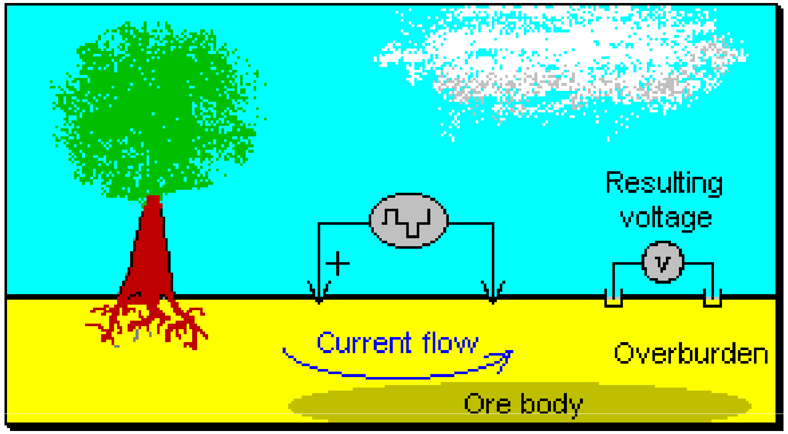
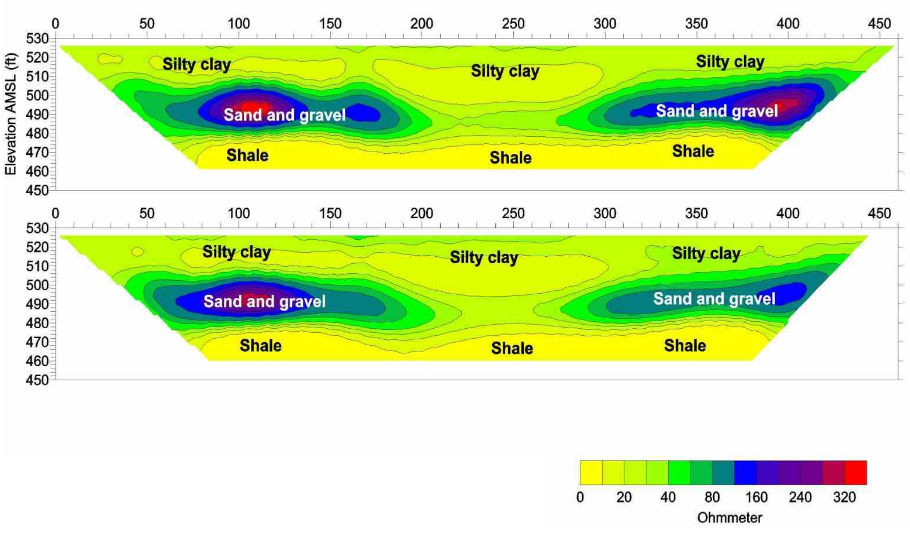
GLE 594:
Introduction to
Applied Geophysics

Electrical Resistivity Methods

Fall 2006

Earth Properties and Basic Theory





Reading

Today : 265-290

Next Lecture : 290-322

Introduction

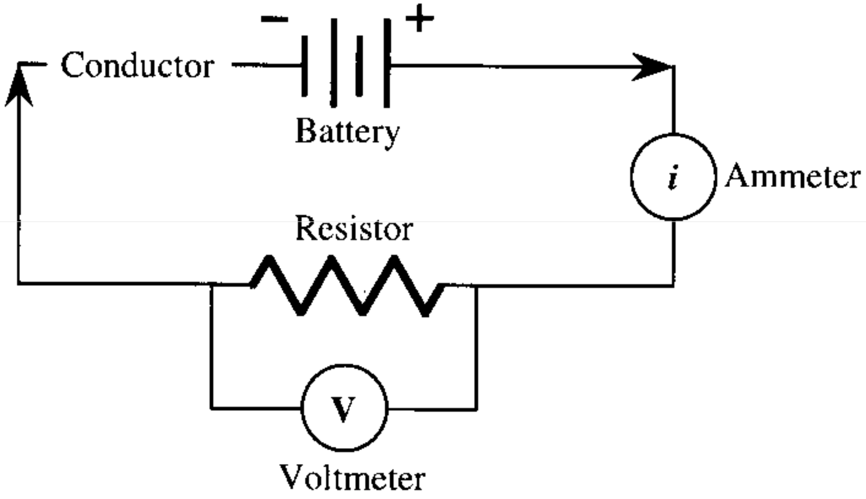
- Link resistivity (i.e., the ability of the earth to prevent the conduction of an electric current) to the subsurface structure.
- Useful because resistivity of earth materials varies by around 10 orders of magnitude.
- Developed by Conrad Schlumberger (France) and Frank Wenner (US) in the early 20th century.
- Uses: archeology, environmental, mineral exploration, and groundwater investigations

Conrad Schlumberger

Electricity Basics

Voltage V - Electrical potential energy per unit charge [volts]
Current *i* - amount of charge per unit time [amperes]

$$\boxed{i = \frac{1}{R} V}$$

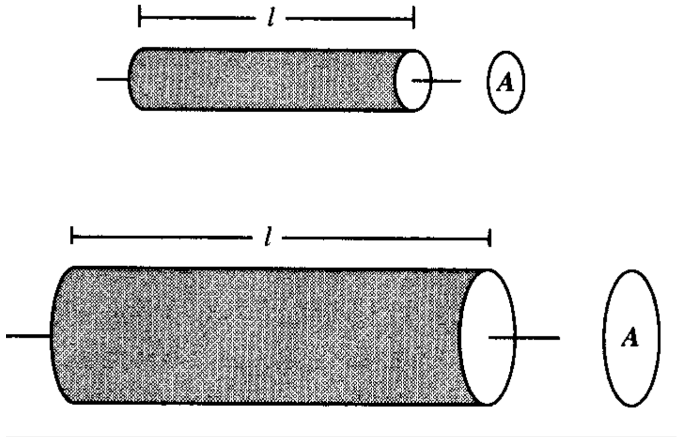


Resistivity R is just a proportionality constant [ohms] that relates current I to voltage V.

However, no units of length in this form of Ohm's law.

Resistivity

Resistance includes length and area
We want resisitivity ρ [ohm m] because:
- It is a material property
- No geometry included



$$R = \rho \frac{L}{A} [\text{ohm}]$$

↑ length → ↑ resistance

↑area → ↓resistance

Conductivity σ [siemens/m] or [mhos/m]:

$$\sigma = \frac{1}{\rho} [\text{mhos m}]$$

It is the ability of the electrical charge to move through the material

More general form of Ohm’s law

$$i = \frac{1}{R}V = \frac{A}{\rho}\frac{V}{l}$$

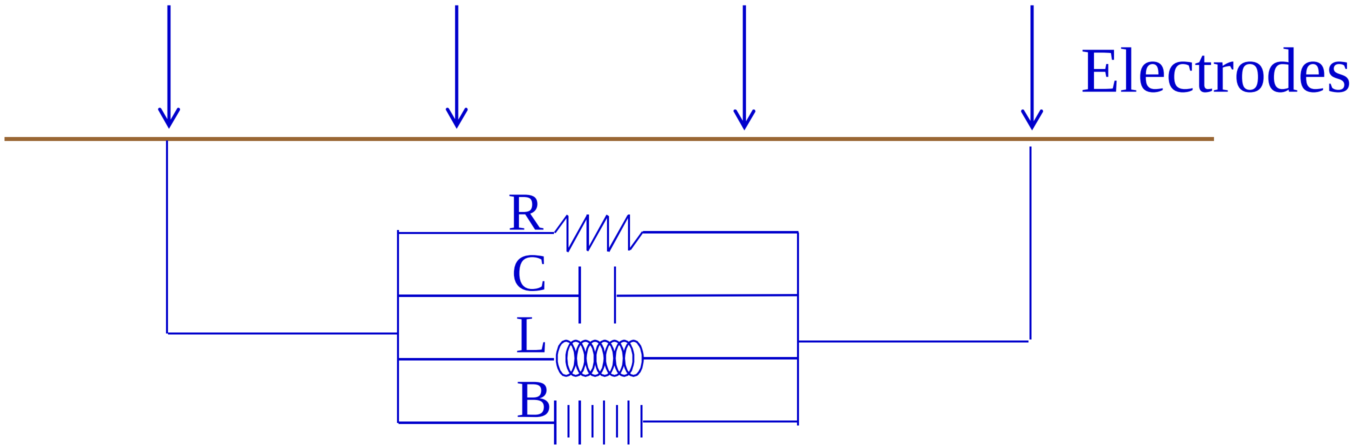
When looking at a solid, Ohm’s law can be written as:

$$i = \frac{A}{\rho}\frac{\Delta V}{\Delta l}$$

And in 3-D we use vectors: $I = \frac{A}{\rho} gradV$

Earth as a Circuit

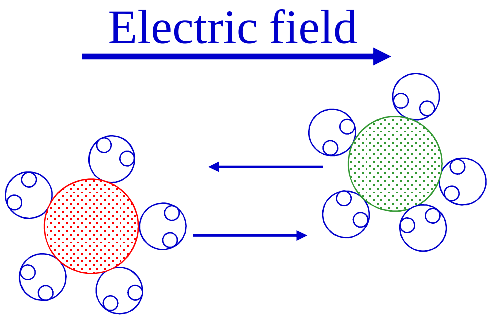
Soils and rocks can be conceptually modeled as a circuit made of a resistor, capacitor, inductor and battery:



Resistor R:	dissipator of applied energy as heat
Capacitor C:	storage of energy as separation of charges
Inductor L:	self voltage associated to electromagnetic methods
Battery B:	electrokinetics and self-potentials

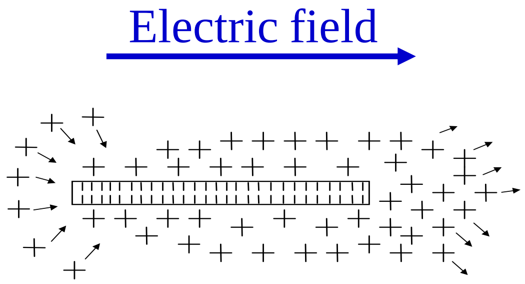
Electrical Conductivity in Geomaterials

- Non-conductive minerals



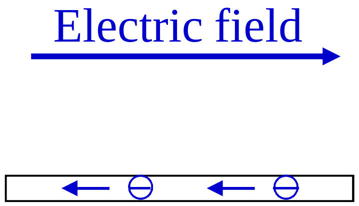
Hydrated ion mobility

+



Double layer surface conduction

+

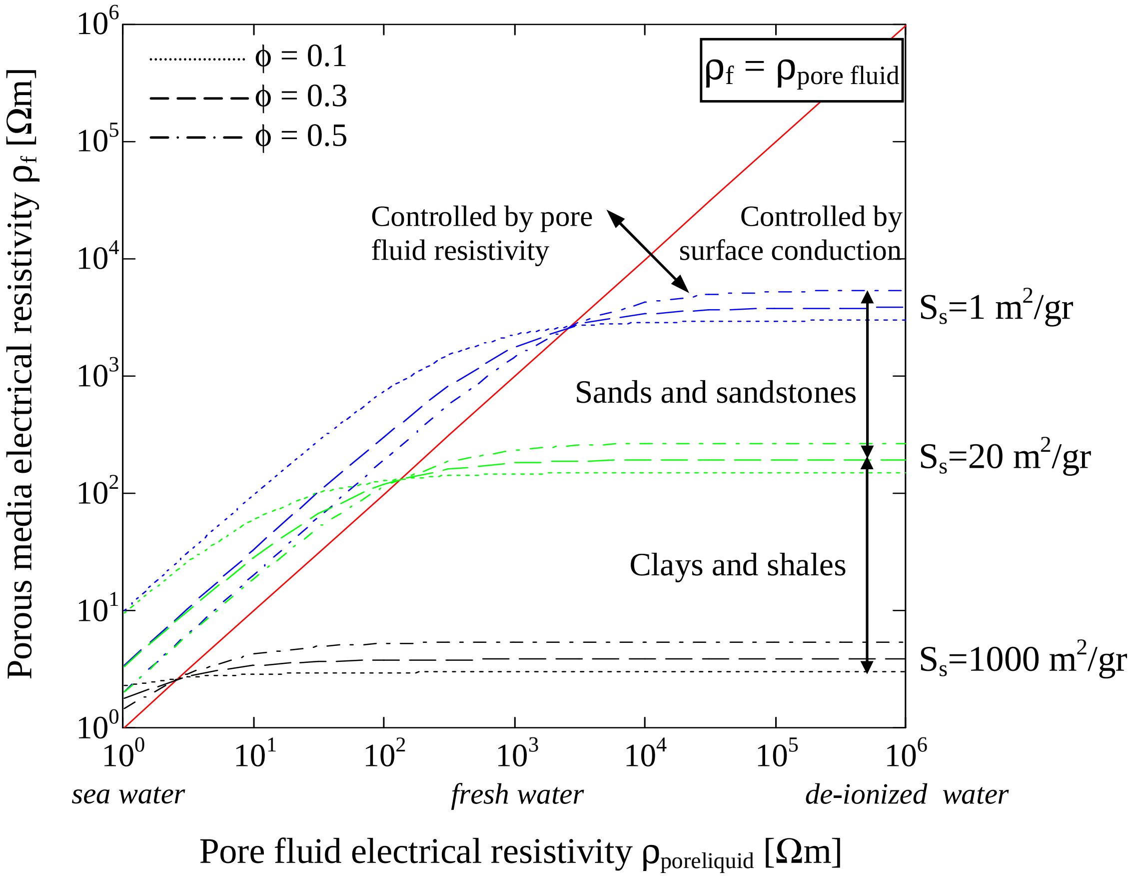


Particle electronic conduction

	Equation	Comments
Electrolyte	$\sigma_{el}\left[\frac{mS}{m}\right] = 0.15\,TDS\left[\frac{mg}{L}\right]$	TDS: total dissolved salts
Soil (Archie's law)	$\sigma_{soil} = a_1 \sigma_{el} S_r^n \phi^m$	$a_1 \approx 0.4\text{-}2.0$; $m \sim 1.3\text{-}2.5$; $n \sim 2$
Soil (clays)	$\sigma_{soil} = n\sigma_{el} + (1-n)\Theta\rho_g S_s$	$\Theta \approx 10^{-9}$ S (for Kaolinite)

Electrical Conductivity of Geomaterials

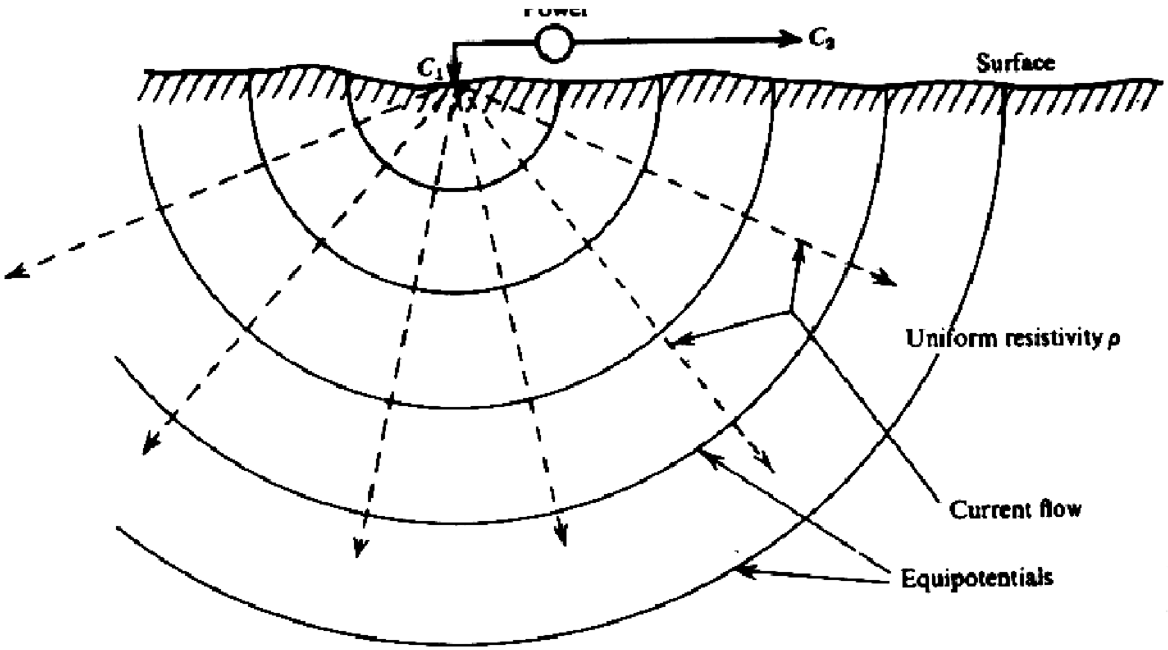
- Non-conductive Minerals



(Attia and Fratta 2006)

Current Source on Surface

Electric potential at distance away from current source on surface given as $V(r)=\rho I/2\pi r$. How?

