Near-surface Geophysics

Resistivity Methods

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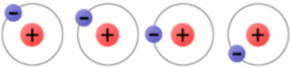
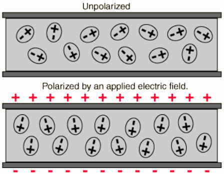
Introduction

Basic Idea

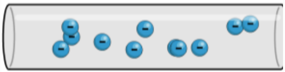
- Measure electrical conductivities or resistivities using artificial fields.



Electric current transport



Dielectric current transport



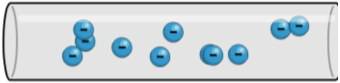
Electrolytic current transport

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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Introduction

Ohm‘s Law

Force on free electrons in a conductor

↓

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

↓

Current density (charge density × 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}

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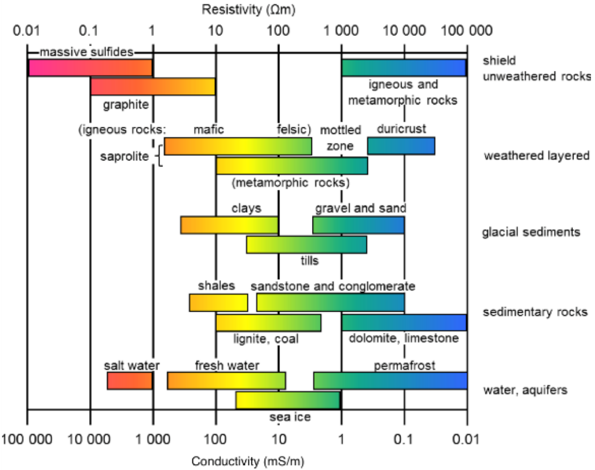
Conductivity / Resistivity of Rocks and Soils

- 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	$1.8*10^7$

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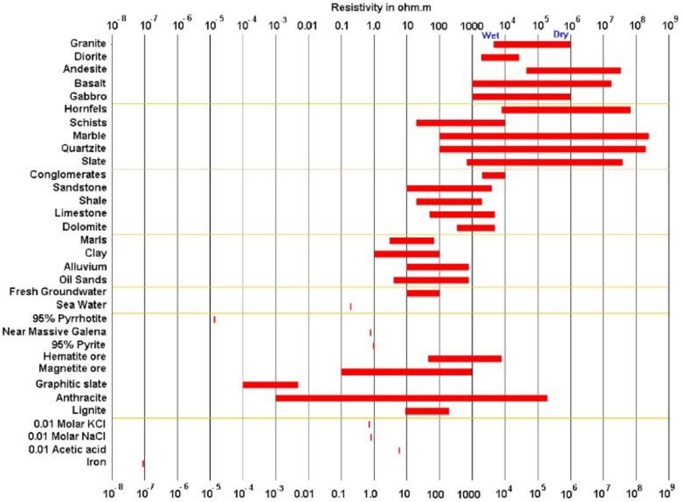
Conductivity / Resistivity of Rocks and Soils

Material	ρ [Ωm]	Material	ρ [Ωm]
halite	$10^5 - 10^7$	limestone	$100 - 7000$
dry sand	10^5	marsh	$30 - 700$
water satur. sand	$1000 - 10000$	glacial moraine	$10 - 300$
quartzite	$3000 - 10^5$	clay shale	$10 - 1000$
ice	$1000 - 10^5$	marl	$5 - 200$
granite	$300 - 30000$	loam	$3 - 300$
sandy soils	$150 - 7000$	dry clay	$30 - 1000$
loamy soils	$50 - 9000$	wet clay	$1 - 30$
clayey soils	$20 - 4000$	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

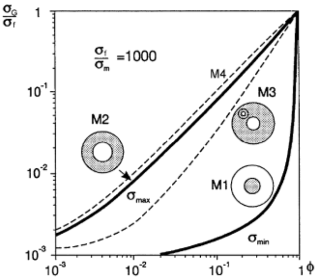
Conductivity / Resistivity of Rocks and Soils

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

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Question

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

Introduction

Conductivity / Resistivity of Rocks and Soils

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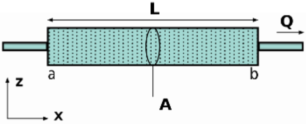
Question

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

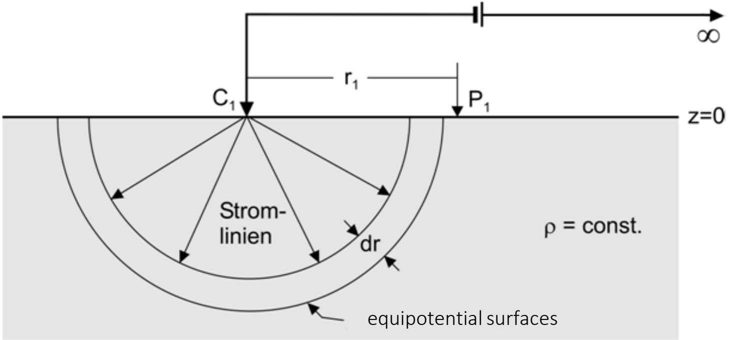
$$Q = \frac{kA}{\mu L} \Delta p$$



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

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)

The Principle of Subsurface Resistivity Measurement

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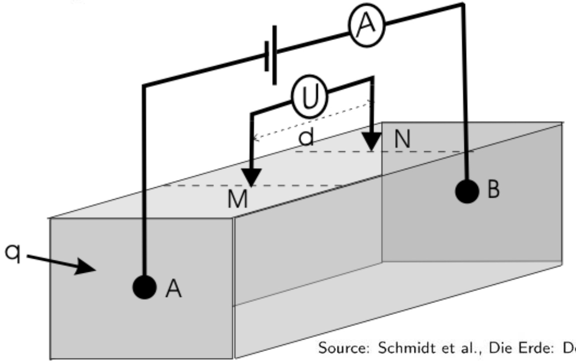
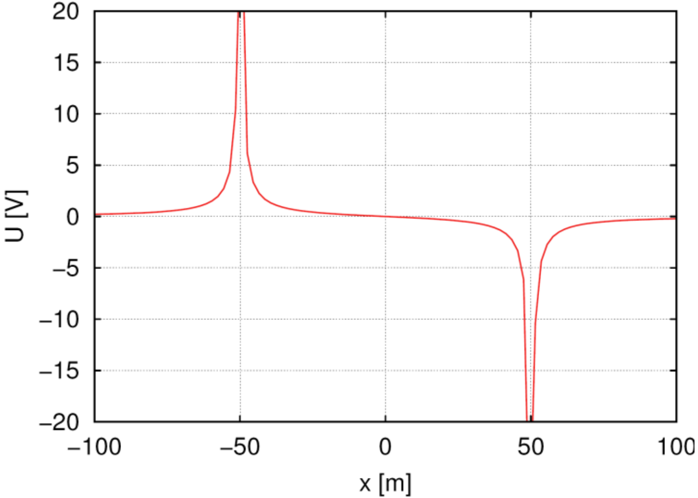


Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

The Potential between the Electrodes



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

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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 $\vec{x}_B$:

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

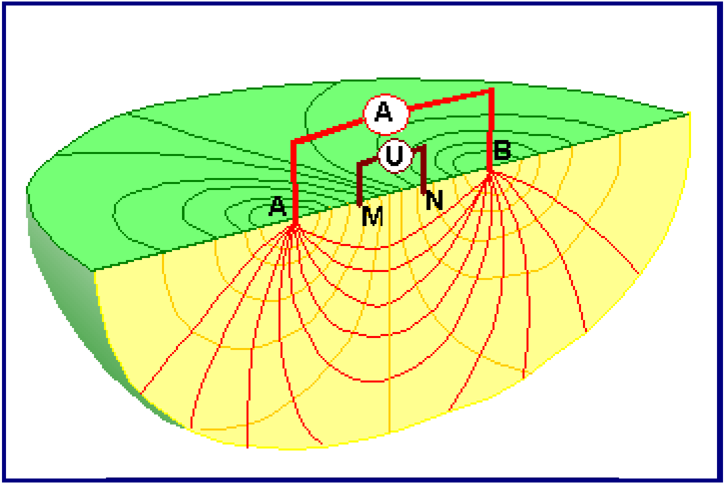
Arbitrary Electrode Configuration in a Homogeneous Half-Space

