NORAD supported project in MRRD covering
Capacity Building and Institutional Cooperation in the field of Hydrogeology for Faryab Province Afghanistan

Geophysics Course
Introduction to DC Resistivity

By Andreas de Jong
June 2013

NORPLAN

Surface Geophysical Methods

NORPLAN

On-Line Courses & References

1. Colorado School of Mines
2. University of Berkeley
3. Ecole Polytechnique Montreal
4. University of Lausanne
5. University of Montana
6. United States Geological Survey (USGS)
7. Tomoquest

PART 1 – Introduction

1. Passive and Active Geophysical Methods
2. Electrical Methods Overview
   - History
   - DC Resistivity
   - Induced Polarisation (IP)
   - Self Potential (SP)
   - Electromagnetic (EM)
   - Magnetotelluric (MT)

Passive Geophysical Methods

- Passive geophysical surveys incorporate measurements of naturally occurring fields or properties of the earth.
- Examples: gravity, magnetic, radiometric surveys.

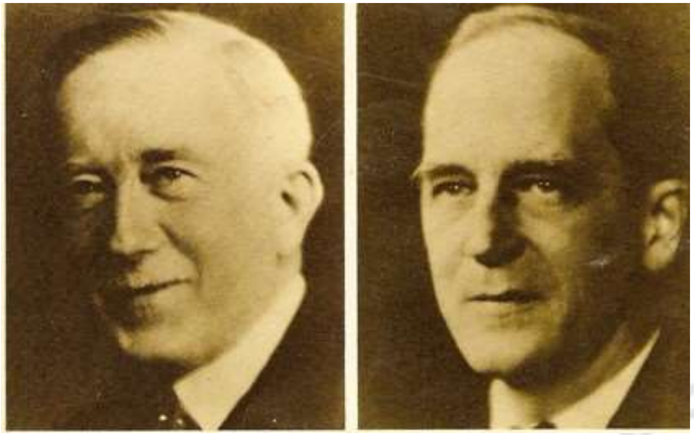
Active Geophysical Methods

- In active geophysical surveys a signal is injected into the earth and we then measure how the earth responds to this signal. Signals include displacement, an electrical current, or an active radiometric source.
- Examples: DC Resistivity, TDEM, EM & Seismic surveys**.**

NORPLAN

Electrical Methods: History

- SP method dates back to the 1830's when it was used in Cornwall, England by Robert Fox to find extensions of known copper deposits.
- Telluric currents (natural electrical currents in the Earth), were first identified by Peter Barlow in 1847.
- The EM method was developed in the 1920's for the exploration of base-metal deposits.
- The Schlumberger brothers developed Schlumberger Array in 1912.

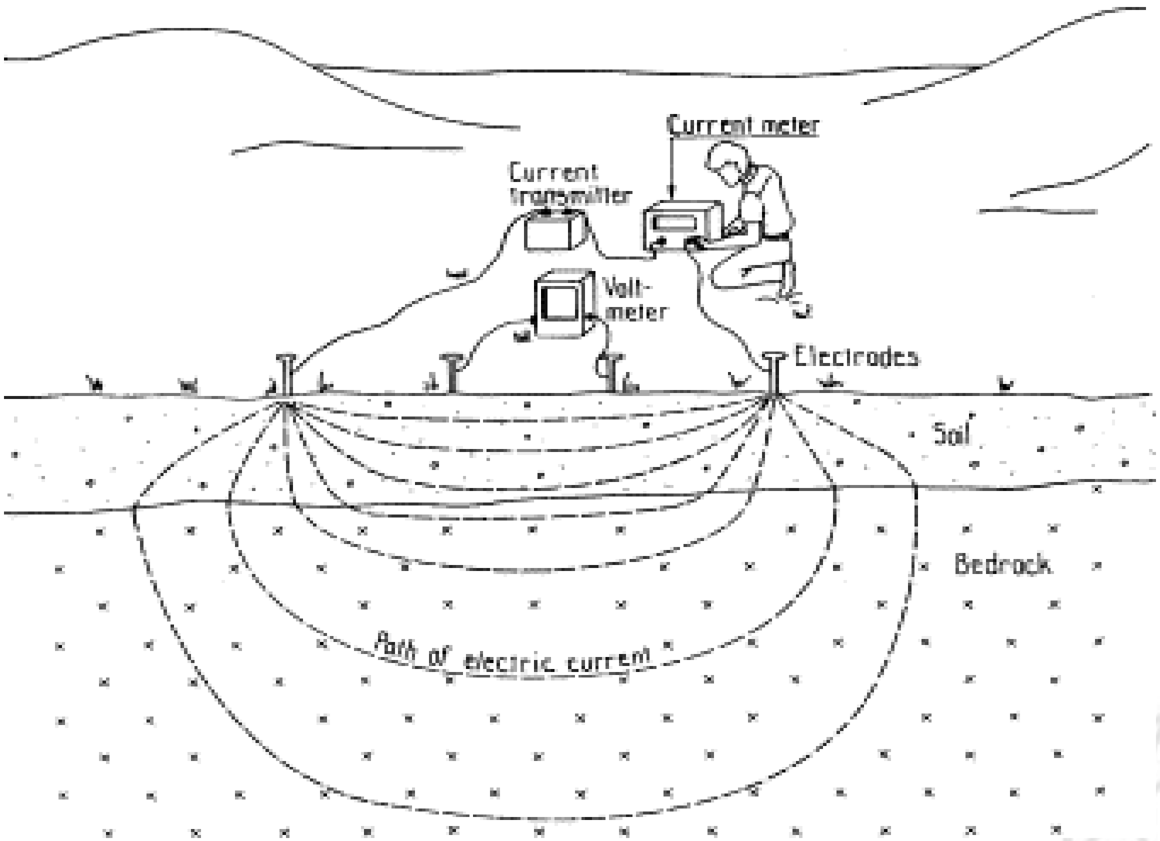


Conrad and Marcel Schlumberger 1936

Source: http://galitzin.mines.edu/INTROGP/

Electrical Methods: DC Restistivity

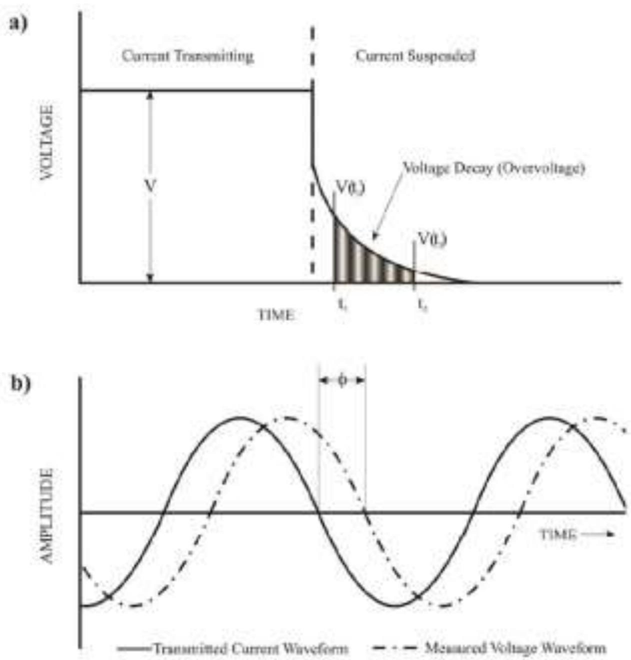
- Active method that employs measurements of electrical potential associated with subsurface electrical current flow generated by a DC, or slowly varying AC, source.



Source: http://ars.els-cdn.com/content/image/1-s2.0-S0098300400001606-gr1.gif

Electrical Methods: Induced Polarization (IP)

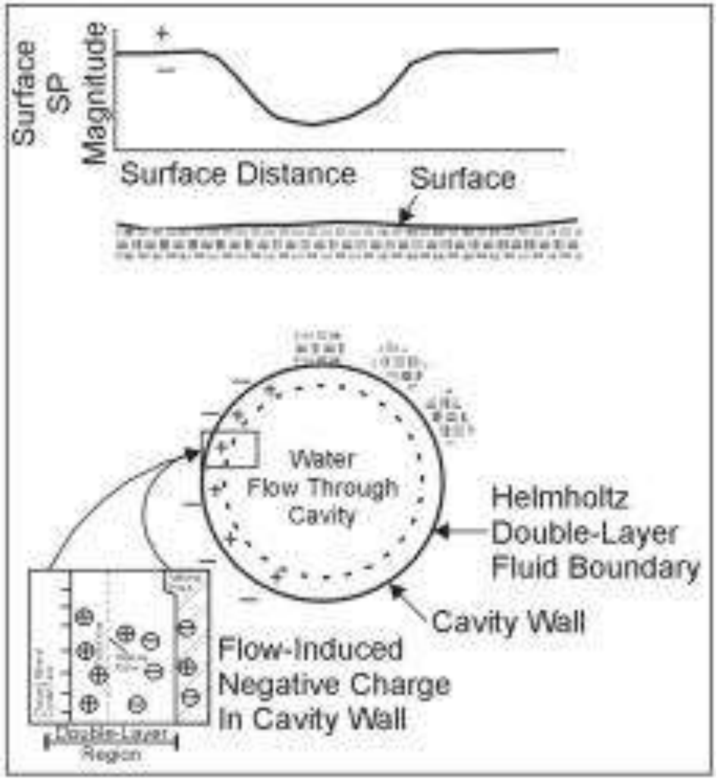
- Active method that is commonly done in conjunction with DC Resistivity. It employs measurements of the transient (short-term) variations in potential as the current is initially applied or removed from the ground.
- IP is commonly used to detect concentrations of clay and electrically conductive metallic mineral grains.



NORPLAN

Electrical Methods: Self Potential (SP)

– Passive method that employs measurements of naturally occurring electrical potentials commonly associated with the weathering of sulphide ore bodies, or groundwater flow.

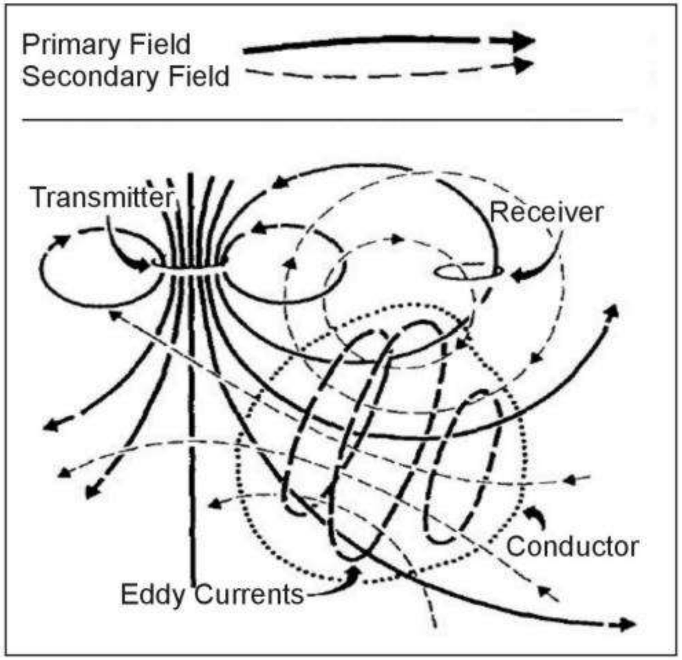


NORPLAN

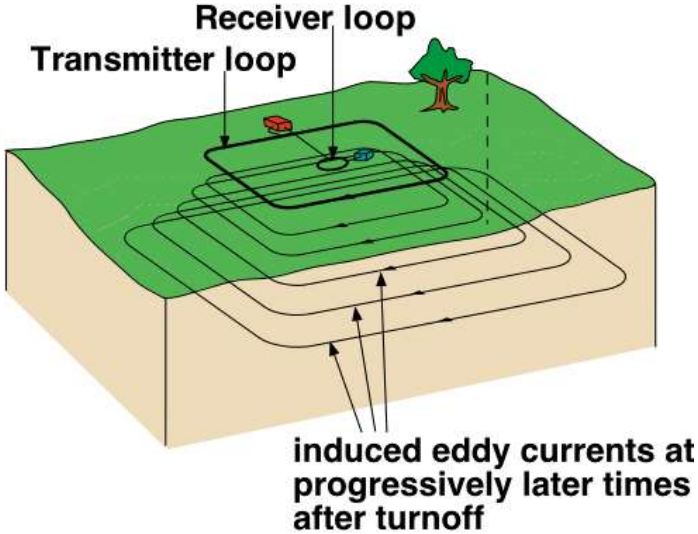
Electrical Methods: Electromagnetic (EM)

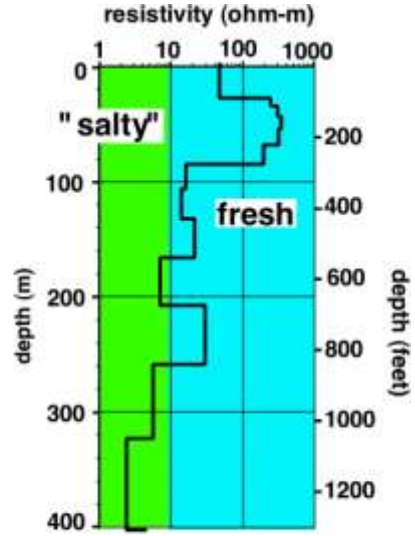
- Active method that employs measurements of a time-varying magnetic field generated by induction through current flow within the earth.

Geonics EM-34



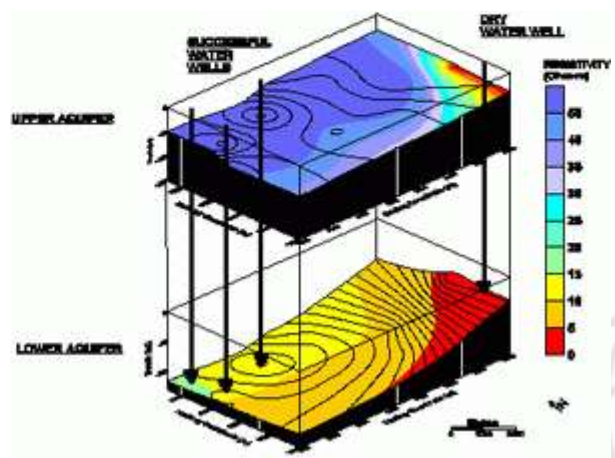
Electrical Methods: TDEM





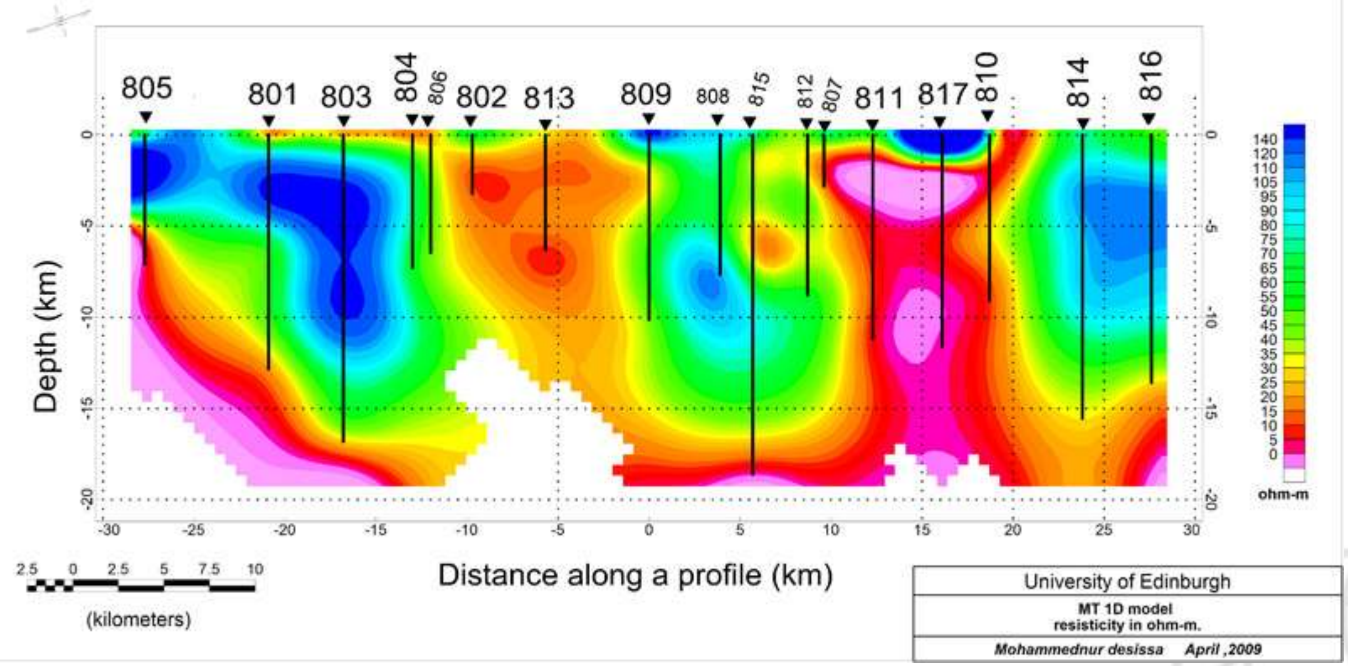
Source: http://www.ncwater.org/Education_and_Technical_Assistance/Ground_Water/TDEM/

Geonics Protem 57



Electrical Methods: Magnetotelluric (MT)

- Passive method that employs measurements of naturally occurring electrical currents, or telluric currents, generated by magnetic induction of electrical currents in the ionosphere.
- This method can be used to determine electrical properties of materials at relatively great depths (down to and including the mantle) inside the Earth.

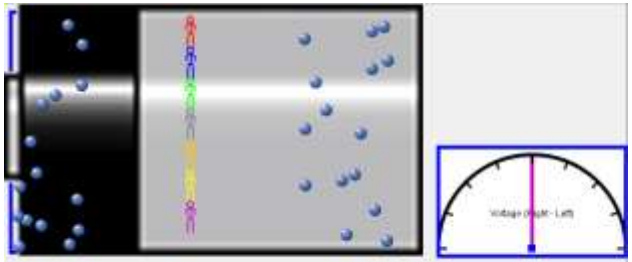


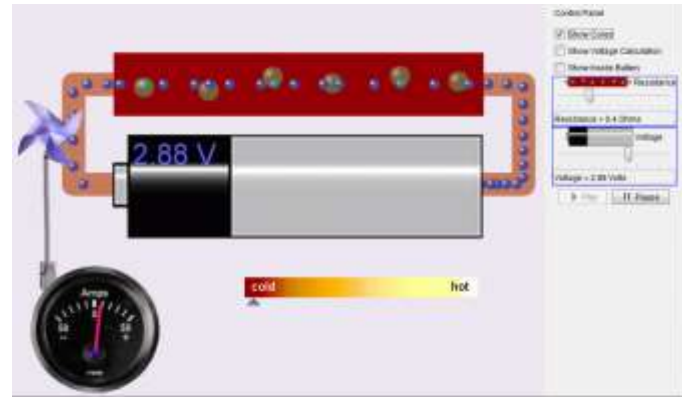
Source: http://www.earthexplorer.com/2009-07/Steamy_Prospects_in_Ethiopia.asp

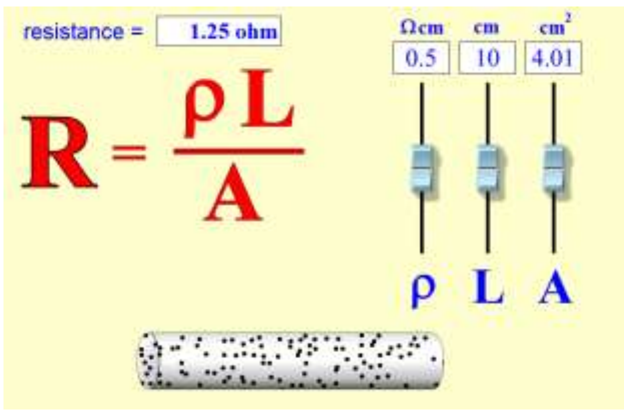
PART 2 – Resistivity Basics

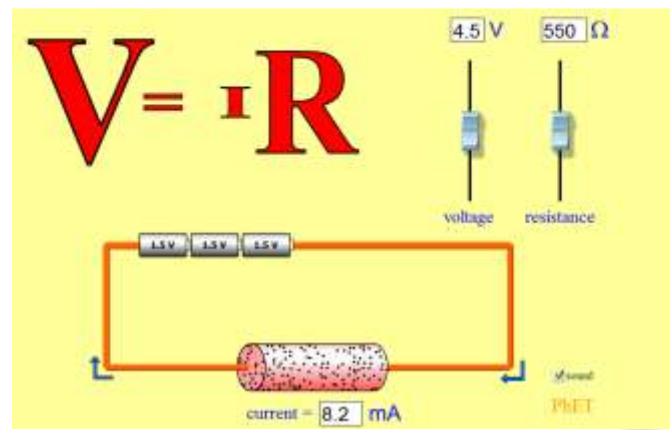
1. Current Flow and Ohm's Law
2. Resistivity & Resistance
3. Conductivity
4. Factors Affecting Resistivity
5. Archie's Law
6. Resistivities for Common Earth Materials
7. Current Density and Electric Field
8. A First Estimate of Resistivity
9. Current Flow From Two Closely Spaced Electrodes
10. A Practical Way of Measuring Resistivity

Practical 1 - Electricity

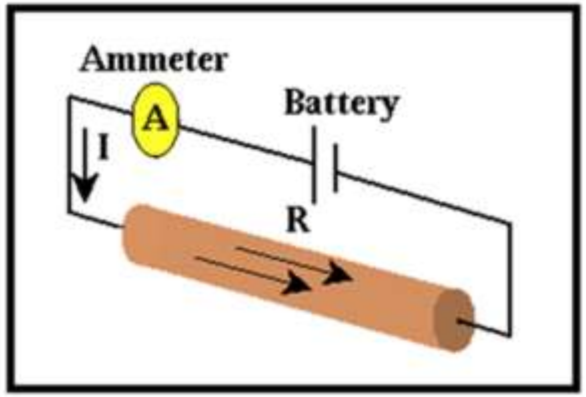








Current Flow & Ohm's Law



$$V = IR$$

Ohm's Law (1827)

- V = voltage (volts)
- I = Current (amperes)
- R = Resistance (ohms)

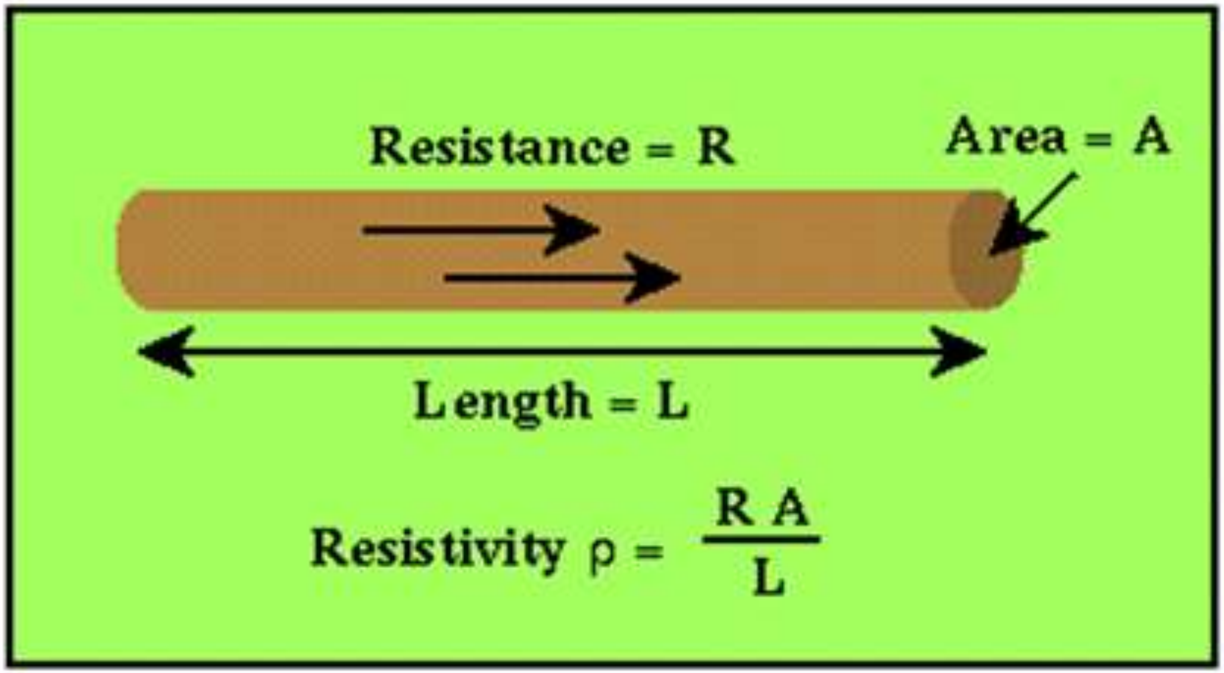
Source: http://galitzin.mines.edu/INTROGP/

NORPLAN

Problems with Resistance

Resistance:

- depends not only on the material from which the wire is made, but also the geometry of the wire. i.e. the length and thickness of the wire affects the reading.
- How can we apply this relatively simple experiment to determine electrical properties of earth materials?

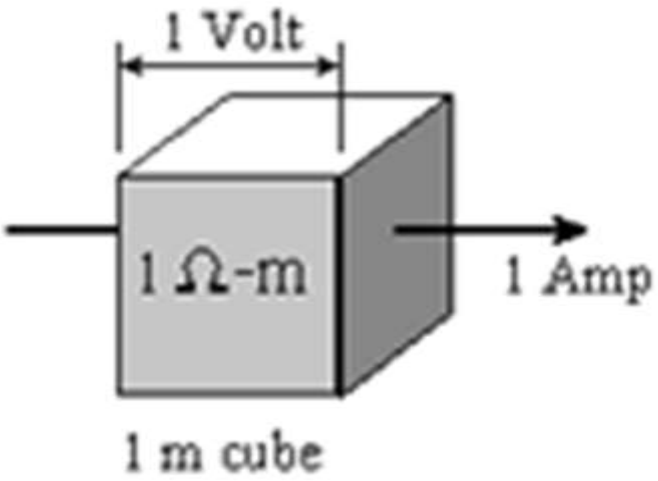


Source: http://galitzin.mines.edu/INTROGP/

Use Resistivity, NOT Resistance

Resistivity = resistance per unit volume

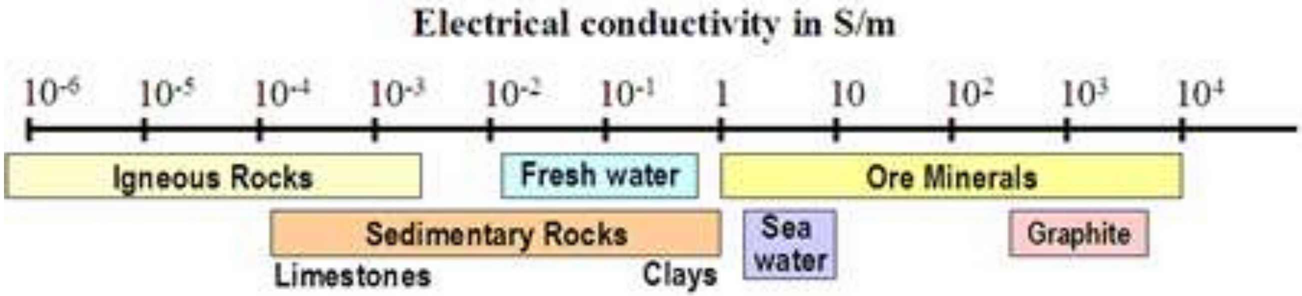
- Resistivity is a geometrically-independent quantity that is usually indicated by the Greek symbol *ρ*.
- Units are ohm-m (ohm-meters).