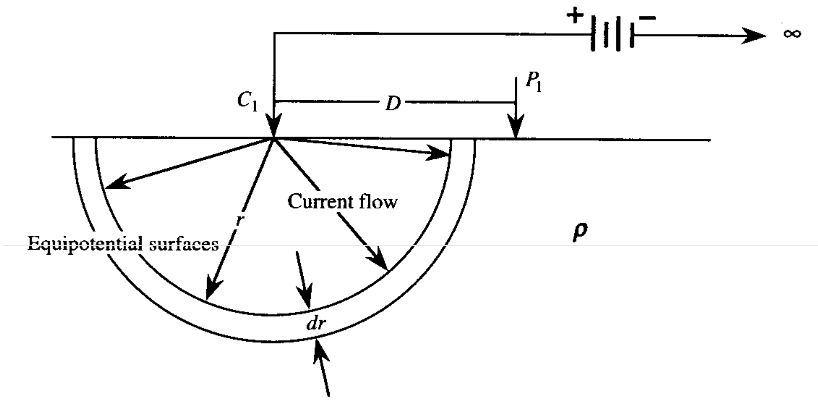


Boundary conditions:

1) As $r \Rightarrow \infty$, $V \Rightarrow 0$.
2) V is continuous across any boundary
3) Tangential **E** continuous across any boundary
4) Normal **i** continuous across any boundary.
5) Surface leads to no vertical current crossing earth-air interface.

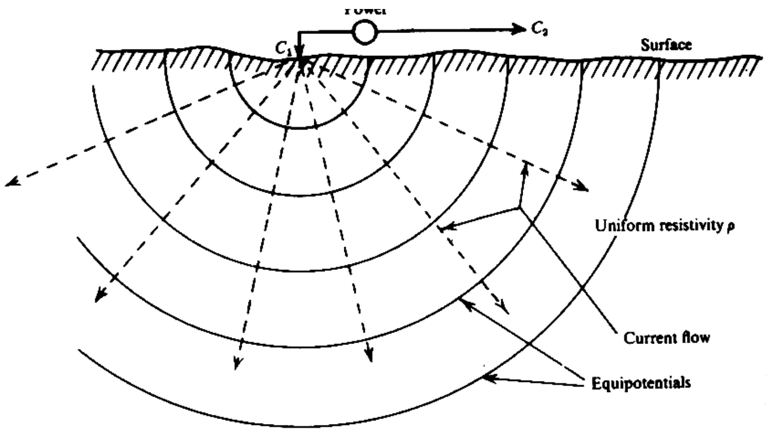
Current Flow in a Homogeneous and Isotropic Medium

Point Current Source:



$$dV = iR_{shell} = i\rho \frac{dr}{A} = i\rho \frac{dr}{2\pi r^2}$$

Voltage decreases as the inverse of the distance from the current source.



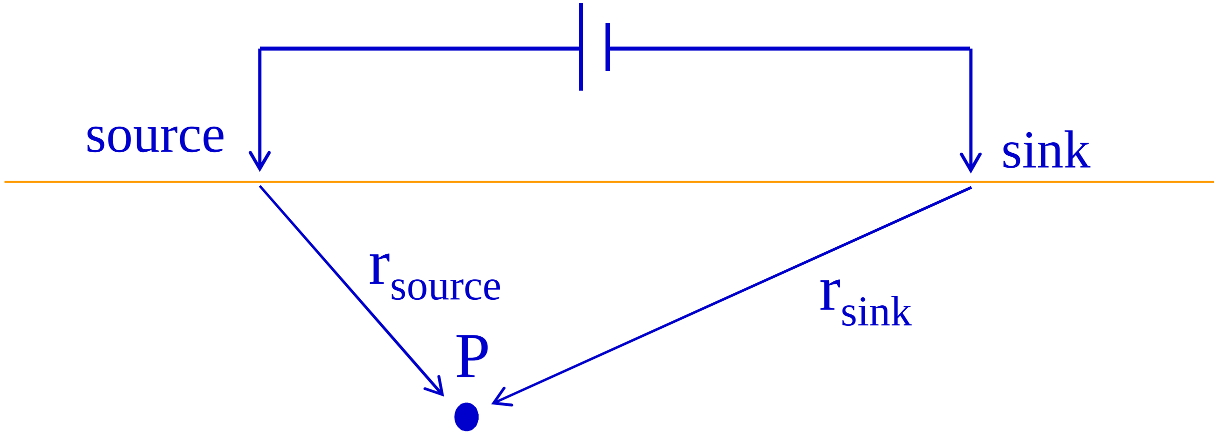
Shape of constant voltages are hemispheres for a single point source

$$V_D = \int_D^\infty dV = \frac{i\rho}{2\pi}\int_D^\infty \frac{dr}{r^2} = \frac{i\rho}{2\pi}(-1)\frac{1}{r}\bigg|_D^\infty$$

$$= \frac{i\rho}{2\pi}(-1)\left(\frac{1}{\infty} - \frac{1}{D}\right) = \frac{i\rho}{2\pi D}$$

Two Current Electrodes: Source and Sink

- Why run an electrode to infinity when we can use it?



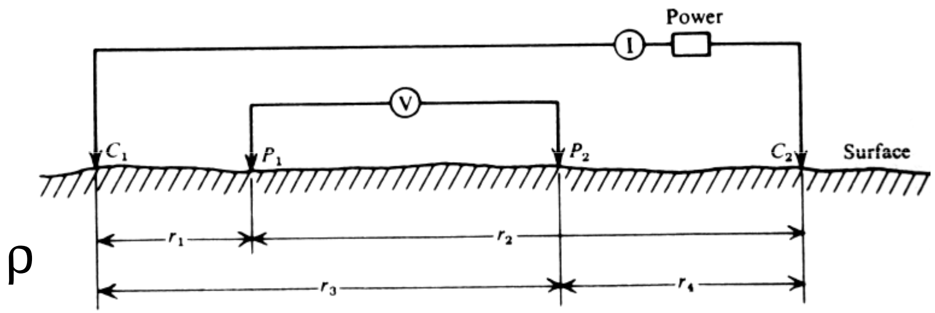
$$V_{source} = \frac{i\rho}{2\pi r_{source}} \qquad V_{sink} = \frac{i\rho}{2\pi r_{sink}}$$

Total Voltage at P:
(superposition)

$$\boxed{V_p = V_{source} - V_{sink} = \frac{i\rho}{2\pi}\left(\frac{1}{r_{source}} - \frac{1}{r_{sink}}\right)}$$

Measurements

You cannot measure potential at single point unless the other end of our volt meter is at infinity. It is easier to measure the *potential difference* (ΔV). This lead to use of four electrode array for each measurement.



Resulting measurement given as

$$\boxed{\Delta V = V_{P1} - V_{P2} = \frac{i\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)}$$

Can be rewritten

$$\boxed{\Delta V = \frac{i\rho}{2\pi G}}$$

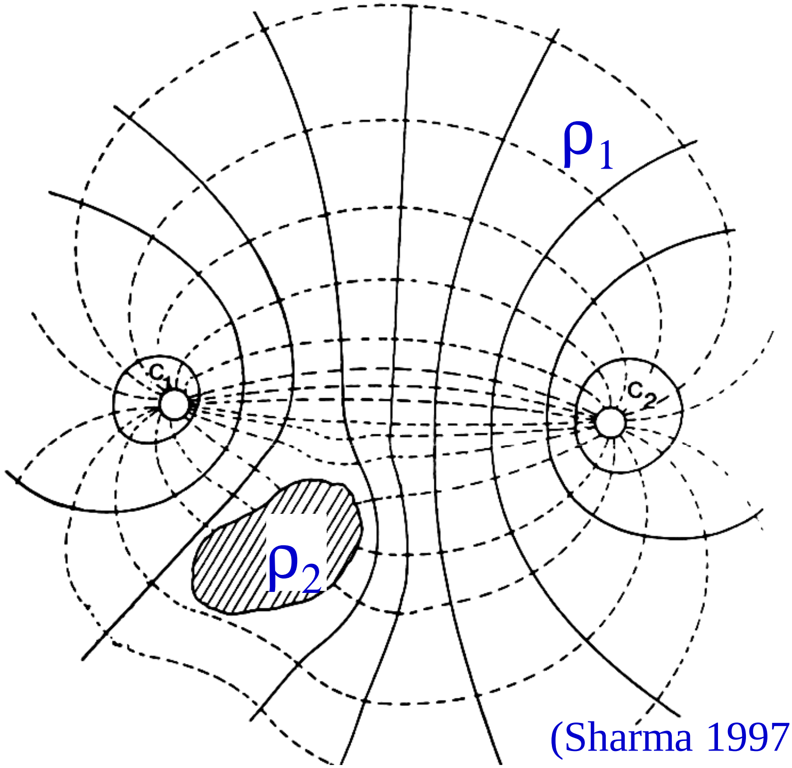
where $2\pi G$ is the ***Geometrical Factor*** of the array.

Apparent Resistivity

Previous expression can be rearranged in terms of resistivity:

$$\boxed{\rho = 2\pi G \frac{\Delta V}{i}}$$

This can be done even when medium is inhomogeneous. The result is then referred to as *Apparent Resistivity* ρ_a.

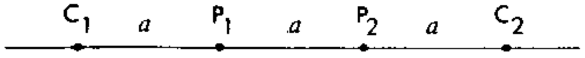


(Sharma 1997)

Definition: Resistivity of a fictitious homogenous subsurface that would yield the same voltages as the earth over which measurements were actually made.

Geometric Factors

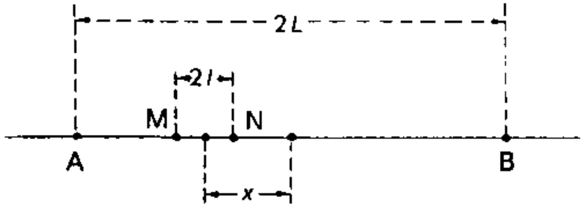
(a)



WENNER

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

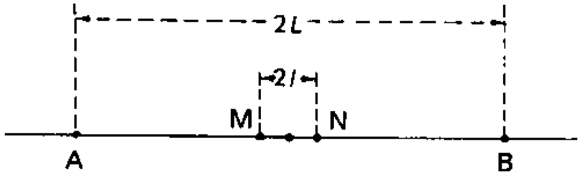
(b)



GRADIENT

$$\boxed{\rho_a = \frac{\pi}{2l} \cdot \frac{\left(L^2 - x^2\right)^2}{L^2 - x^2} \frac{\Delta V}{i}}$$

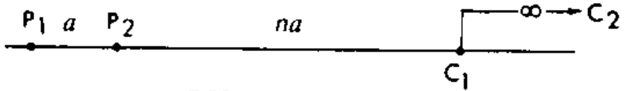
(c)



SCHLUMBERGER

$$\boxed{\rho_a = \pi \frac{L^2}{2l} \frac{\Delta V}{i}}$$

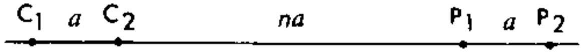
(d)



POLE–DIPOLE

$$\boxed{\rho_a = 2\pi a n (n+1) \frac{\Delta V}{i}}$$

(e)



DIPOLE–DIPOLE

$$\boxed{\rho_a = \pi a n (n+1)(n+2) \frac{\Delta V}{i}}$$

(Sharma 1997)

Array advantages and disadvantages

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

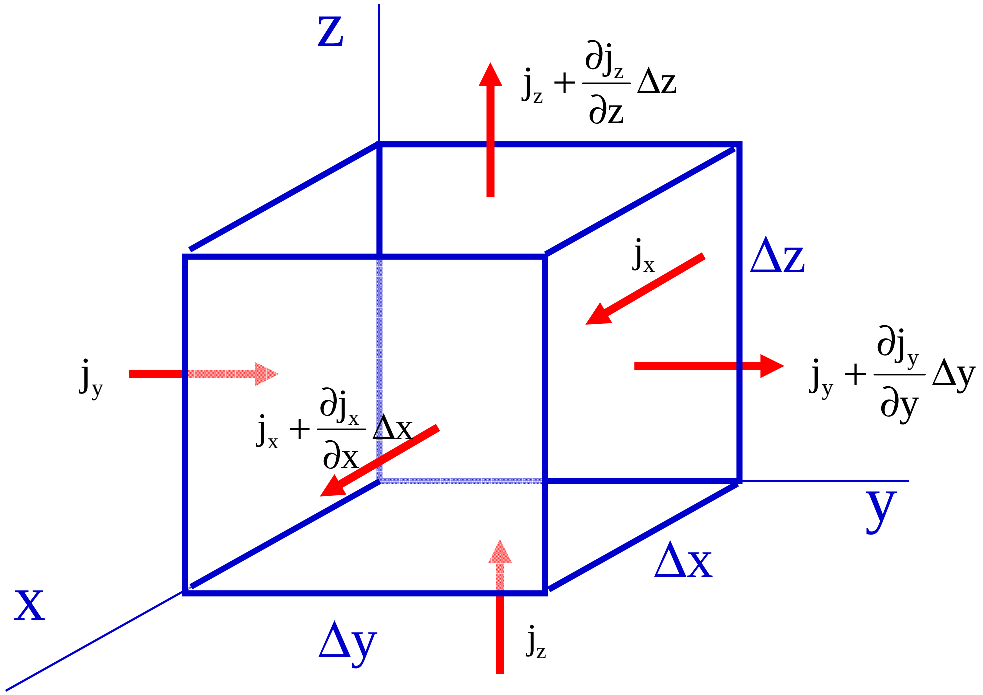
Governing Equation

Continuity: what goes in must comes out

$$\left(j_x+\frac{\partial j_x}{\partial x}\Delta x-j_x\right)\Delta y\Delta z+\left(j_y+\frac{\partial j_y}{\partial y}\Delta y-j_y\right)\Delta x\Delta z+\left(j_z+\frac{\partial j_z}{\partial z}\Delta z-j_z\right)\Delta x\Delta y=0$$

$$\frac{\partial j_x}{\partial x}\Delta x\Delta y\Delta z+\frac{\partial j_y}{\partial y}\Delta x\Delta y\Delta z+\frac{\partial j_z}{\partial z}\Delta x\Delta y\Delta z=0$$

then $\frac{\partial j_x}{\partial x}+\frac{\partial j_y}{\partial y}+\frac{\partial j_z}{\partial z}=0$