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

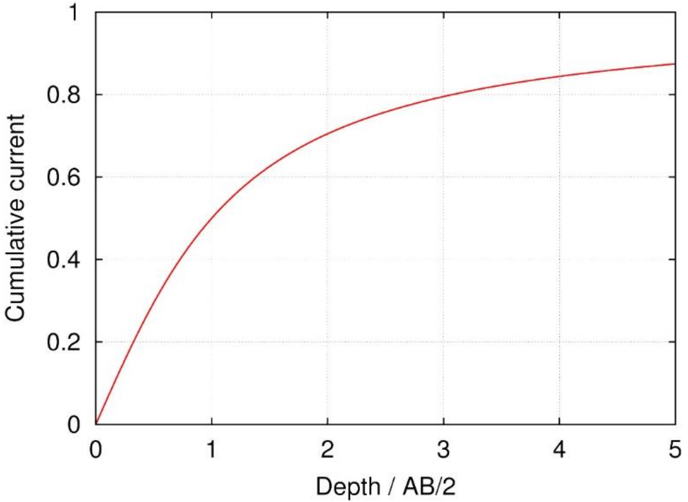
Dipole Field in a Homogeneous Half-Space



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

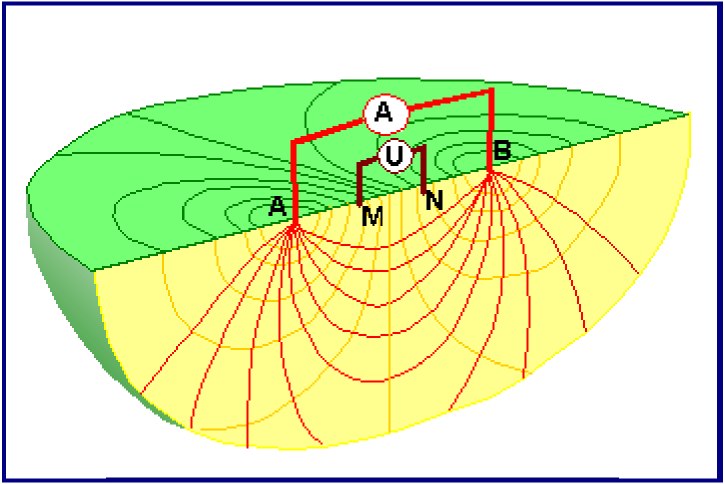
Basics

Penetration Depth of the Current



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

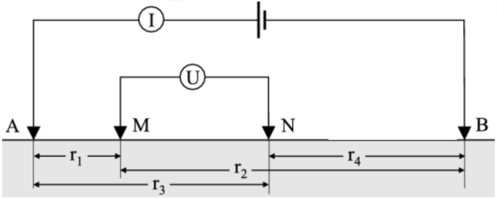
The resistivity of a homogeneous half-space can be determined according to

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

with the geometric factor

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

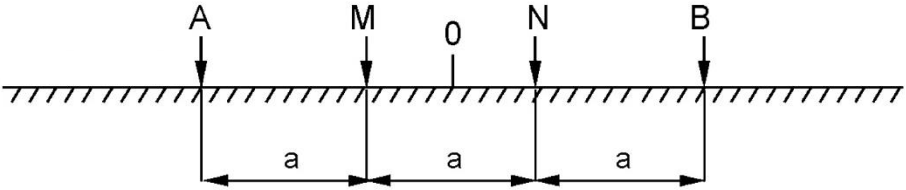
of the selected electrode configuration.



(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

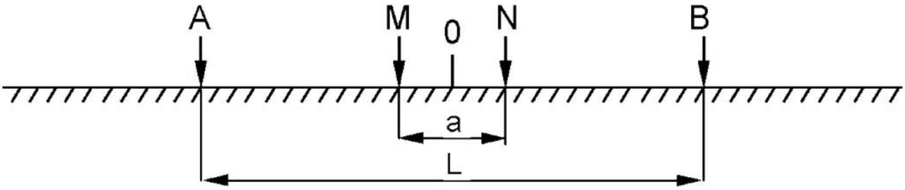
Variants of the Wenner Configuration

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

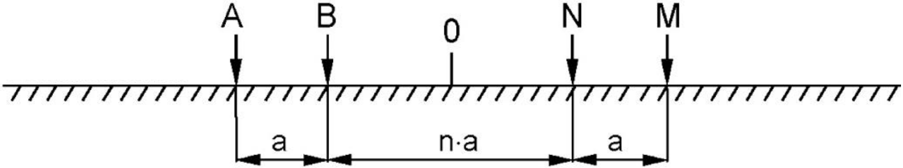
$$K = \frac{\pi\left(L^2 - a^2\right)}{4a} \approx \frac{\pi L^2}{4a} \quad \text{für } L \gg a$$

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



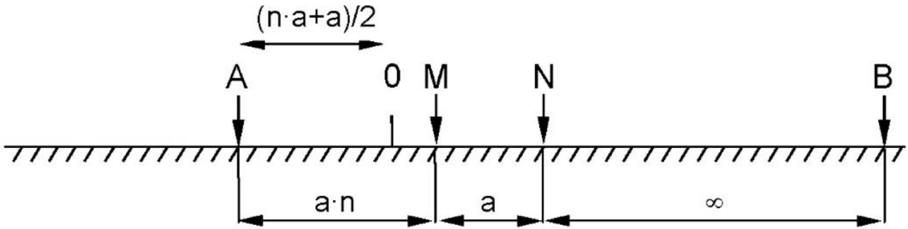
Source: Wikipedia

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

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

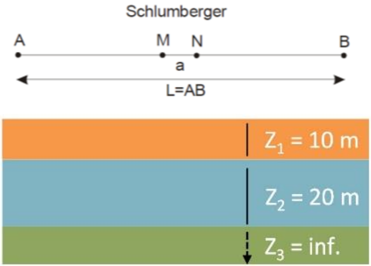
Resistivity tomography: variable location and variable electrode spacing

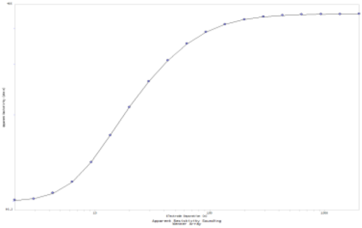
↓

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

Measuring Principle

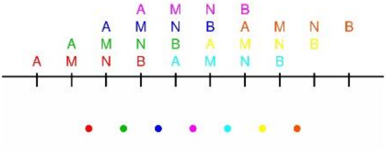
Surveys – Vertical Sounding

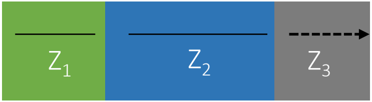


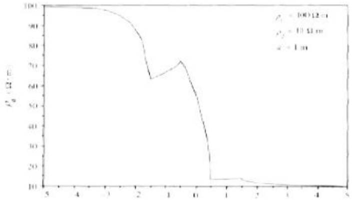


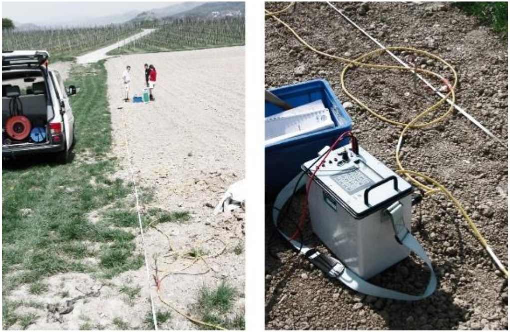
Measuring Principle

Surveys – Horizontal Profiling/Constant Separation Traversing (CST)





