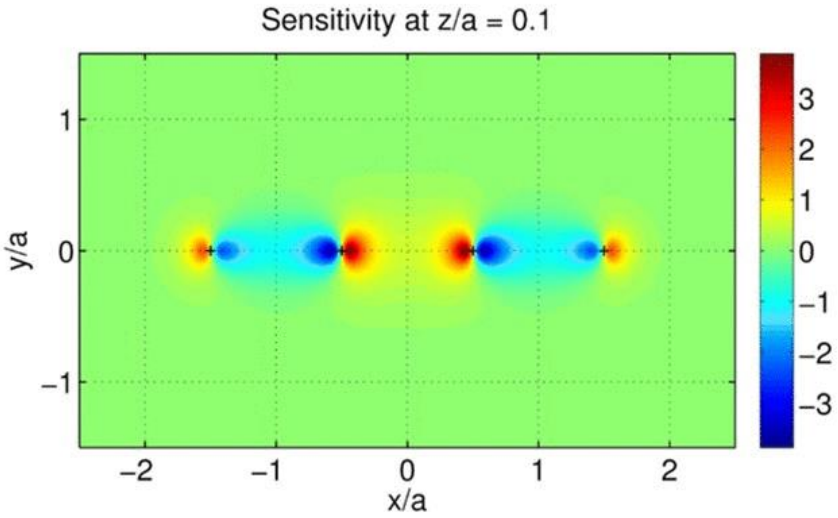
$$F_4(z) = \frac{2zI_A}{\pi}\Big[\left(r_{AM}^2 + 4z^2\right)^{-1.5} - \left(r_{AN}^2 + 4z^2\right)^{-1.5} - \left(r_{BM}^2 + 4z^2\right)^{-1.5} + \left(r_{BN}^2 + 4z^2\right)^{-1.5}\Big]$$

Source: Butler, 2015 after Roy and Apparo, 1971

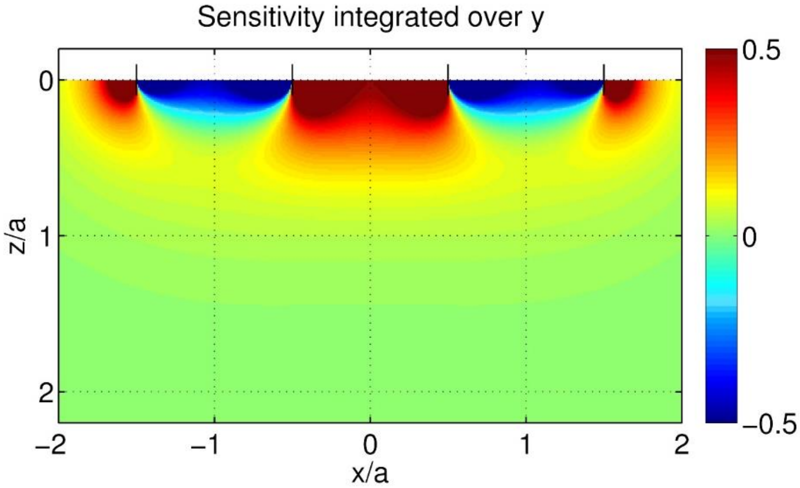
Principle of the Sensitivity Analysis and DIC formula

- Assume a given configuration of electrodes in a homogeneous medium with a resistivity ρ.
- Assume that ρ is increased (decreased) by a small amount $\delta\rho$ in a small region around a given point $\vec{x}$ in the subsurface.
- Determine how this small change affects the voltage between M and N if the current between A and B is given.