Conductivity

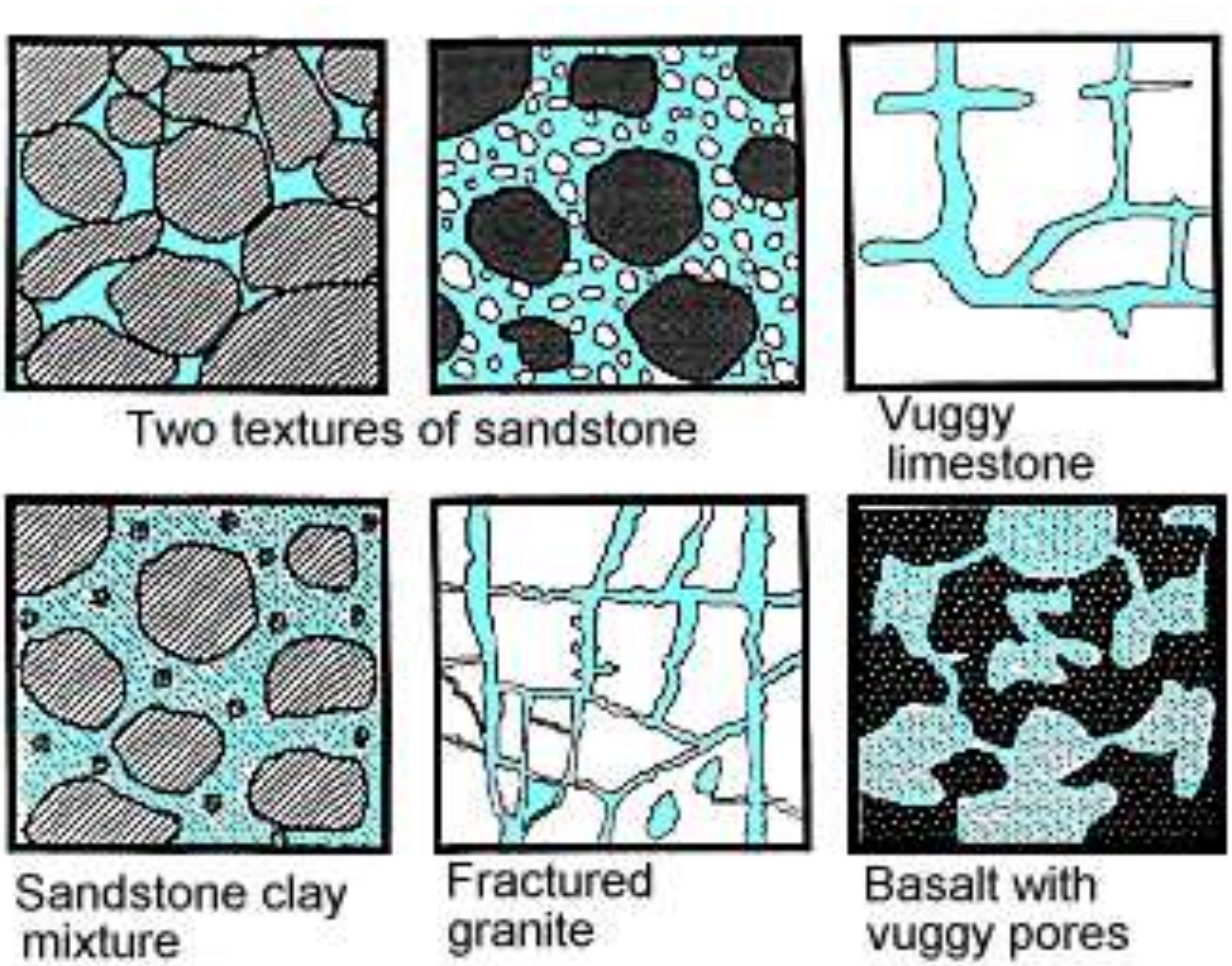
Conductivity = inverse of resistivity: 1/ρ

- Conductivity is often represented using sigma, σ
- Conductivity is given in units of Siemens per metre, or S/m.
- Units of millisiemens per metre (mS/m) are often used for small conductivity values.
- 1000mS/m = 1S/m. So 1mS/m = 1000 Ohm-m, since resistivity and conductivity are inversely related.



Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

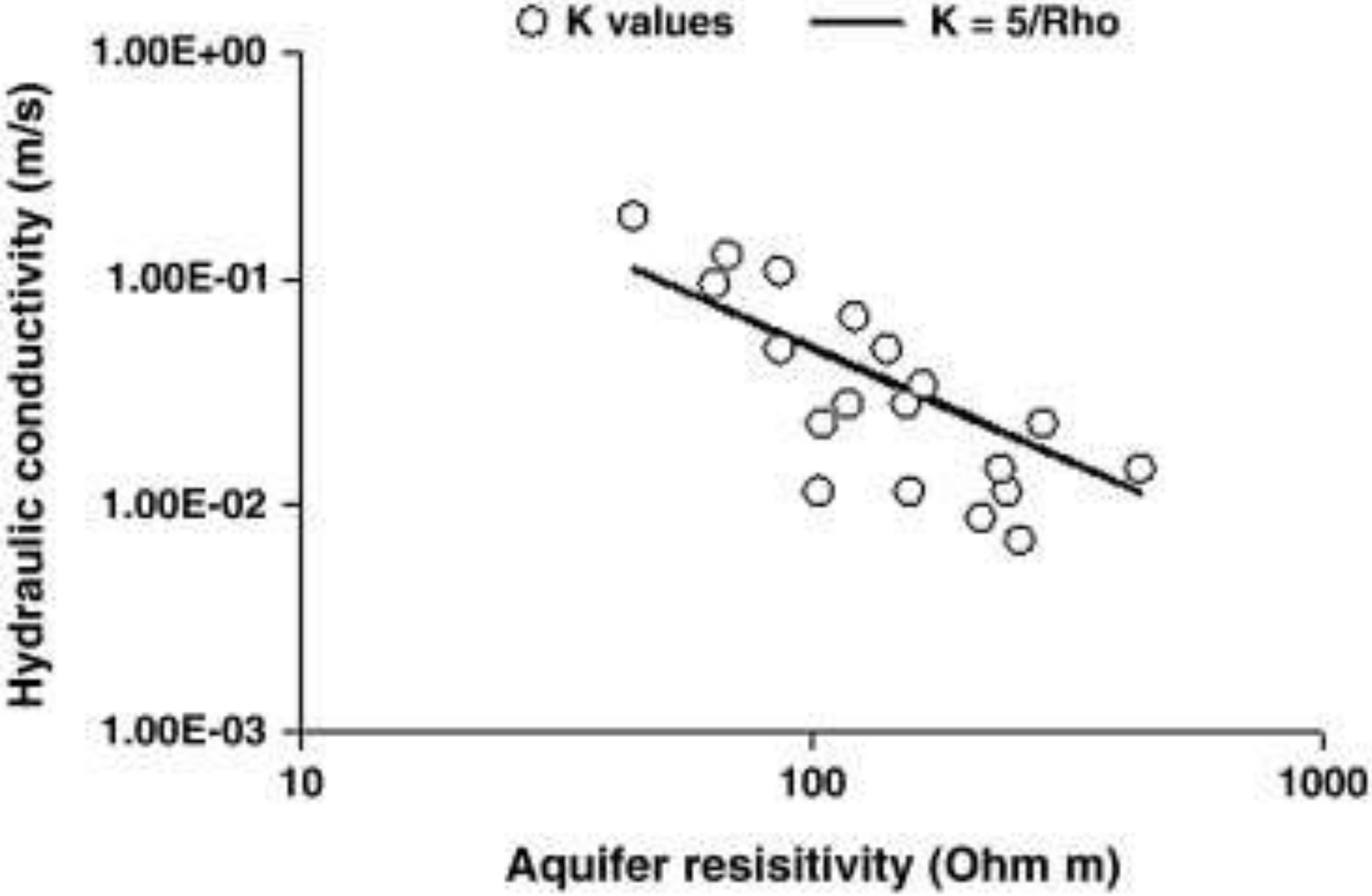
Factors Affecting Resistivity - Porosity



Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

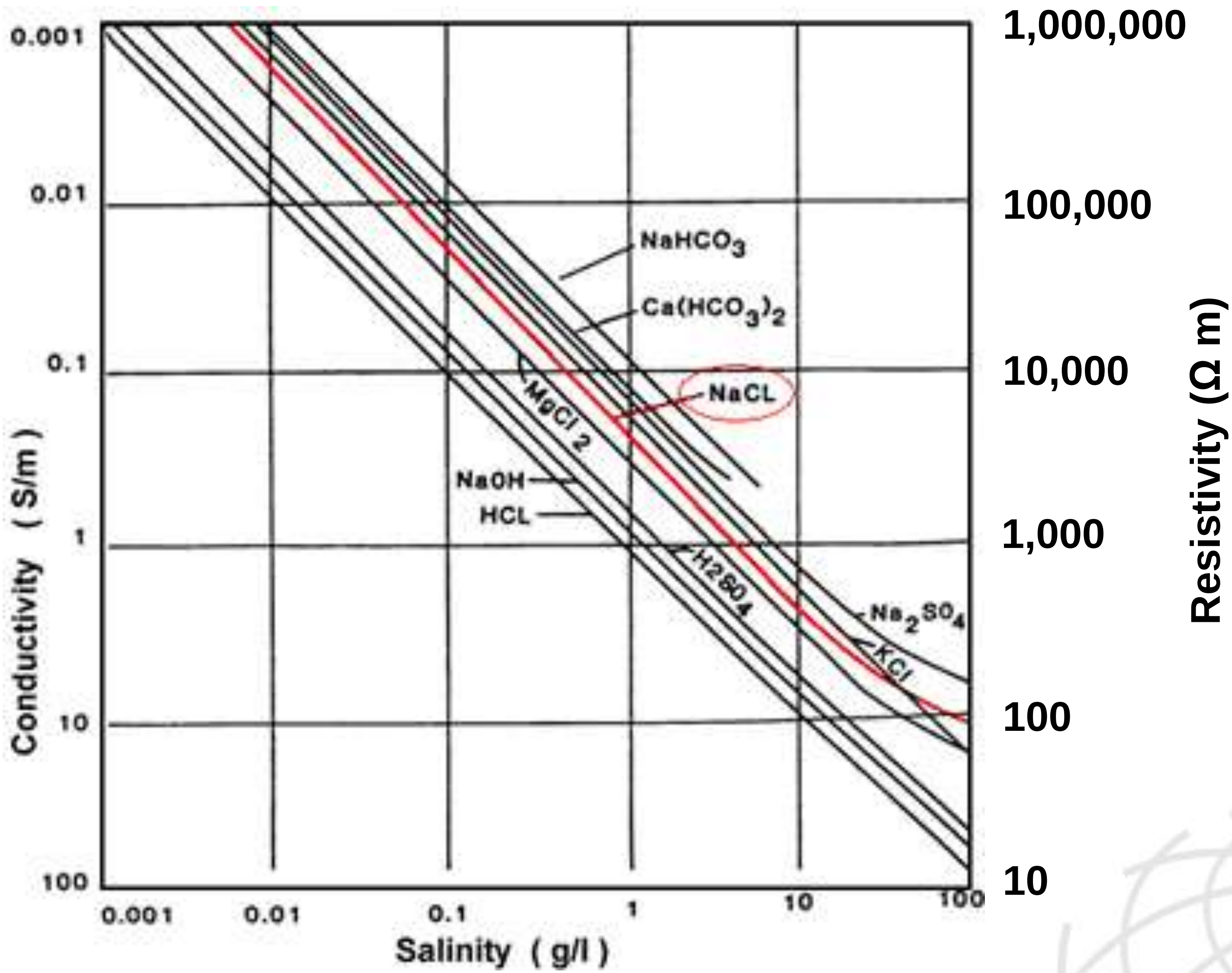
NORPLAN

Factors Affecting Resistivity - Permeability



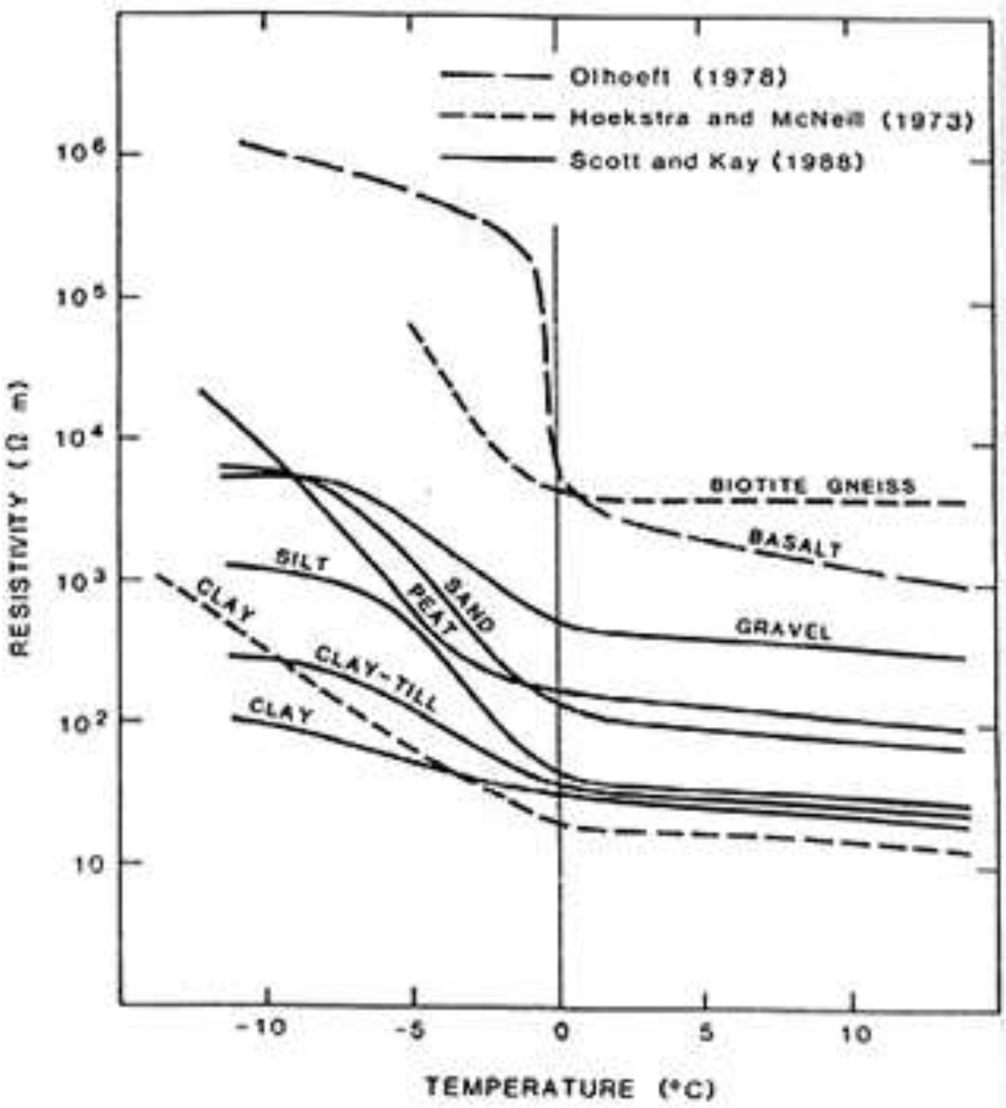
Source: http://www.sciencedirect.com/science/article/pii/S0926985112000985

Factors Affecting Resistivity - Salinity



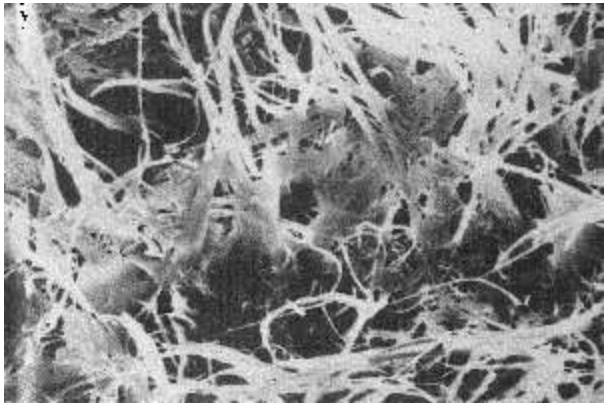
Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

Factors Affecting Resistivity - Temperature



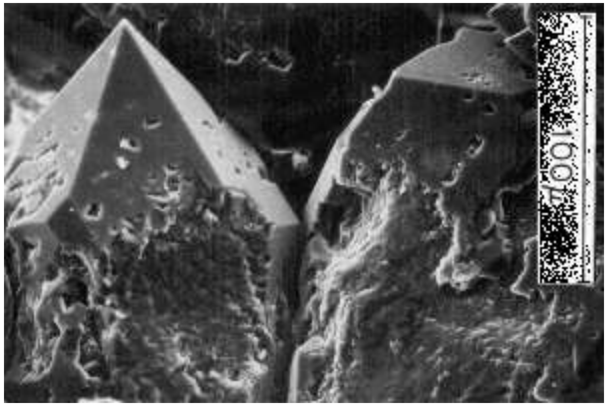
Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

Factors Affecting Resistivity – Clay Content



Illite (a clay mineral) with total surface area of **100m²/gm**

(photo Credit: R. Knight.)



Quartz overgrowths in sandstone with total surface area of **0.1m²/gm**

(photo credit: R. Knight.)

Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

Archie's Law (1942)

$$\frac{\rho_r}{\rho_f} = \alpha\phi^{-m}$$

Where,

ρ_r	is the rock resistivity, in ohm-meters
ρ_f	is the resistivity of the pore fluid
α	is the coefficient of saturation
	1 = complete saturation
ϕ	is the porosity
m	is the cementation factor

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Trans. Am. Inst. Min., Metal. and Petr. Eng., v. 146, p. 54-62.

Formation Factor

$$F = \alpha\phi^{-m}$$

Where,

F	is the formation factor
α	is the coefficient of saturation
	1 = complete saturation
ϕ	is the porosity
m	is the cementation factor

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Trans. Am. Inst. Min., Metal. and Petr. Eng., v. 146, p. 54-62.

Archie's Law

$$\rho_r = F\rho_f$$

Where,

ρ_r is the rock resistivity, in ohm-meters

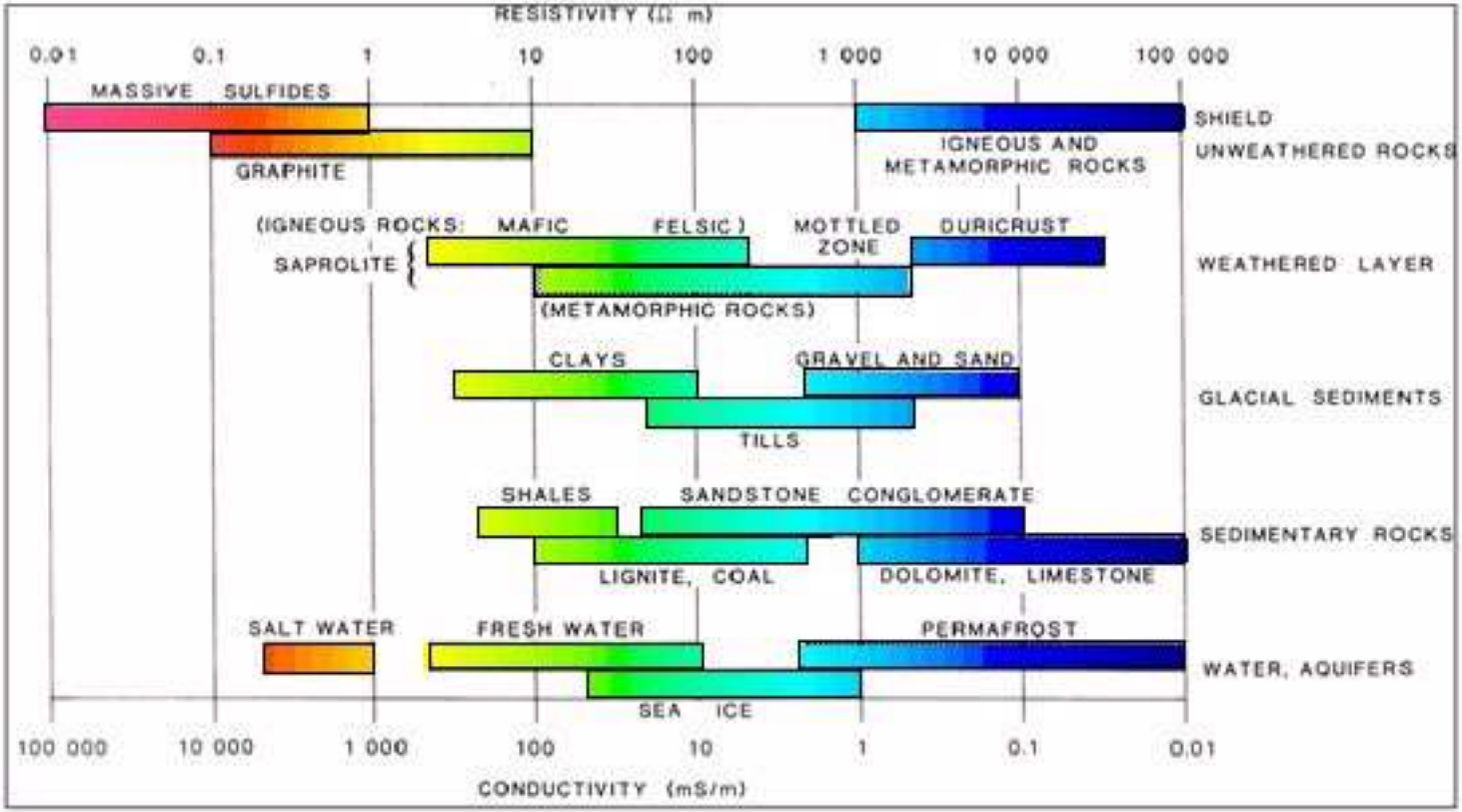
F is the formation factor

ρ_f is the resistivity of the pore fluid

Note: Archie's Law does not work when the rocks contain CLAY!

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Trans. Am. Inst. Min., Metal. and Petr. Eng., v. 146, p. 54-62.