Current density: $\vec{j}=\frac{\vec{I}}{A}$

Governing Equation

Applying Ohm's Law:

$$j_x = -\frac{1}{\rho}\frac{\partial V}{\partial x};\ j_y = -\frac{1}{\rho}\frac{\partial V}{\partial y};\ j_z = -\frac{1}{\rho}\frac{\partial V}{\partial z}$$

Homogeneous and isotropic medium

$$\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial V}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial V}{\partial z}\right)=0$$

or using

$x = r\cos\theta$, $y = r\sin\theta$, and $x^2 + y^2 = r^2$

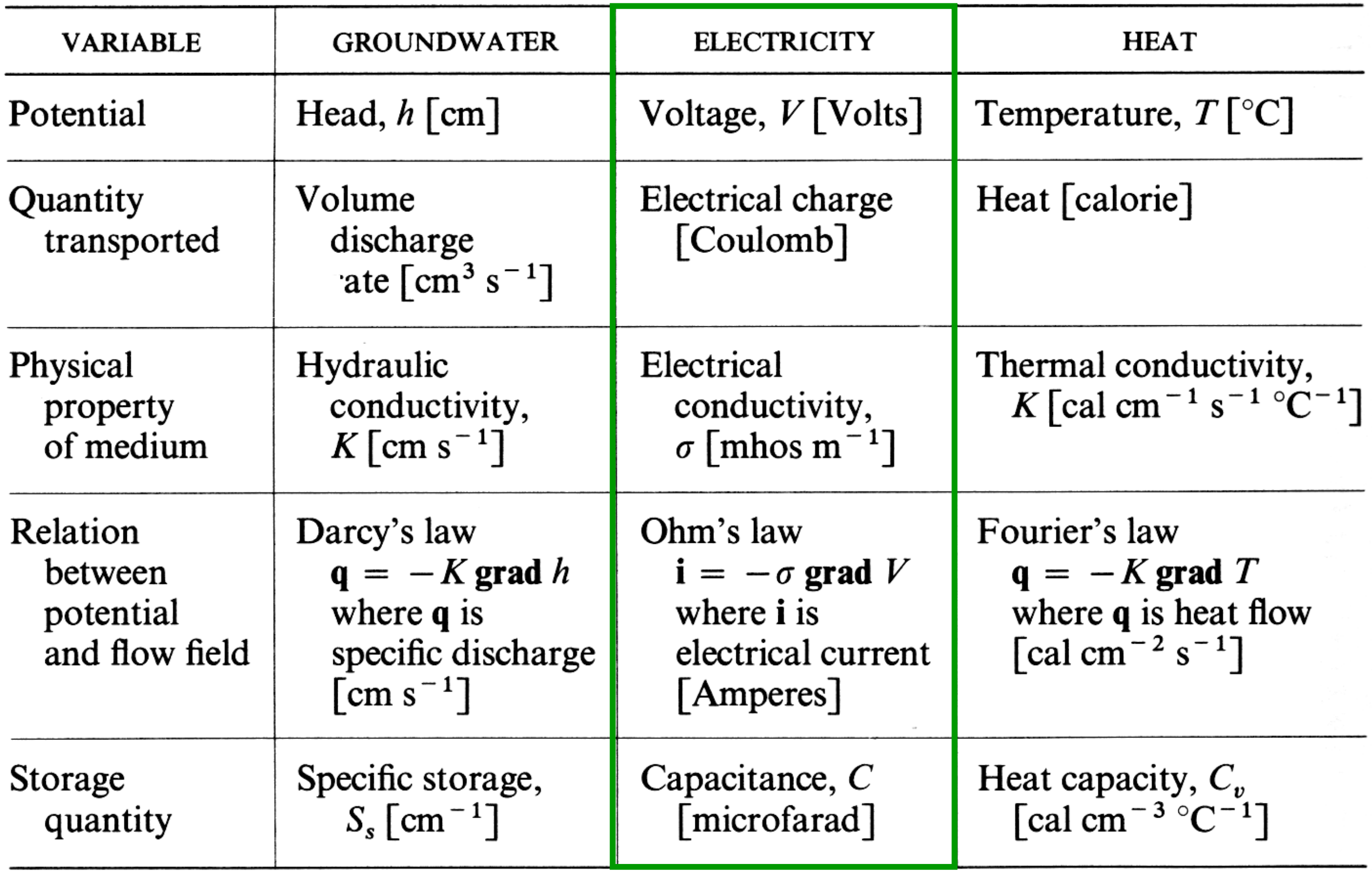
$$\boxed{\left.\begin{aligned}&\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}+\frac{\partial^2 V}{\partial z^2}=0\\ &\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{\partial^2 V}{\partial z^2}=0\end{aligned}\right\}\nabla^2 V = 0 \quad \Rightarrow \quad \text{Laplace's equation}}$$

Governing Equation - Solution

- The Laplace’s equation is a homogeneous, partial second order differential equation
- Solution:
  - Exact solutions: only for simple geometries
  - Graphical solutions: Flow nets, master charts
  - Numerical solutions: finite difference and finite elements solutions
  - Physical analogies (electrical, hydraulic and heat flow)

Analogous to Heat and Fluid Flow

Any solution you know for one of these flows works for the others with the analogous boundary and initial conditions.

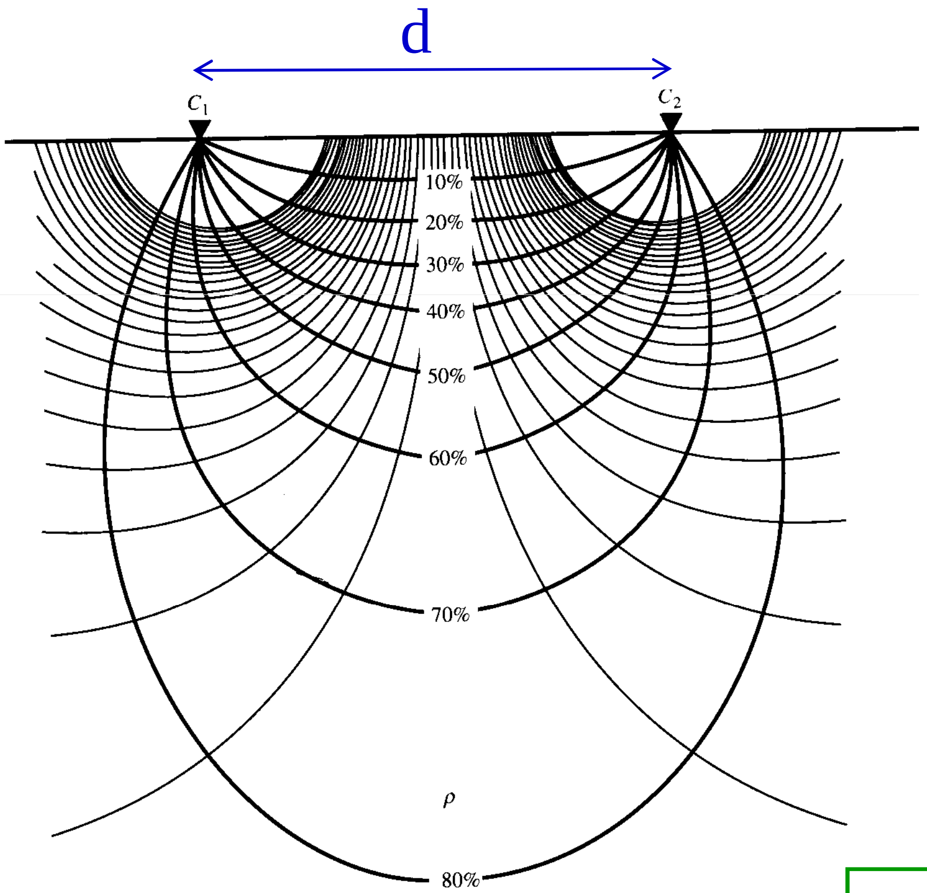


VARIABLE	GROUNDWATER	ELECTRICITY	HEAT
Potential	Head, h [cm]	Voltage, V [Volts]	Temperature, T [°C]
Quantity transported	Volume discharge rate [$\mathrm{cm}^3\ \mathrm{s}^{-1}$]	Electrical charge [Coulomb]	Heat [calorie]
Physical property of medium	Hydraulic conductivity, K [$\mathrm{cm\ s}^{-1}$]	Electrical conductivity, σ [$\mathrm{mhos\ m}^{-1}$]	Thermal conductivity, K [$\mathrm{cal\ cm}^{-1}\ \mathrm{s}^{-1}\ {}^{\circ}\mathrm{C}^{-1}$]
Relation between potential and flow field	Darcy's law $\mathbf{q} = -K\ \mathbf{grad}\ h$ where **q** is specific discharge [$\mathrm{cm\ s}^{-1}$]	Ohm's law $\mathbf{i} = -\sigma\ \mathbf{grad}\ V$ where **i** is electrical current [Amperes]	Fourier's law $\mathbf{q} = -K\ \mathbf{grad}\ T$ where **q** is heat flow [$\mathrm{cal\ cm}^{-2}\ \mathrm{s}^{-1}$]
Storage quantity	Specific storage, S_s [cm^{-1}]	Capacitance, C [microfarad]	Heat capacity, C_v [$\mathrm{cal\ cm}^{-3}\ {}^{\circ}\mathrm{C}^{-1}$]

(Wang and Anderson 1982)

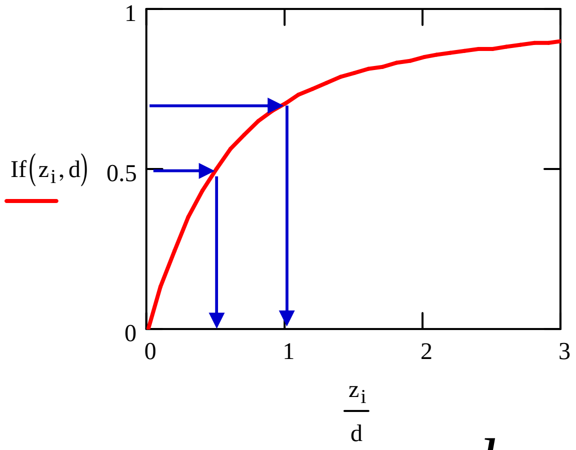
Current Distribution

Homogeneous medium



fraction total current

$$I_f = \frac{2}{\pi}\arctan\left(\frac{2z}{d}\right)$$



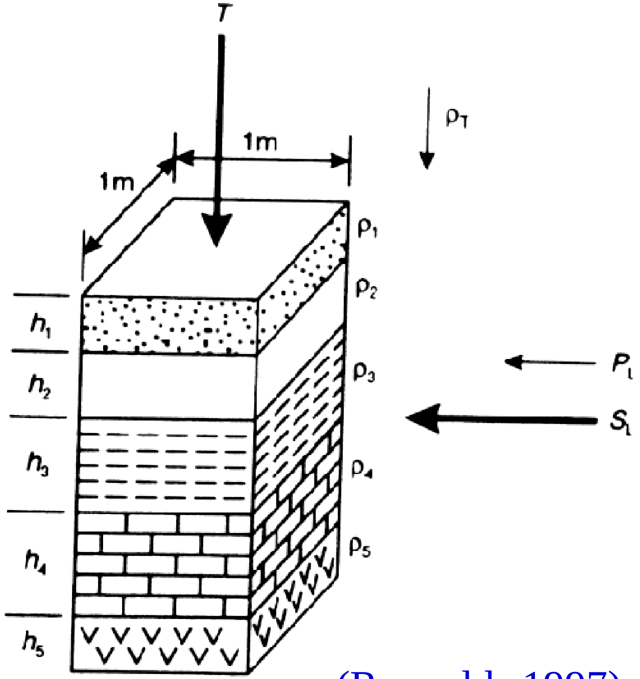
$i_f=0.5$ at $z = \frac{d}{2}$

$i_f=0.7$ at $z = d$

Wider spacing → Deeper currents

Geo-electric Layering

- Goal of the resistivity survey is to determine thickness and resistivity of near surface layers.
- Often the earth can be simplified within the region of our measurement as consisting of a series of horizontal beds that are infinite in extent.



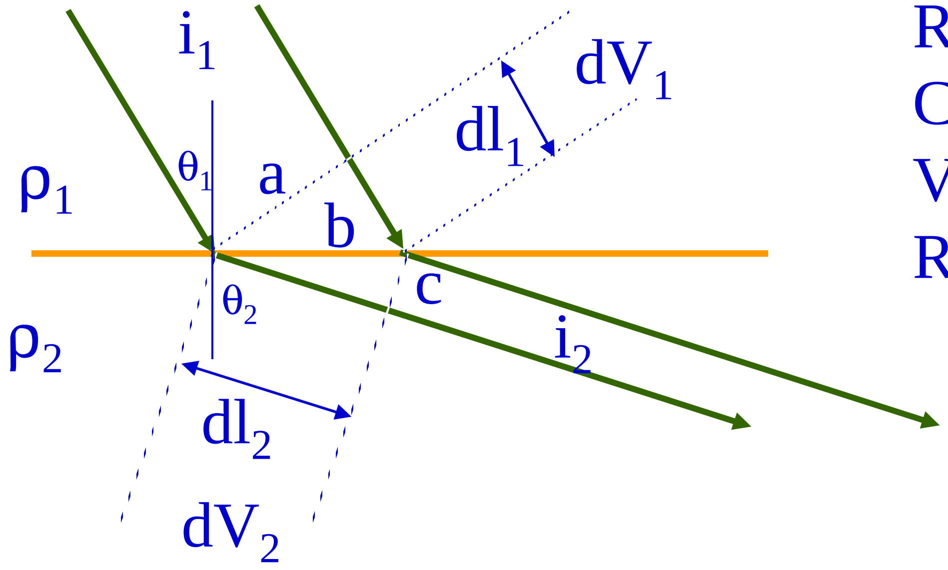
(Reynolds 1997)

Longitudinal conductance (one layer): $S_L = h/\rho = h\,\sigma$ [S]
Transverse resistance (one layer): $T = h\,\rho$ [Ω]
Longitudinal resistivity (one layer): $\rho_L = h/S_L$ [Ωm]
Transverse resistivity (one layer): $\rho_T = T/h$ [Ωm]

Longitudinal conductance (for n-layers): $S_L = \Sigma(h_i/\rho_i)$ [S]
Transverse resistance (for n-layers): $T = \Sigma(h_i\,\rho_i)$ [Ω]

Voltage and Flow in Layers

Tangent Law: The electrical current lines are bent at a boundary



Relations:

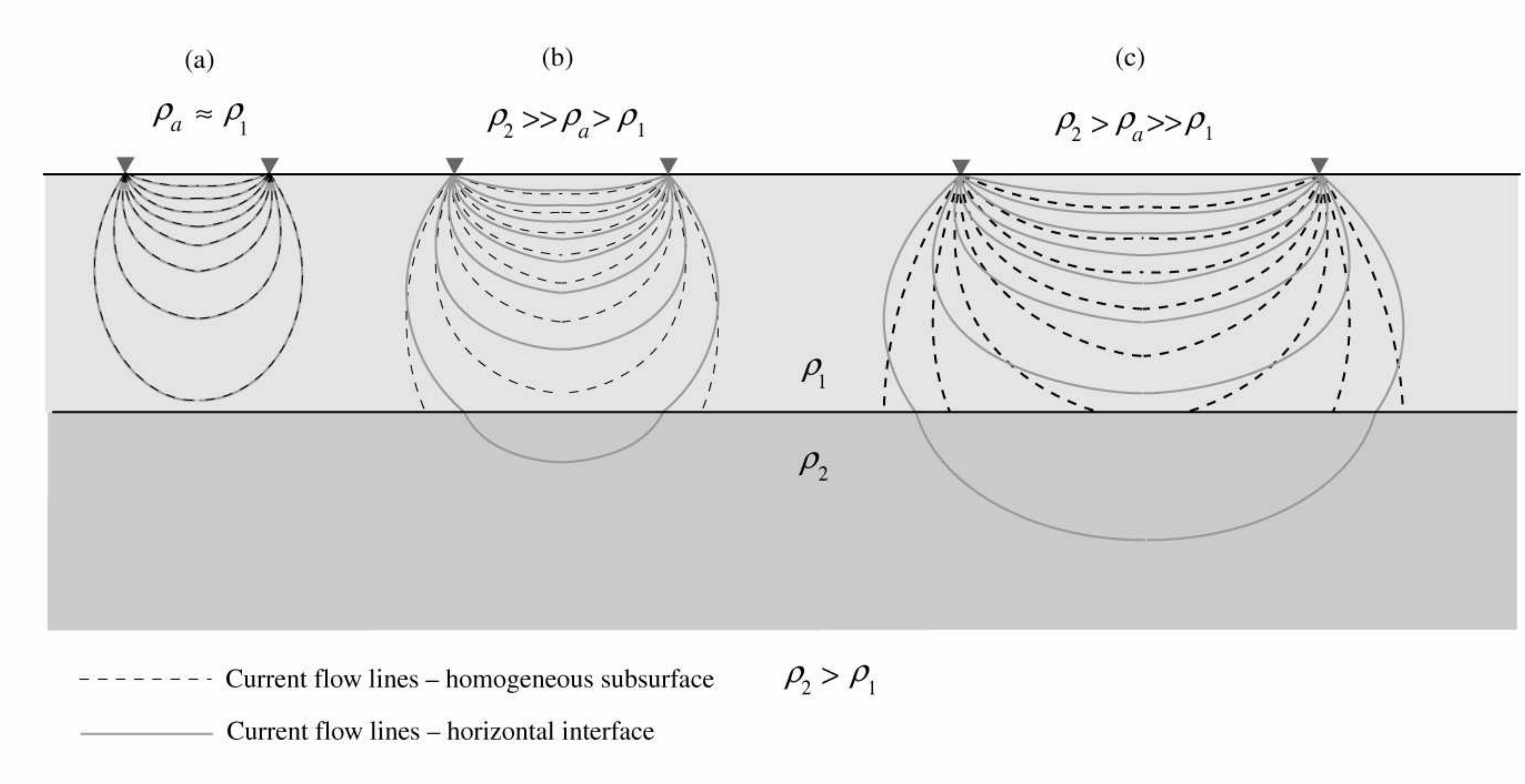
Current:	$i_1=i_2$
Voltage:	$dV_1=dV_2$
Resistivity:	$\rho_1>\rho_2$

$$\boxed{\frac{\rho_2}{\rho_1}=\frac{\tan\theta_1}{\tan\theta_2}}$$

If $\rho_2<\rho_1$ then the current lines will be refracted away from the normal

If $\rho_2>\rho_1$ then the current lines will be refracted closer to the normal

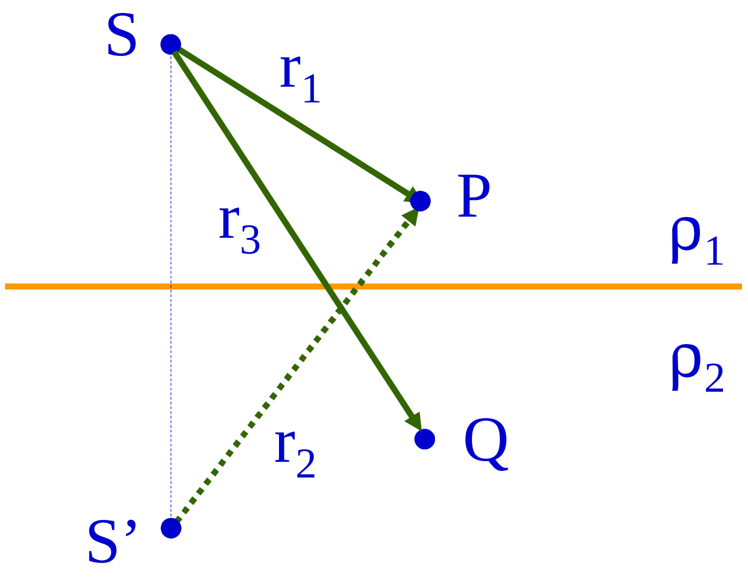
Resistivity Pattern in a One-Layer System



(Burger et al. 2005)

Voltage and Flow in Layers

Method of electrical image



Note: S' is the mirror image of S

Voltages at points P and Q:

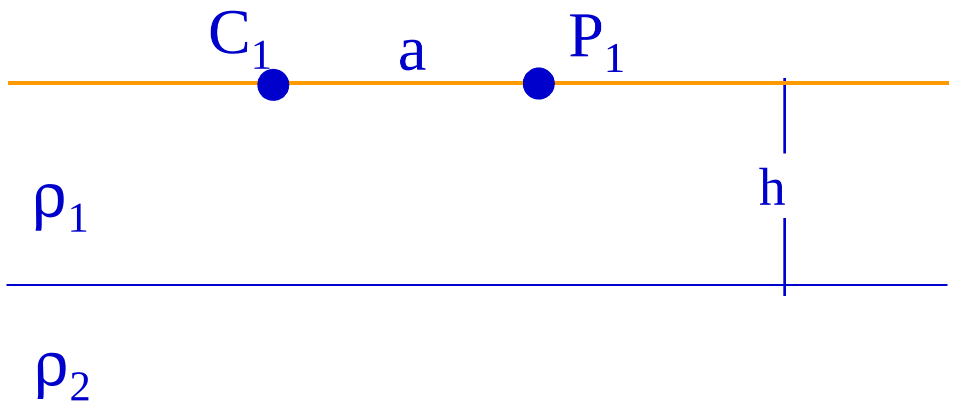
$$\boxed{V_P = \frac{i\rho_1}{4\pi}\left(\frac{1}{r_1} + \frac{k}{r_2}\right)}$$

$$\boxed{V_Q = \frac{i\rho_2}{4\pi}\left(\frac{1-k}{r_3}\right)}$$

Where k is the "reflection coefficient" is:

$$\boxed{k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}}$$

Solving the differential equation for two layers and a source and sink



Governing Equation

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{\partial^2 V}{\partial z^2}=0$$

Boundary Conditions

1. $i_z = 0\big|_{z=0}$	No current at surface
2. $V_1 = V_2$ at h	Voltage is continuous
3. $\frac{1}{\rho_1}\frac{\partial V_1}{\partial z} = \frac{1}{\rho_2}\frac{\partial V_2}{\partial z}$ at h	Normal current density is continous
4. $V = \frac{i\rho_1}{2\pi\left(r^2+z^2\right)^{\frac{1}{2}}}$ at r = 0, z = 0	Particular solution

Layer Calculations

- Can use for image theory for multiple boundaries. For a two-layer case:

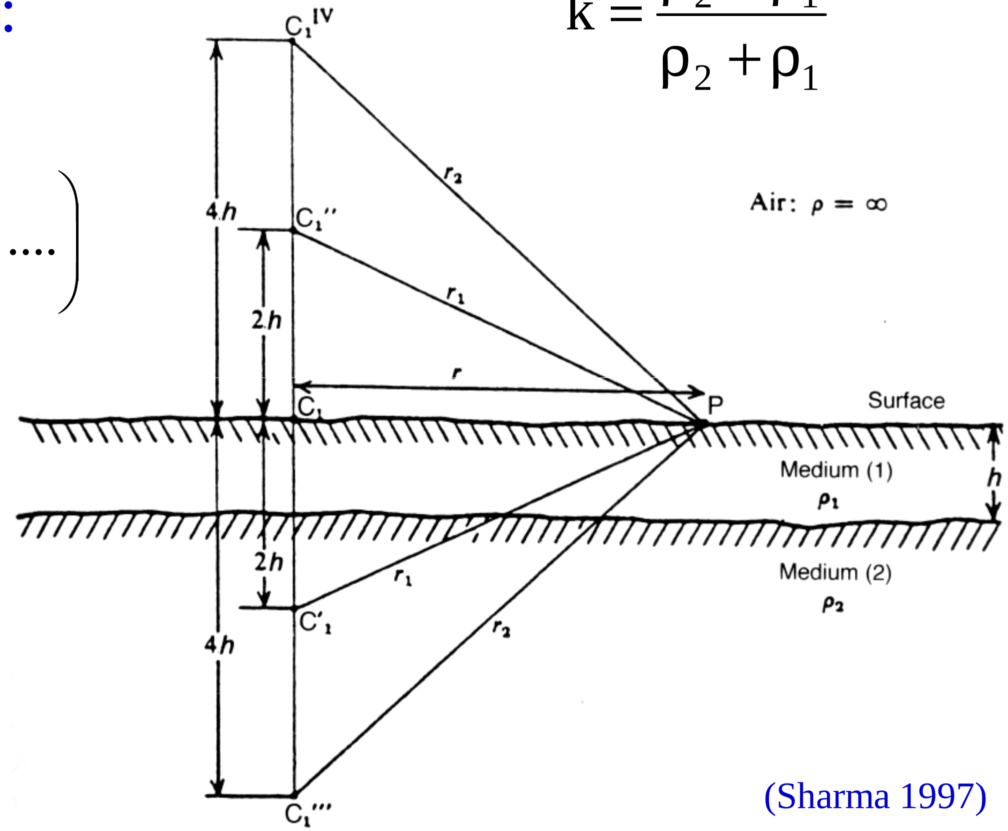
$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

$$V_p = \frac{I\rho_1}{2\pi}\left(\frac{1}{r} + \frac{2k}{r_1} + \frac{2k^2}{r_2} + ... + \frac{2k^n}{r_n} + ...\right)$$

$$= \frac{I\rho_1}{2\pi}\left(\frac{1}{r} + 2\sum_{n=1}^{\infty}\frac{k^n}{r_n}\right)$$

where

$$r_n = \sqrt{r^2 + (2nh)^2}$$



(Sharma 1997)

- It obviously gets much more difficult with more layers.

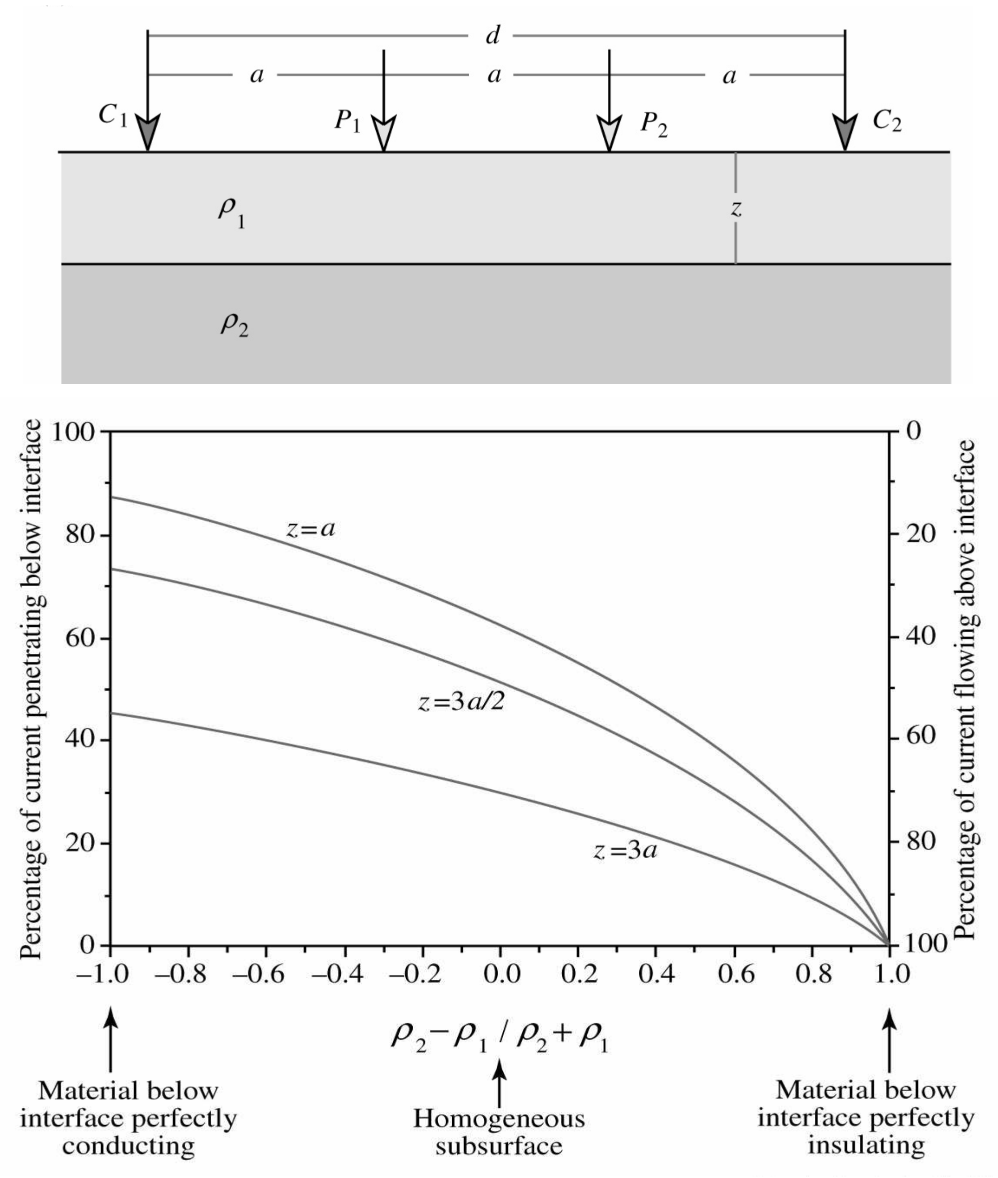
Current Distribution

Layered medium medium

Current fraction:

$$i_F = \frac{2}{\pi}\frac{\rho_1}{\rho_2}(1+k)\sum_{n=0}^{\infty} k^n \left[\frac{\pi}{2} - \tan^{-1}\left(\frac{2(2n+1)z}{3a}\right)\right]$$

where: $k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$

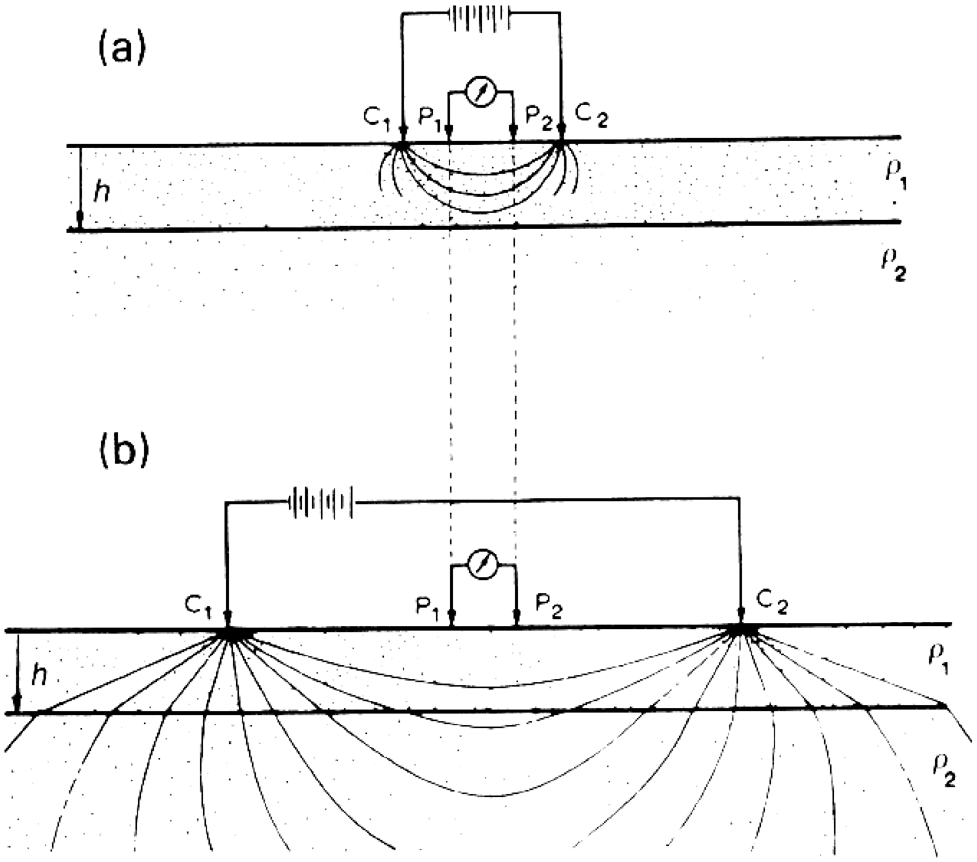


(Burger et al. 2005)

Vertical Electric Sounding

- When trying to probe how resistivity changes with depth, need multiple measurements that each give a different depth sensitivity.