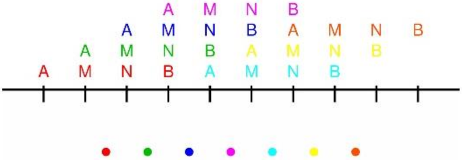


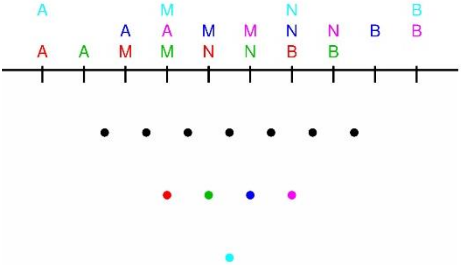


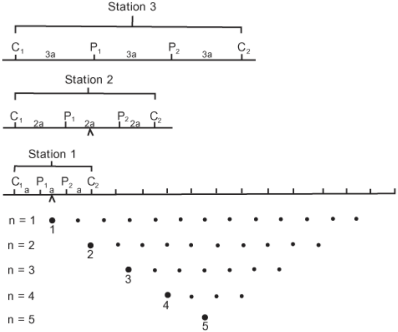
Source: Teaching material A. Henk

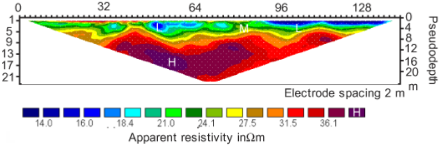
Measuring Principle

Surveys – Resistivity Tomography (ERT)



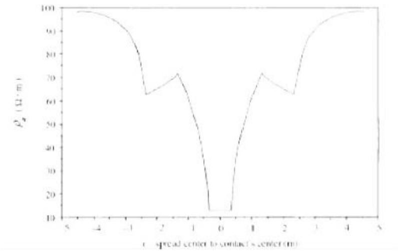


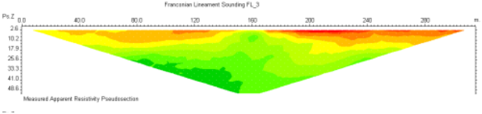




Measuring Principle

Surveys – ERT vs. Horizontal Profiling (CST)





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

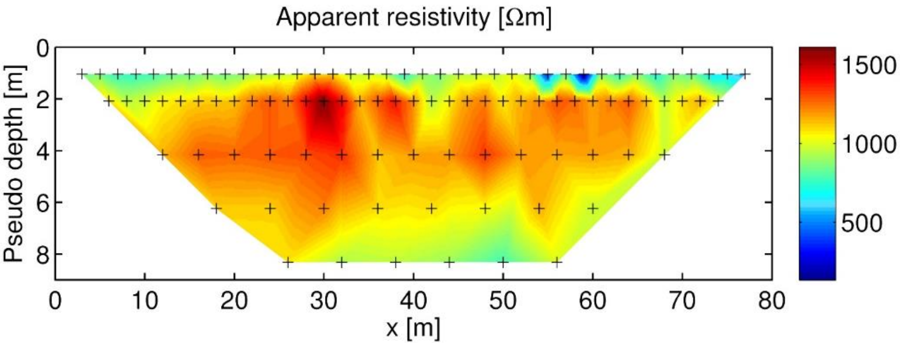
Measuring Principle

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

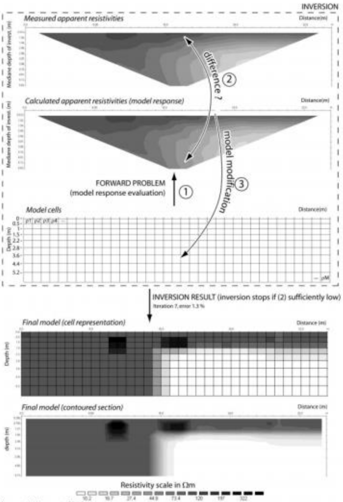
Surveys – Resistivity Tomography (ERT)



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

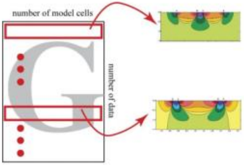
$$\Delta \mathbf{m} = \left[\mathbf{G}^T\mathbf{G} + \mathbf{W}\right]^{-1} \mathbf{G}^T \, \Delta \mathbf{d}$$

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



Measuring Principle

Surveys – Electrodes

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

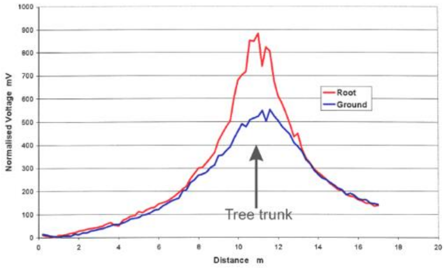
Contact resistance to the ground should be low.

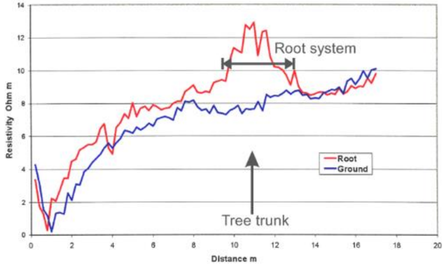
Contact voltage should be small.

- 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

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

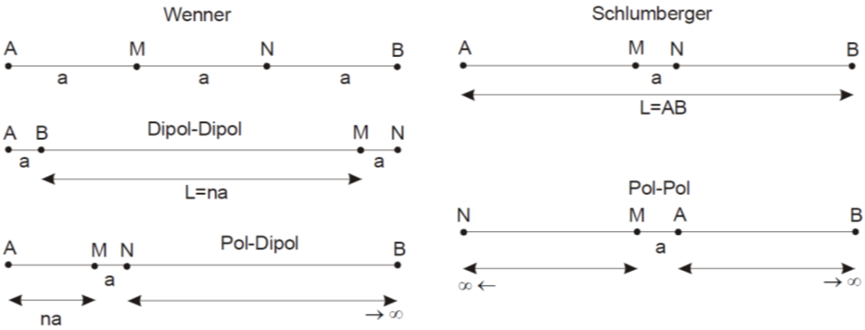
Currents mostly between 10 mA and 1 A

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



Apparent Resistivity

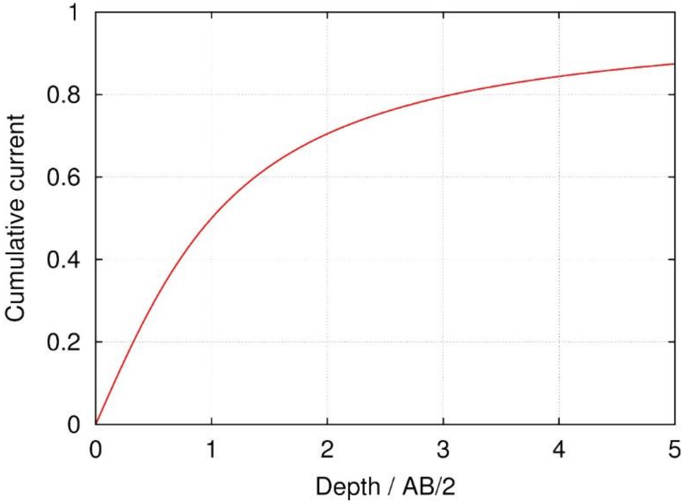
In a inhomogeneous medium,

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

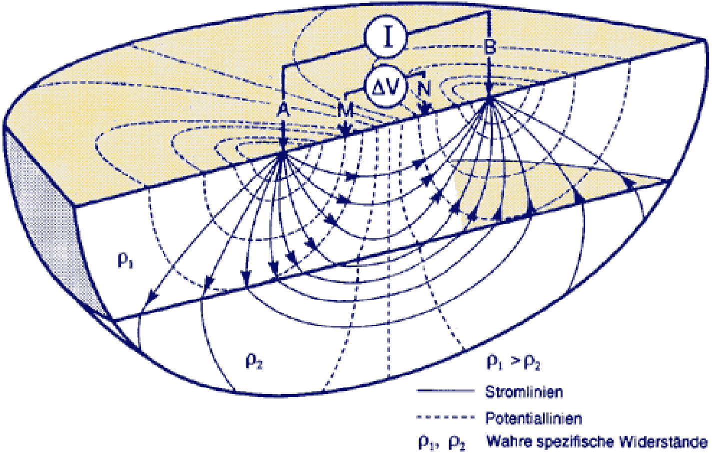
is called the apparent resistivity obtained from one measurement.