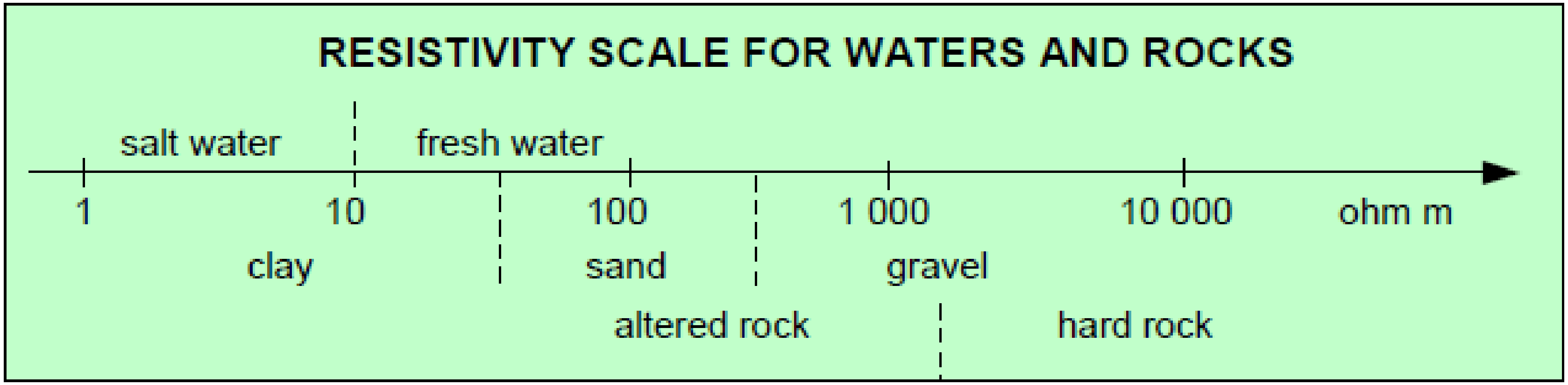
Resistivity of Rock Forming Materials



Source; http://www.eos.ubc.ca/ubcgif/iag/foundations/properties/resistivity.htm

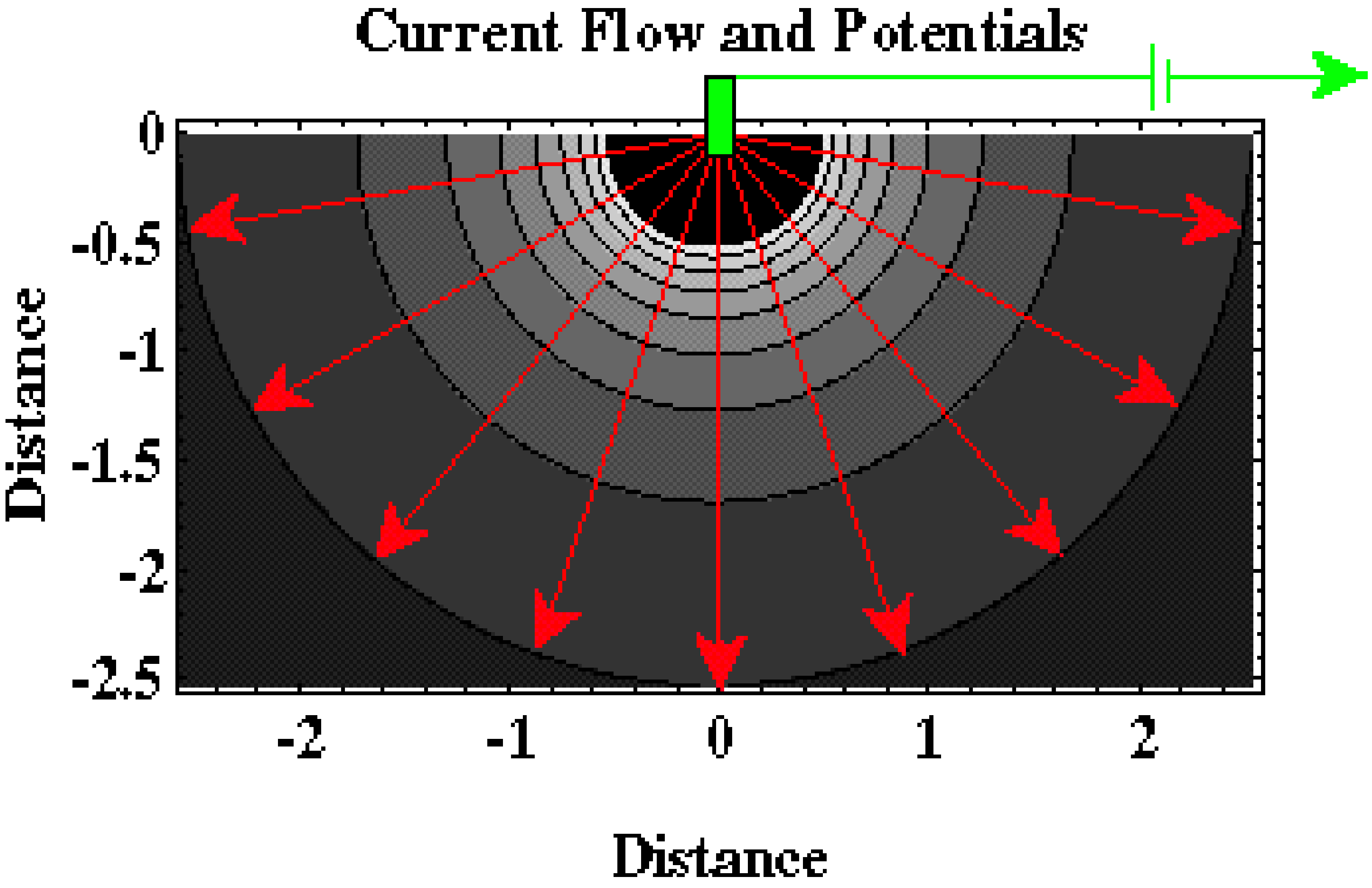
NORPLAN

Resistivity of Rock Forming Materials



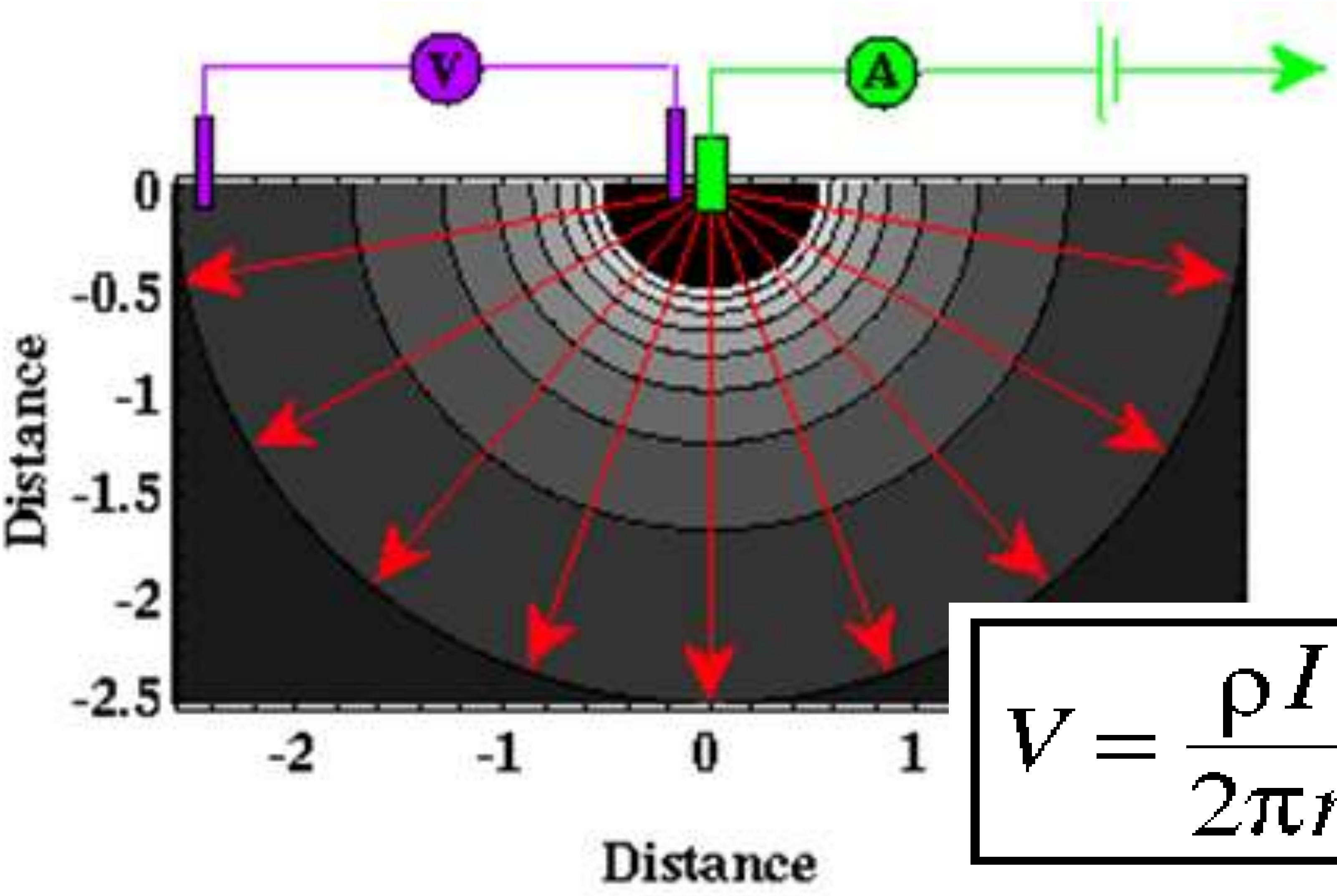
Source: http://www.iris-instruments.com

Current Density and Electric Field



Source: http://galitzin.mines.edu/INTROGP/

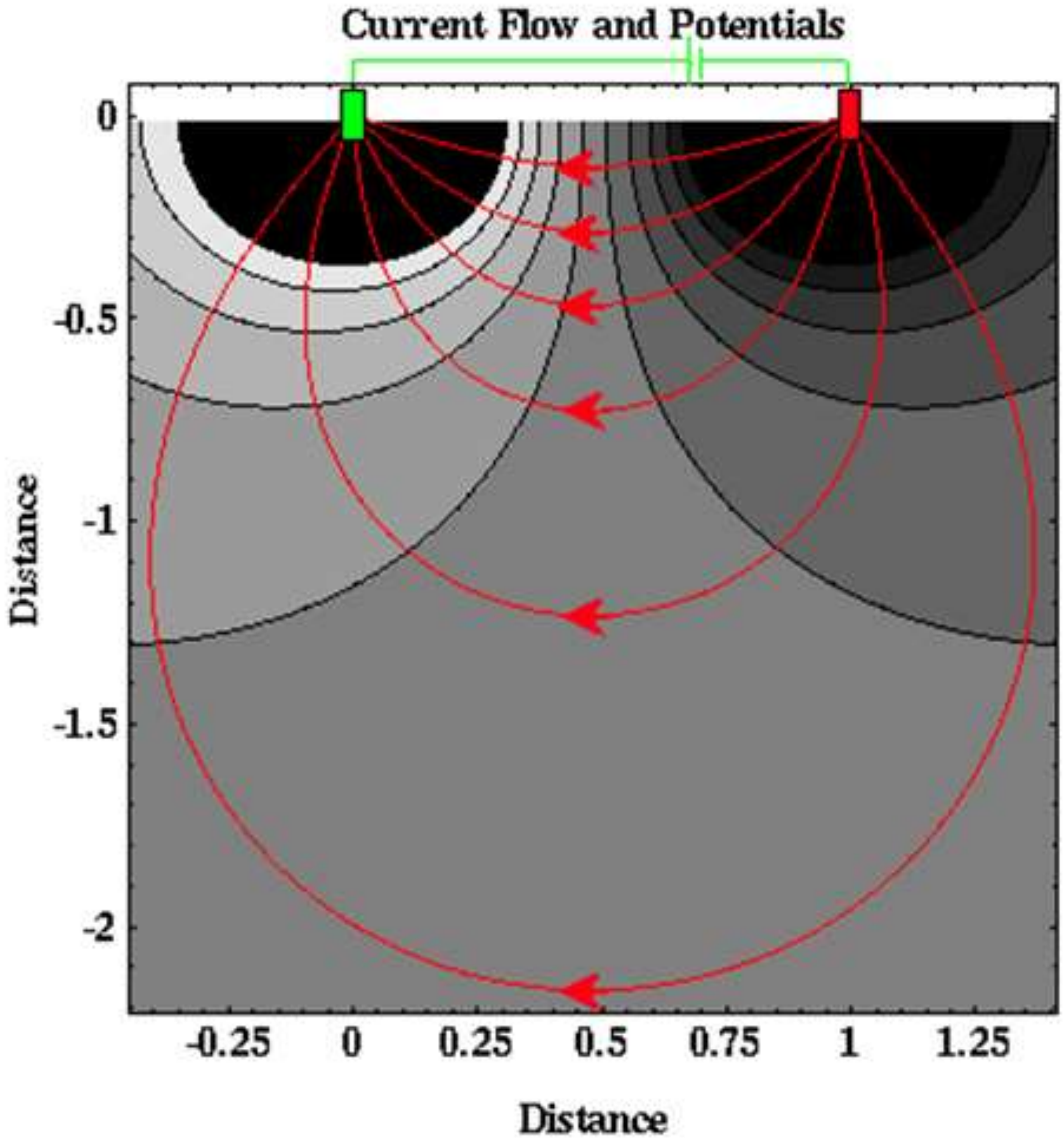
A First Estimate of Resistivity



$$V = \frac{\rho I}{2\pi r}$$

Source: http://galitzin.mines.edu/INTROGP/

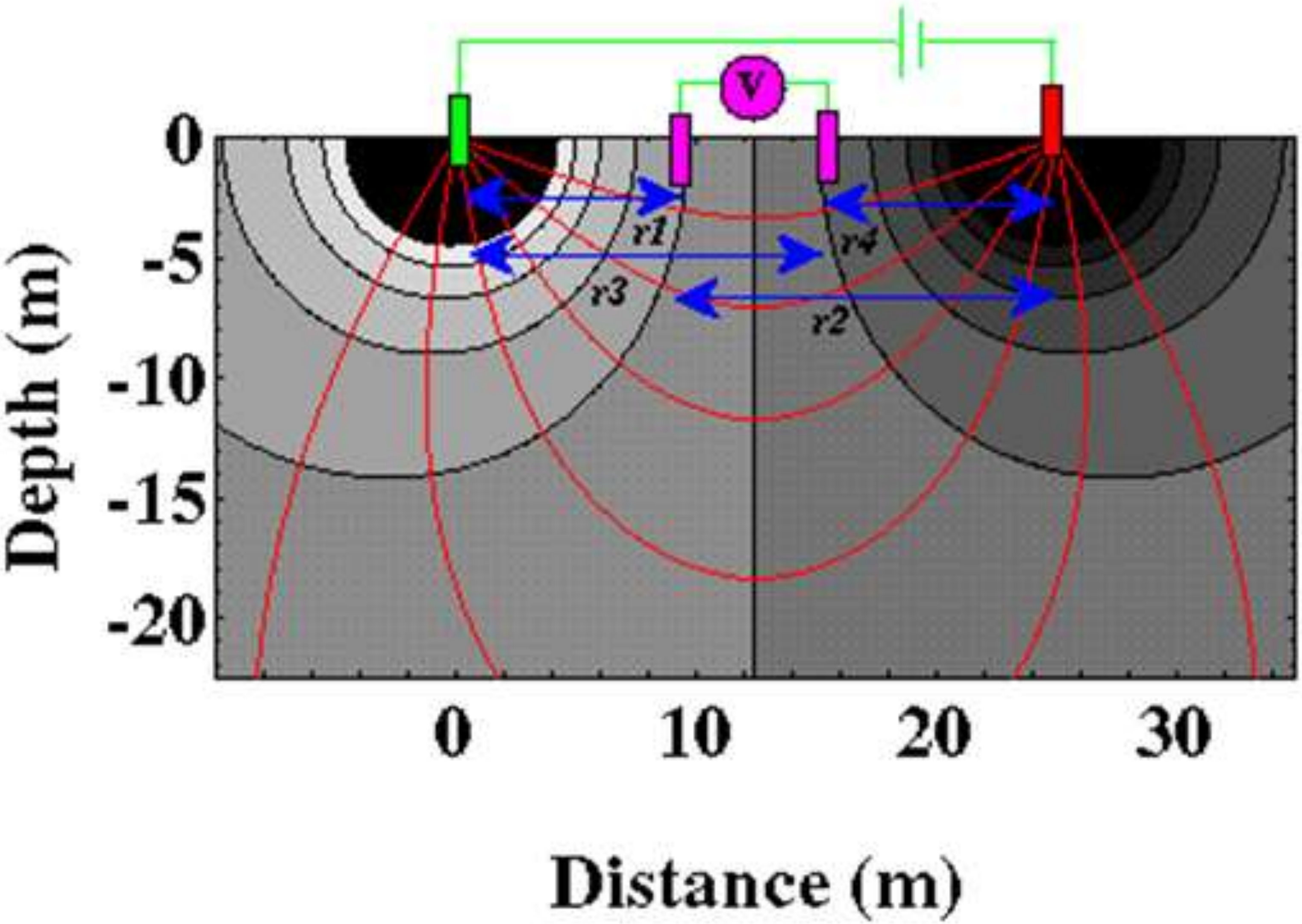
Current Flow - Two Closely Spaced Electrodes



Current Path	% of Total Current
1	17
2	32
3	43
4	49
5	51
6	57

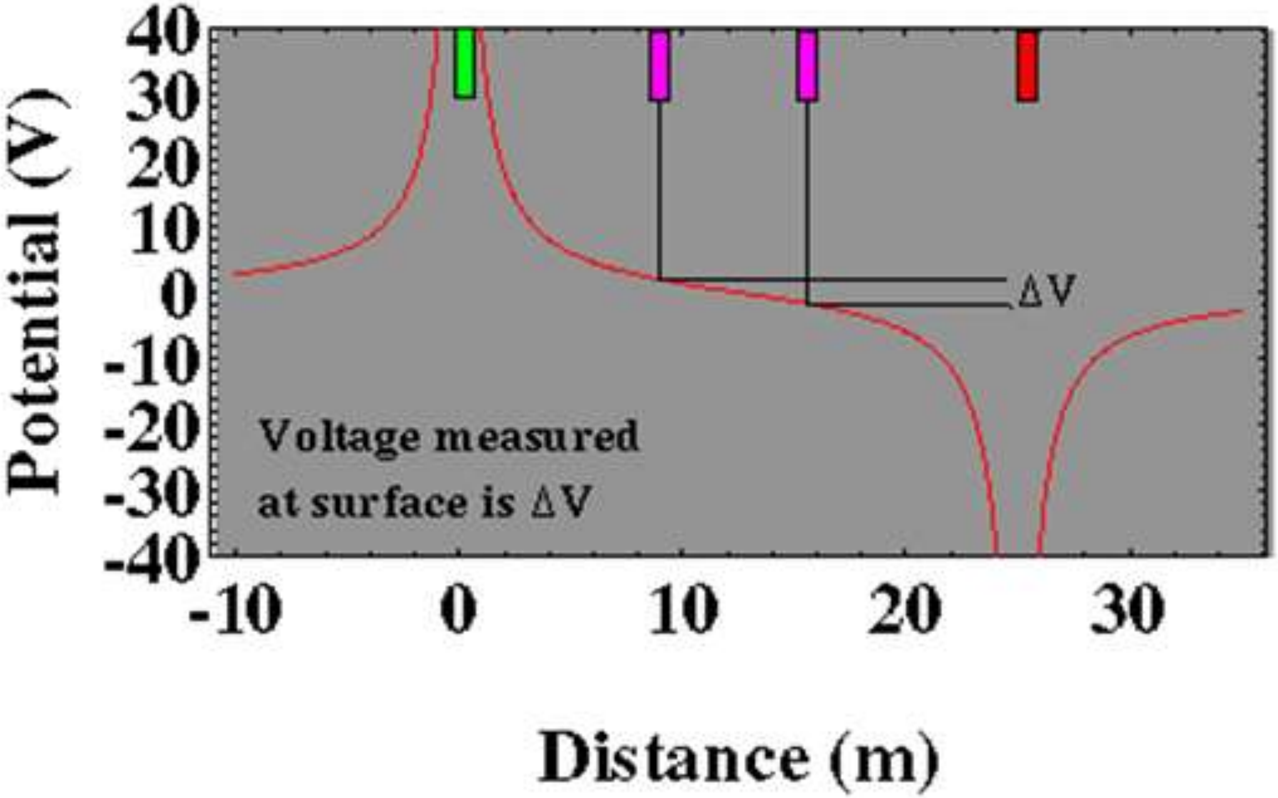
Source: http://galitzin.mines.edu/INTROGP/

A Practical Way of Measuring Resistivity



Source: http://galitzin.mines.edu/INTROGP/

A Practical Way of Measuring Resistivity



$$\rho_a = \frac{2\pi\Delta V}{i}\left[\frac{1}{\left(\frac{1}{r_1}-\frac{1}{r_2}-\frac{1}{r_3}+\frac{1}{r_4}\right)}\right]$$

Source: http://galitzin.mines.edu/INTROGP/

NORPLAN

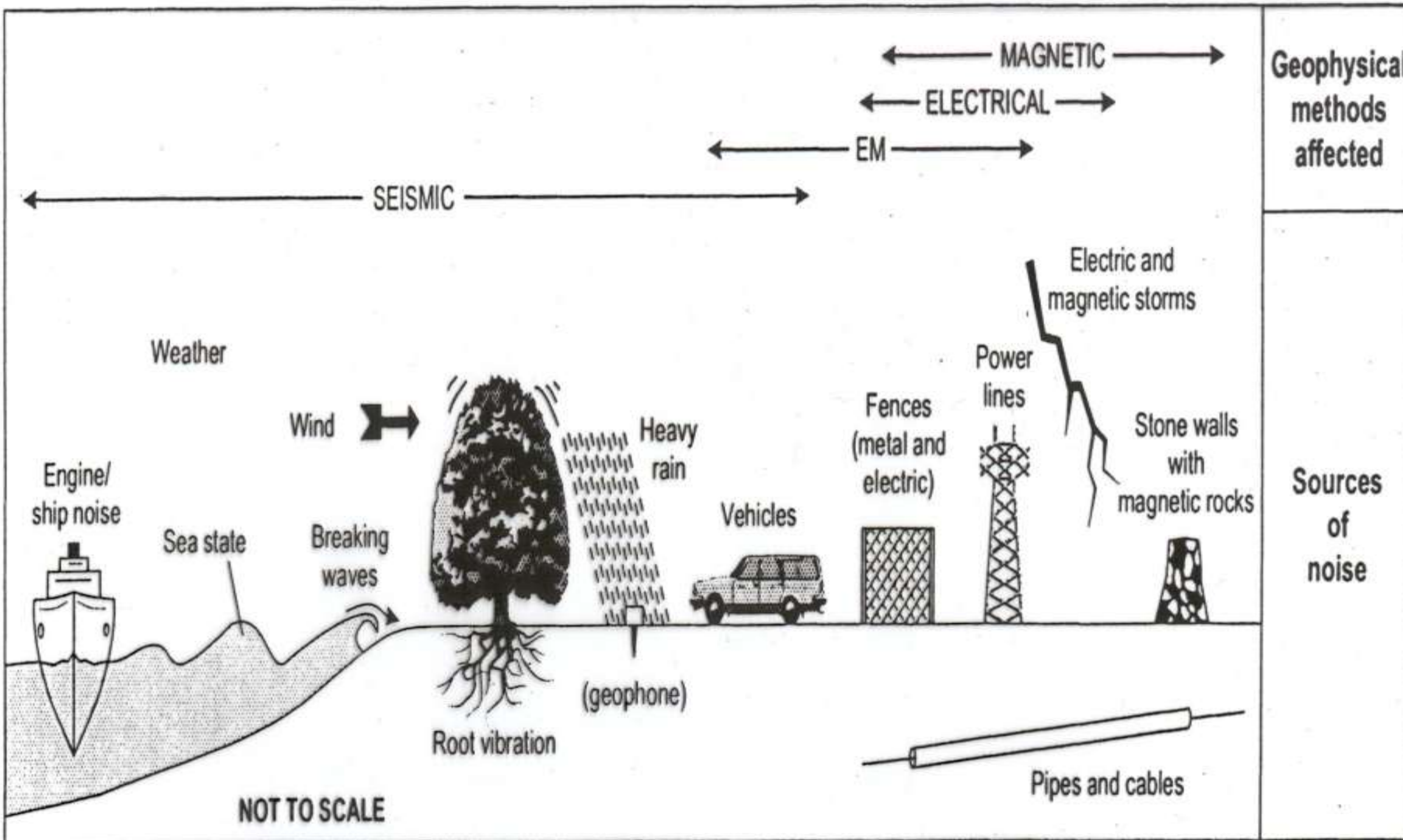
PART 3 – Resistivity Surveys and Geology

1. Sources of Noise
2. Depth of Current Penetration Versus Current Electrode Spacing
3. Current Flow in Layered Media
4. Variation in Apparent Resistivity: Layered Versus Homogeneous Media
5. Current Flow in Layered Media Versus Electrode Spacing

Sources of Noise

- Electrode Polarization
  - Use non-polarizing electrodes
  - Reverse current flow in the current electrodes
- Telluric Currents
- Presence of Nearby Conductors
- Low Resistivity at the Near Surface
- Near-Electrode Geology and Topography
- Current Induction in Measurement Cables

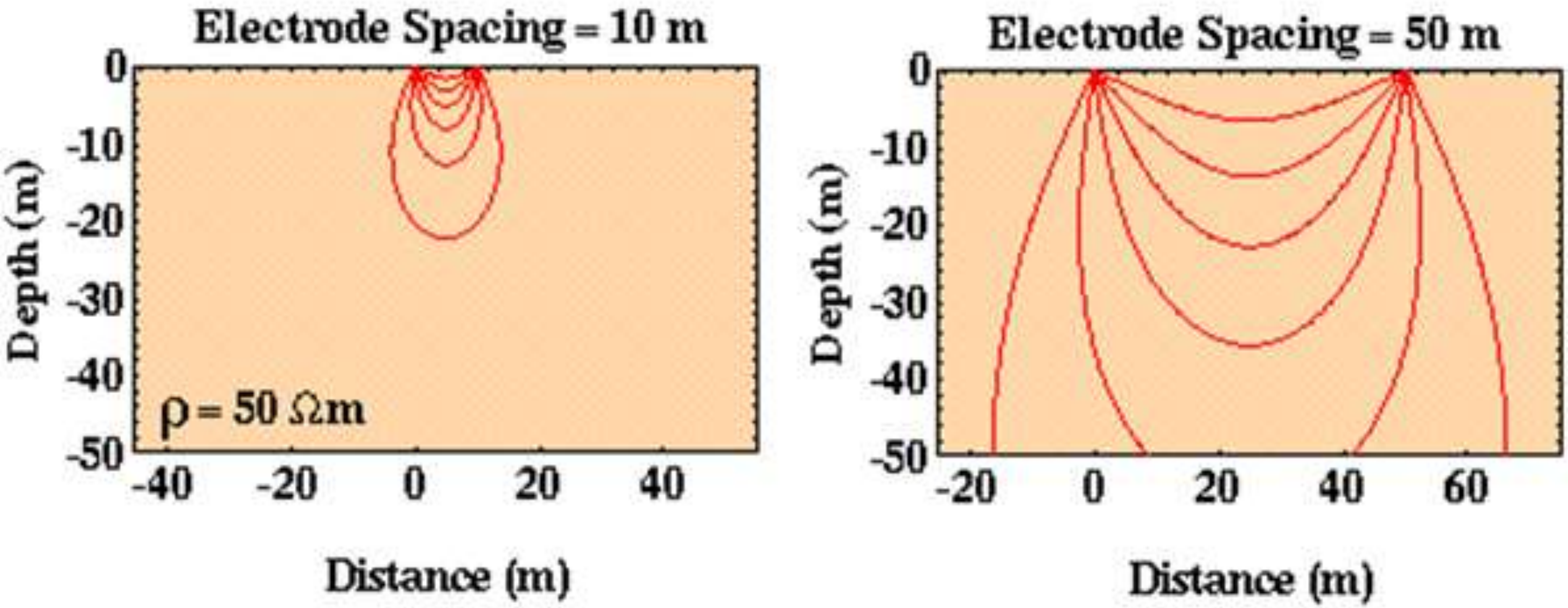
Sources of Noise



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

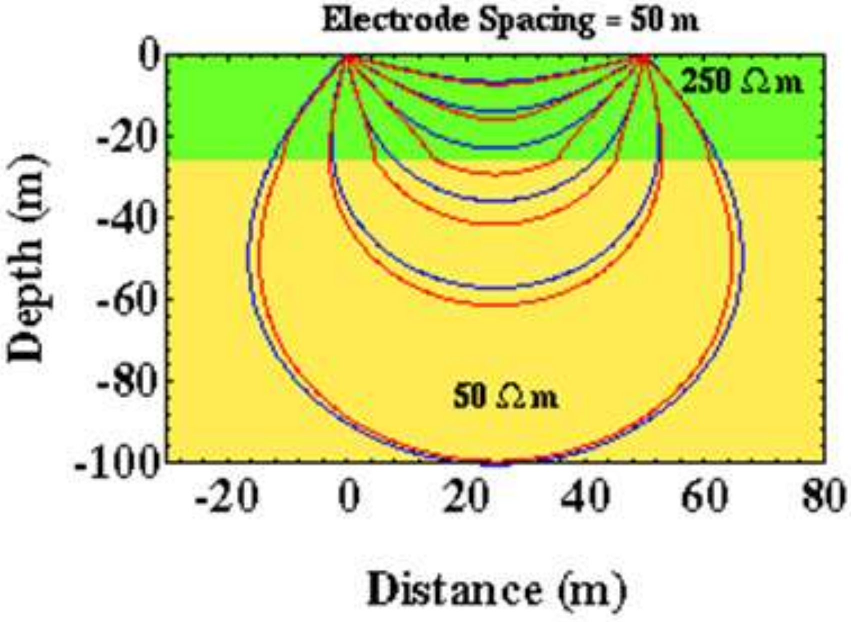
NORPLAN

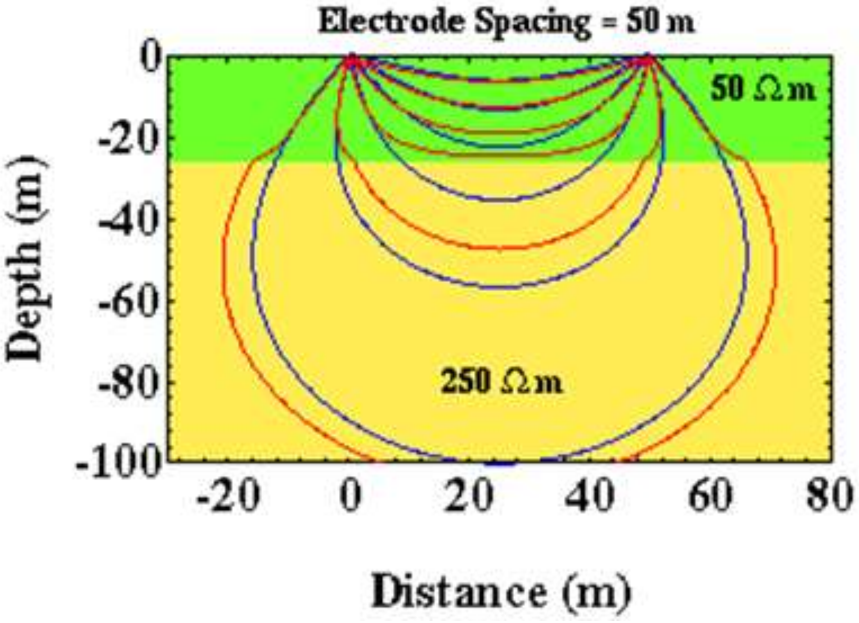
Depth of Current Penetration Versus Current Electrode Spacing



Source: http://galitzin.mines.edu/INTROGP/

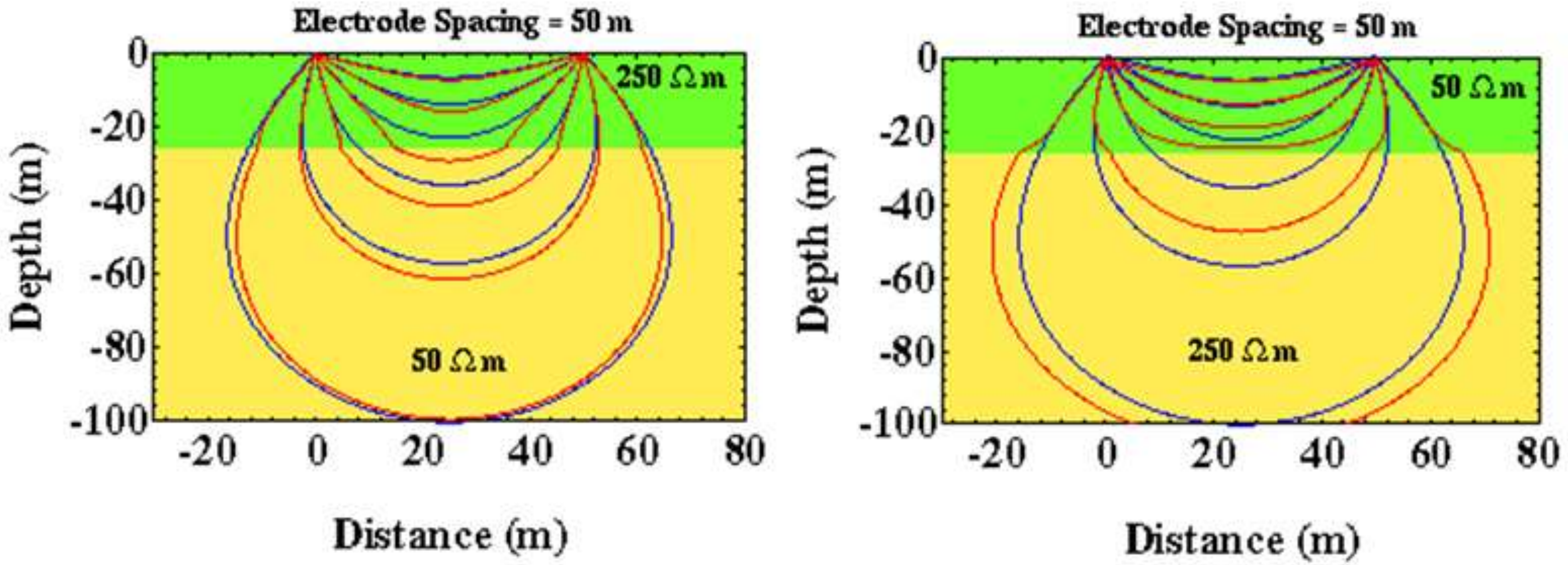
Current Flow in Layered Media





Source: http://galitzin.mines.edu/INTROGP/

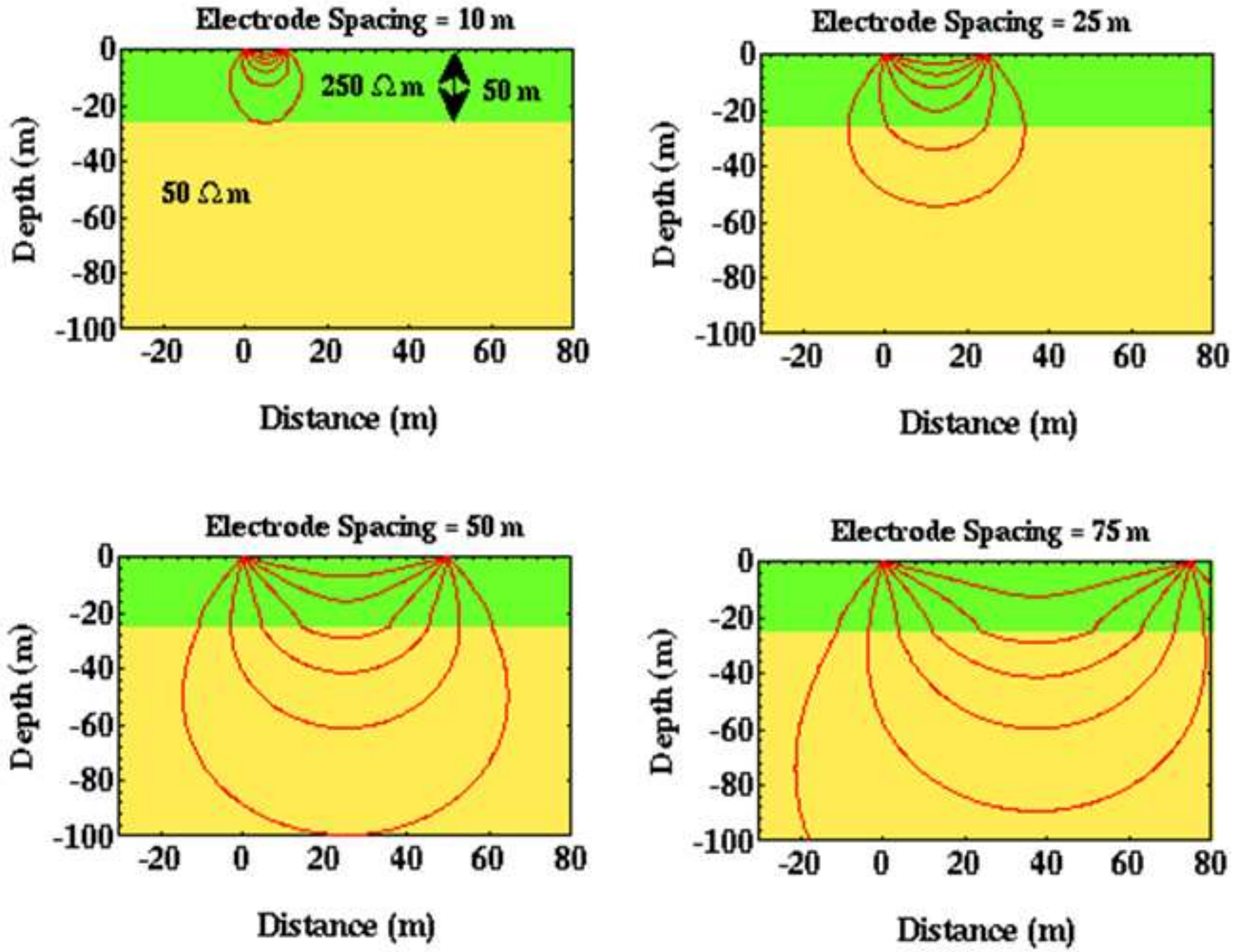
Variation in Apparent Resistivity: Layered Versus Homogeneous Media



$$\rho_a = \frac{2\pi\Delta V}{i}\left[\frac{1}{\left(\frac{1}{r_1}-\frac{1}{r_2}-\frac{1}{r_3}+\frac{1}{r_4}\right)}\right]$$