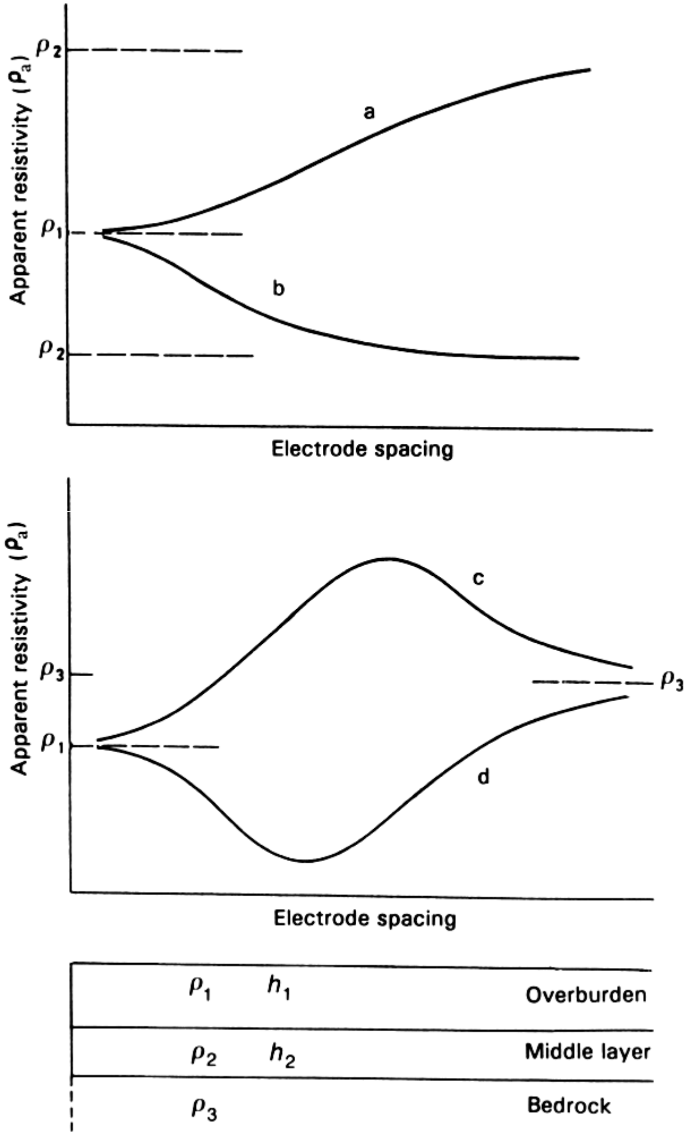
- This is accomplished through *resistivity sounding* where greater electrode separation gives greater depth sensitivity.



(Sharma 1997)

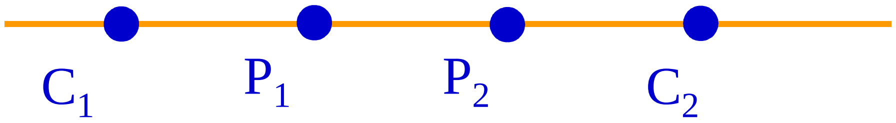
VES Data Plotting Convention

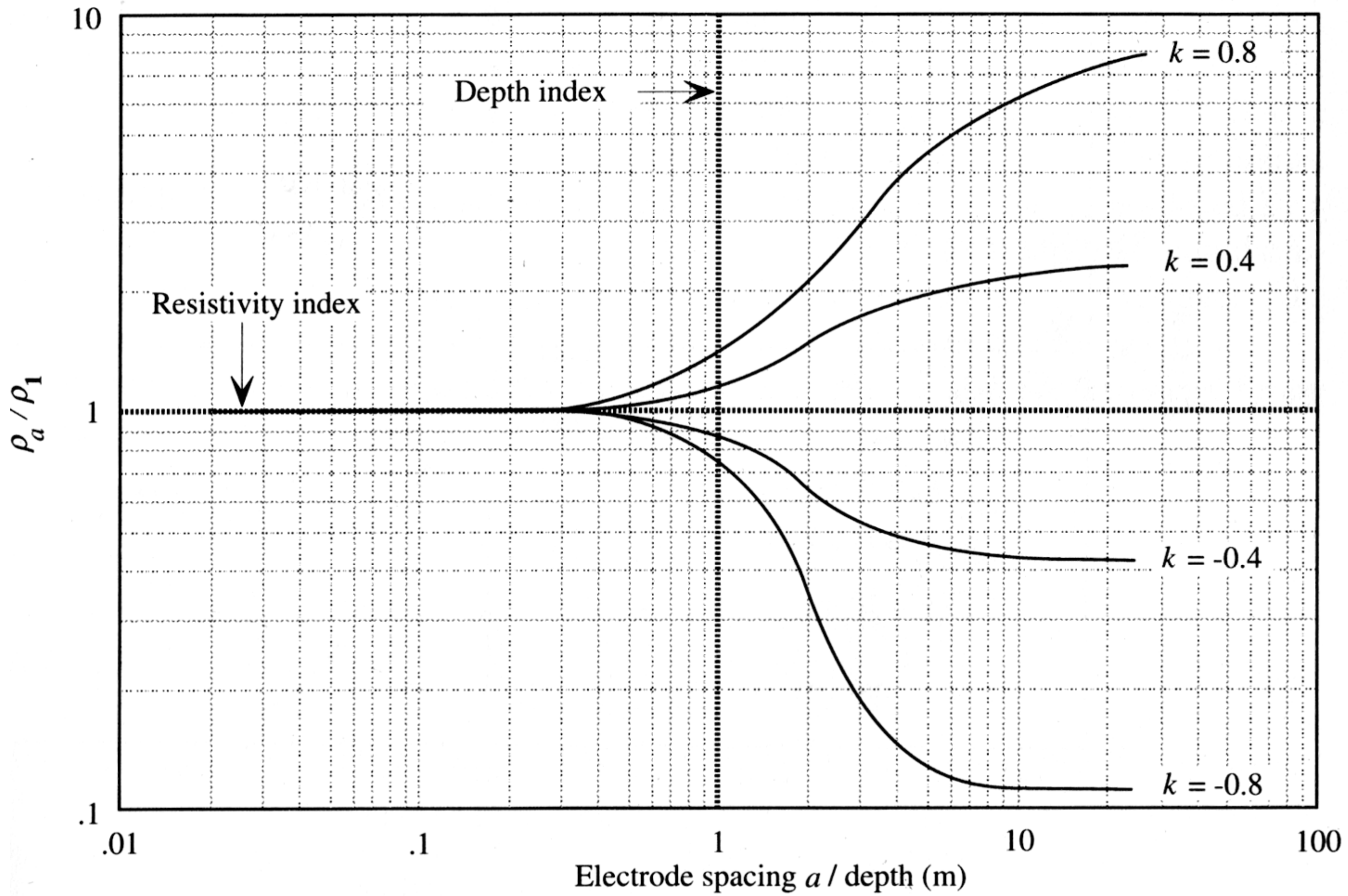
- Plot apparent resistivity as a function of the log of some measure of electrode separation.
  - Wenner – *a spacing*
  - Schlumberger – AB/2
  - Dipole-Dipole – *n spacing*
- Asymptotes:
  - Short spacings << h_1, $\rho_a = \rho_1$.
  - Long spacings >> total thickness of overlying layers, $\rho_a = \rho_n$
- To get $\rho_a = \rho_{true}$ for intermediate layers, layer must be thick relative to depth.



(Sharma 1997)

Solutions for a Wenner Array for two layers





$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

Solutions for a Wenner Array for two layers

- Simple for two layer case.
  - Plot data at same scales as master curves.
  - Overlie shallow-layer resistivity asymptote with '1' on master curves.
  - Determine depth to layer, and resistivity of lower layer by comparing scaled master-curve values to data values
- Gets rapidly more difficult as more layers added.

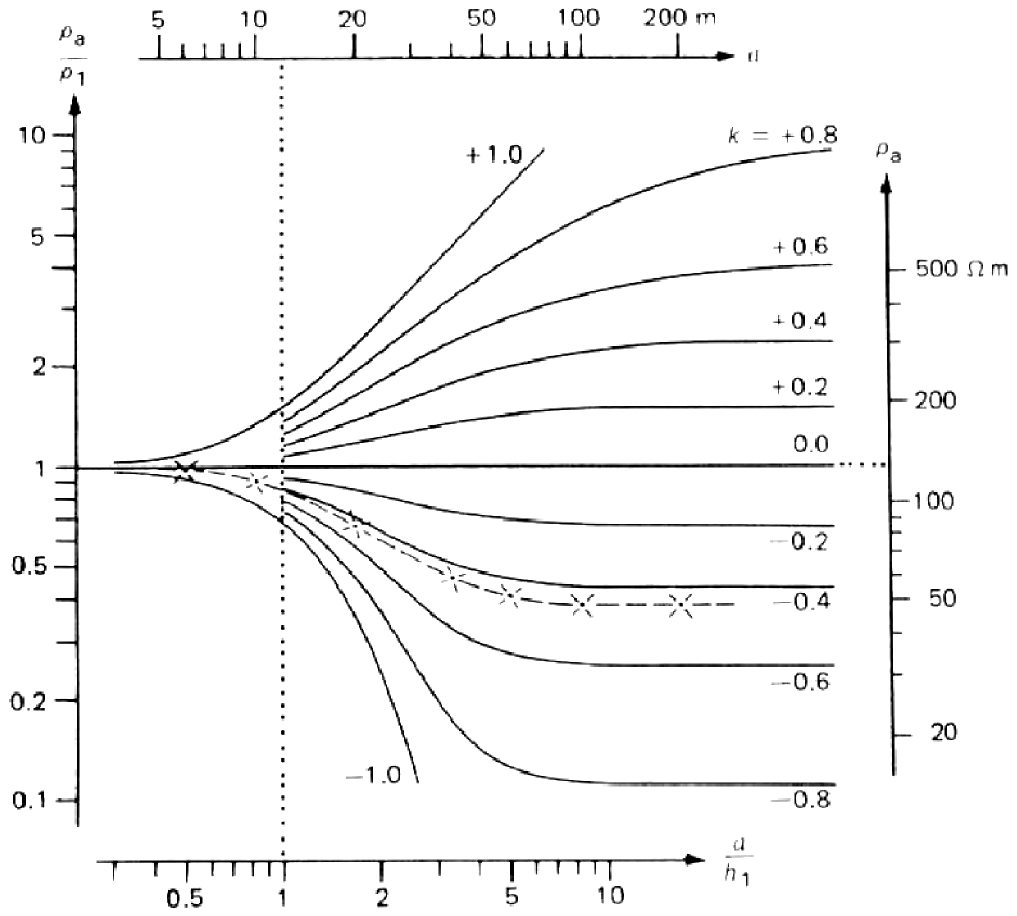


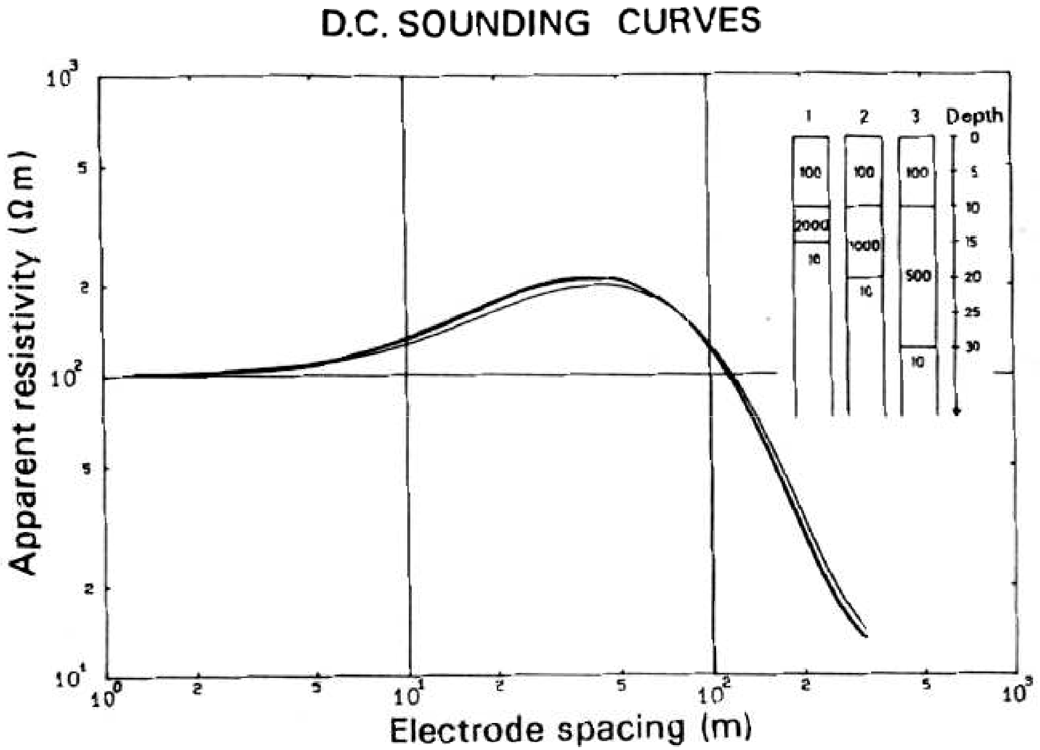
Fig. 6.16 Example of the interpretation of a field curve (dashed line with crosses) by matching it with a set of master two-layer resistivity curves (for explanation see text).

(Sharma 1997)

Equivalence: several models produce the same results

- Ambiguity in physics of 1D interpretation such that different layered models basically yield the same response.
- Different Scenarios:
  - Conductive layers between two resistors, where longitudinal conductance (σ h) is the same.
  - Resistive layer between two conductors with same transverse resistance (ρ h).