- 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

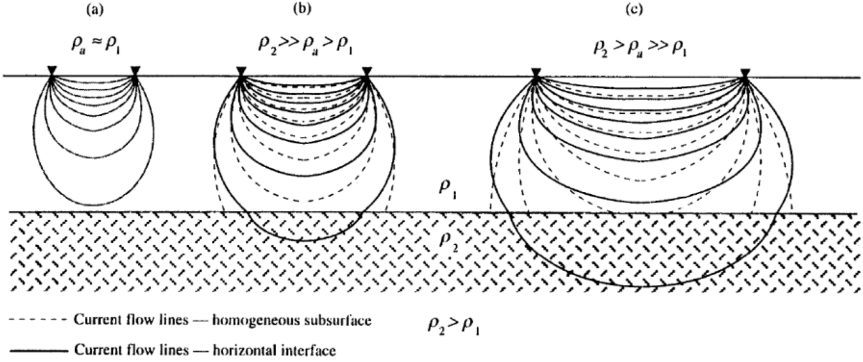


Vertical Sounding in the Two-Layer Case



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.

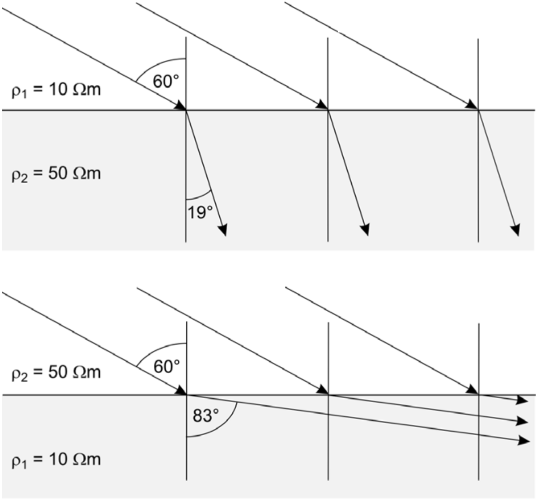
Target properties:

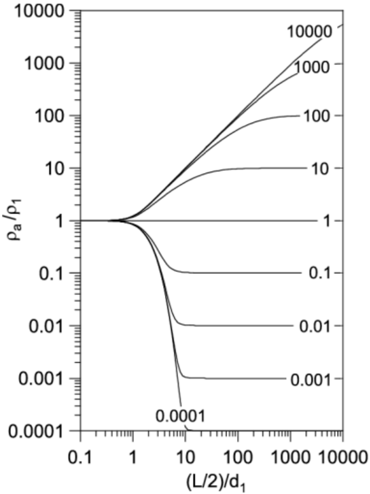
$$
\begin{aligned}
\rho_1 &= \text{resistivity of the upper layer} \\
\rho_2 &= \text{resistivity of the lower region} \\
d &= \text{thickness of the upper layer}
\end{aligned}
$$

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:

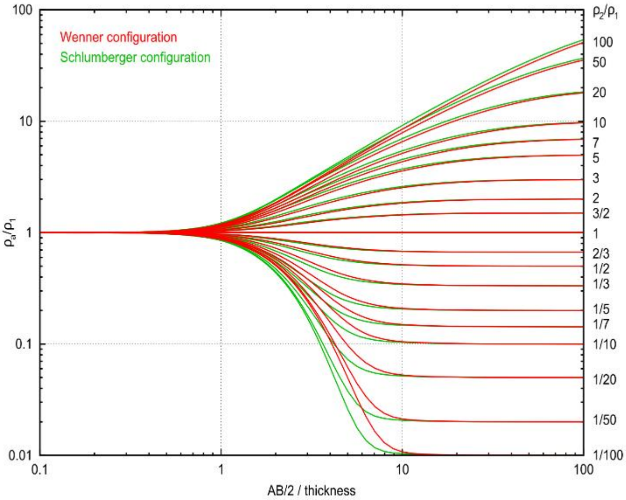
- If I is kept constant, all potentials change by the factor $\frac{1}{\lambda}$.
- K changes by the factor λ.

$\Downarrow$

ρ_a remains the same.

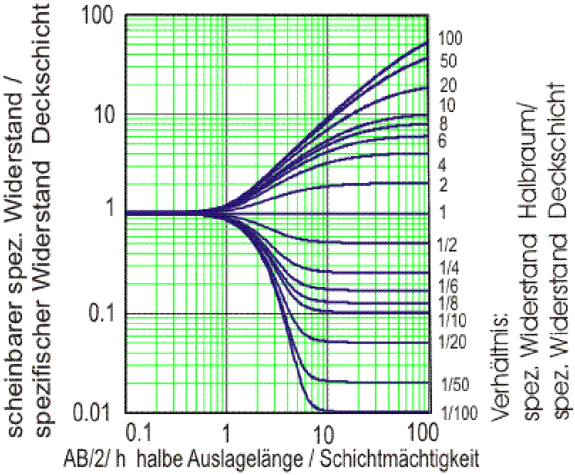
Consequence for the two-layer case: For any given electrode configuration at variable offset, $\frac{\rho_a}{\rho_1}$ depends only on $\frac{\rho_2}{\rho_1}$ and $\frac{AB}{d}$ (or $\frac{AB/2}{d}$ or $\frac{a}{d}$).

Wenner and Schlumberger Configurations in the Two-Layer Case



Data Analysis I

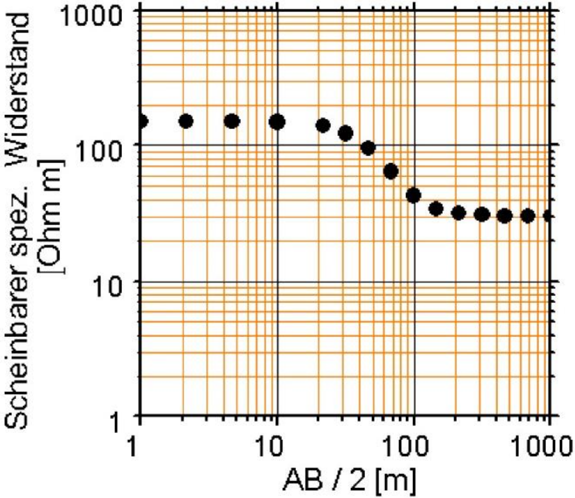
Graphical Data Analysis in the Two-Layer Case



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

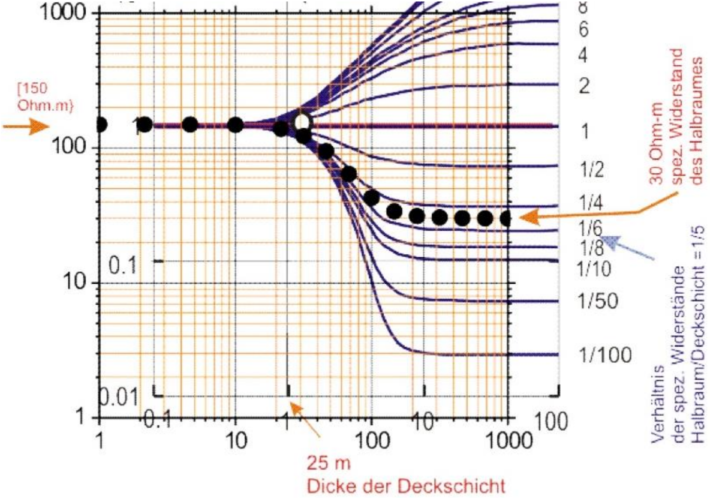
Data Analysis I

Graphical Data Analysis in the Two-Layer Case



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

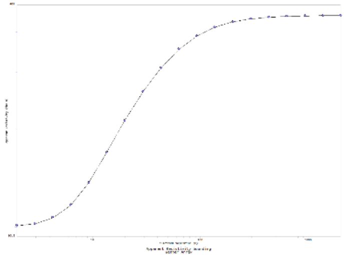
Graphical Data Analysis in the Two-Layer Case



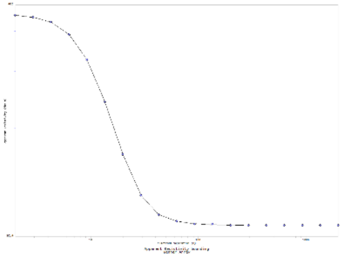
Source: Schmidt et al., Die Erde: Der dynamische Planet (CD-ROM)