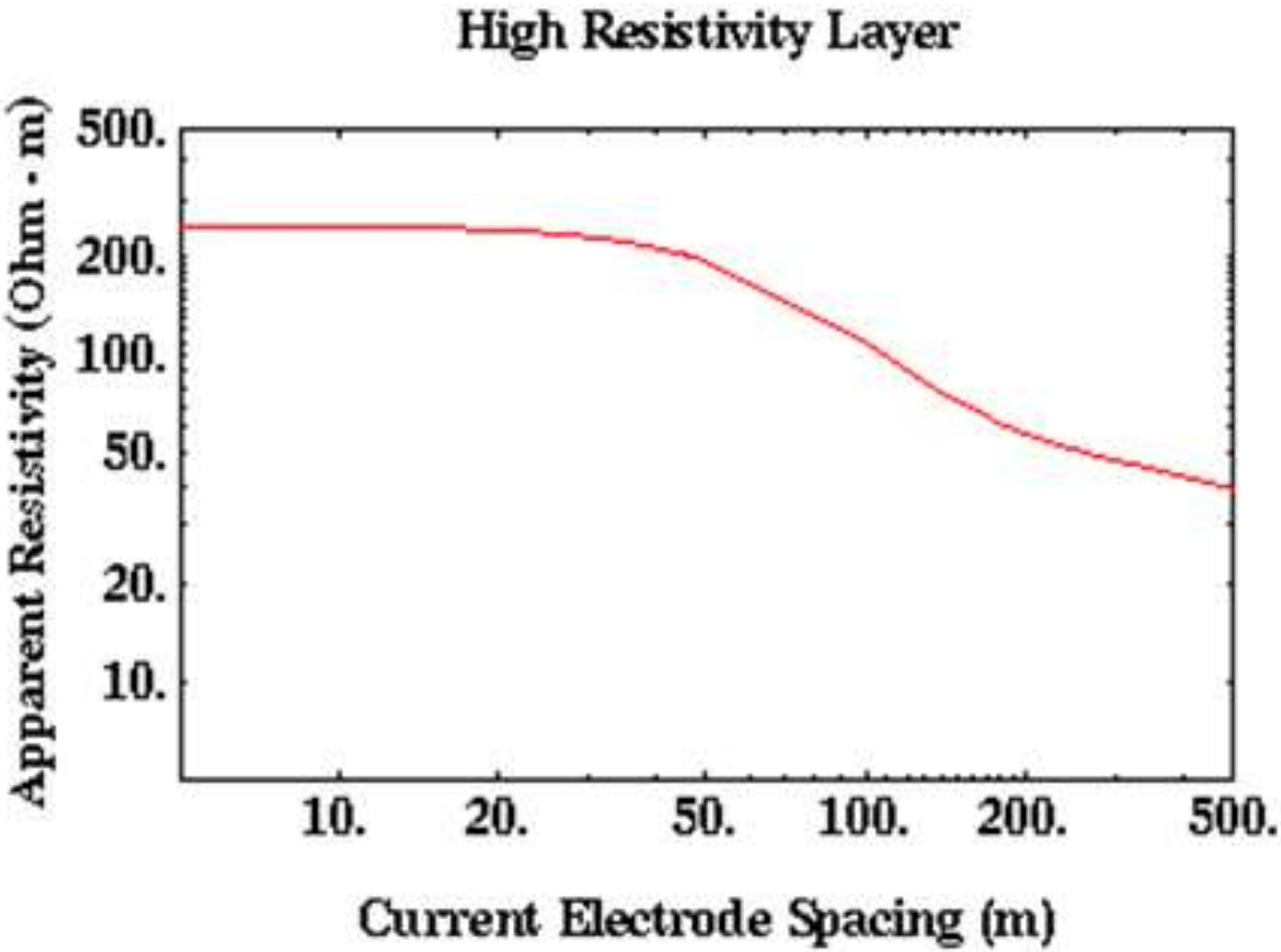
Source: http://galitzin.mines.edu/INTROGP/

Current Flow in Layered Media Versus Electrode Spacing: Example 1



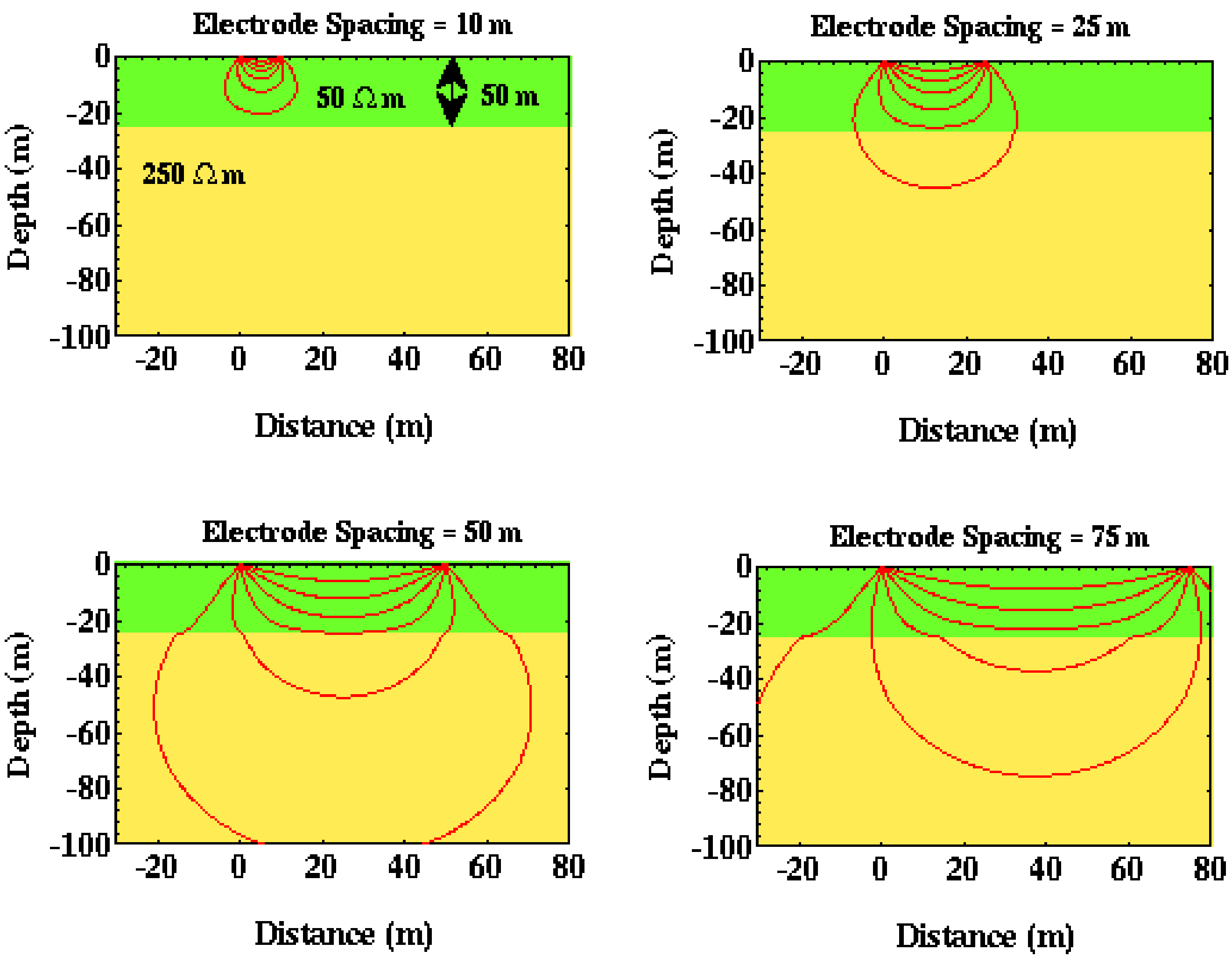
Source: http://galitzin.mines.edu/INTROGP/

Current Flow in Layered Media Versus Electrode Spacing: Example 1



Source: http://galitzin.mines.edu/INTROGP/

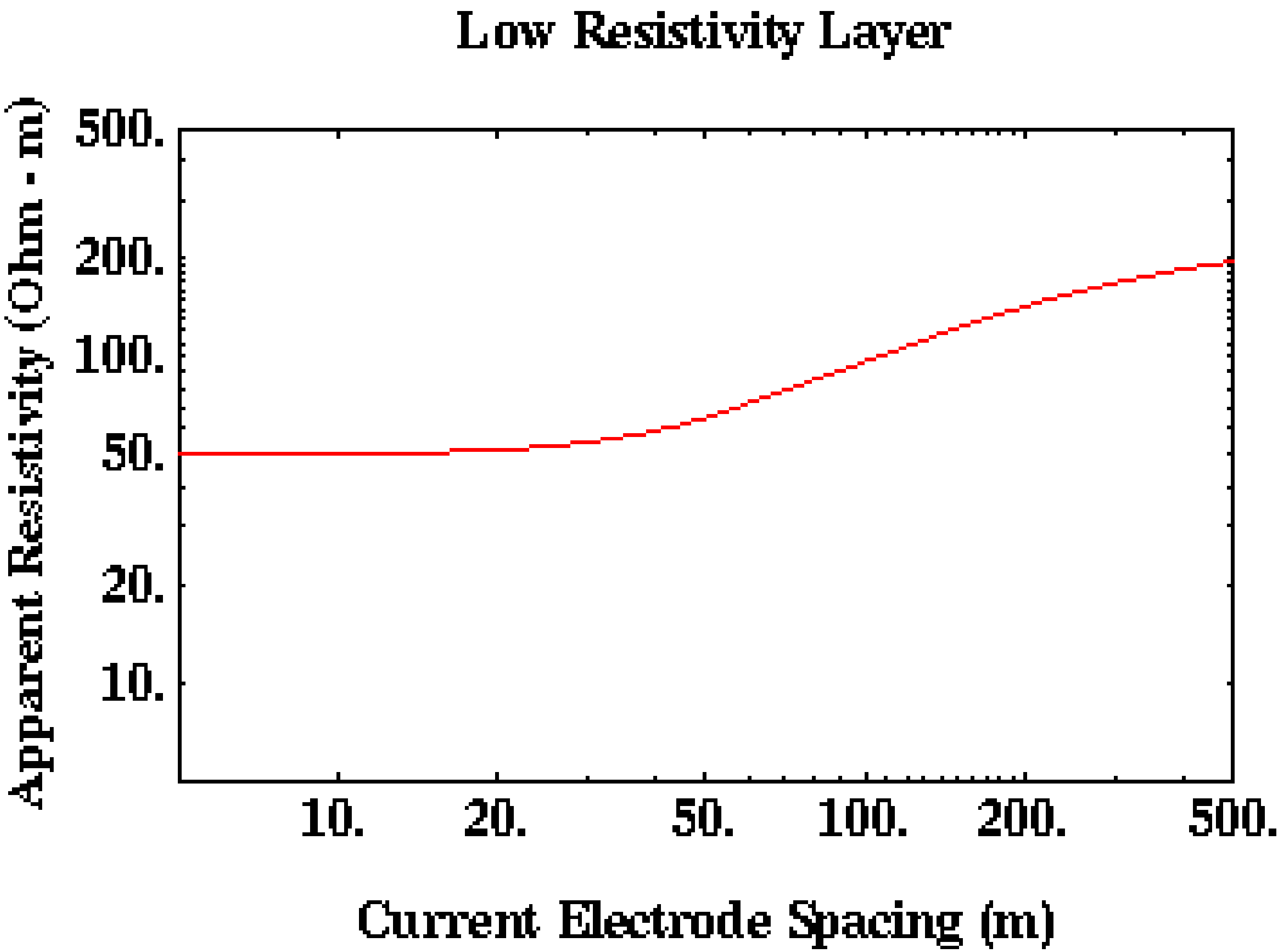
Current Flow in Layered Media Versus Electrode Spacing: Example 2



Source: http://galitzin.mines.edu/INTROGP/

NORPLAN

Current Flow in Layered Media Versus Electrode Spacing: Example 2



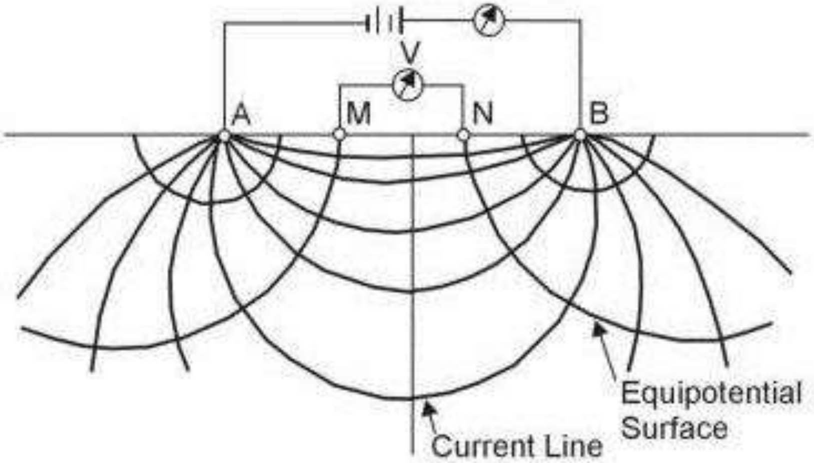
Source: http://galitzin.mines.edu/INTROGP/

PART 4 – Resistivity Equipment and Field Procedures

1. DC Resistivity Equipment
2. Survey Types Overview: Soundings and Profiles
3. Soundings: Wenner and Schlumberger
4. Electrode Spacings and Apparent Resistivity Plots
5. Advantages and Disadvantages of Wenner and Schlumberger Arrays
6. Resistivity Profiles

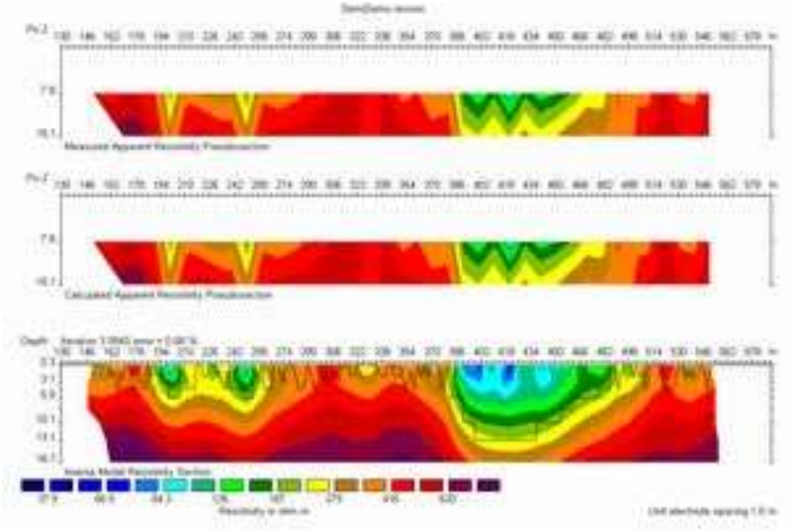
DC Resistivity Equipment

1. Current Source
2. Ammeter
3. Voltmeter
4. Electrodes
5. Cables



Source: http://www.iris-instruments.com

DC Resistivity Equipment – ABEM Terrameter

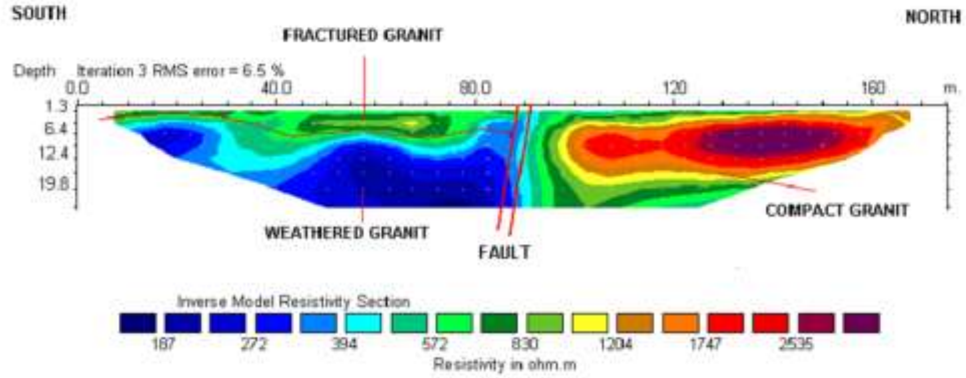


DC Resistivity Equipment – ABEM Terrameter LS

DC Resistivity Equipment – IRIS SYSCAL

SYSCAL Pro

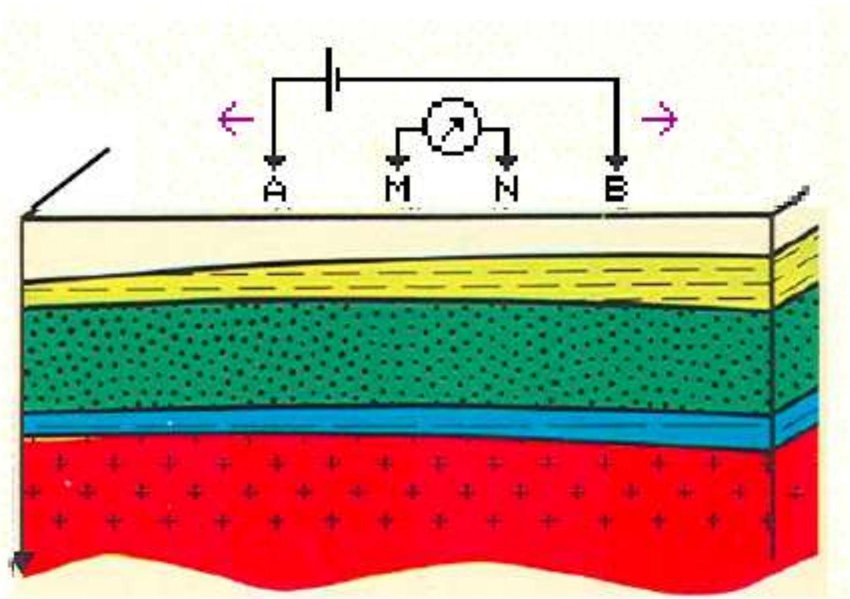
1000V, 250W, 2.5A

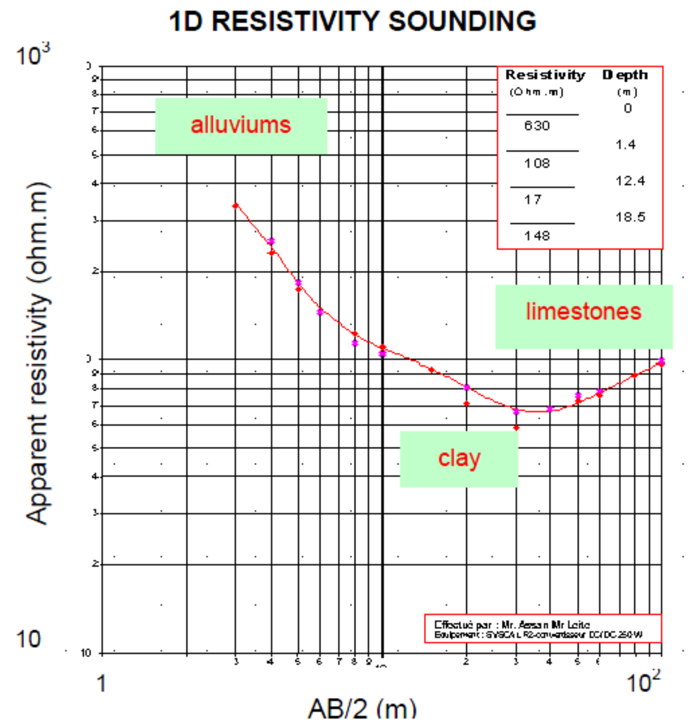


PRODUCT name	power W	voltage V	current A	power converter	IP windows	receiving dipoles	display
SYSCAL Kid	25	200	0.5	internal	1	1	alpha num
SYSCAL Junior	100	400	1.2	internal	4	1	alpha num
SYSCAL R1 Plus	200	600	2.5	internal	4	1	alpha num
SYSCAL R2	250	800	2.5	DC/DC ext	4	1	alpha num
»	1200	»	»	AC/DC ext	»	»	»
SYSCAL Pro	250	1000	2.5	internal	20	10	graphical
»	500	1500	»	DC/DC ext	»	»	»

Source: http://www.iris-instruments.com

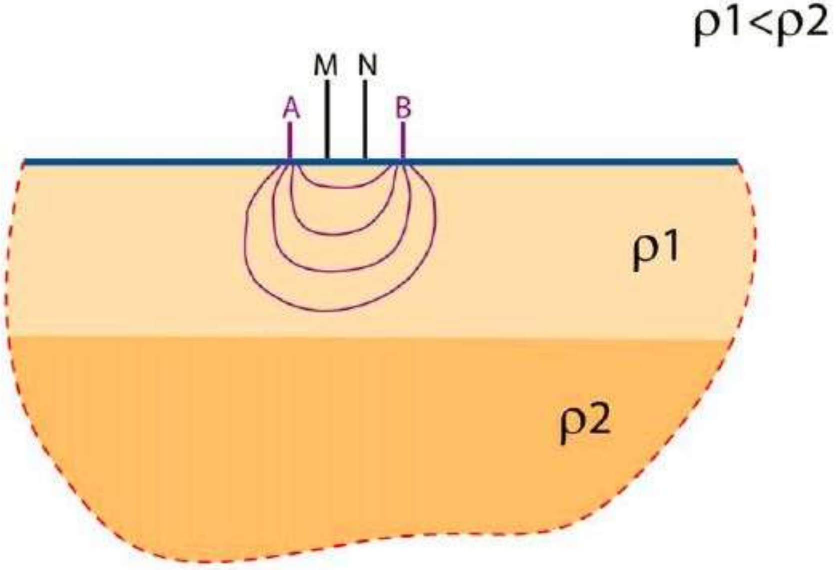
Survey Types Overview: Soundings

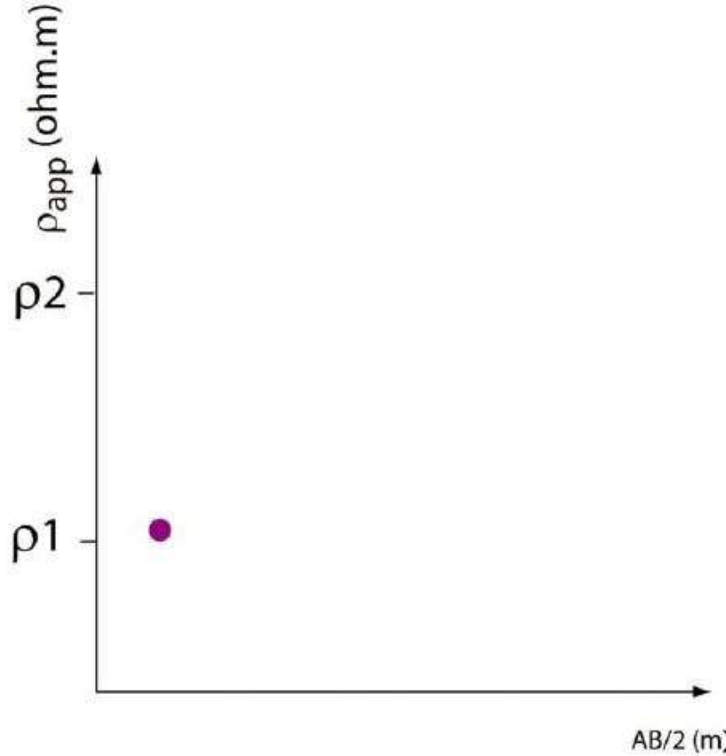




Source: http://www.iris-instruments.com

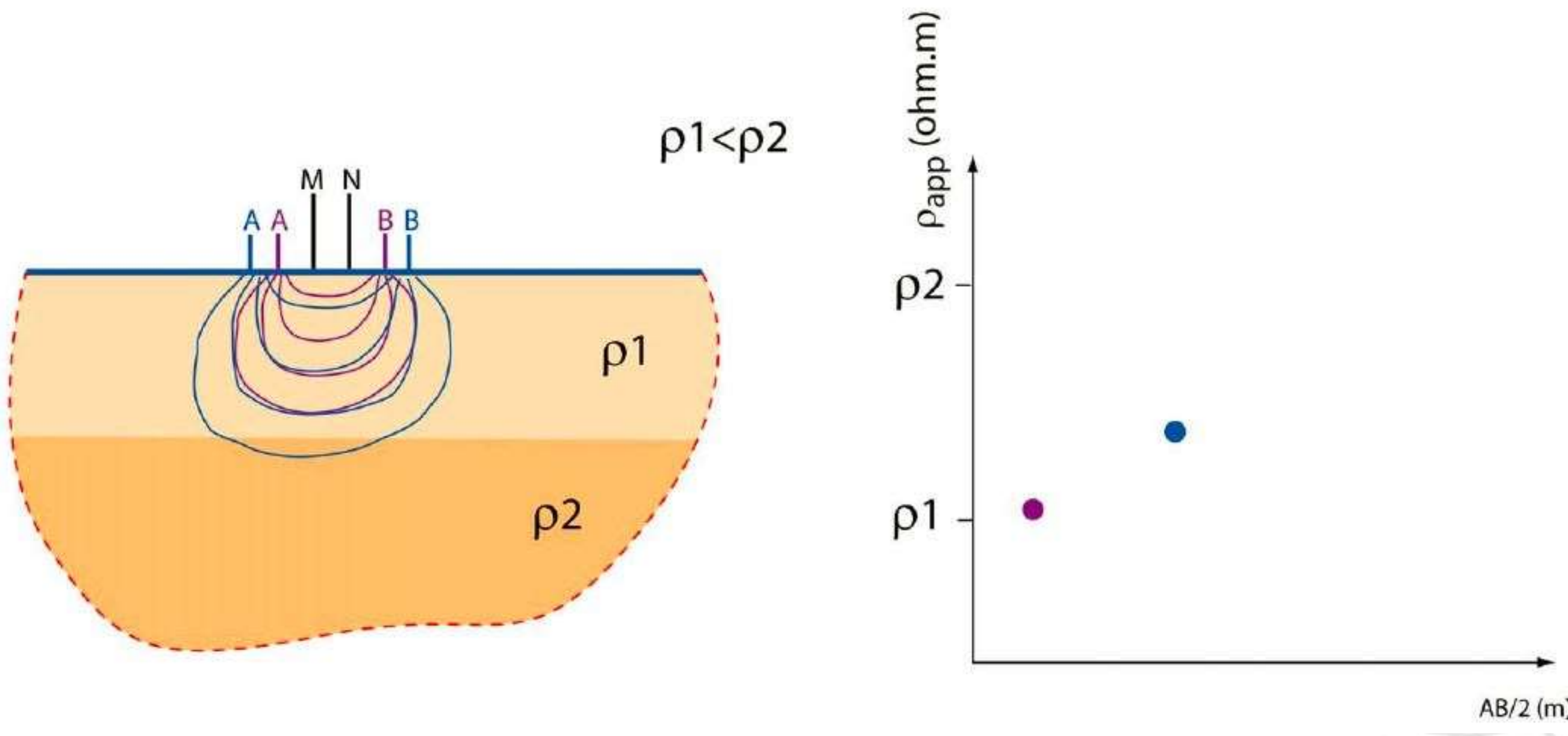
Vertical Electrical Sounding (VES)