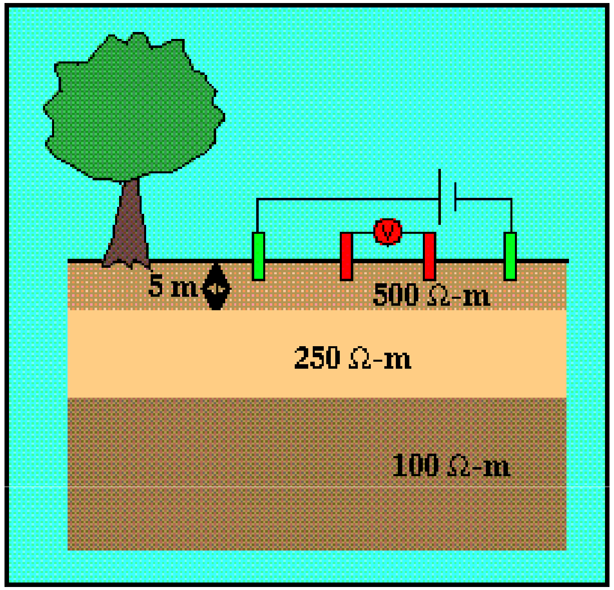
Equivalence: several models produce the same results

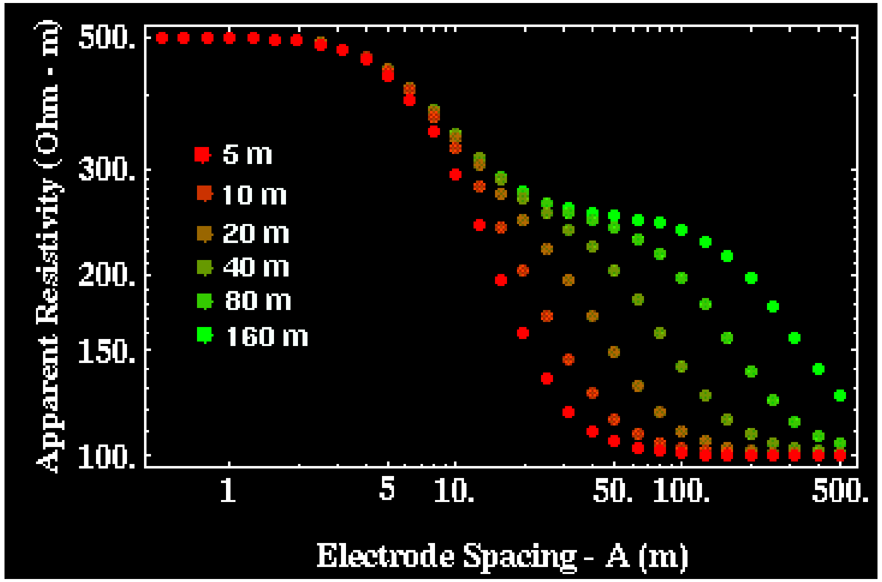


- Although ER cannot determine unique parameters, can determine range of values.
- Also exists in 2D and 3D, but much more difficult to quantify. In these multidimensional cases simply referred to as *non-uniqueness*.

Suppression

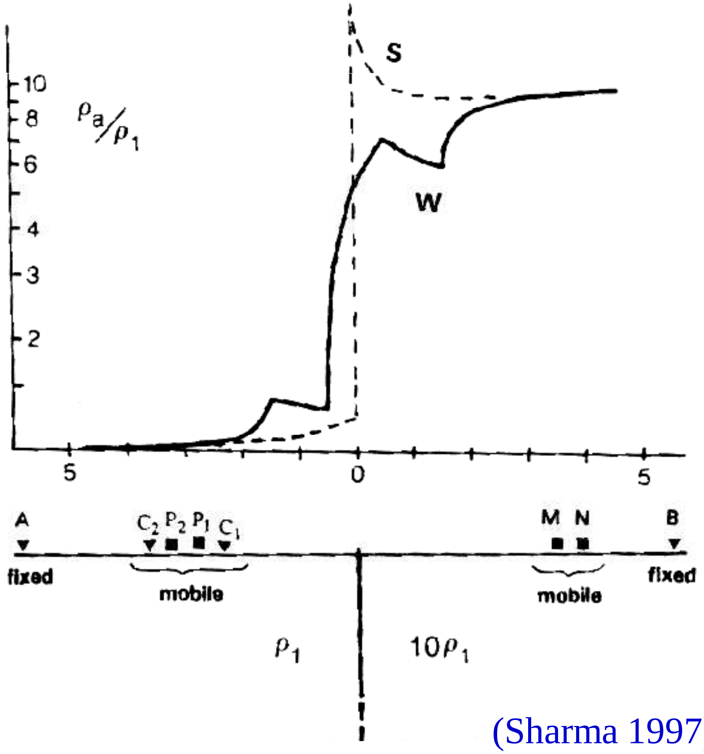
- Principle of *suppression:* Thin layers of small resistivity contrast with respect to background will be missed.
- Thin layers of greater resistivity contrast will be detectable, but equivalence limits resolution of boundary depths, etc.



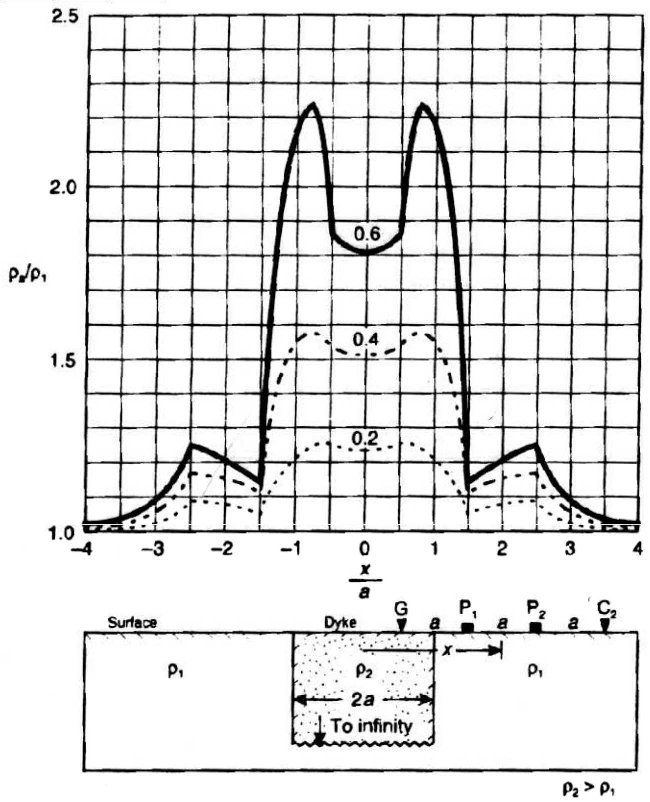


Horizontal Profiling

- Used for rapid location/delineation of lateral variations in resistivity.
- Usually involves moving an electrode array of constant separation horizontally along surface.



(Sharma 1997)

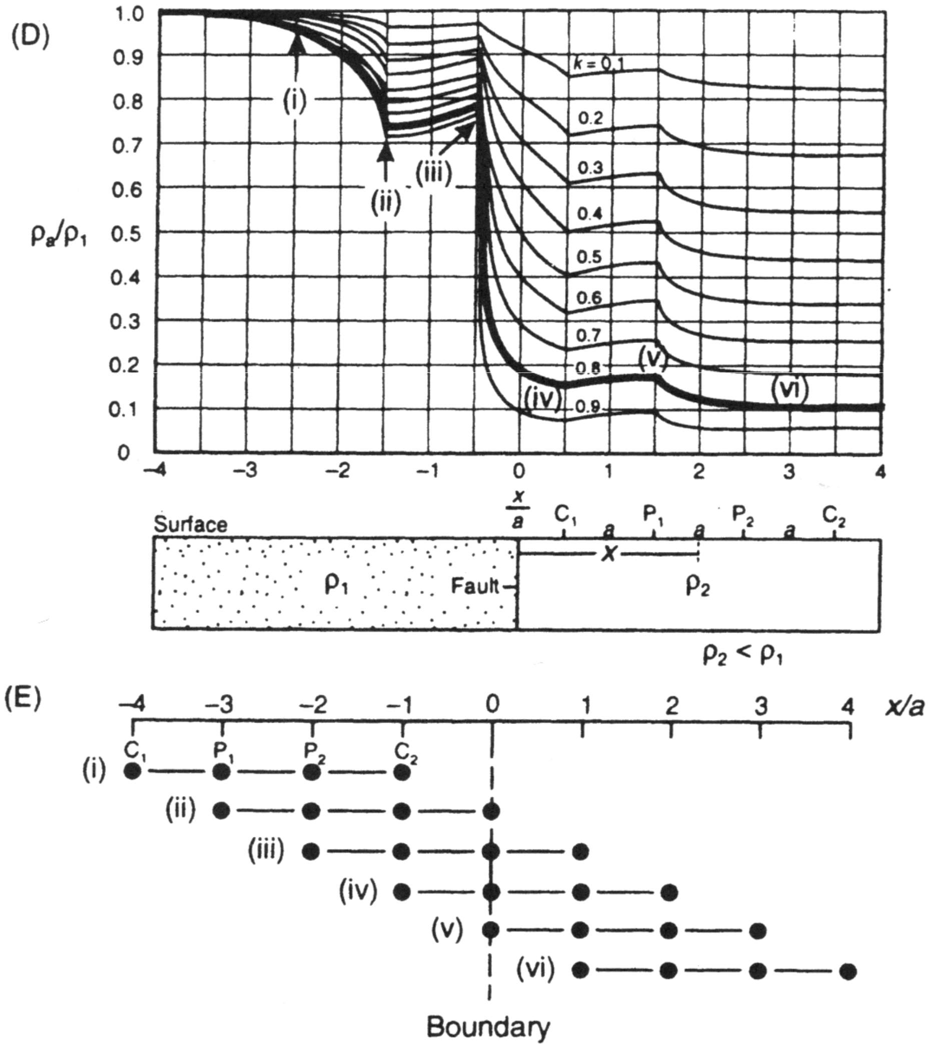


(Reynolds 1997)

- Can be difficult to interpret directly from resulting curve due to formation of ‘cusps’. Also, different arrays produce somewhat different results.

Profile Cusps – Wenner Array

Apparent resistivity: $\boxed{\rho_a = 2\pi a(\Delta V/I)}$



i. Current lines converge toward boundary, decrease potential gradient at potential electrodes

ii. C2 at boundary

iii. Current density increases adjacent to boundary in low resistivity unit, causes potential gradient between potential electrodes to rise

iv. Both potential electrodes are in the low resistivity unit so potential gradient between them falls dramatically

v. C1 enters the low resisitivy unit

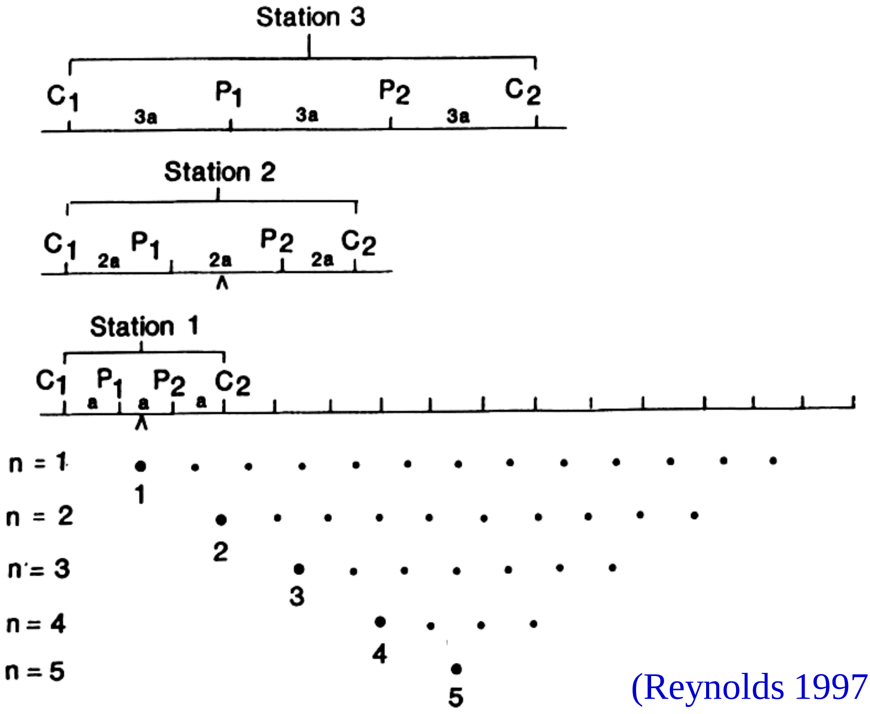
vi. Current flow becomes dipolar

(Reynolds 1997)

Combined Sounding and Profiling

- Increase electrode separation as well as make measurements at multiple locations along the horizontal axis.
- Provides data for two dimensional interpretation of subsurface.
- Data often plotted in *pseudo-section* for qualitative analysis.

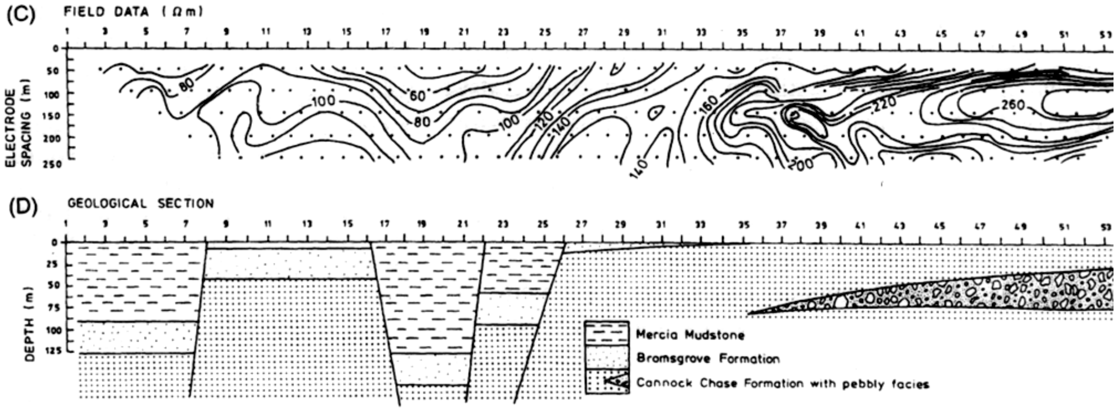
Wenner Pseudo-Section



(Reynolds 1997)

Wenner: h=a/2
Schlumberger: h=L/3
Dipole Dipole: h=n a

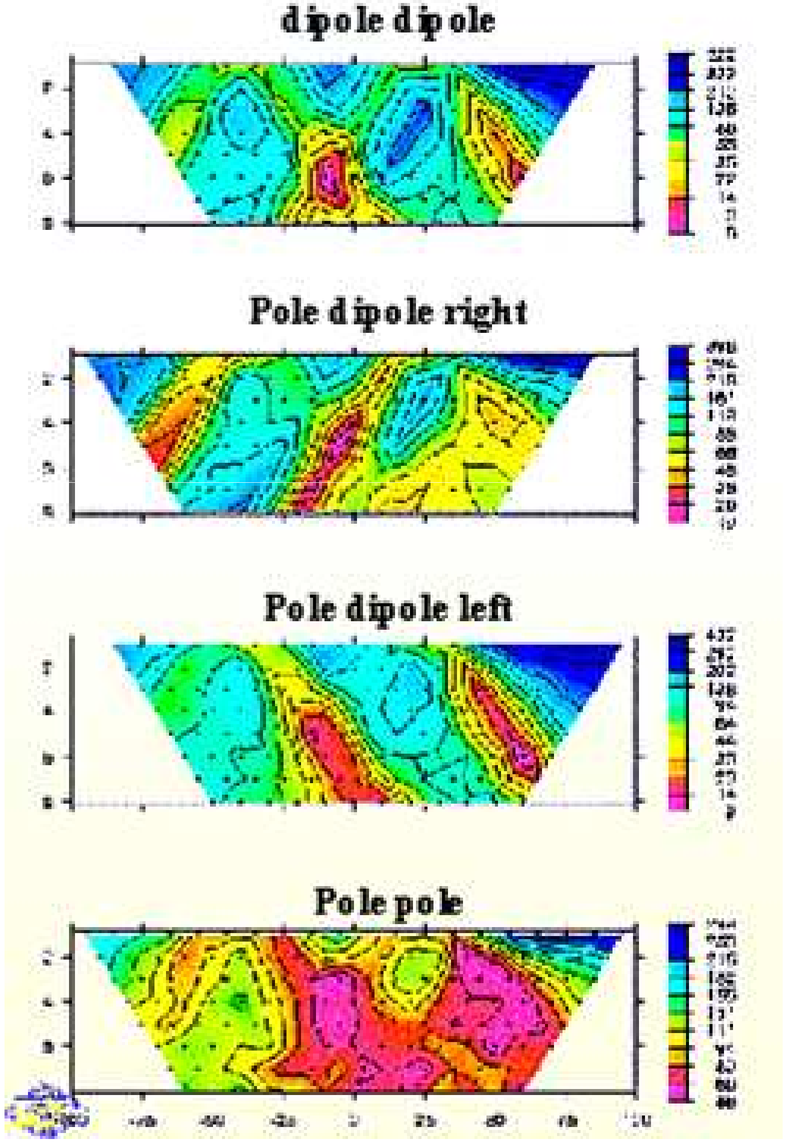
Pseudo-Sections



(Reynolds 1997)

- Can sometimes be used to qualitatively assess geology

- <u>Warning</u>: Can also prove to be very difficult to interpret directly, with different arrays yielding very different results.