Data Analysis I

Analysis in the Two-Layer Case

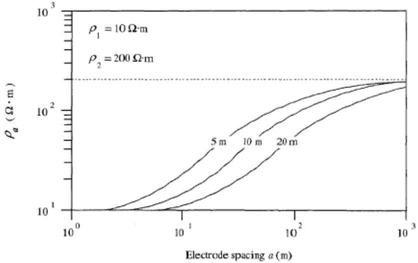


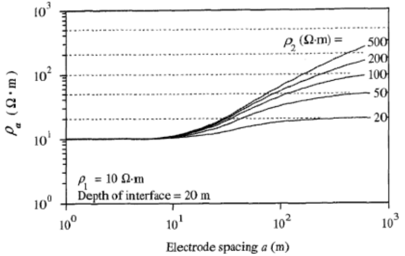
- material with greater resistivity lies below the interface



- material with greater resistivity lies above the interface

Analysis in the Two-Layer Case



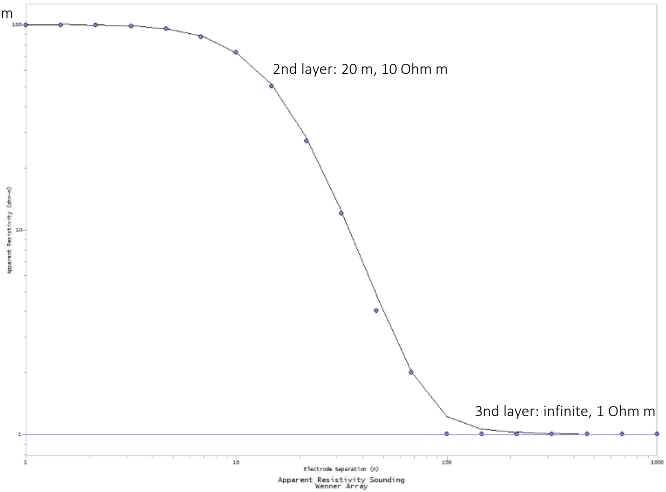


- constant resistivity
- constant depth

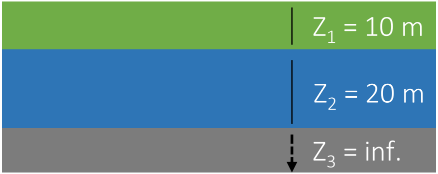
Data Analysis I

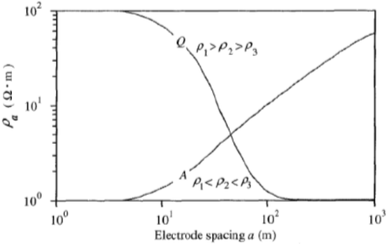
Analysis in the Two-Layer Case

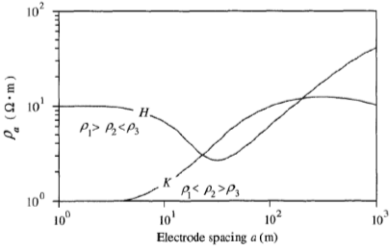
1st layer: 10 m, 100 Ohm m



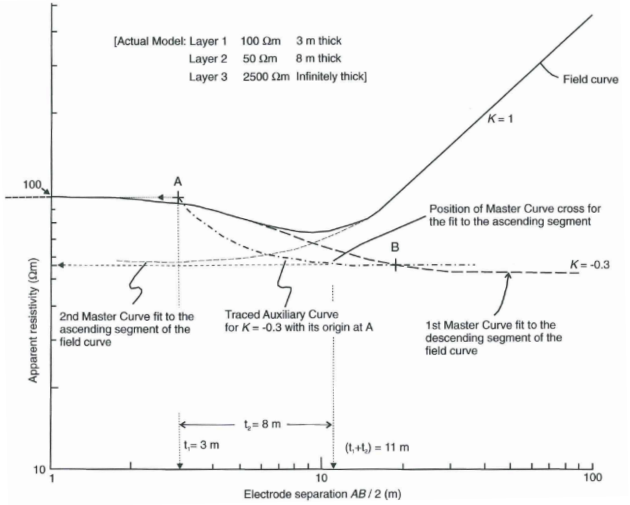
Analysis in the Three-Layer Case



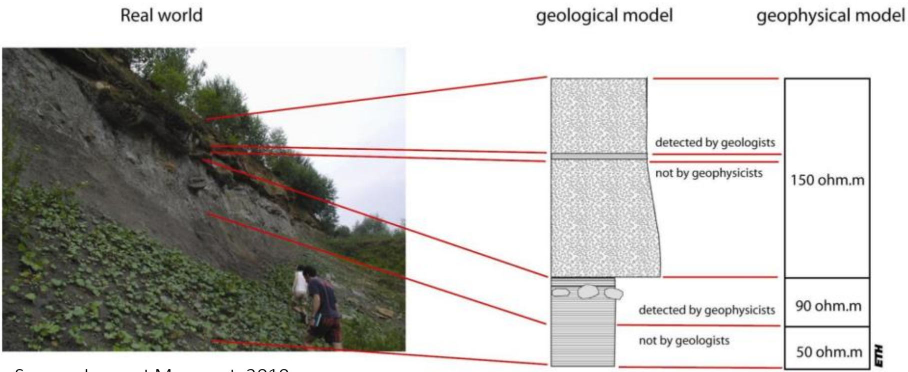




Analysis in the Three-Layer Case



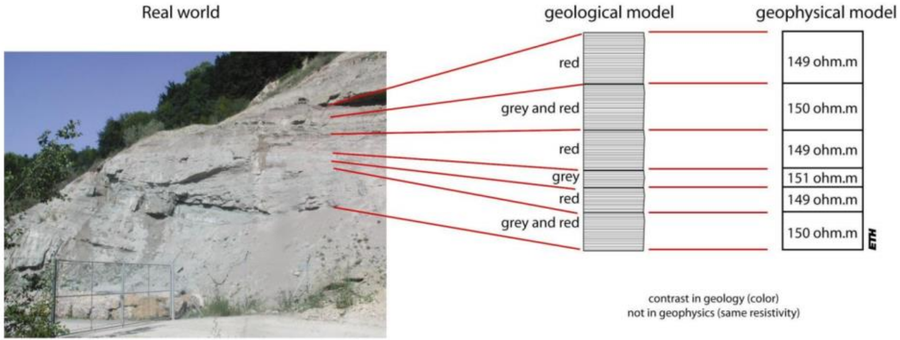
Multi-Layer Case



Source: Laurent Marescot, 2010

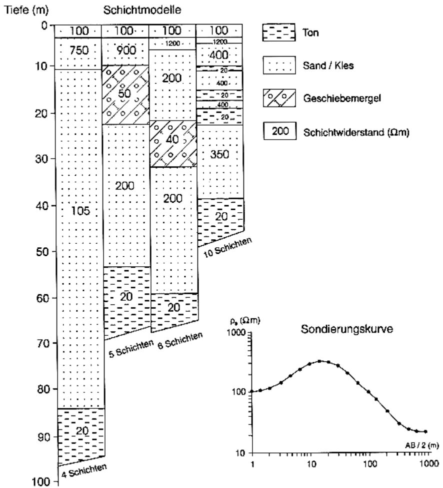
Multi-Layer Case

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.

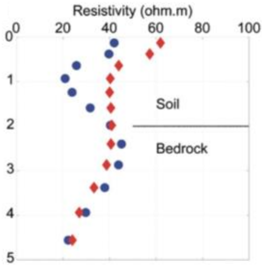
N-Layer Case

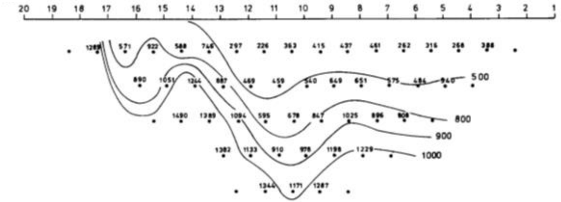
- Must be inverted numerically. Resistivities and thicknesses of the layers are adjusted to obtain the best fit to the measured apparent resistivities.
- The uppermost layer has a strong influence on the result.
- A deep, thin layer with a high contrast in resistivity may have a similar effect as a thicker 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.

$\Downarrow$

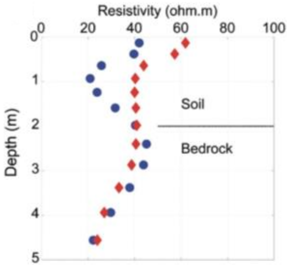
Quantitative analysis often hinges on independent information, e. g., from seismics or boreholes.