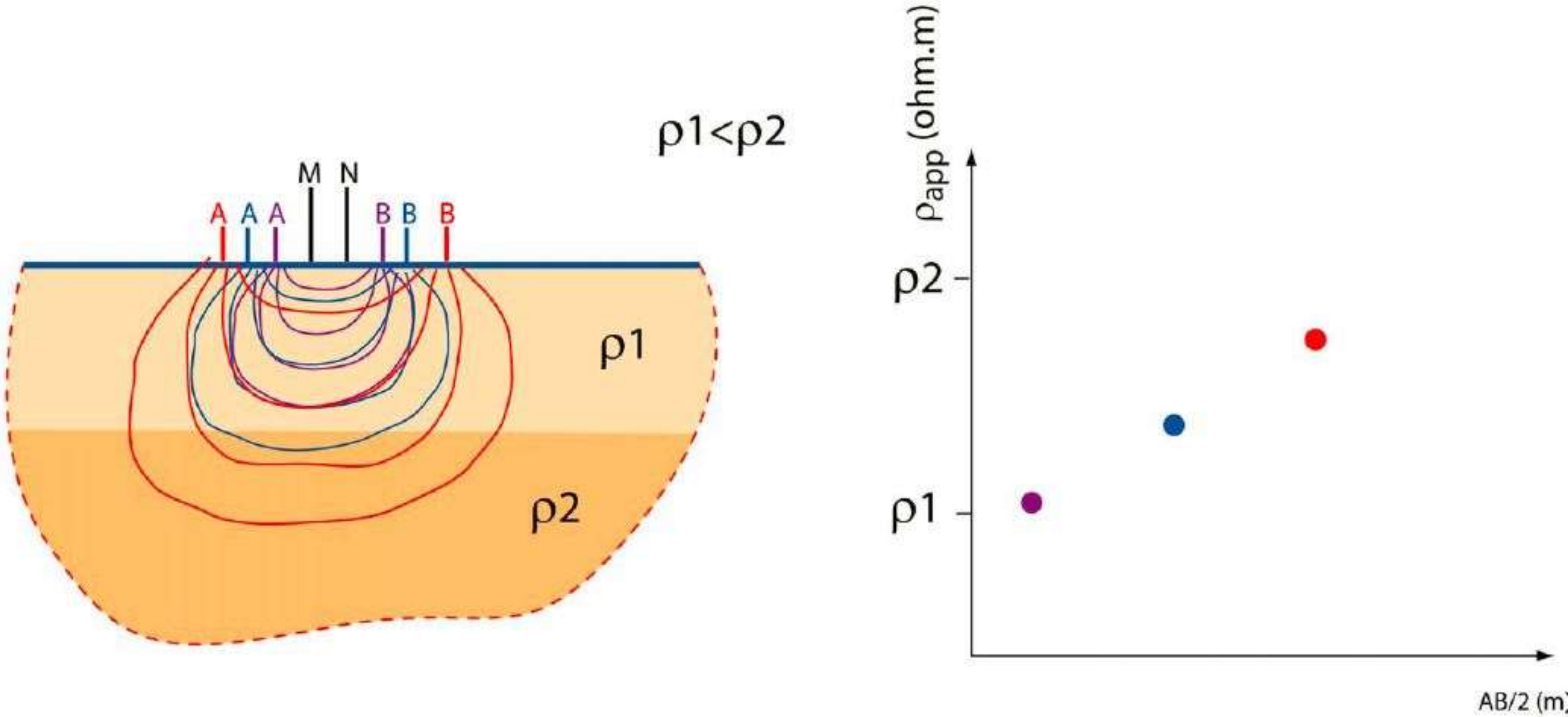
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Vertical Electrical Sounding (VES)



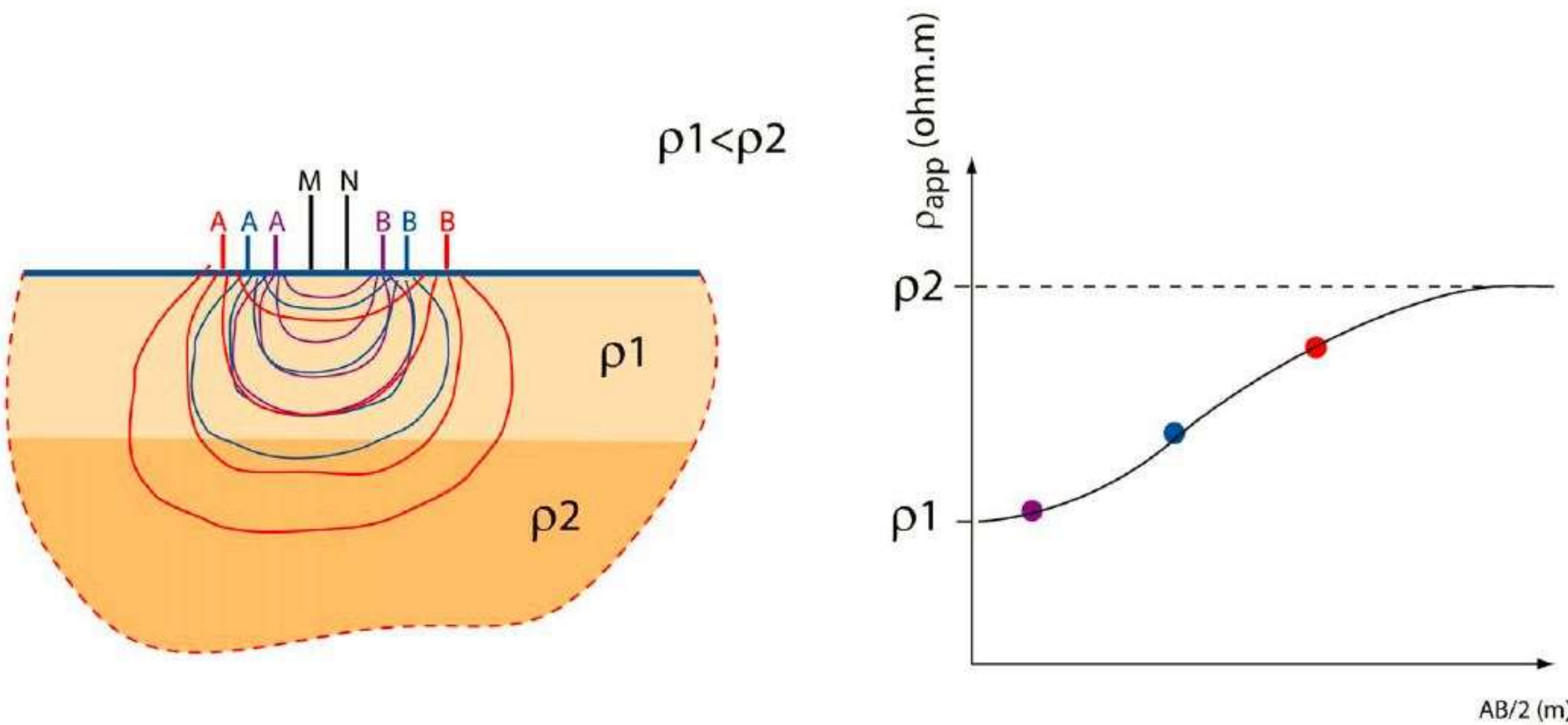
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Vertical Electrical Sounding (VES)



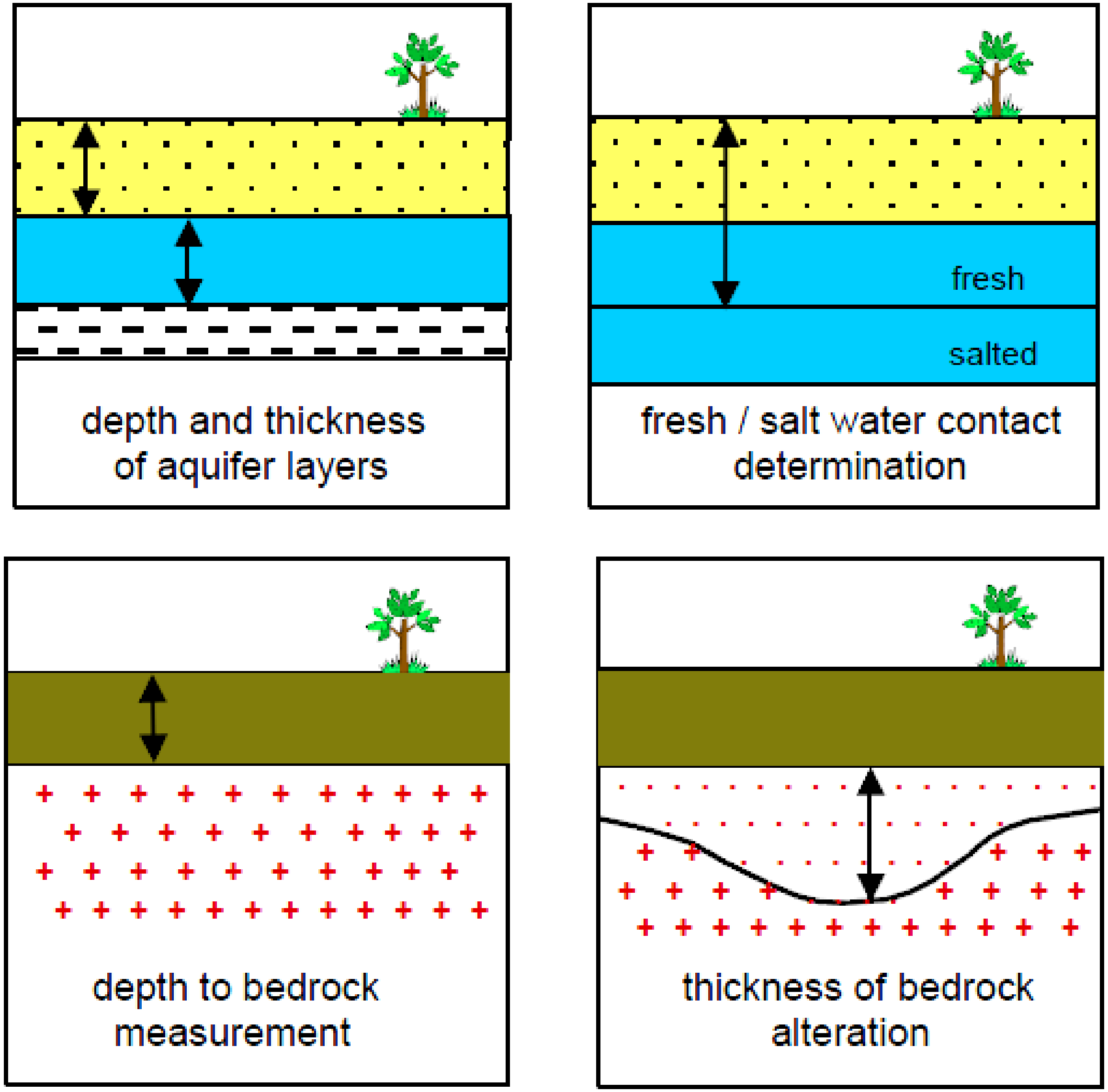
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Vertical Electrical Sounding (VES)



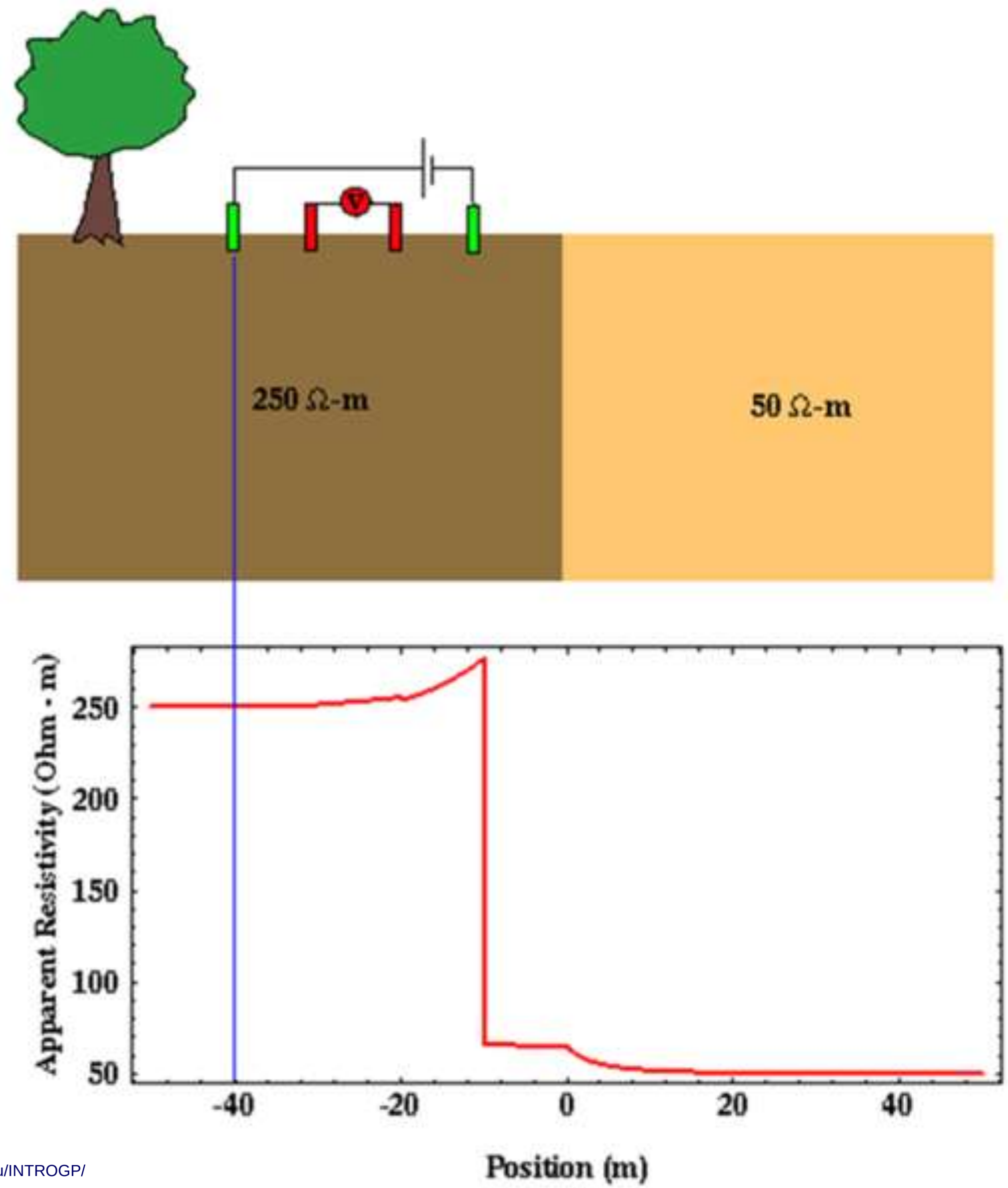
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Applications of Soundings



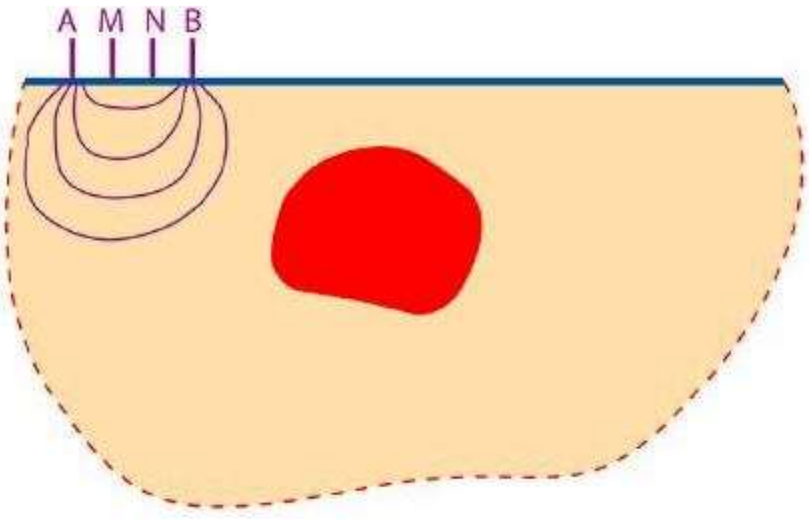
Source: http://www.iris-instruments.com

Survey Types Overview: Profiles



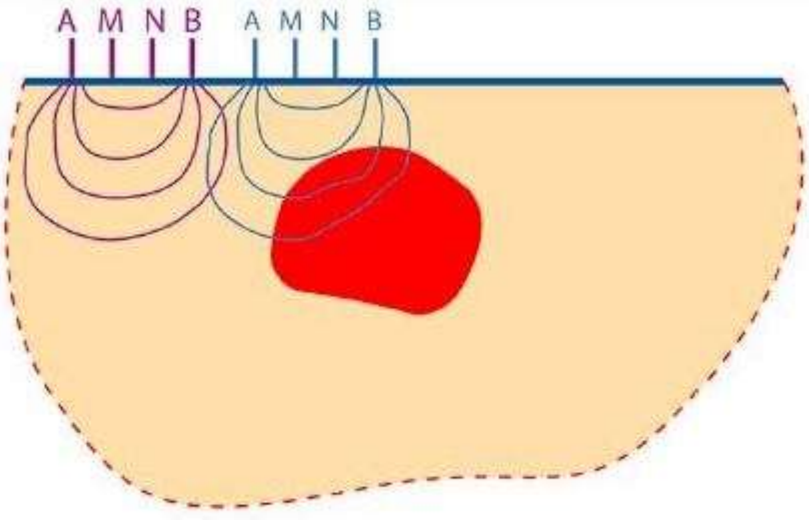
Source: http://galitzin.mines.edu/INTROGP/

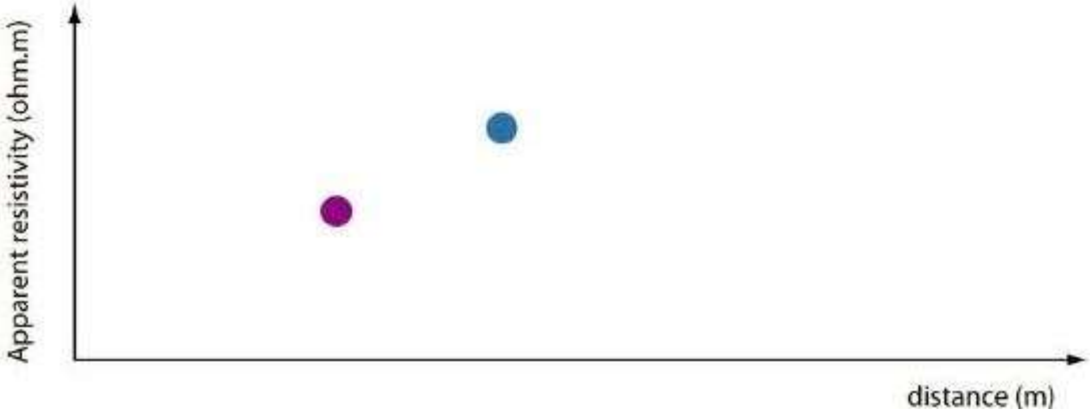
Constant Separation Traversing (CST)



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

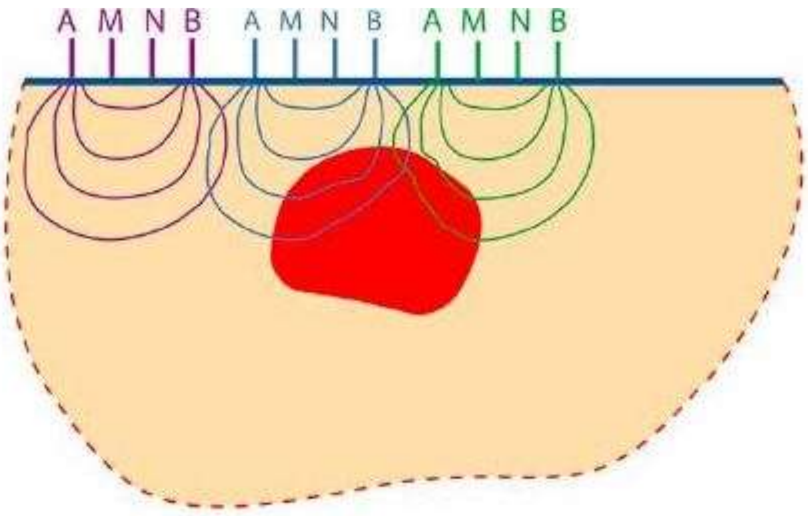
Constant Separation Traversing (CST)

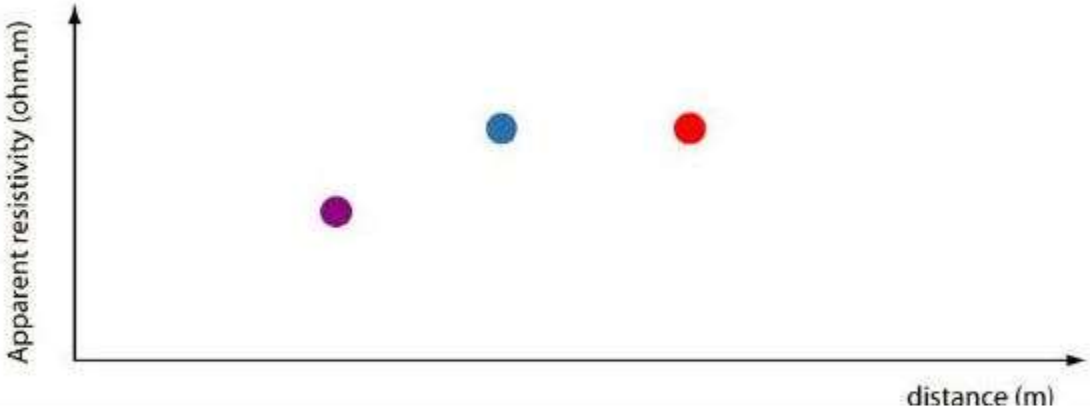




Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

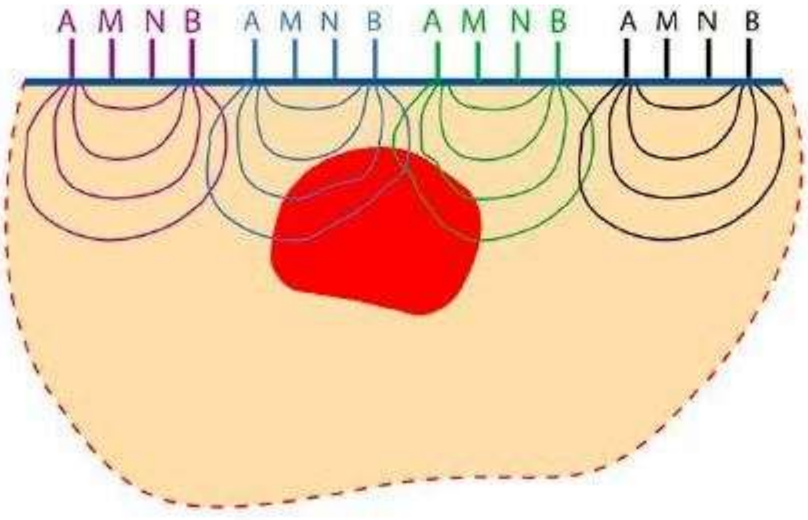
Constant Separation Traversing (CST)

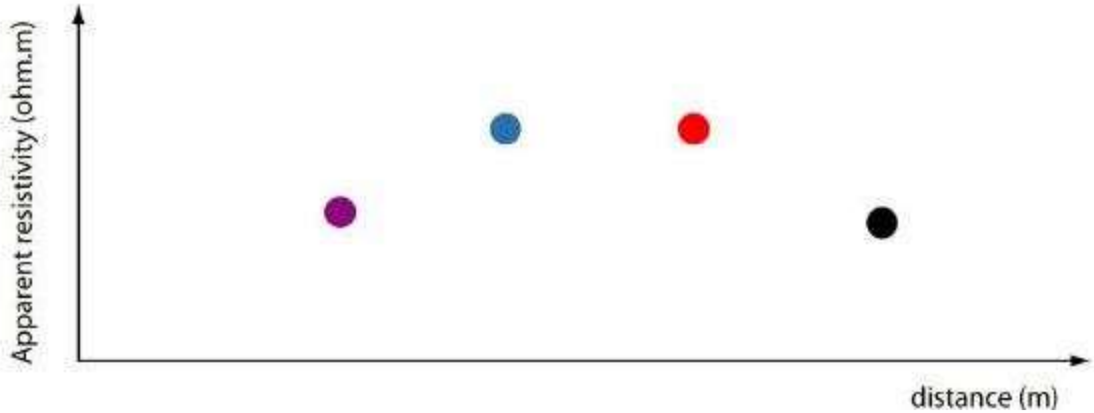




Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

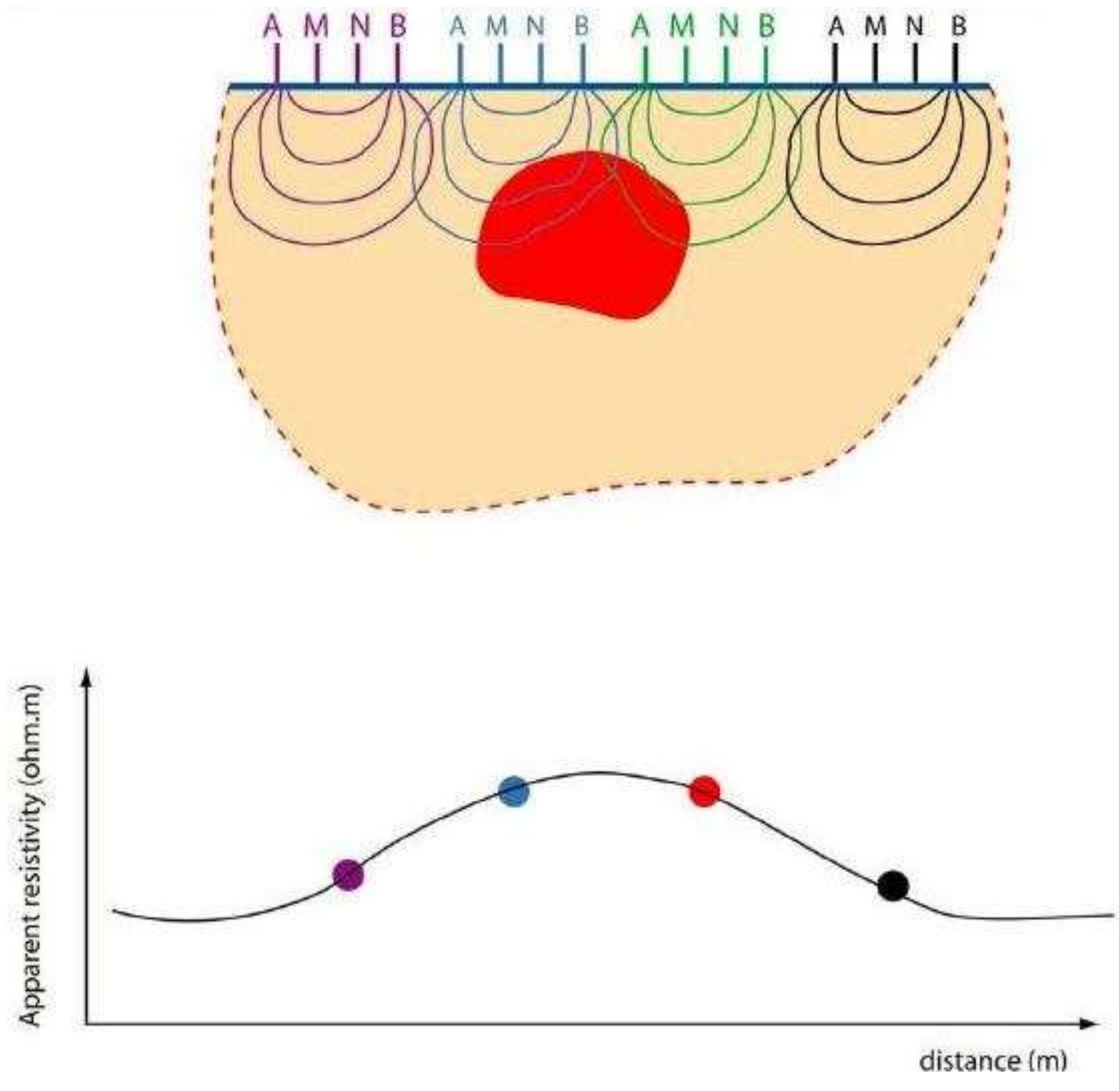
Constant Separation Traversing (CST)