Measurement Systems

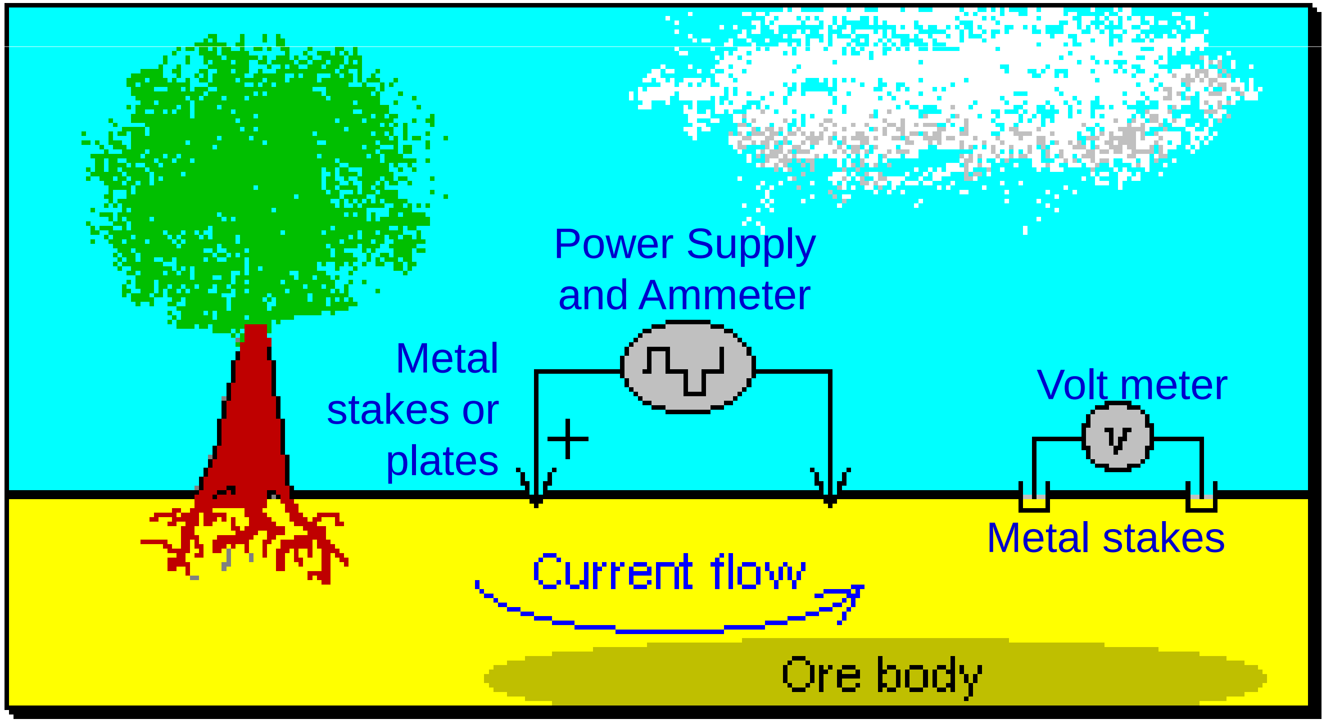
Transmitter

- Power Supply
  - DC
  - AC (more common)

- Ammeter
- Metal electrodes

Receiver

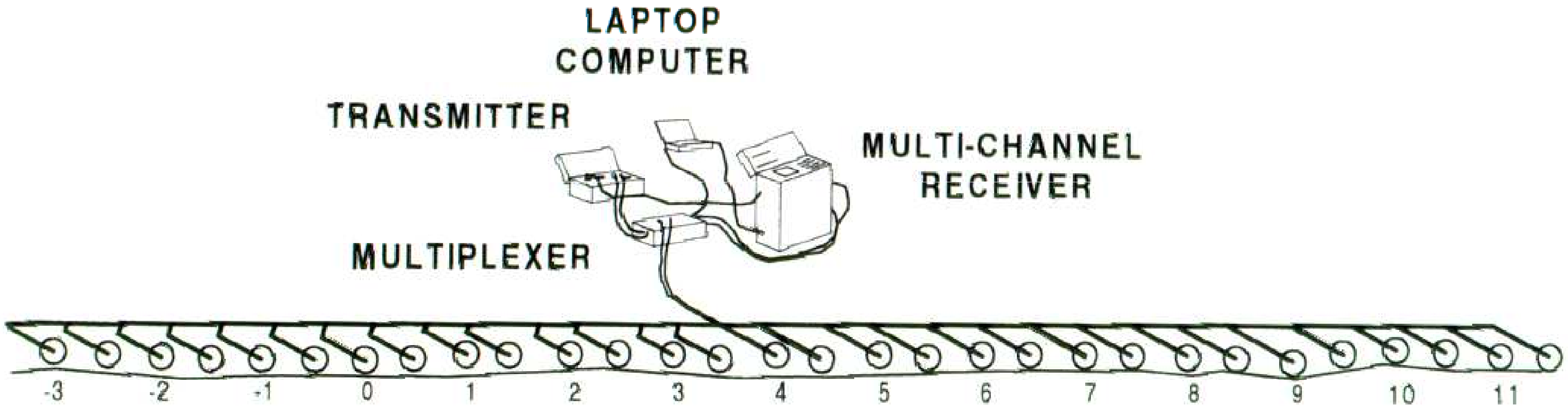
- Voltmeter
- Metal Electrodes



Fully Automated Systems

Zeta Setup

30 Electrode Spread Shown



Electrodes: 30
Station Spacing: 1/2 Dipole
N-spacings: 12 per diagonal (n=0.5, 1, 1.5, 2, ...)
Data points per Spread: 234

(Source: Zonge)

Field Considerations for DC Resistivity

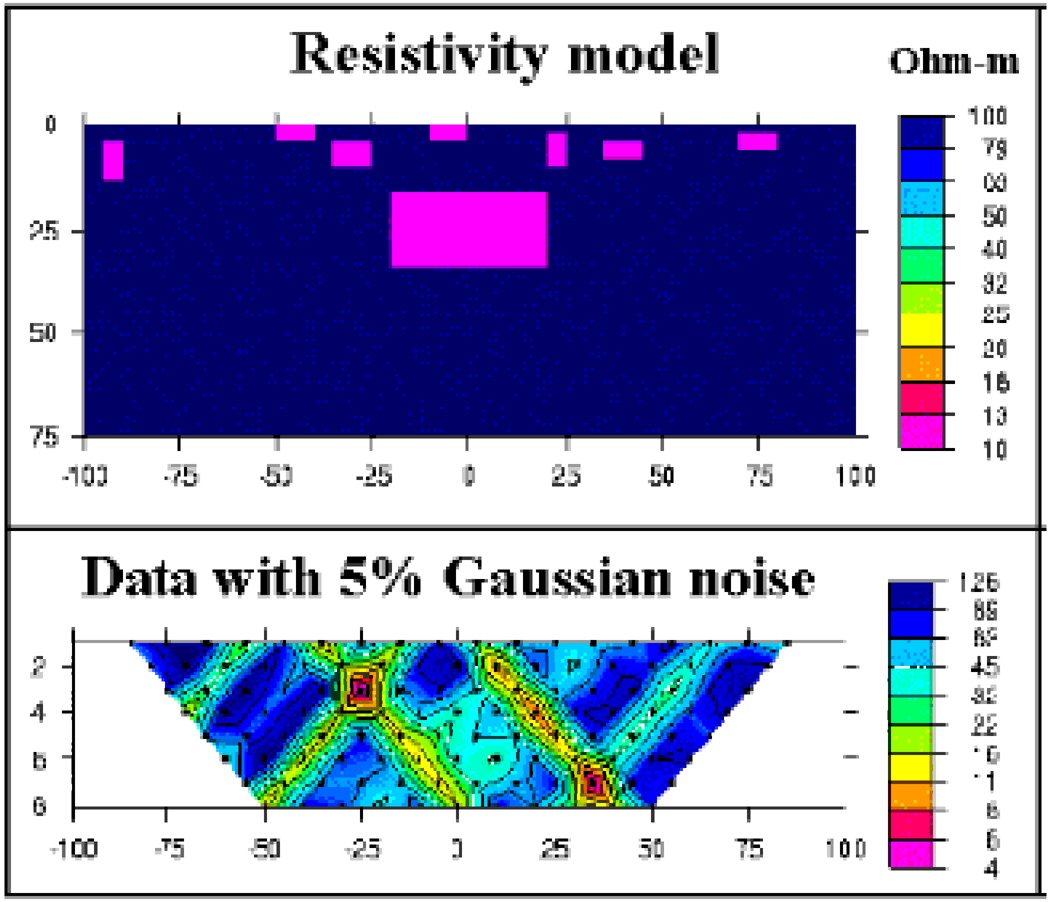
- Good electrode contact with the earth
  - Wet electrode location
  - Add NaCl solution or bentonite.
- Surveys should be conducted along a straight line whenever possible
- Try to stay away from cultural features whenever possible (power lines, pipes, grounded metal fences, pumps, etc)

Sources of Noise in Data

- Instrument noise
- Cultural Features
- Telluric Currents – naturally occurring earth currents.
  - Self potentials – generally caused by either geochemical reactions or greater than normal subsurface fluid flow.
  - Magnetotelluric Currents – Electromagnetically induced by naturally occurring or man-made magnetic fields.
  - In some cases, it may be unavoidable

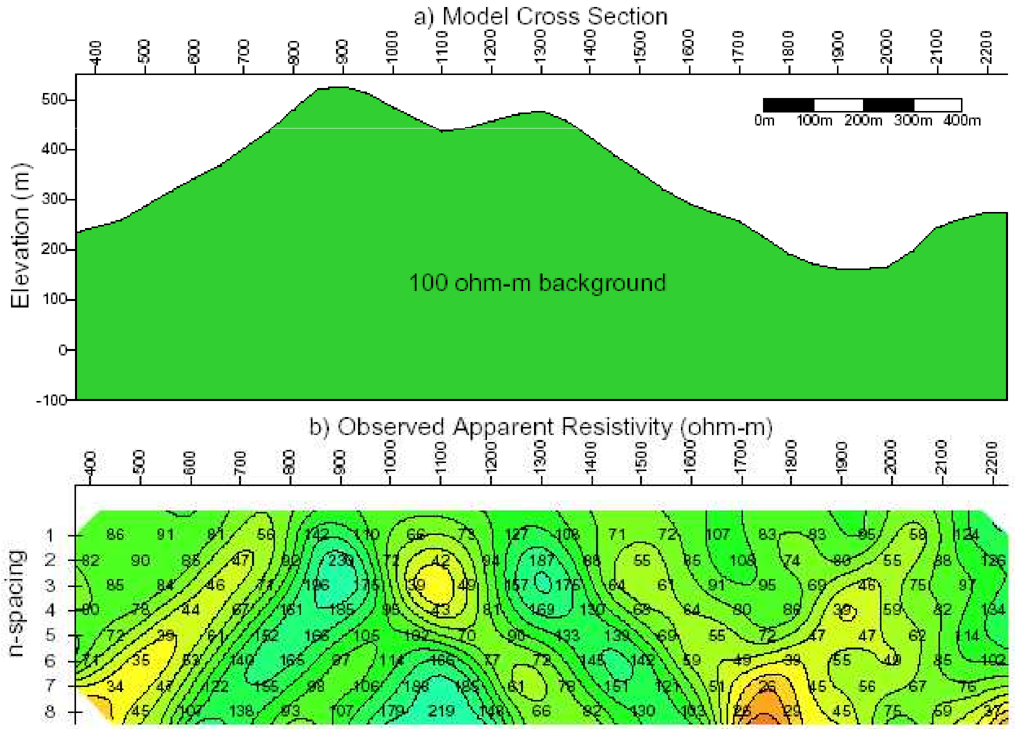
Sources of Noise in Data

- Geologic Noise
  - Near surface variations: Can dominate response thus masking signature of deeper targets.