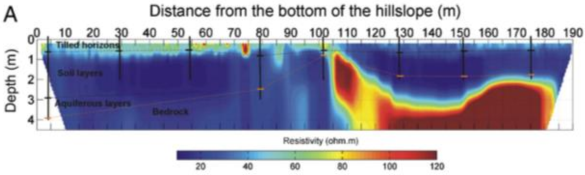
Penetration Depth of Current





Penetration Depth of Current

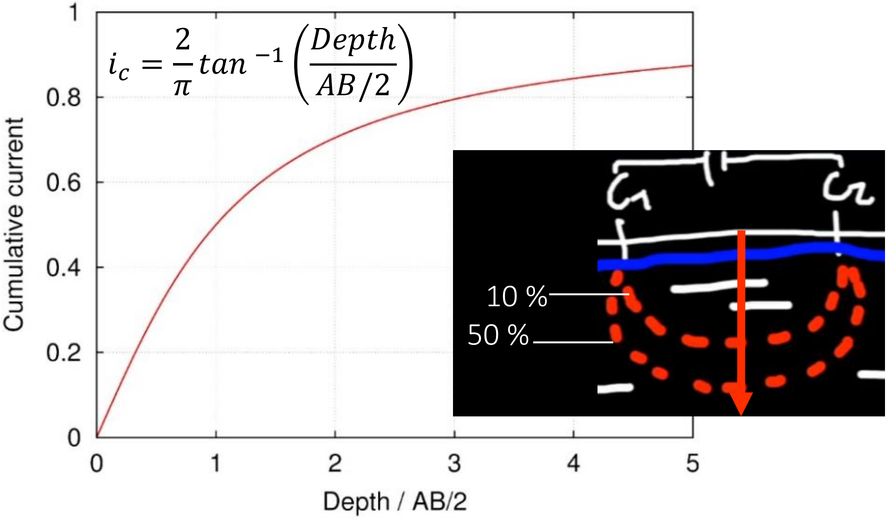




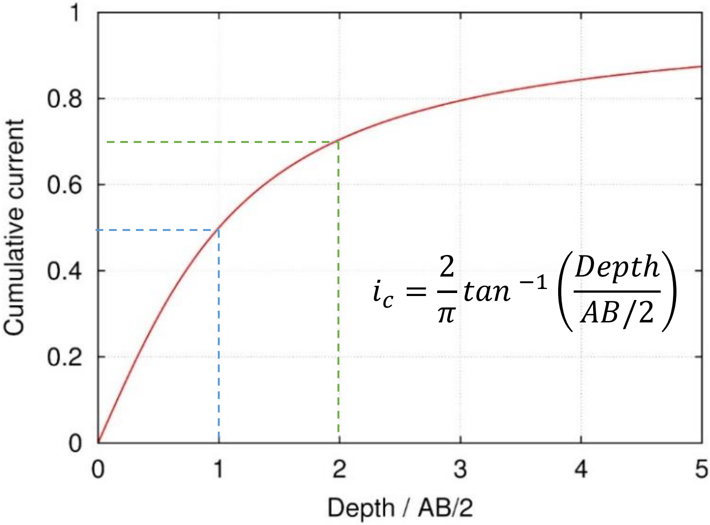
G. Coulouma et al. / Geoderma 170 (2012) 39–47

Penetration Depth of Current

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



Penetration Depth of Current



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.

↓

Typical depth of investigation is lower than AB/2.

Principle of the Sensitivity Analysis and Depth of Investigation Characteristic formula

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

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

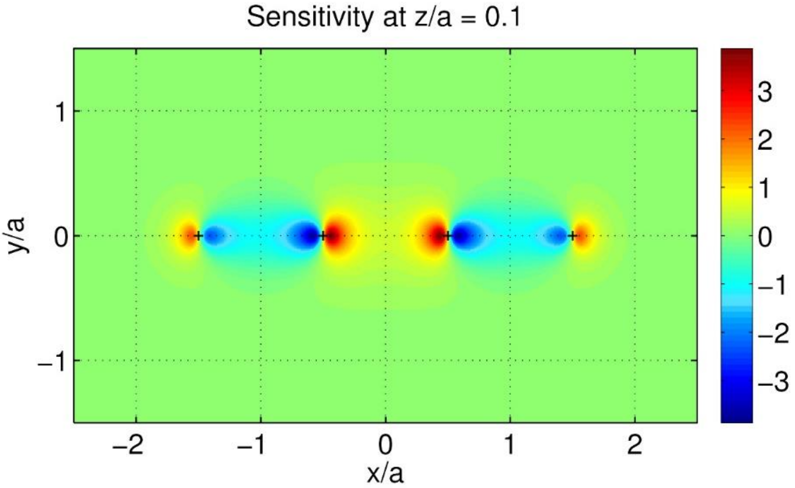
$$F_4(z) = \frac{2zI_A}{\pi}\left[\left(r_{AM}^2 + 4z^2\right)^{-1.5} - \left(r_{AN}^2 + 4z^2\right)^{-1.5} - \left(r_{BM}^2 + 4z^2\right)^{-1.5} + \left(r_{BN}^2 + 4z^2\right)^{-1.5}\right]$$

Source: Butler, 2015 after Roy and Apparo, 1971

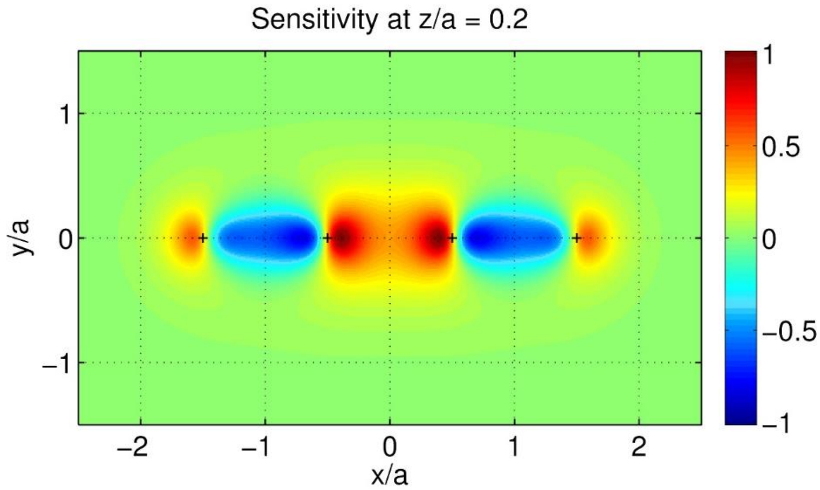
Principle of the Sensitivity Analysis and DIC formula

- 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.