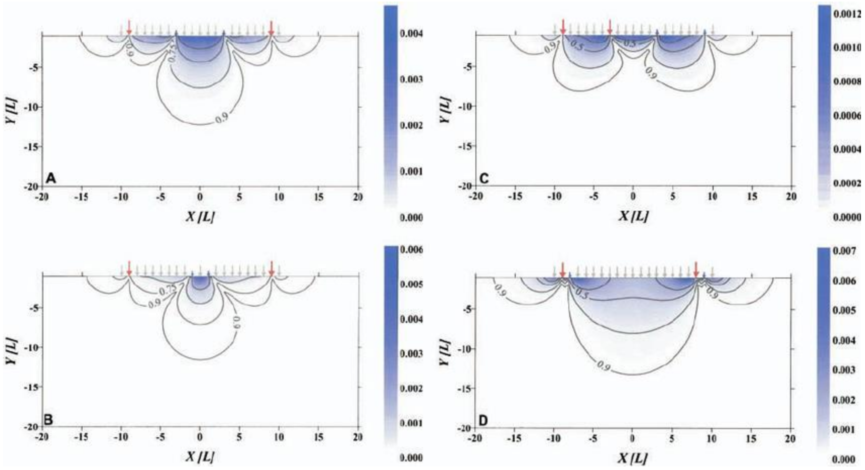
Sensitivity of the Wenner Configuration



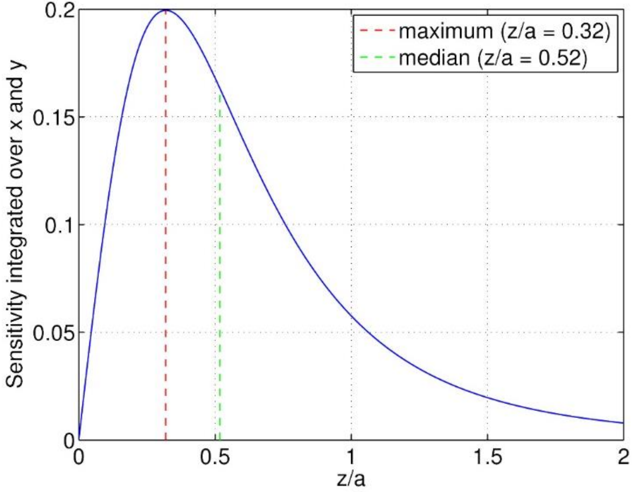
Sensitivity / Signal contribution section of the Wenner Configuration



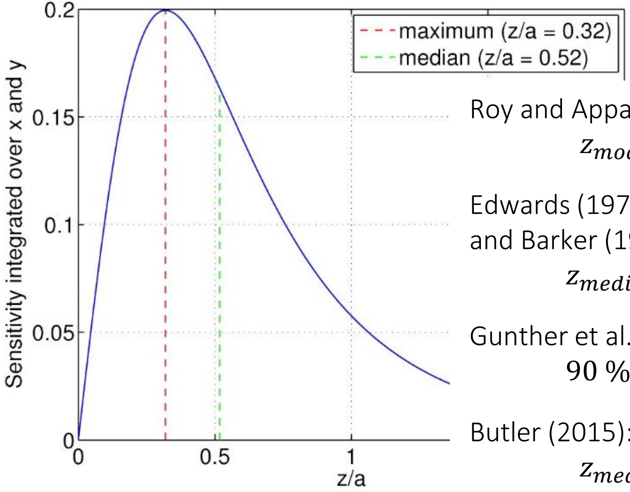
Sensitivity maps for Wenner, Schlumberger, double-dipole, & partial



Sensitivity of the Wenner Configuration



Sensitivity of the Wenner Configuration



Roy and Apparao (1971):

z_{mode}

Edwards (1977)
and Barker (1989):

z_{median}

Gunther et al. (2006):

90 %

Butler (2015):

z_{mean}

Sensitivity of the Wenner Configuration

- Sensitivity is always highest at low depth, in particular close to the electrodes M and N.
- Sensitivity changes its sign at low depths.
- Horizontally integrated sensitivity is highest at $z \approx 0.32\ a$.
- Median of the horizontally integrated sensitivity distribution is at $z \approx 0.52\ a$.

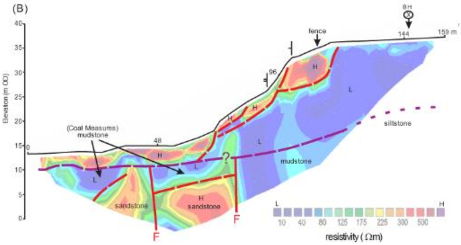
$\Downarrow$

Regions with $z < 0.52\ a$ and $z > 0.52\ a$ contribute equally to the sensitivity in total.