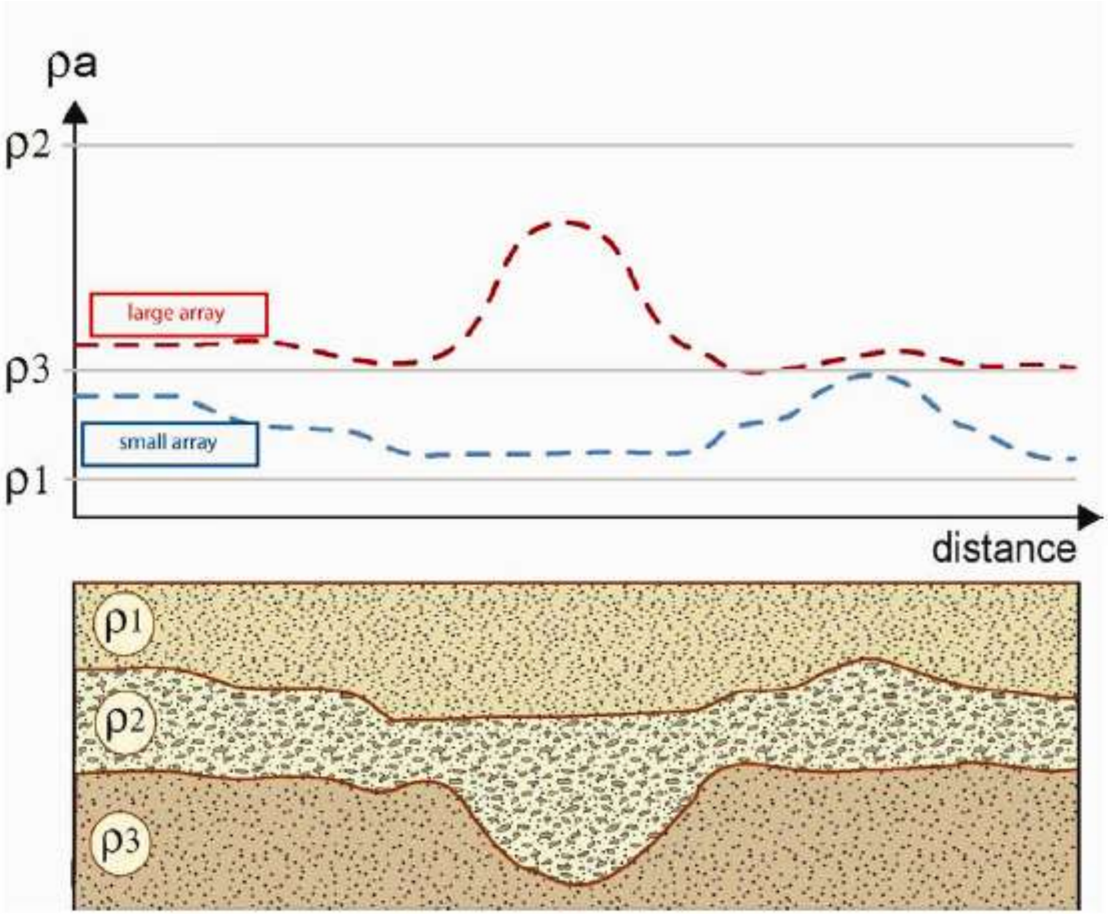
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Constant Separation Traversing (CST)



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Interpretation of CST



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

NORPLAN

Survey Types Overview: Profiles

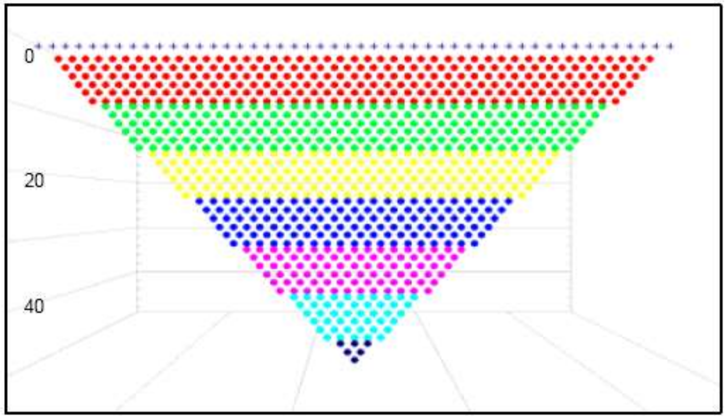
Geometrics OhmMapper

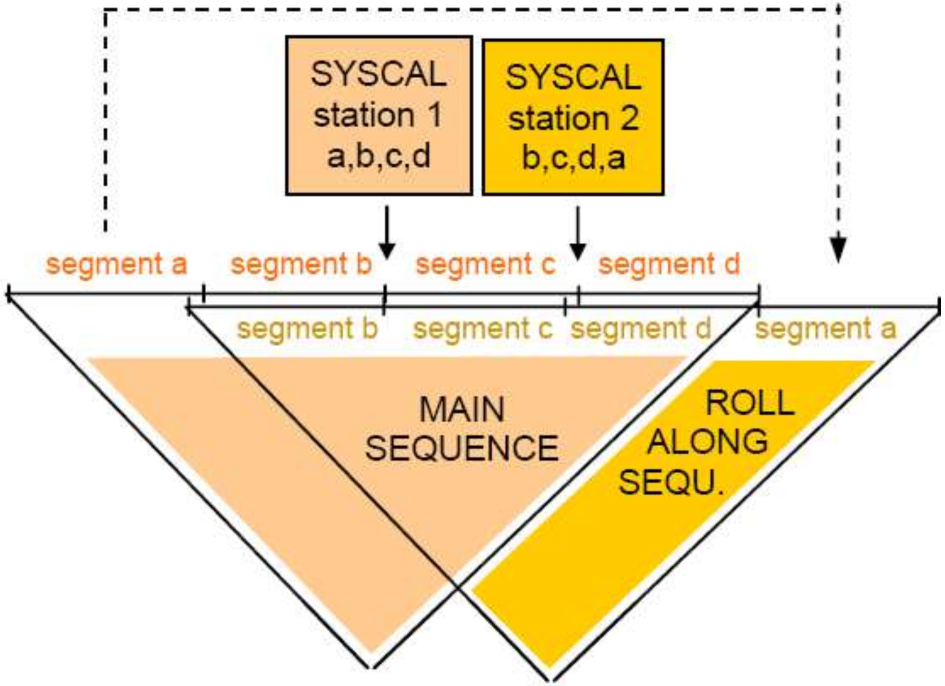
OhmMapper being towed over grass and pavement. Contact is made capacitively with the ground through insulated cables.

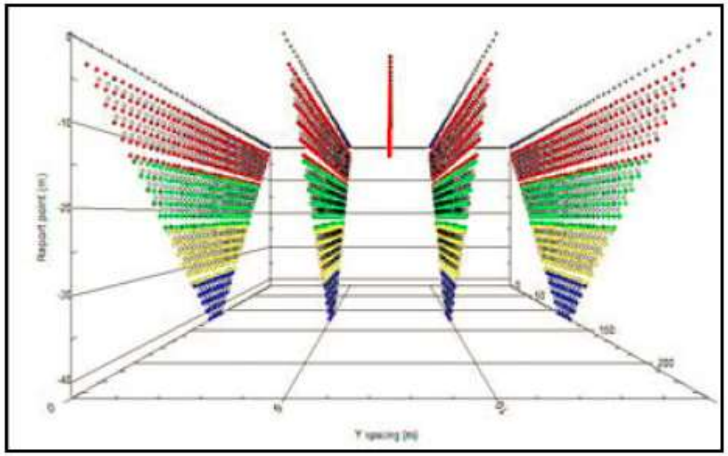
Source: http://galitzin.mines.edu/INTROGP/

Survey Types Overview: Resistivity Imaging

SYSCAL Pro
Switch 48
multi-electrode
equipment
10m spacing



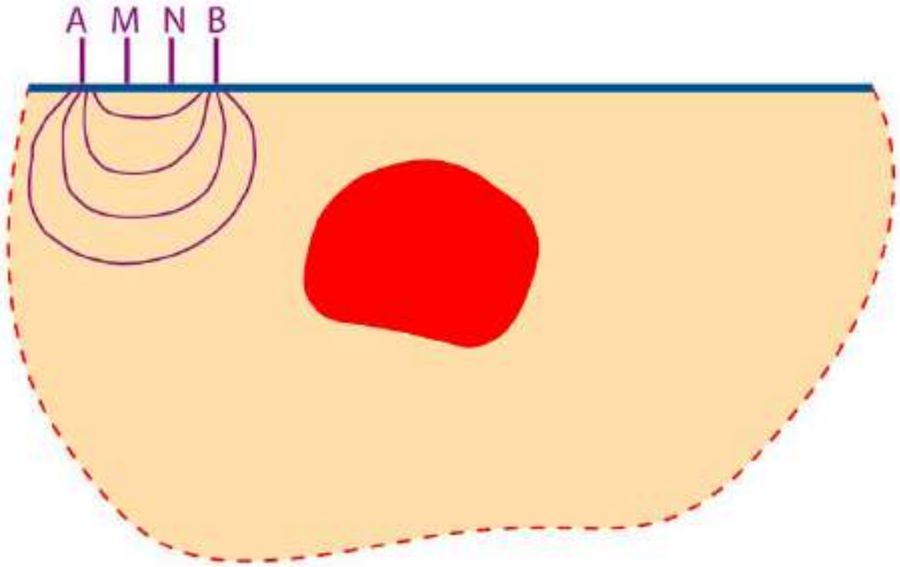




Source: http://www.iris-instruments.com

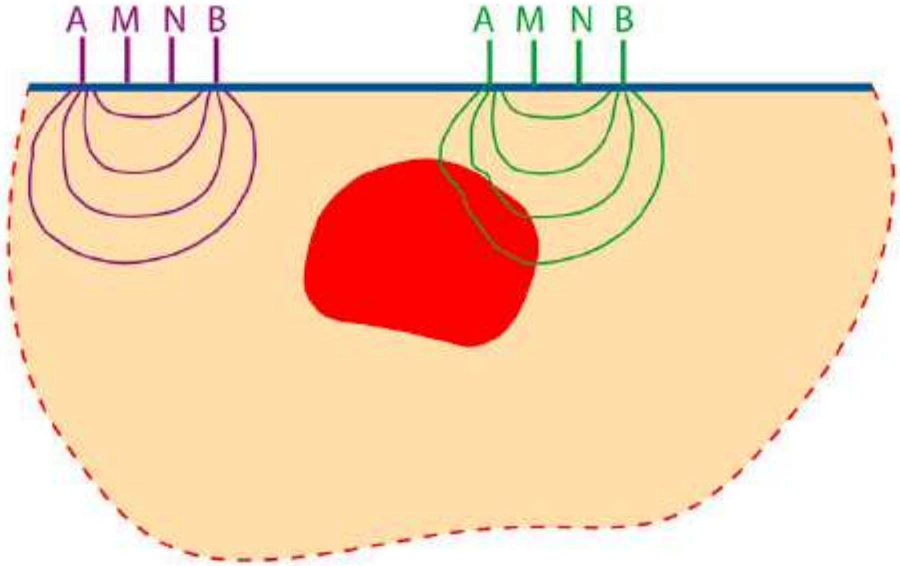
NORPLAN

Resistivity Imaging



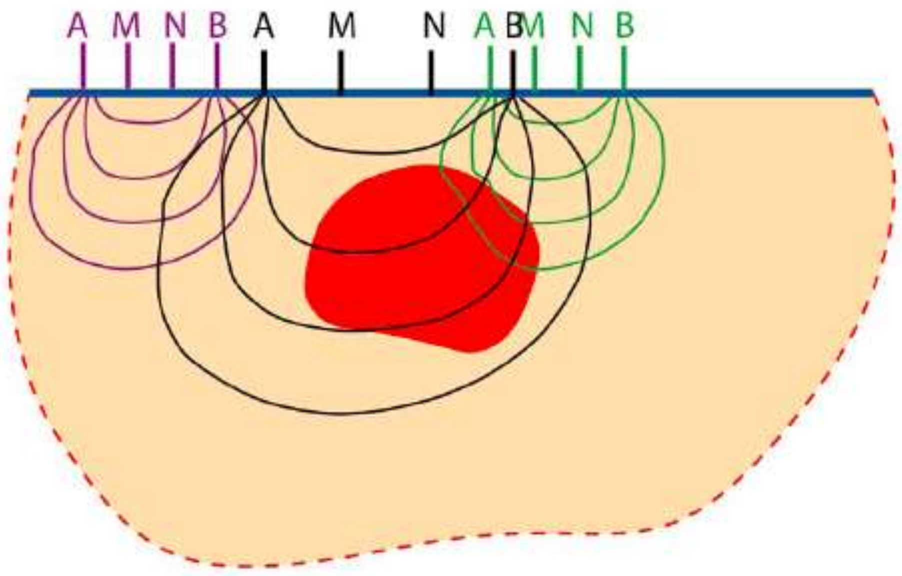
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

Resistivity Imaging



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

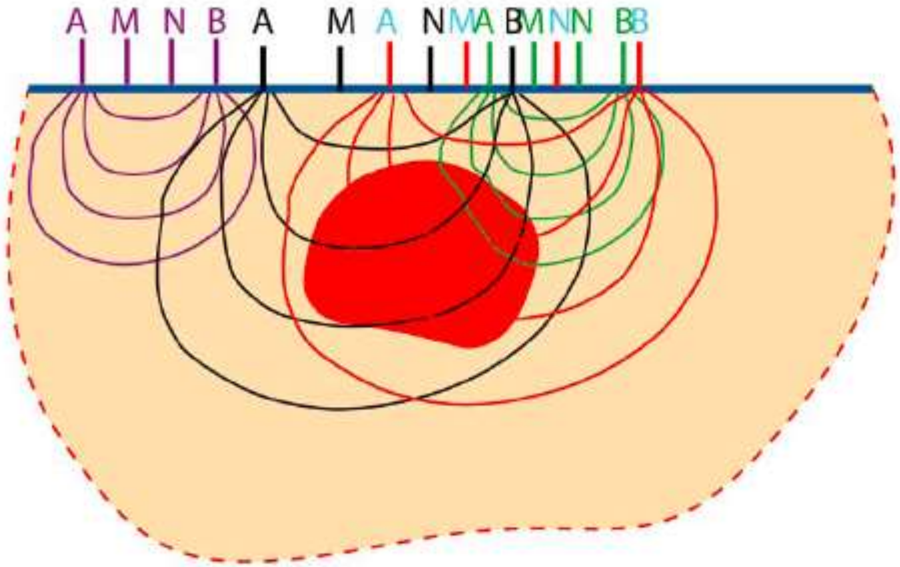
Resistivity Imaging



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

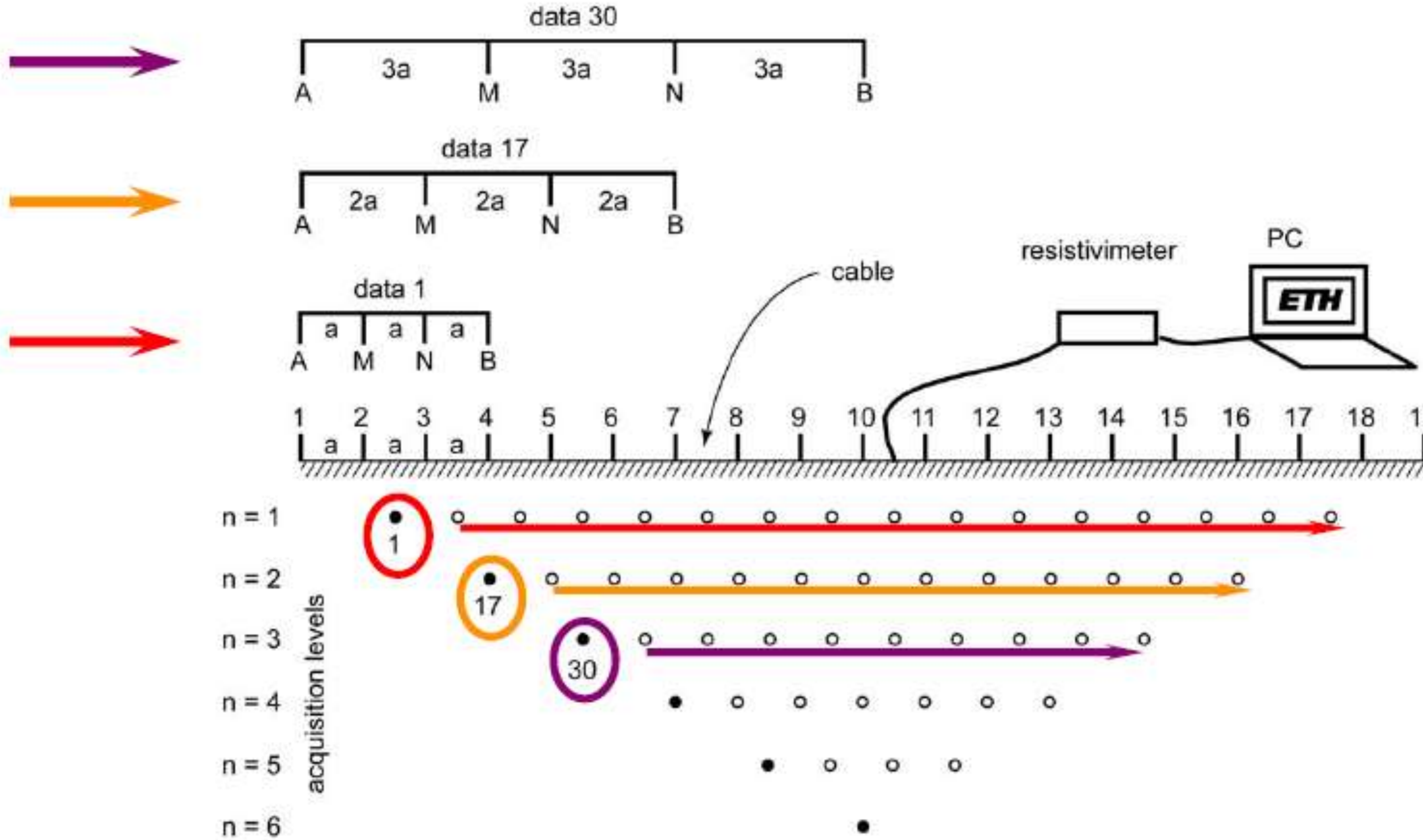
NORPLAN

Resistivity Imaging



Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

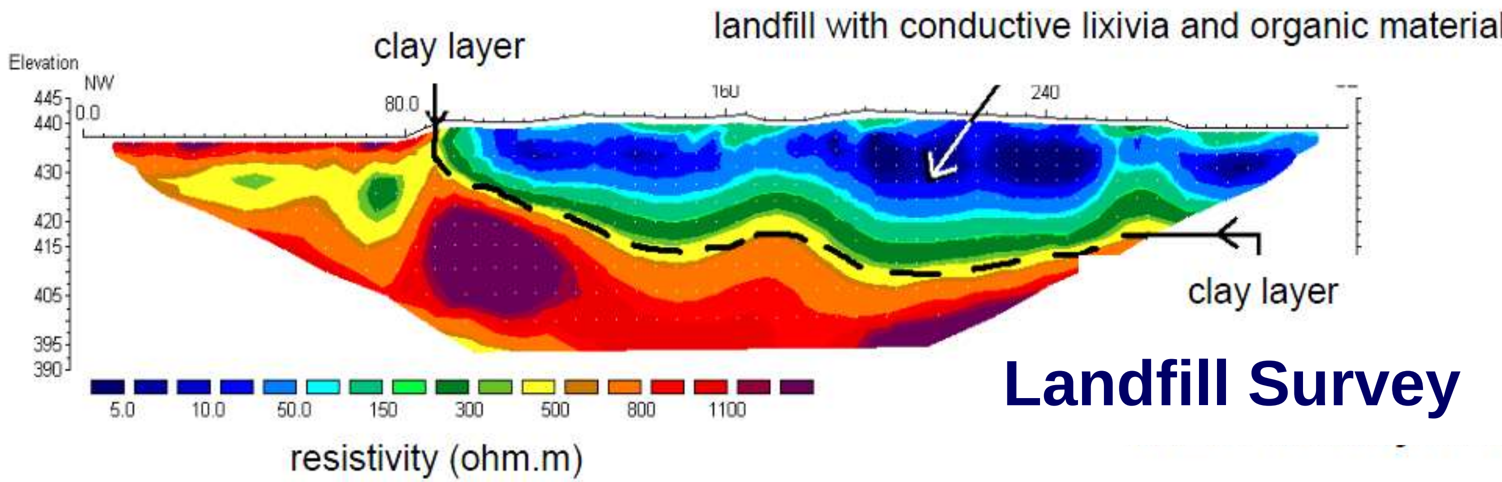
Resistivity Imaging



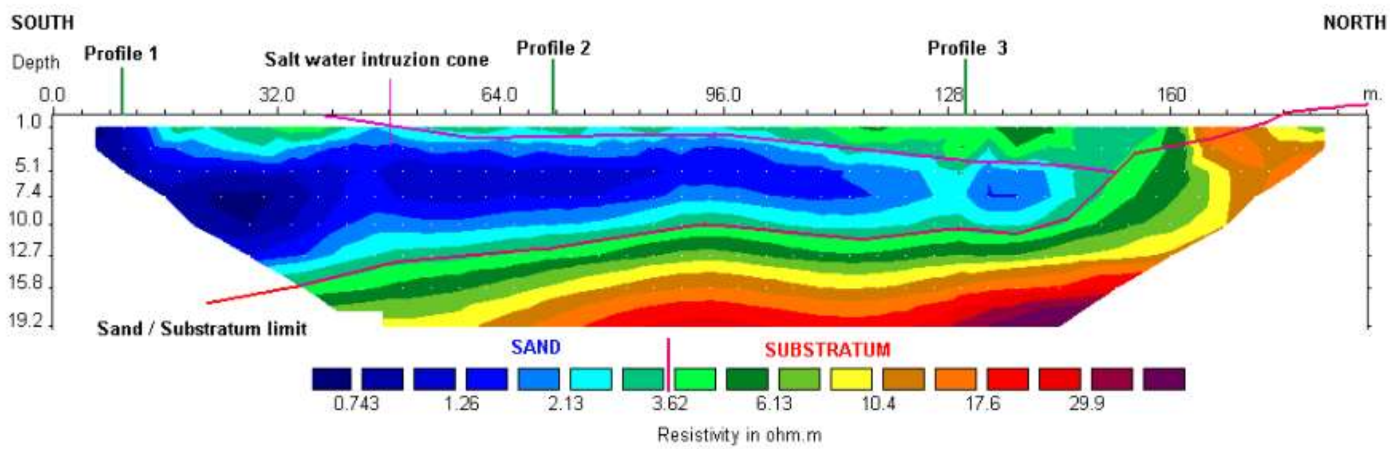
Source: http://www.tomoquest.com/Lectures_in_Geophysics.php

NORPLAN

Applications of Resistivity Imaging – 1



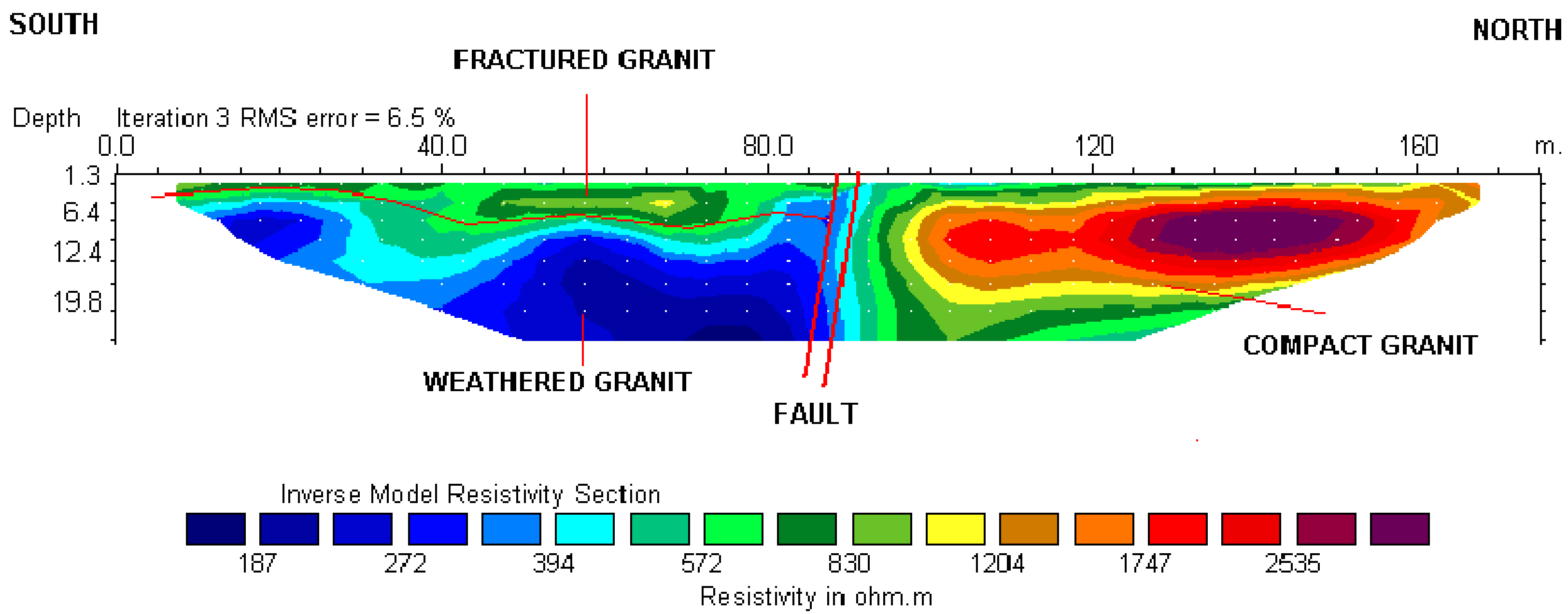
Landfill Survey



Salt Water Intrusion Survey

Source: http://www.iris-instruments.com

Applications of Resistivity Imaging – 2

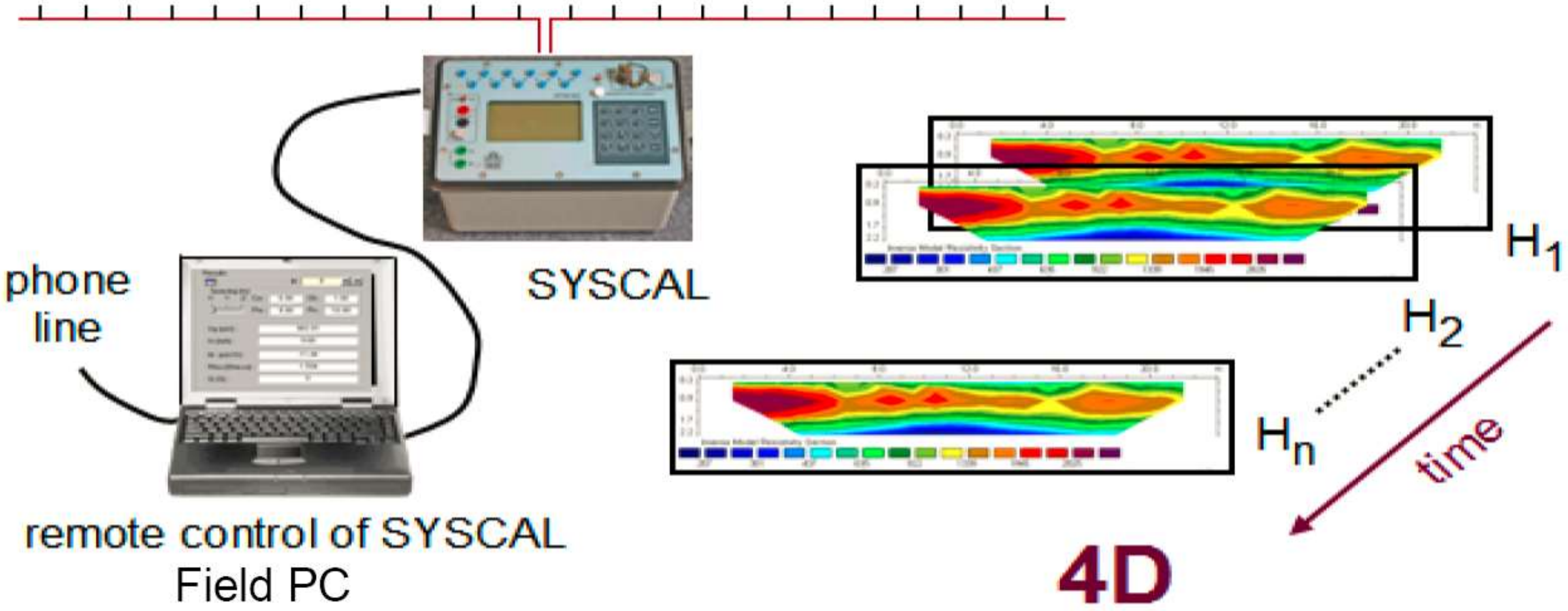


Fracture Survey

Source: http://www.iris-instruments.com

NORPLAN

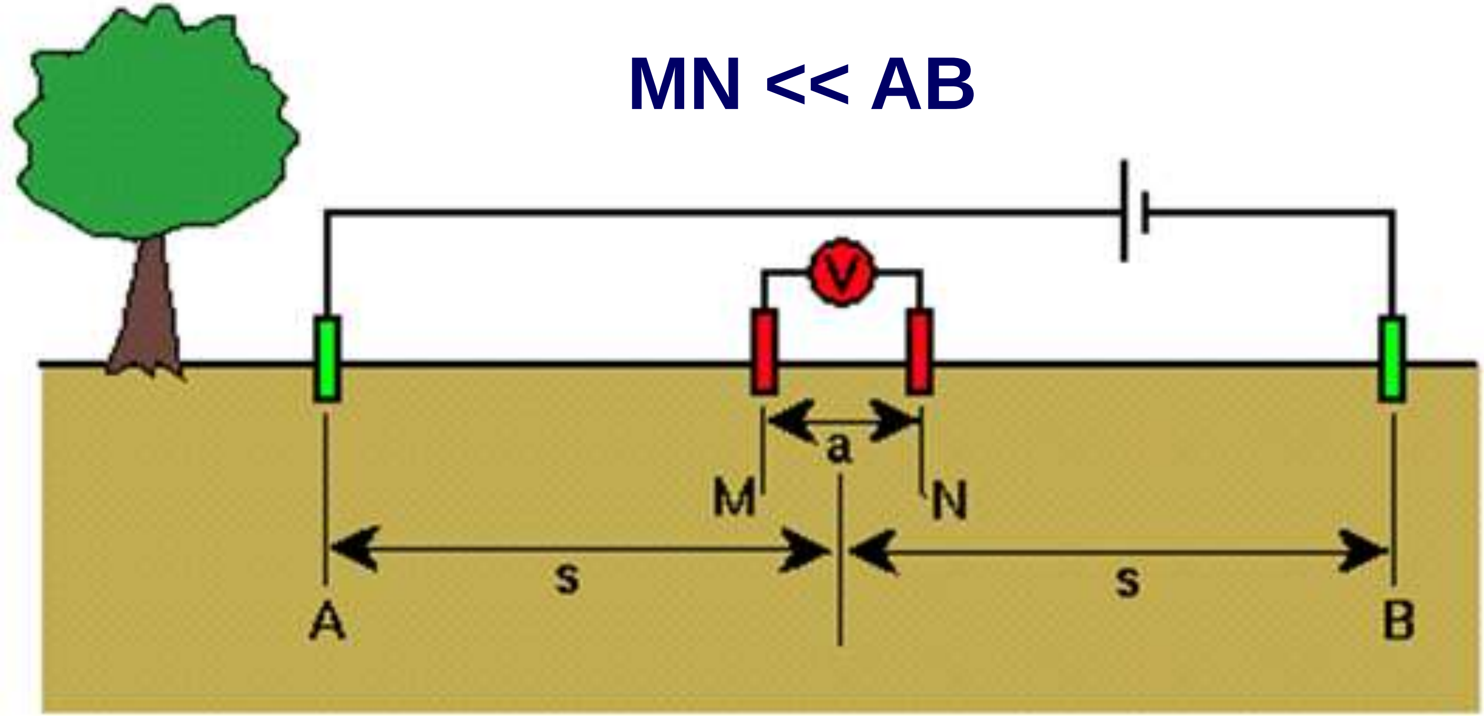
Survey Types Overview: Resistivity Monitoring