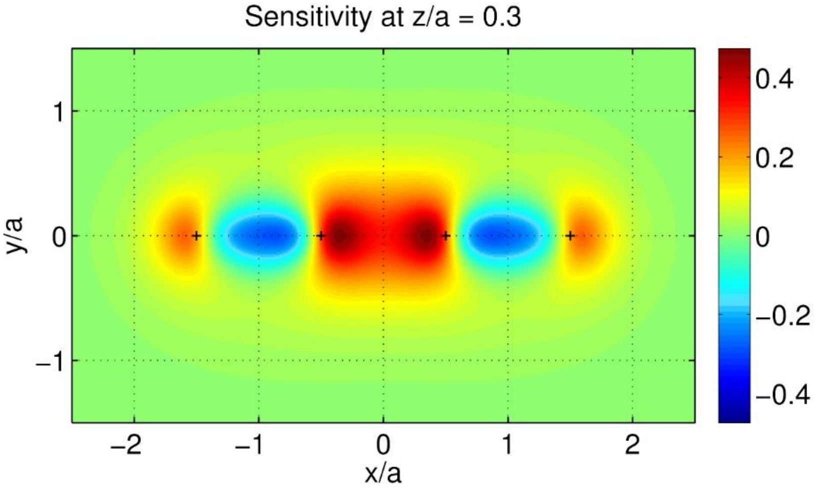
Sensitivity of the Wenner Configuration



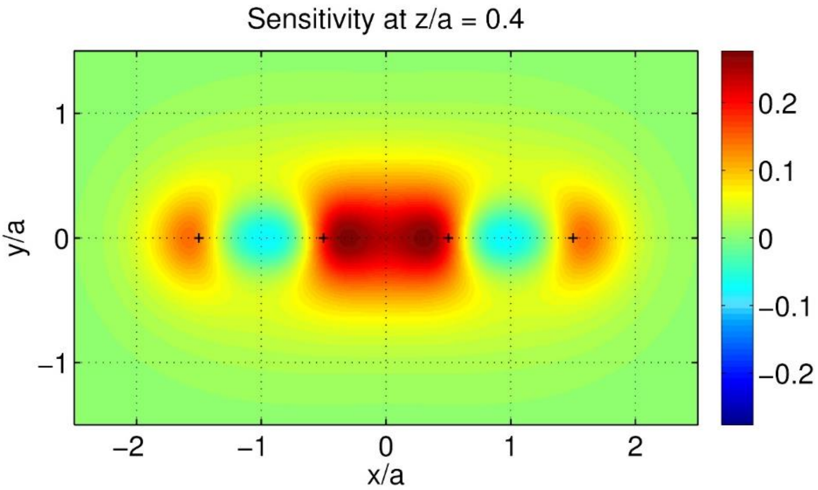
Sensitivity of the Wenner Configuration



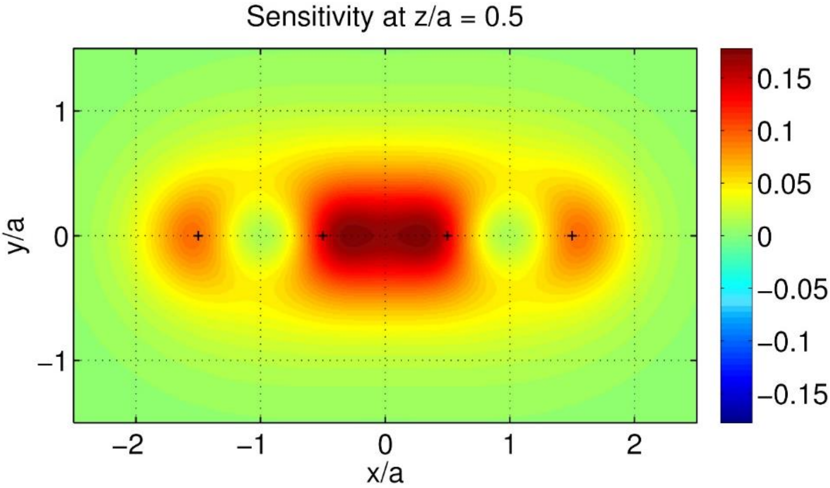
Sensitivity of the Wenner Configuration



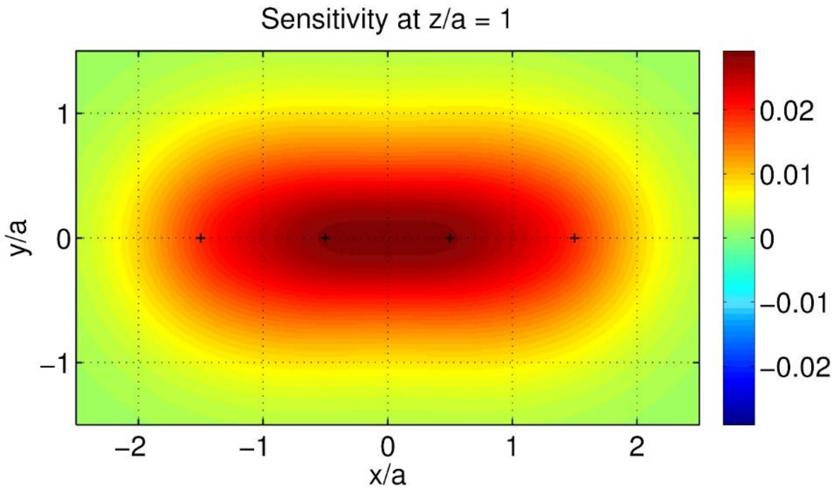
Sensitivity of the Wenner Configuration



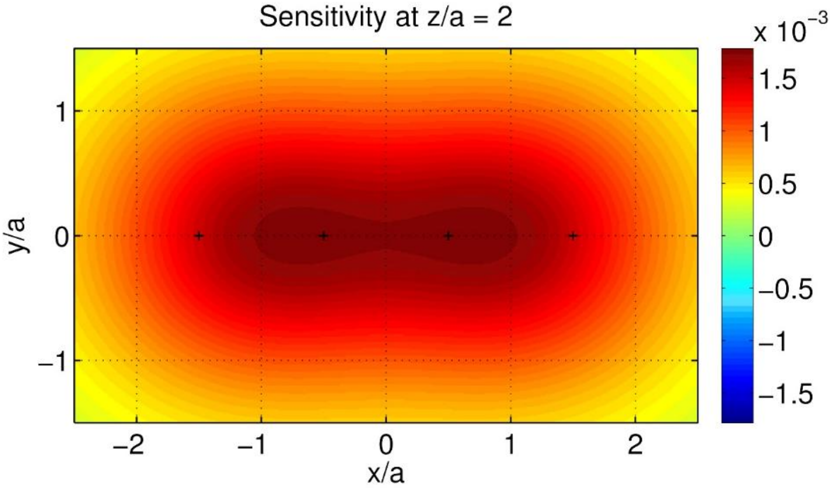
Sensitivity of the Wenner Configuration



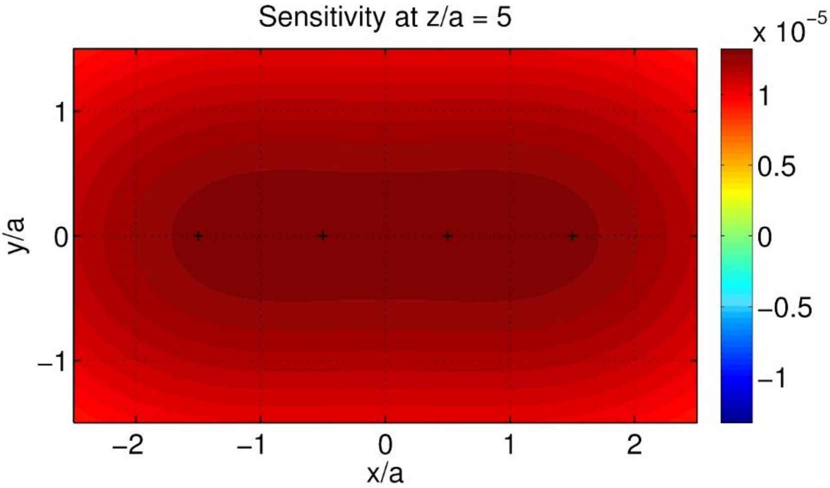
Sensitivity of the Wenner Configuration



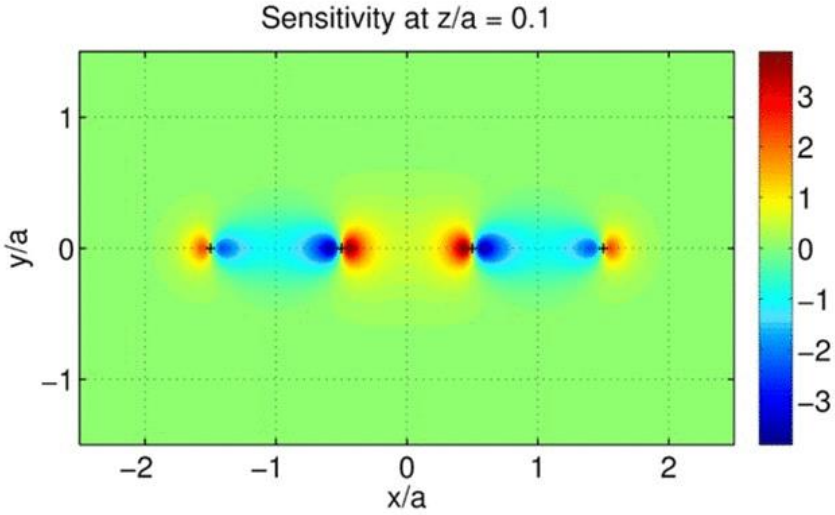
Sensitivity of the Wenner Configuration



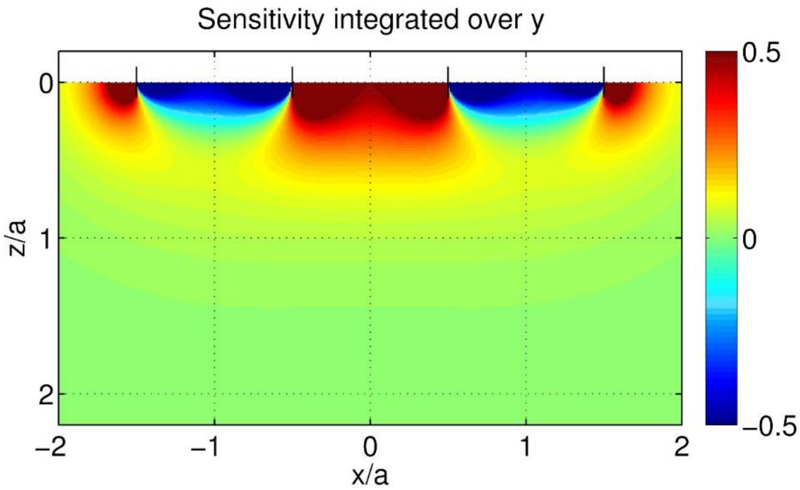
Sensitivity of the Wenner Configuration



Sensitivity of the Wenner Configuration

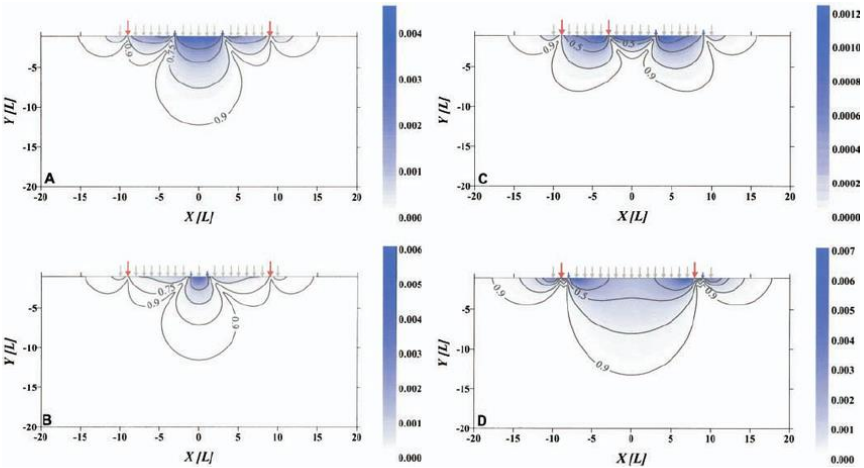


Sensitivity / Signal contribution section of the Wenner Configuration