$\Downarrow$

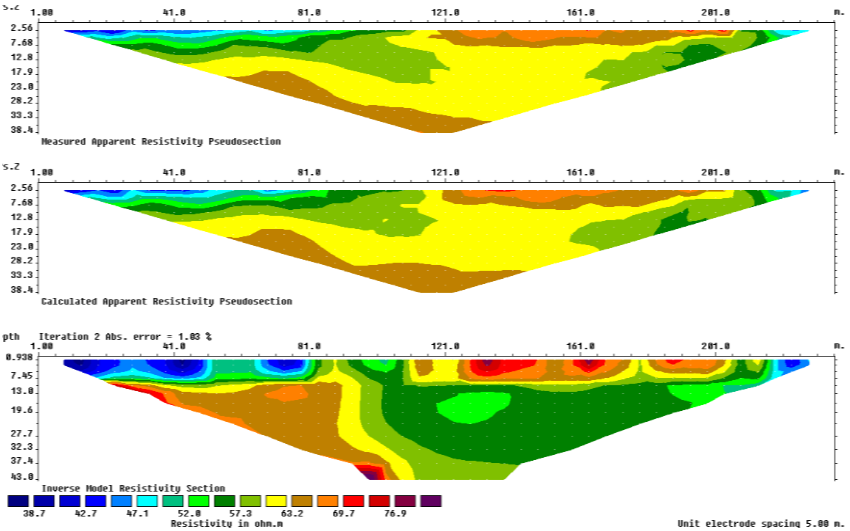
$0.52\ a$ is often assumed as the typical depth of investigation.

Pseudosections

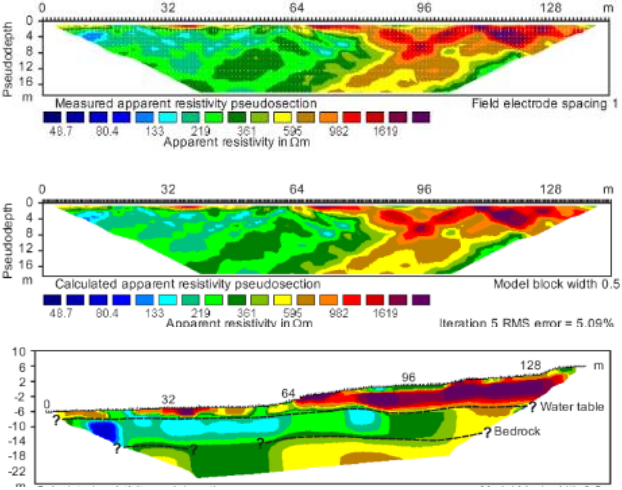


Source: Reynolds 2011

Pseudosections



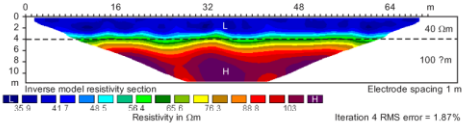
Pseudosections



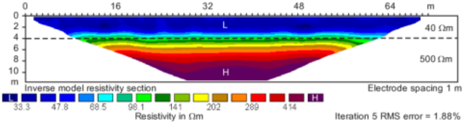
Data Analysis II

Pseudosections

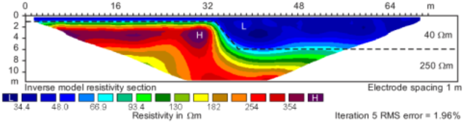
(A)



(B)



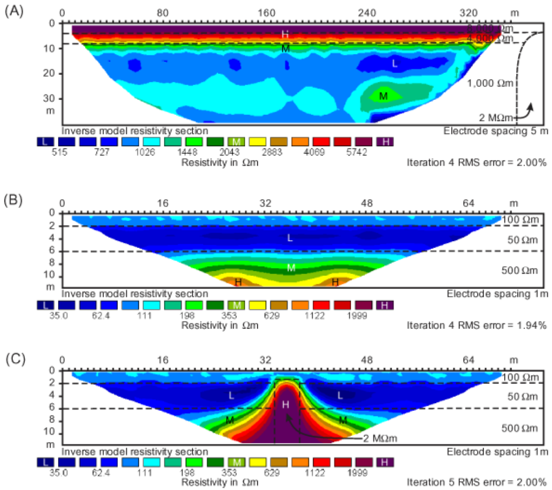
(C)



1. Normal fault
2. High contrast two-layer case
3. Low contrast two-layer case

Data Analysis II

Pseudosections



1. Section with a lateral Discontinuity

2. Lateral homogenous three-layer section