Source: http://www.iris-instruments.com

Main Electrode Arrays: Schlumberger Array

MN << AB

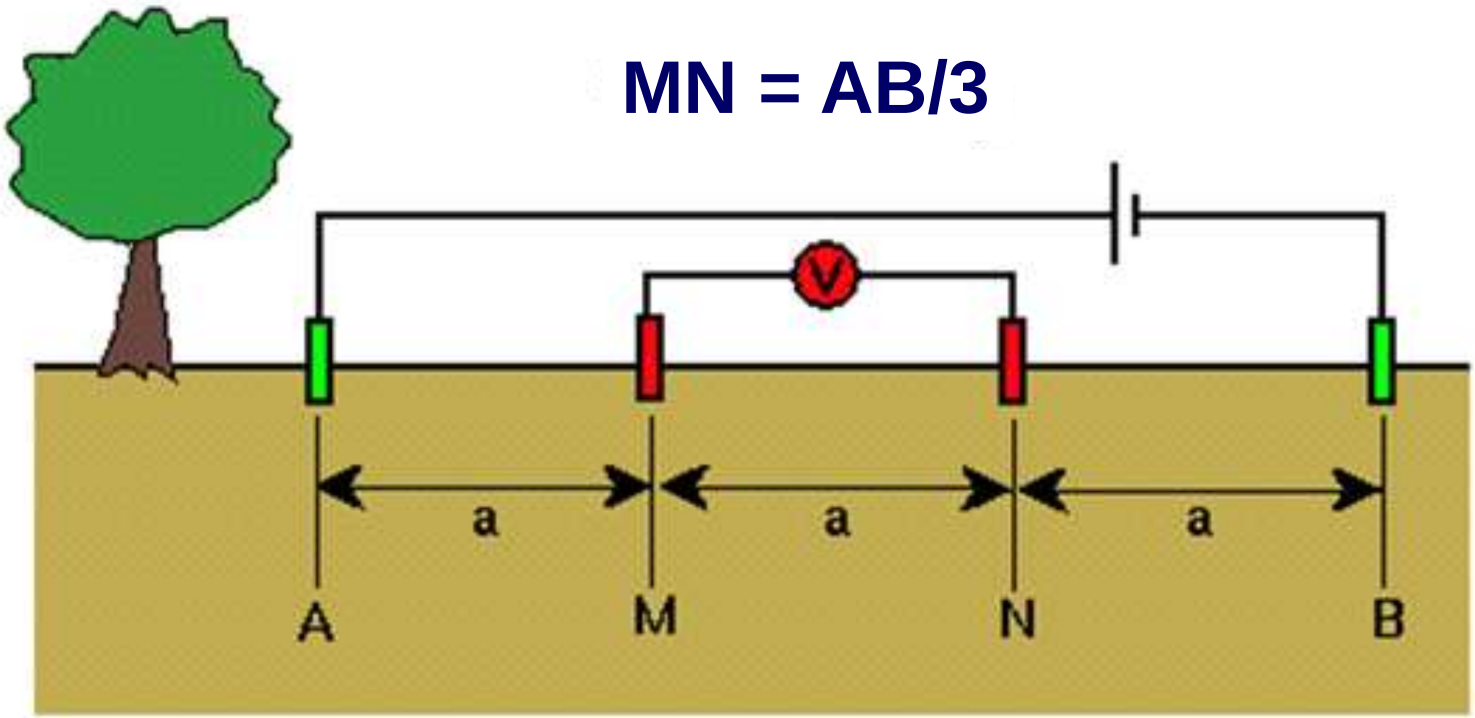


$$\rho_a = \frac{\pi(s^2 - a^2/4)}{a}\frac{\Delta V}{i}$$

Source: http://galitzin.mines.edu/INTROGP/

Main Electrode Arrays: Wenner Array

MN = AB/3

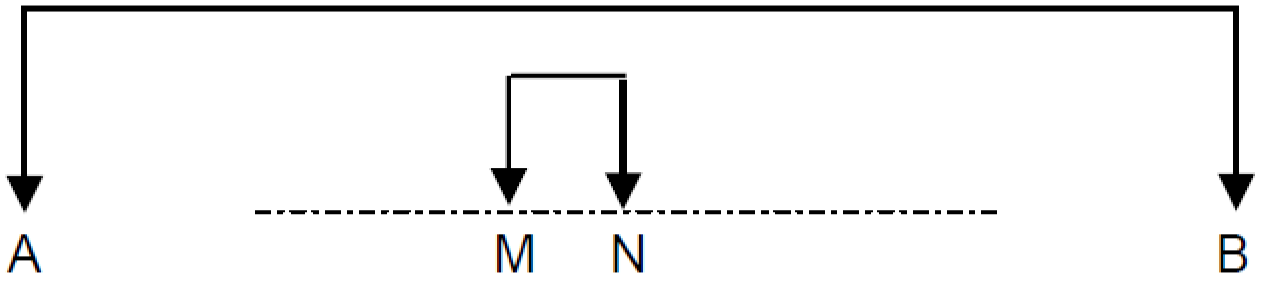


$$\rho_a = 2\pi a \frac{\Delta V}{i}$$

Source: http://galitzin.mines.edu/INTROGP/

Main Electrode Arrays: Gradient Array

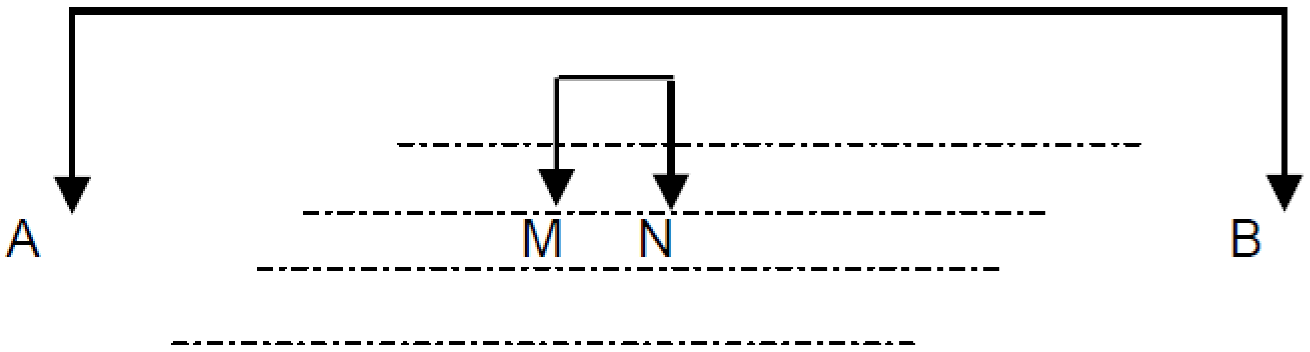
MN is moved within the middle part of AB



Source: IRIS INSTRUMENTS, Training course on Electrical methods, 2006

Main Electrode Arrays: Rectangle Array

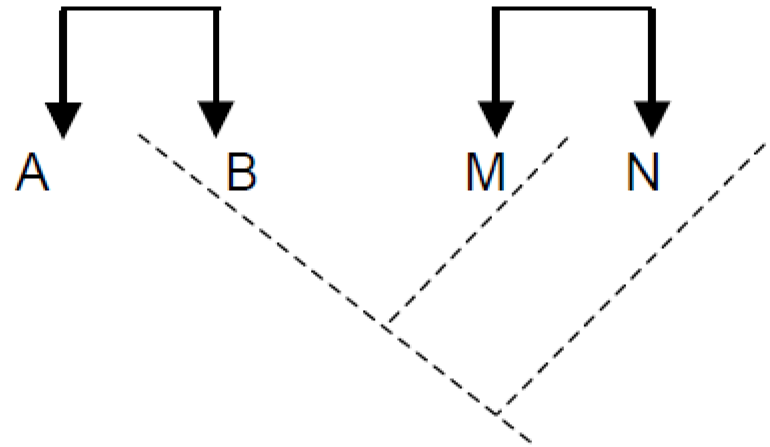
MN is moved along various lines parallel to AB



Source: IRIS INSTRUMENTS, Training course on Electrical methods, 2006

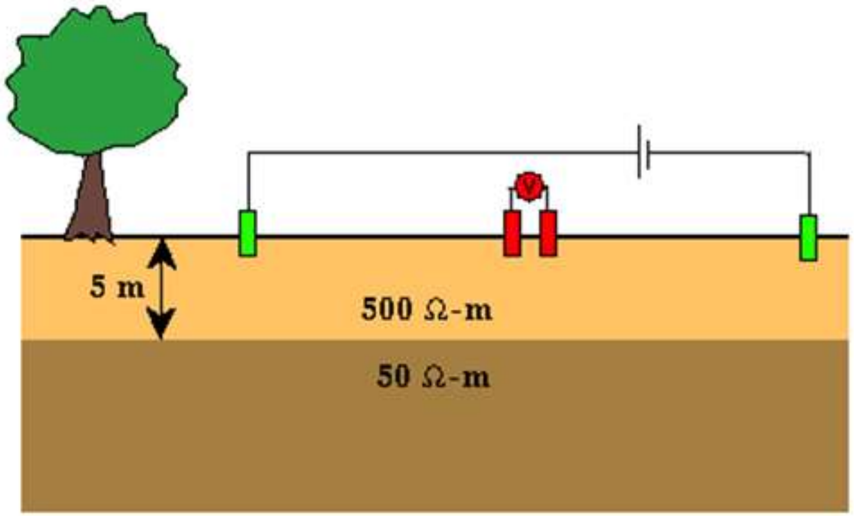
Main Electrode Arrays: Dipole Dipole Array

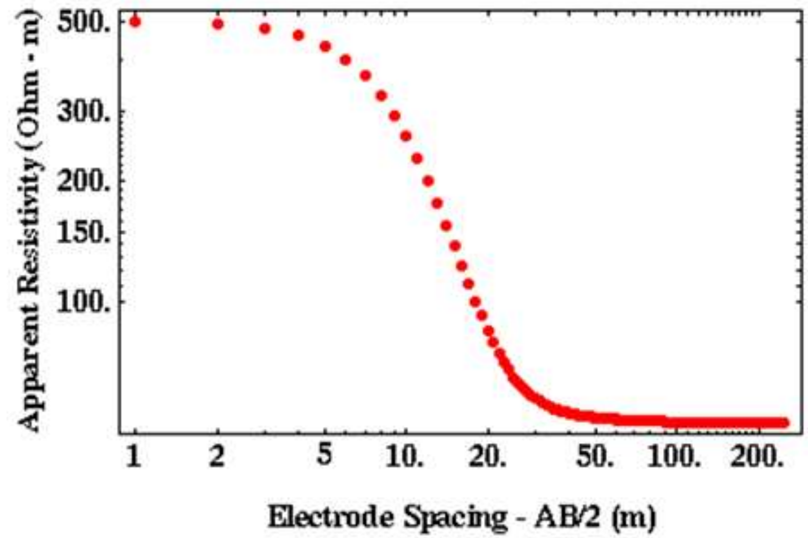
MN is moved a certain number of times away from AB, then AB is shifted of one spacing and so on. A pseudo section is obtained, a combination of profiling and shallow sounding

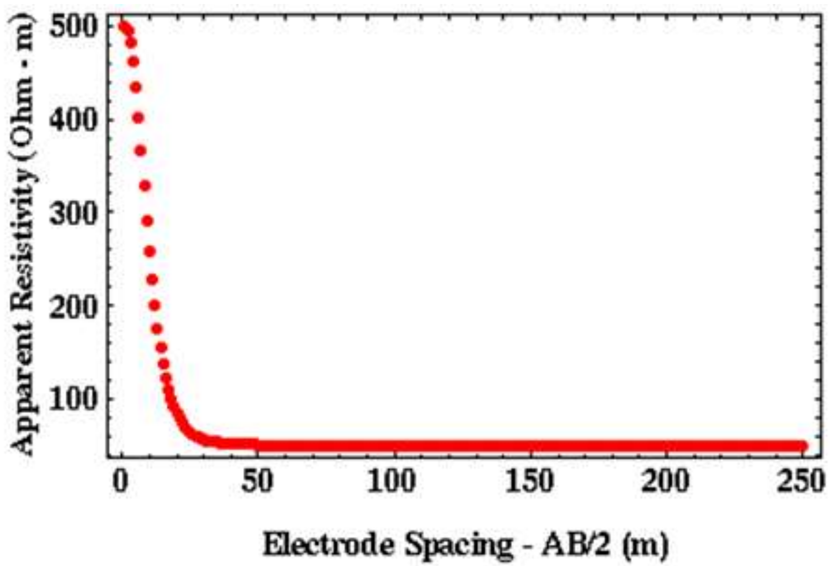


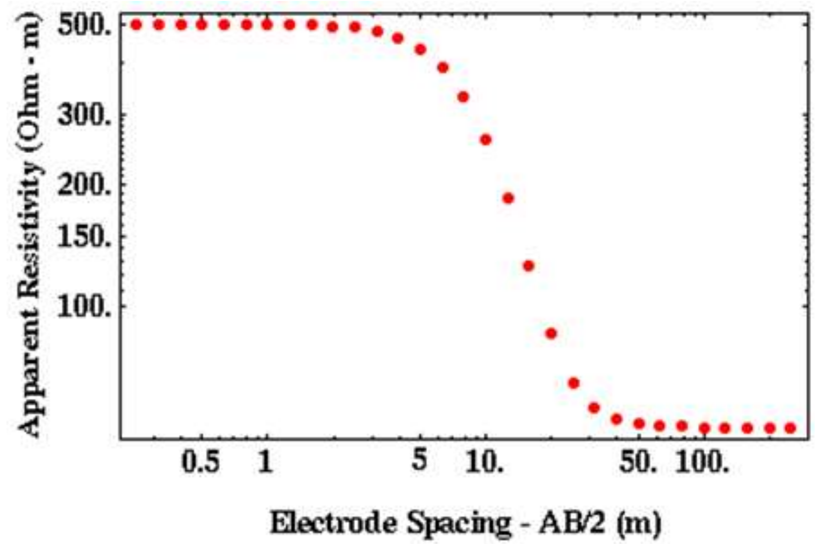
Source: IRIS INSTRUMENTS, Training course on Electrical methods, 2006

Electrode Spacings and Apparent Resistivity Plots









Source: http://galitzin.mines.edu/INTROGP/

Advantages and Disadvantages of Schlumberger Arrays

Advantage	Disadvantage
Need to move the two current electrodes only for most readings. This can significantly decrease the time required to acquire a sounding.	Because the potential electrode spacing is small compared to the current electrode spacing, for large current electrode spacings, very sensitive voltmeters are required.
Because the potential electrodes remain in fixed locations, the effects of near-surface lateral variations in resistivity are reduced.	In general, interpretations based on DC soundings will be limited to simple, horizontally layered structures.

Source: http://galitzin.mines.edu/INTROGP/

Advantages and Disadvantages of Wenner Arrays

Advantage	Disadvantage
Potential electrode spacing increases as current electrode spacing increases. Less sensitive voltmeters are required.	All four electrodes, two current and two potential, must be moved to acquire each reading.
	Because all electrodes are moved for each reading, this method can be more susceptible to near-surface, lateral variations in resistivity. These near-surface lateral variations could potentially be misinterpreted in terms of depth variations in resistivity.
Source: http://galitzin.mines.edu/INTROGP/	In general, interpretations based on DC soundings will be limited to simple, horizontally layered structures.

NORPLAN

Choice of Array

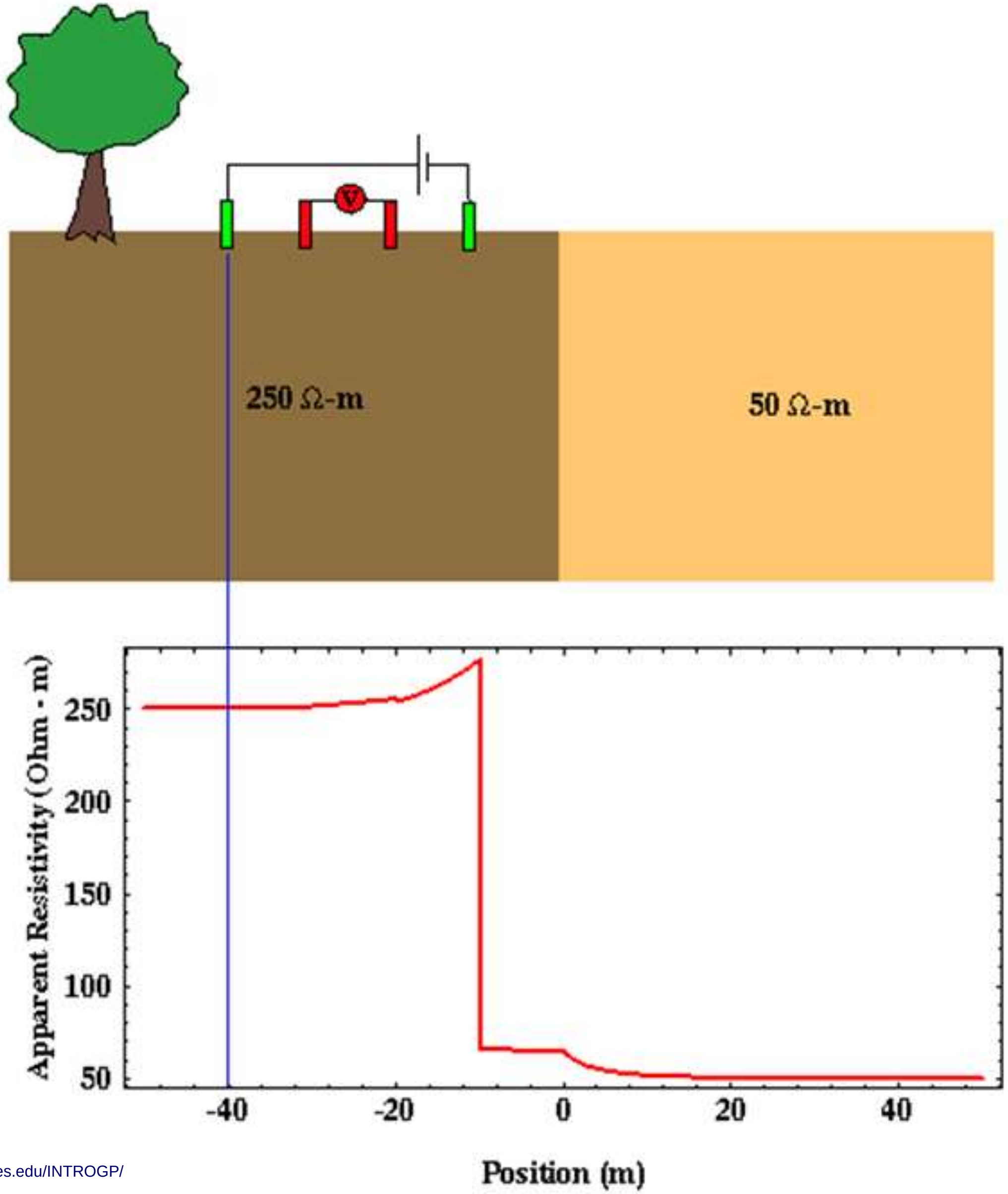
Key Questions:

- Which type of structure needs to be mapped?
- How sensitive is the resistivity meter?
- What is the background noise level?

Considerations

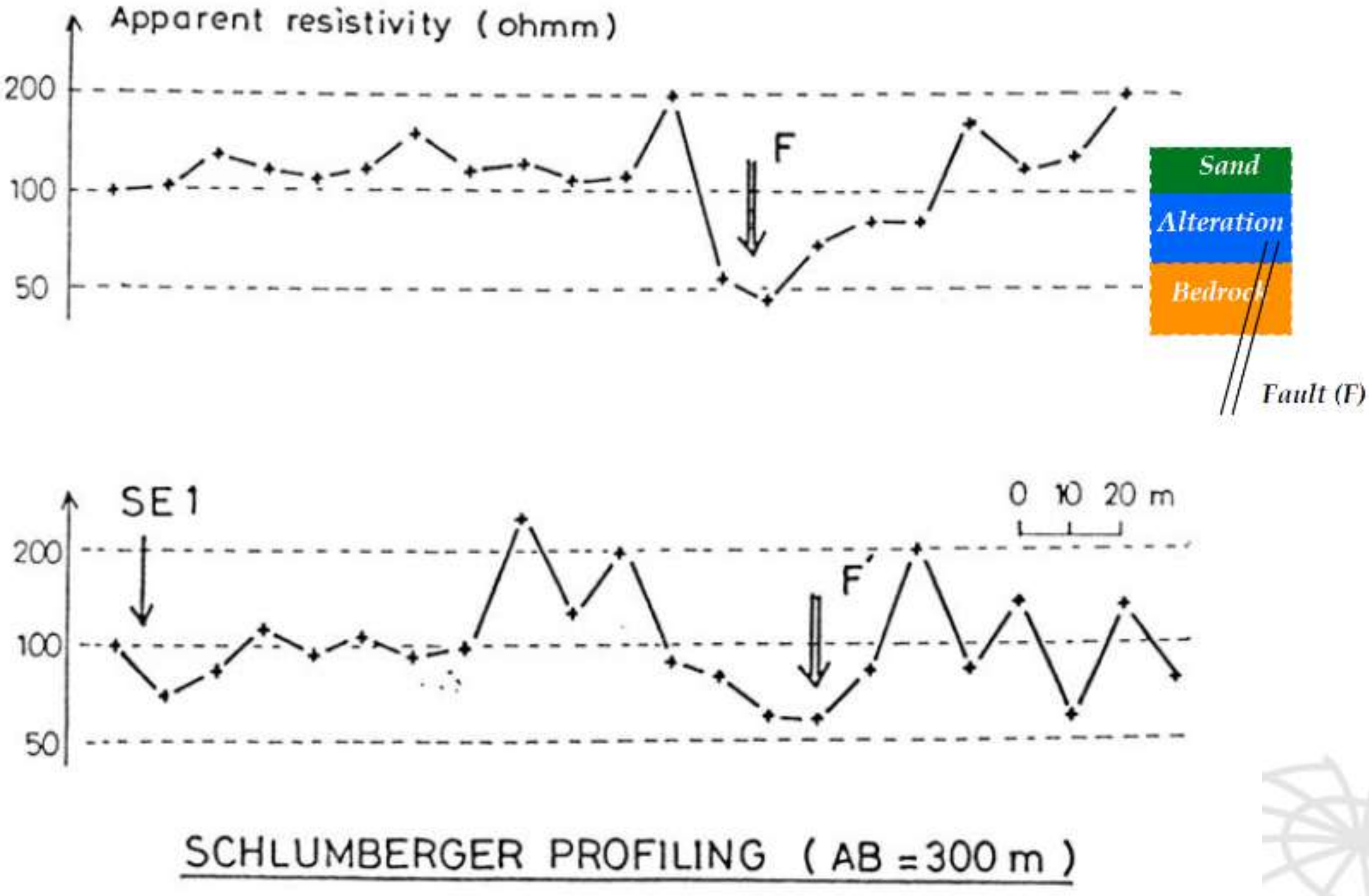
- Depth of investigation
- Sensitivity of the array to vertical and horizontal structures
- Horizontal data coverage
- Signal strength

Resistivity Profiles



Source: http://galitzin.mines.edu/INTROGP/

Profile Example: Niger Village Water Supply

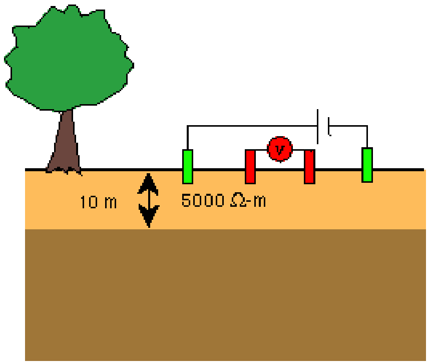


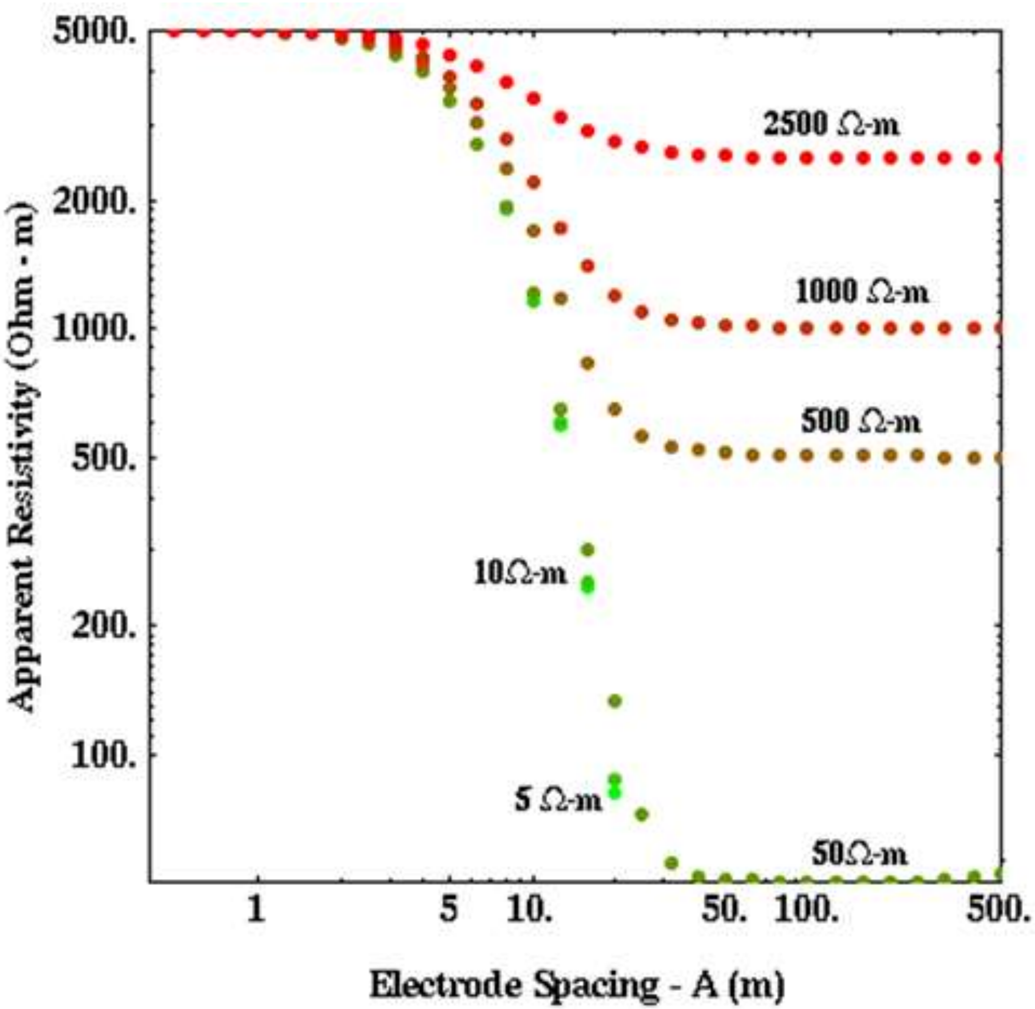
Source: http://www.iris-instruments.com

PART 5 – Interpretation of Resistivity Measurements

1. Apparent Resistivity Curves for Soundings Over One-Layered Media
2. Apparent Resistivity Curves in Two-Layered Media
3. Resistivity Modelling and Inversion