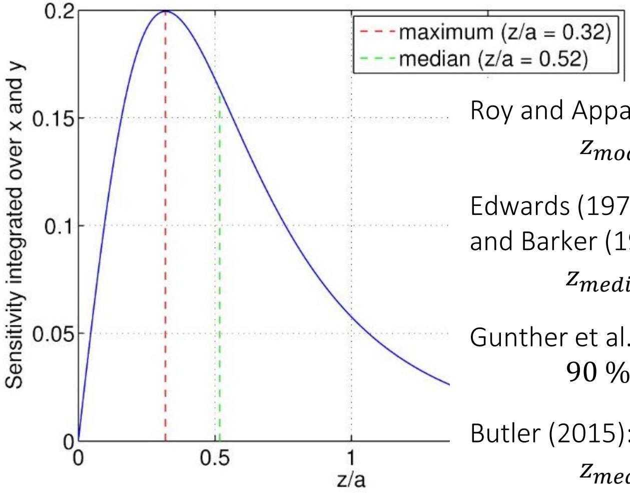


Data Analysis II

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



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 $z \approx 0.52\ a$.

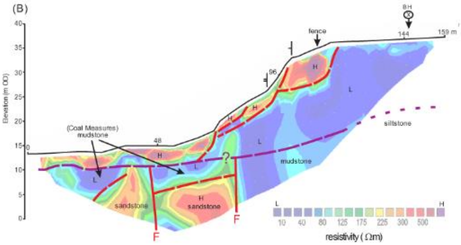
↓

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

↓

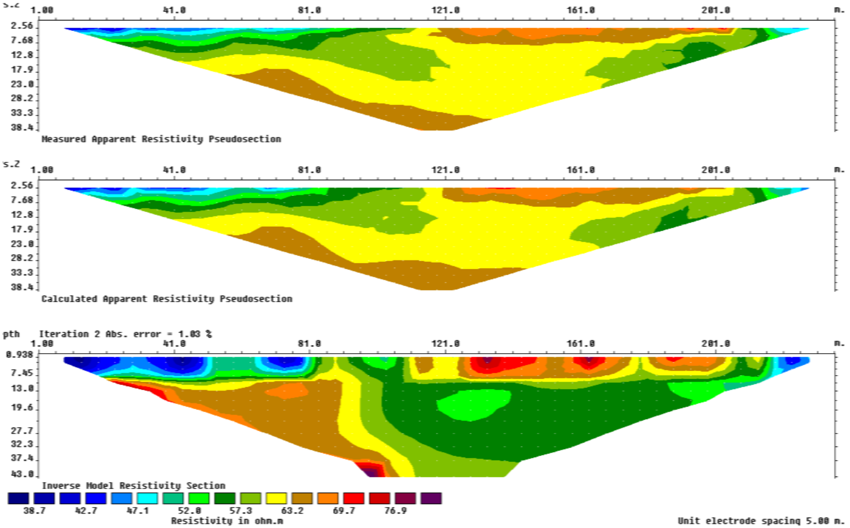
$0.52\ a$ is often assumed as the typical depth of investigation.

Pseudosections



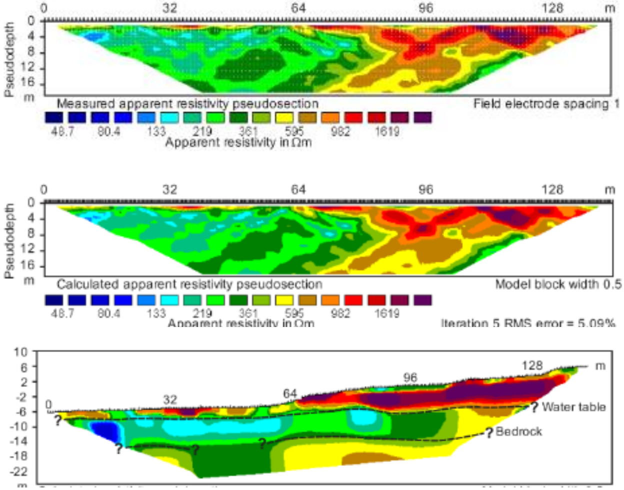
Source: Reynolds 2011

Pseudosections



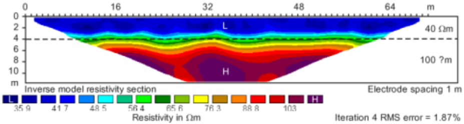
Data Analysis II

Pseudosections

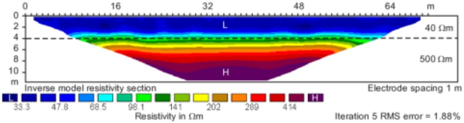


Pseudosections

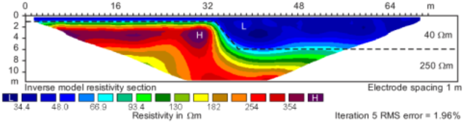
(A)



(B)



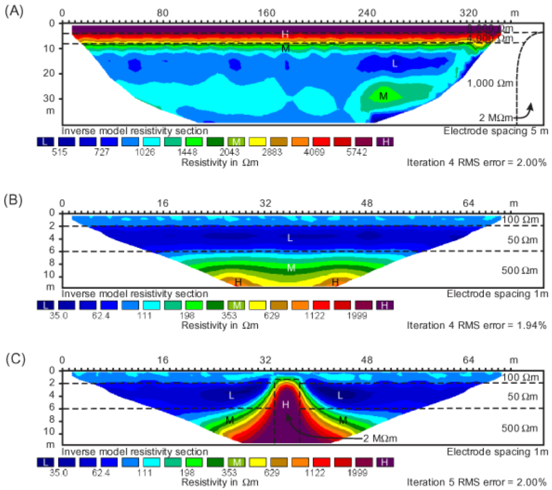
(C)



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