Apparent Resistivity Curves for Soundings Over One-Layered Media: Case 1

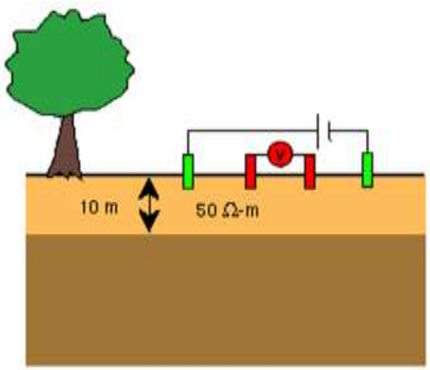


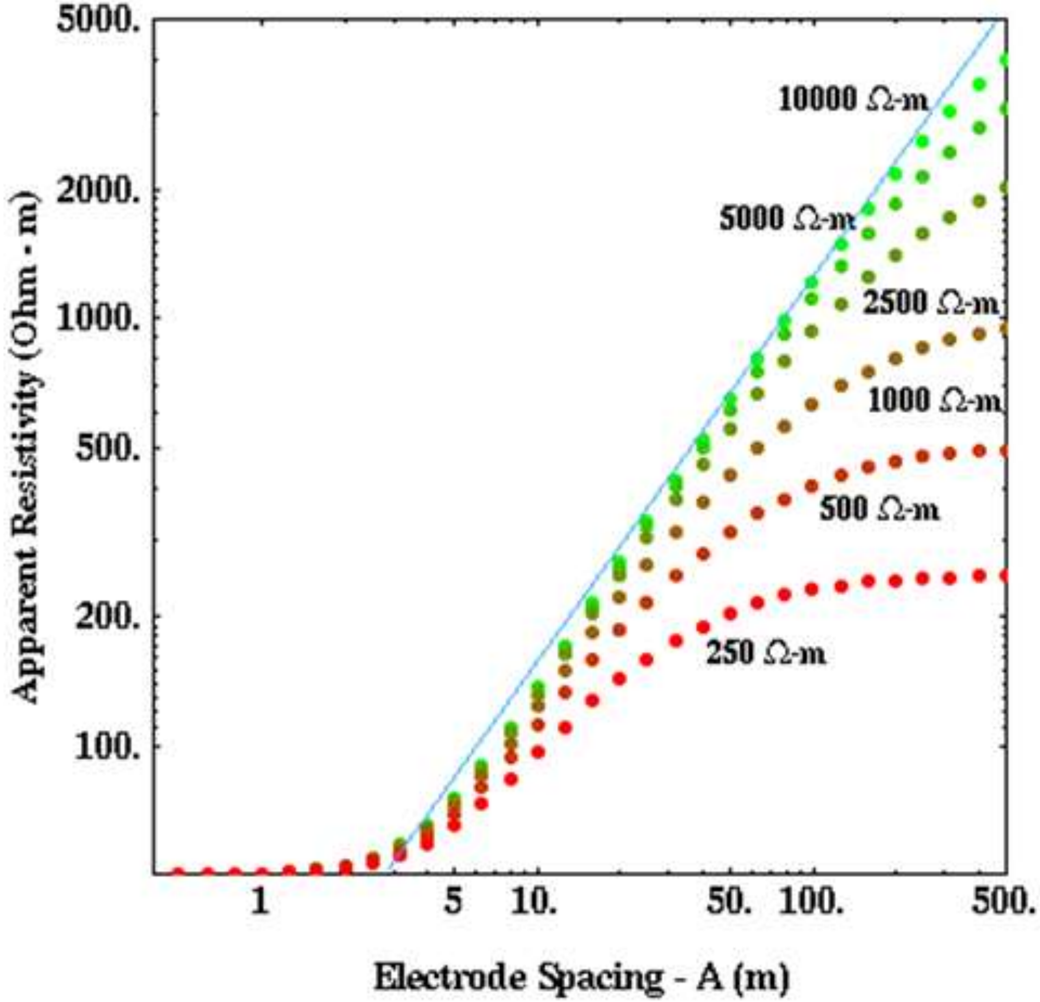


Source: http://galitzin.mines.edu/INTROGP/

NORPLAN

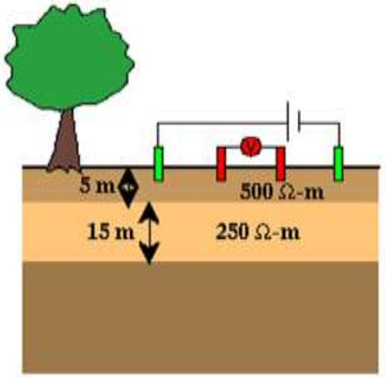
Apparent Resistivity Curves for Soundings Over One-Layered Media: Case 2

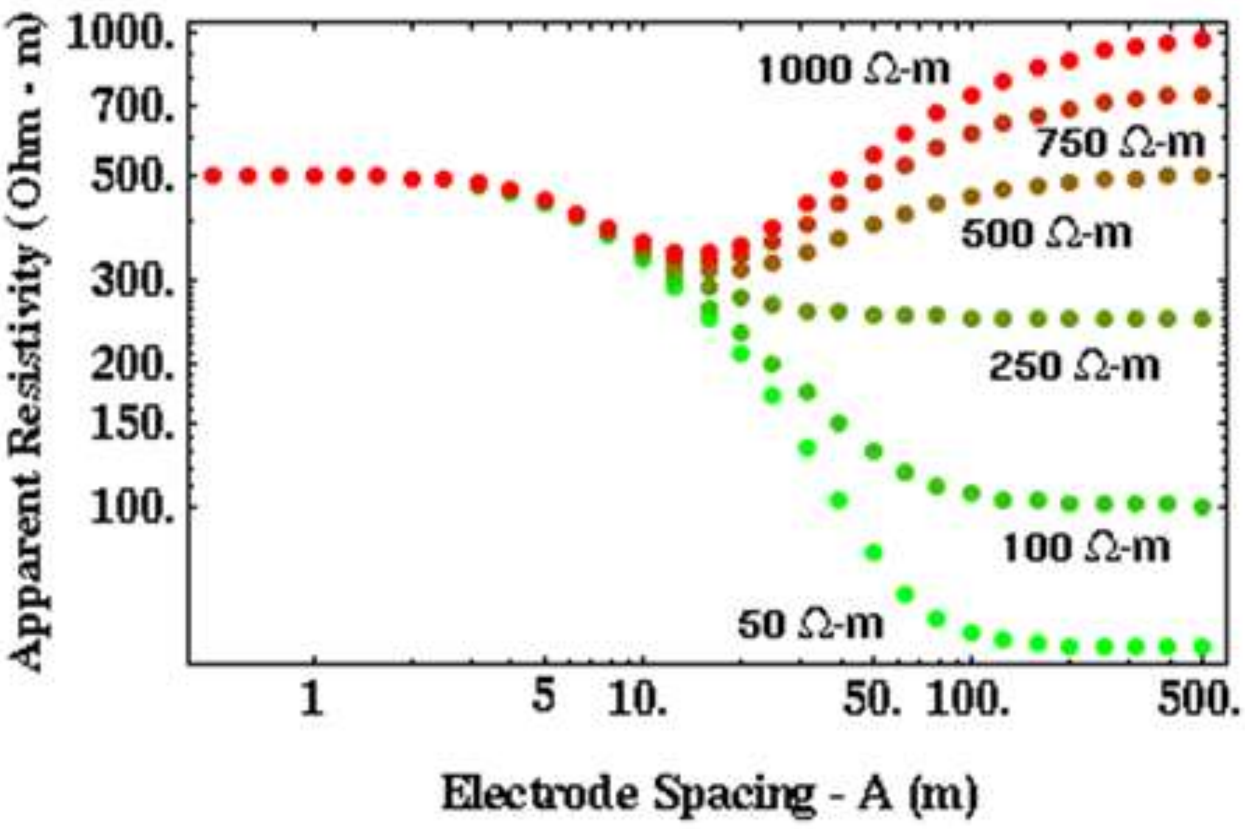




Source: http://galitzin.mines.edu/INTROGP/

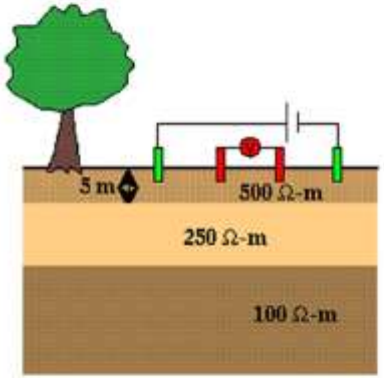
Apparent Resistivity Curves in Two-Layered Media: Case 1

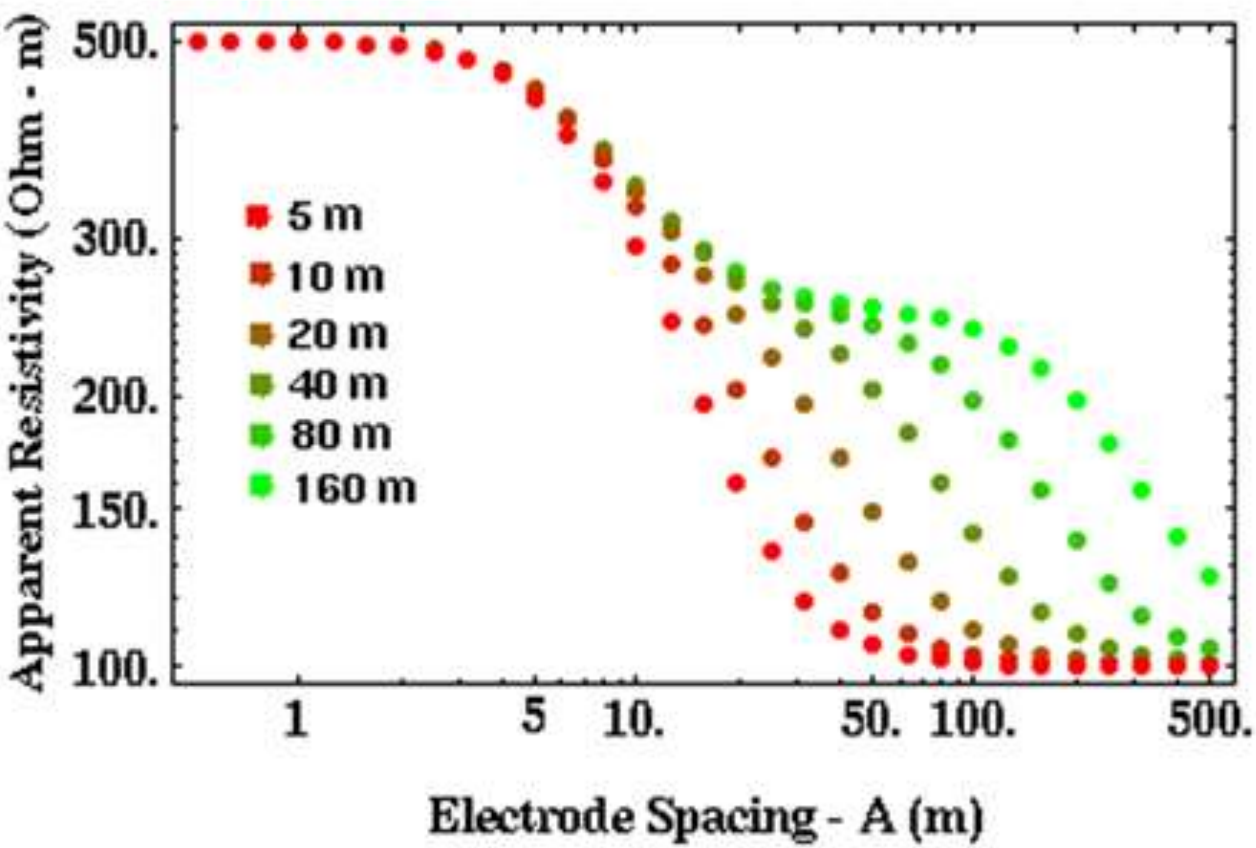




Source: http://galitzin.mines.edu/INTROGP/

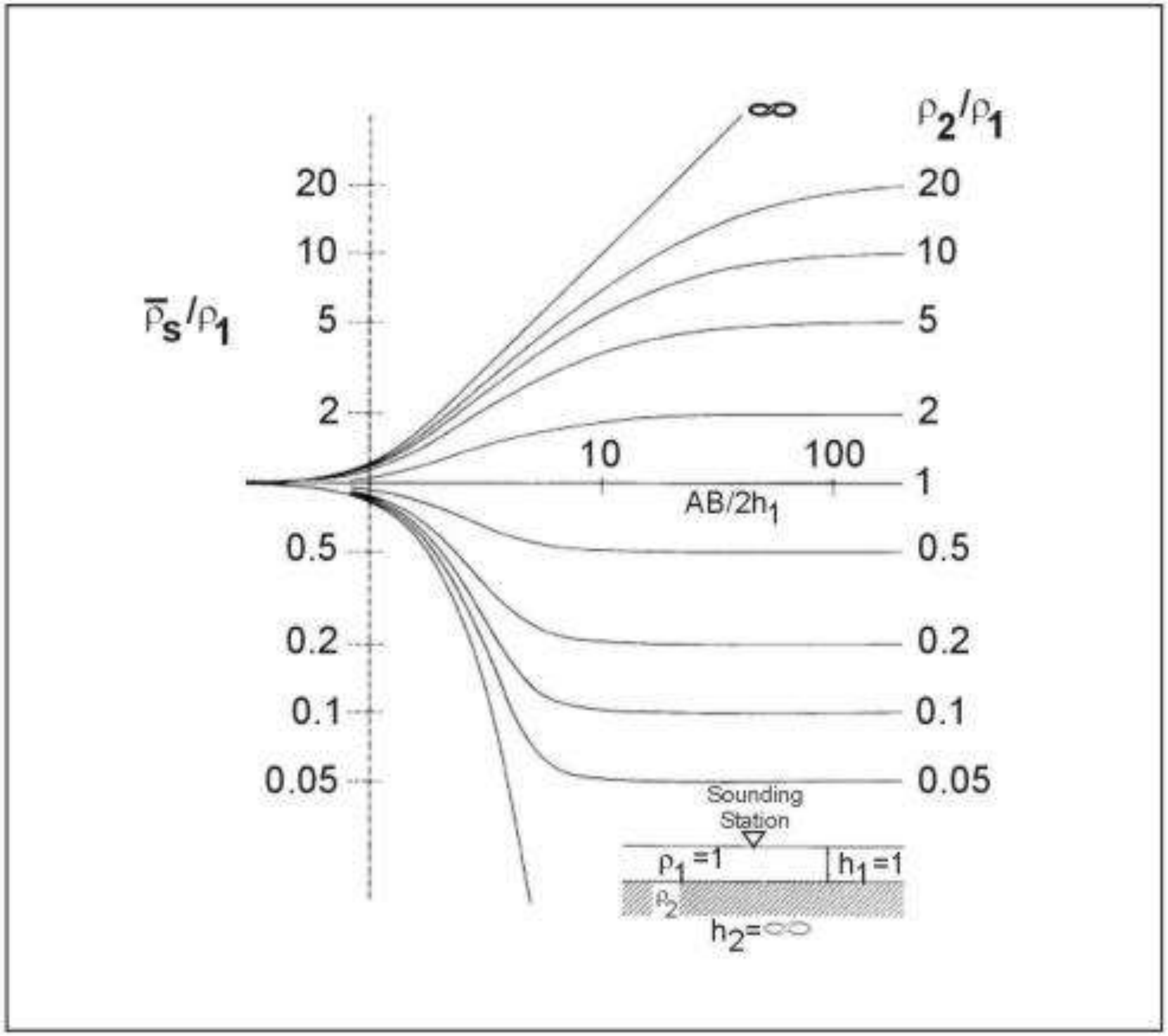
Apparent Resistivity Curves in Two-Layered Media: Case 2





Source: http://galitzin.mines.edu/INTROGP/

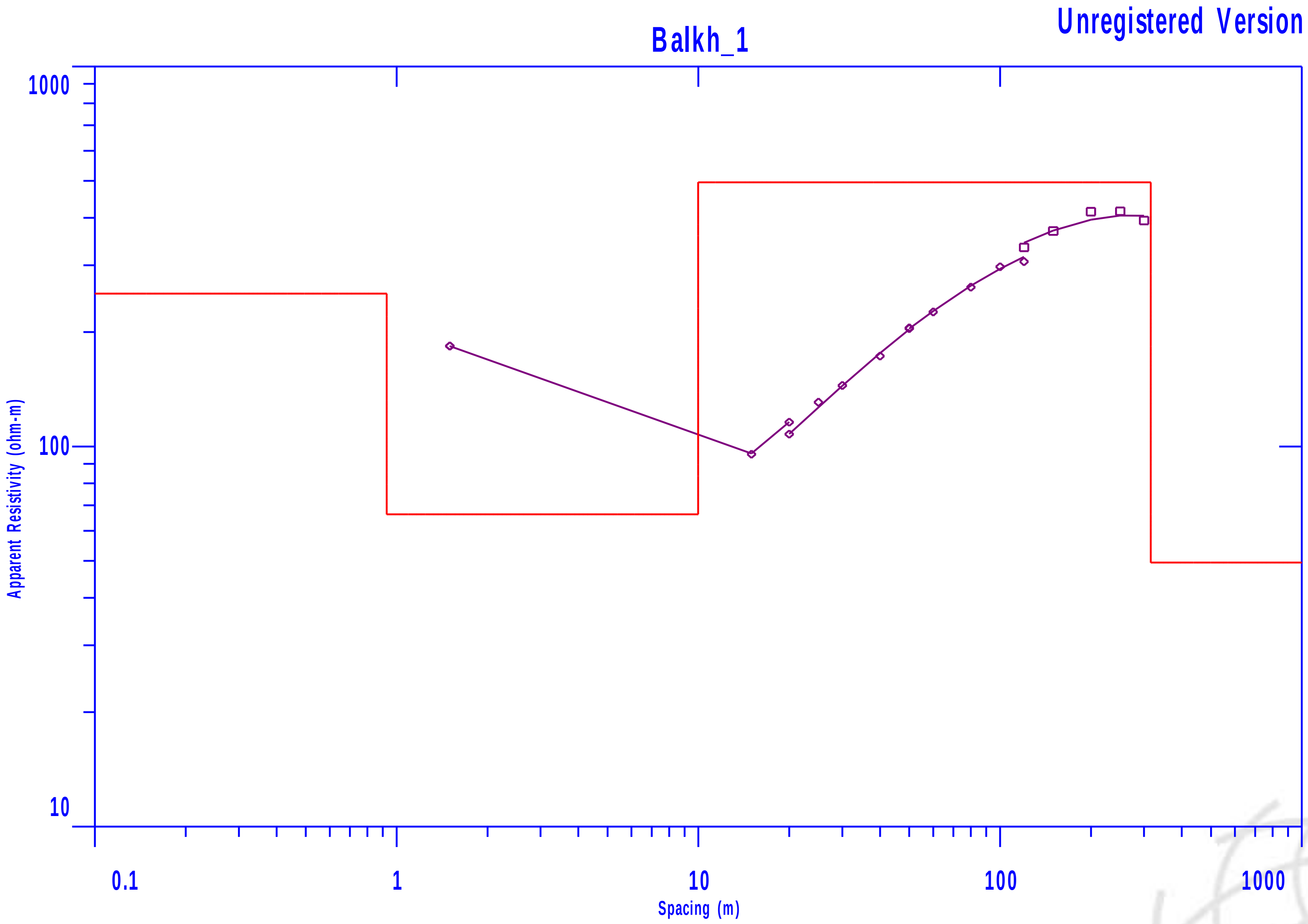
Apparent Resistivity Curves in Two-Layered Media



Two-layer master set of sounding curves for the Schlumberger array. (Zohdy, 1974)

Source: http://www.epa.gov/esd/cmb/GeophysicsWebsite/pages/reference/methods/Surface_Geophysical_Methods/Electrical_Methods/Resistivity_Methods.htm

1D Inversion – 1X1D (Interpex Limited)



NORPLAN

1D Inversion – GeoVES 1.4

Client : Irrigation Department
Project : Balkh
District :
Date : 2013
Field Operator : Ahmad Jawid
Interpreted by : AdJ

Community : Balkh
Sounding Number : S-01
Coordinates East : E XX.XXXXX
Coordinates North : N XX.XXXXX
GPS Datum : WGS84
Azimuth : XX˚

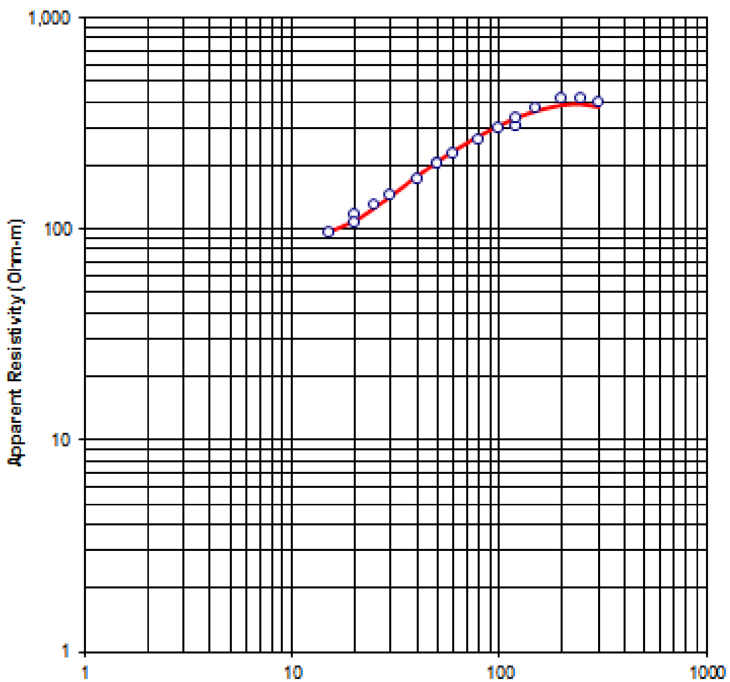
Balkh - S-01

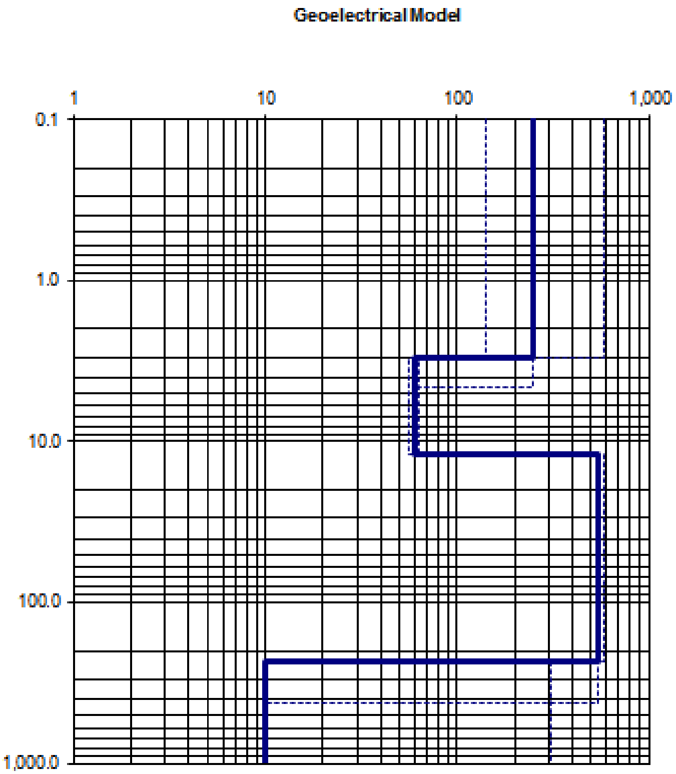
GeoVES 1.4
MS Excel based modelling of Vertical Electrical Soundings in the Schlumberger Array using Gosh linear filters

Geoelectrical Model   RMS Error : 14

Layer Number	1	2	3	4	5	6	7	8
Resistvity (Ohm-m)	250	60	540	10				
Thickness (m)	3.0	9.0	220.0					
Depth (m)	3.0	12.0	232.0					

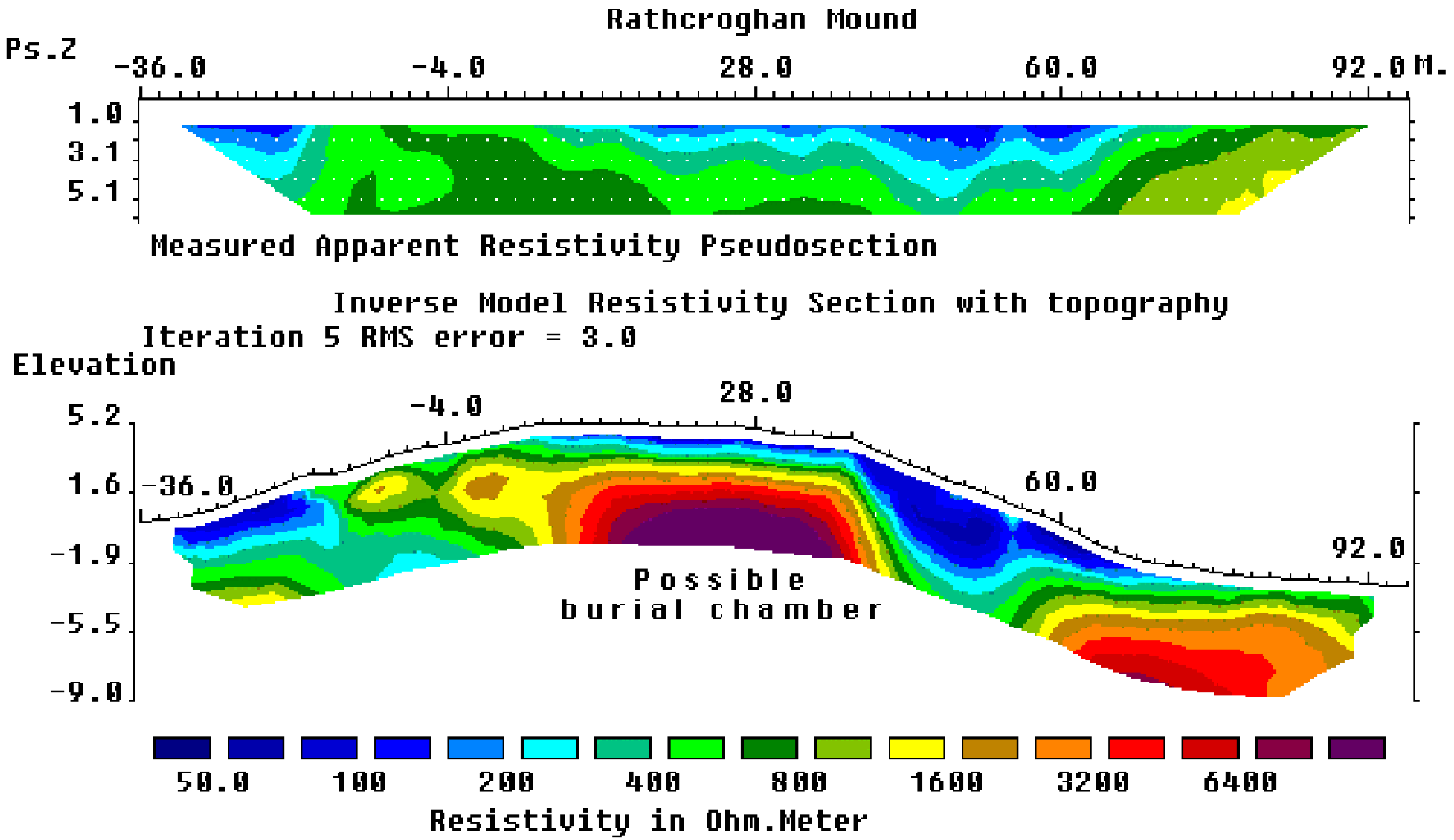
Sensitivity Analysis   Remove Error Bars





NORPLAN

2D Inversion



NORPLAN