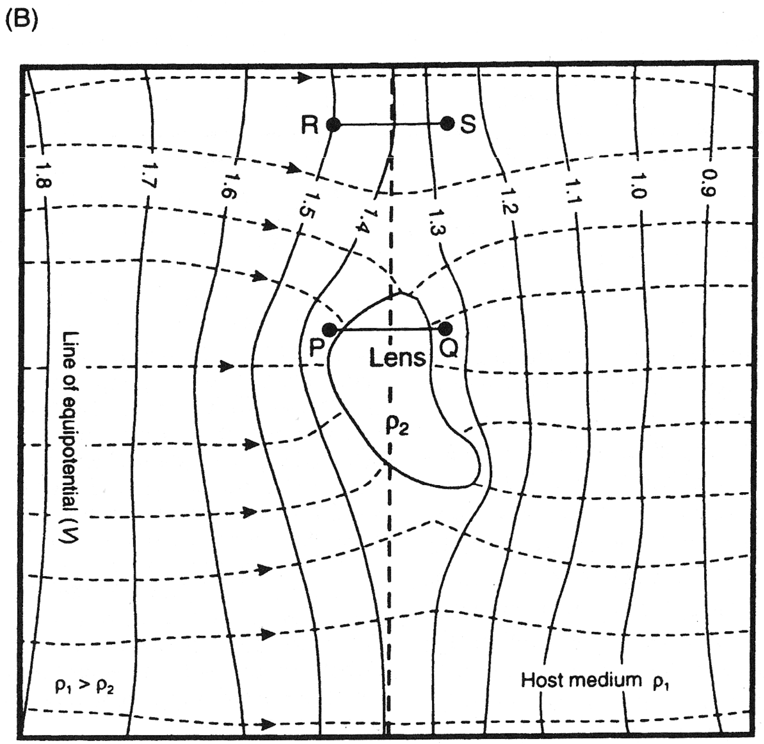
Sources of Noise in Data

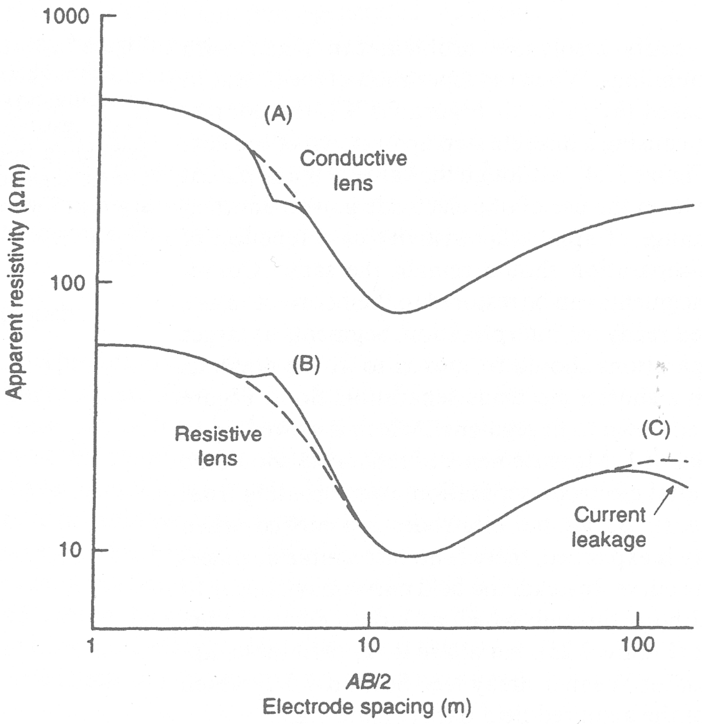
- Geologic Noise
  - Topography: Currents will be *focused* under valleys, and *dispersed* under hills, thus causing perturbations in measured voltages.



Sources of Noise in Data

- Small heterogeneities produce cusps
- Long linear features (rivers, wires) may produce current leakage.





(Reynolds 1997)

Generalized Profile Interpretation

- Looking for changes in apparent resistivity that will enhance your understanding of what you already know about the geology.

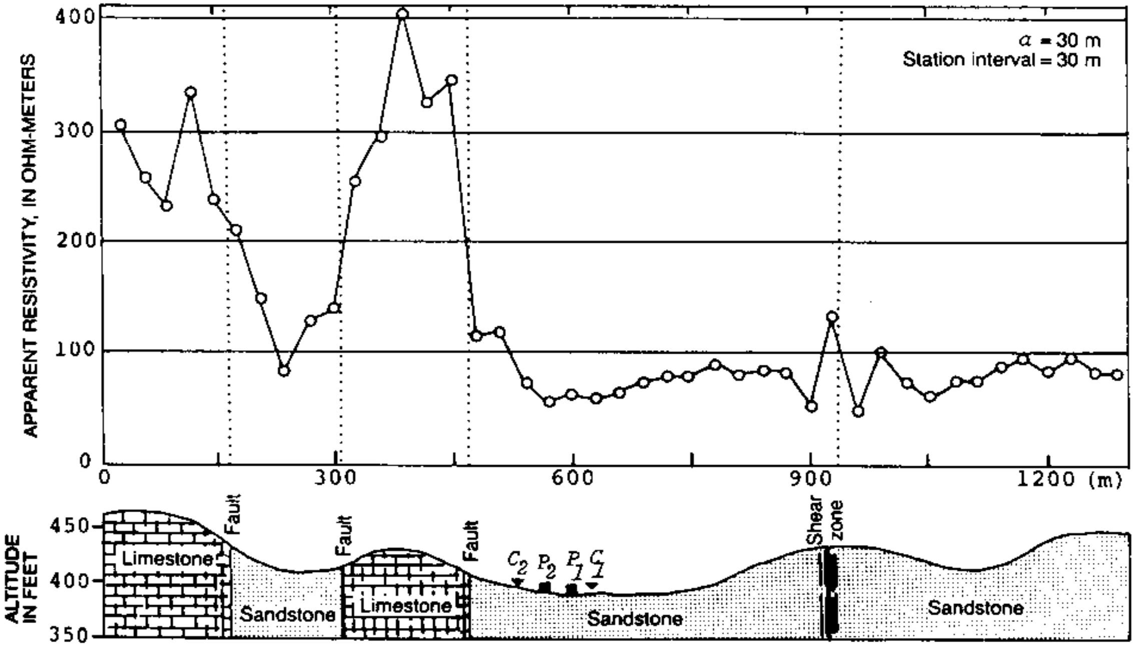
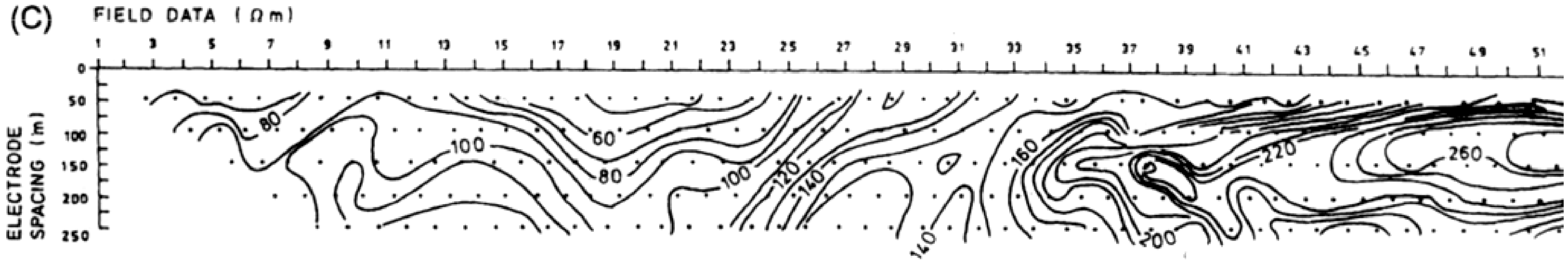
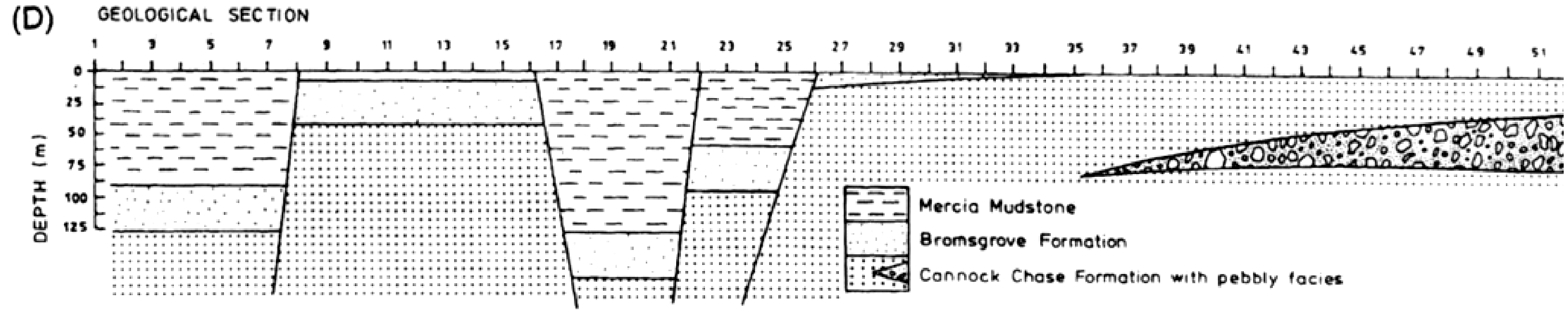


Fig. 6.19 Horizontal resistivity profile across a shear zone and limestone fault block in Illinois; Wenner configuration. (After Hubbert, 1932.)

Qualitative 2D Profile Interpretation

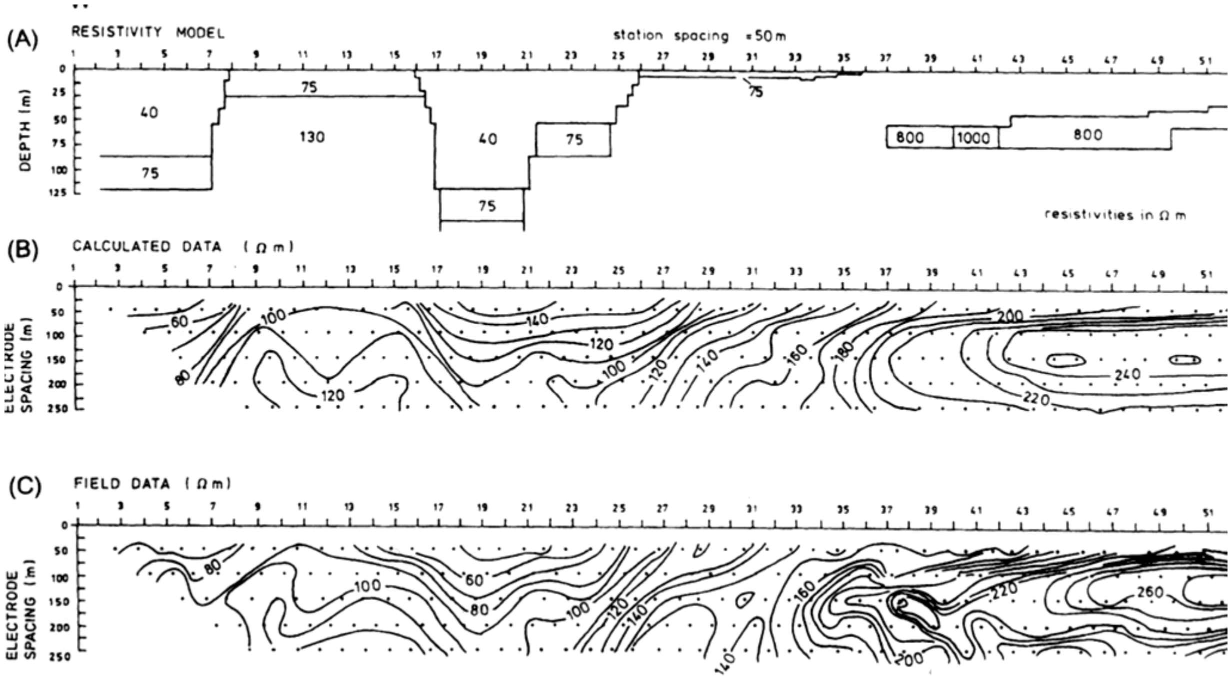
- Sometimes pseudo-sections can be interpreted qualitatively directly if
  - Good data quality
  - Simplified geology
- This is the exception rather than the norm





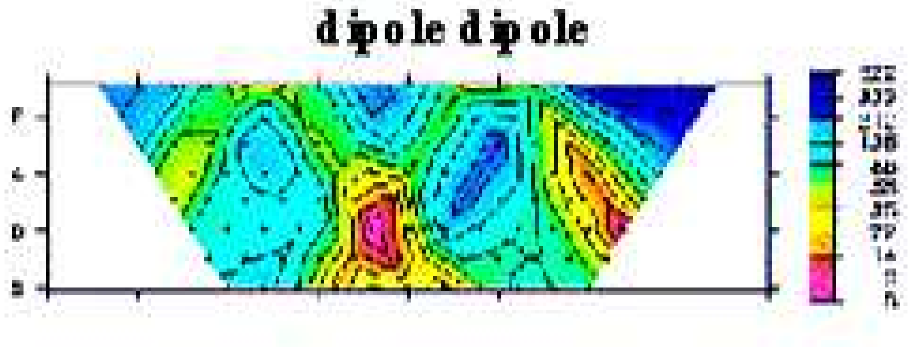
Computerized Interpretation: Forward Modeling

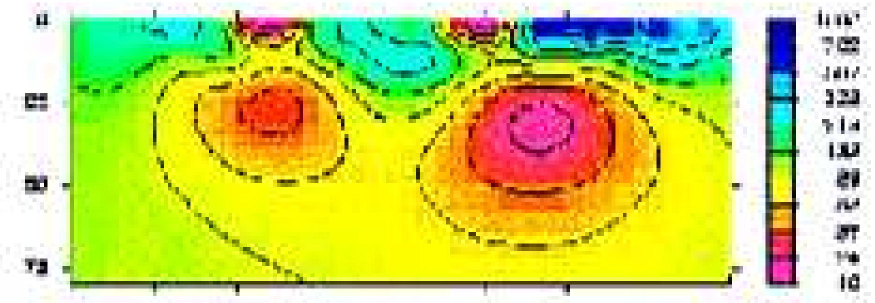
- Using mathematical expressions that describe the physics to calculate the data that would result from a given combination of geoelectric model and electrode configuration.
- Generally a *linear* process.
- Forward modeling produces *unique* results.



Computerized Interpretation: Inverse Modeling

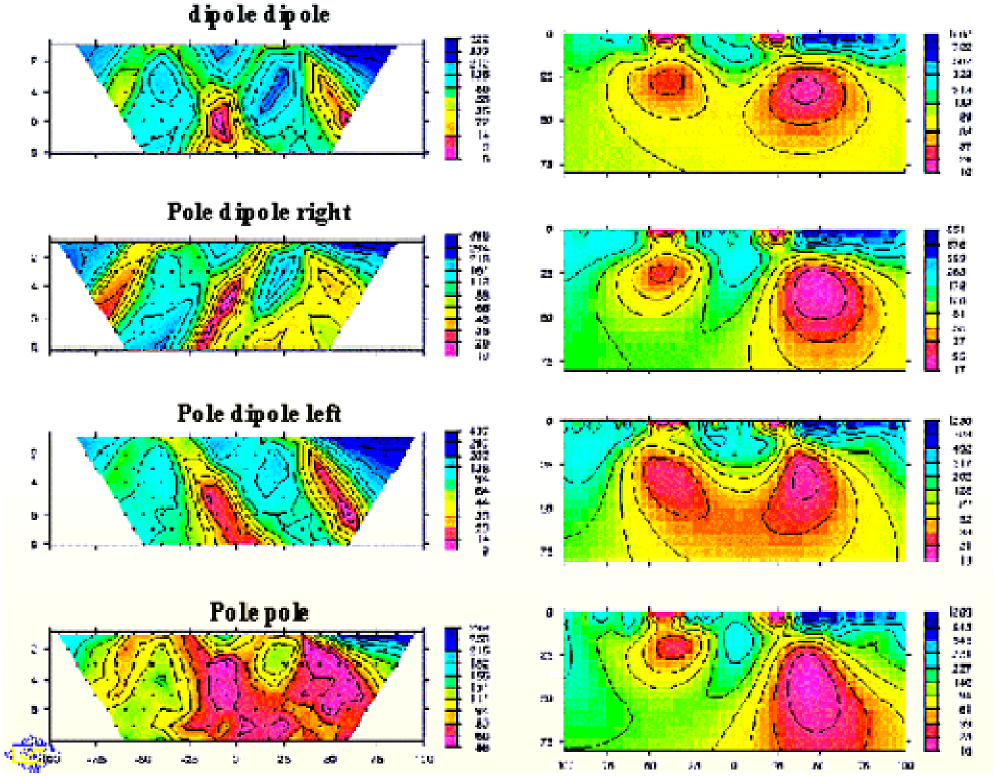
- Going the opposite direction. We measure data and know the array configuration, and through *inversion* wish to determine a geoelectric model that would produce data similar to those measured.
- Problems:
  - Generally problem is non-linear.
  - Problem is non-unique. Thus must add constraints of some sort to provide a reasonable answer.
  - Danger in over-interpreting the results.





Inverse Modeling

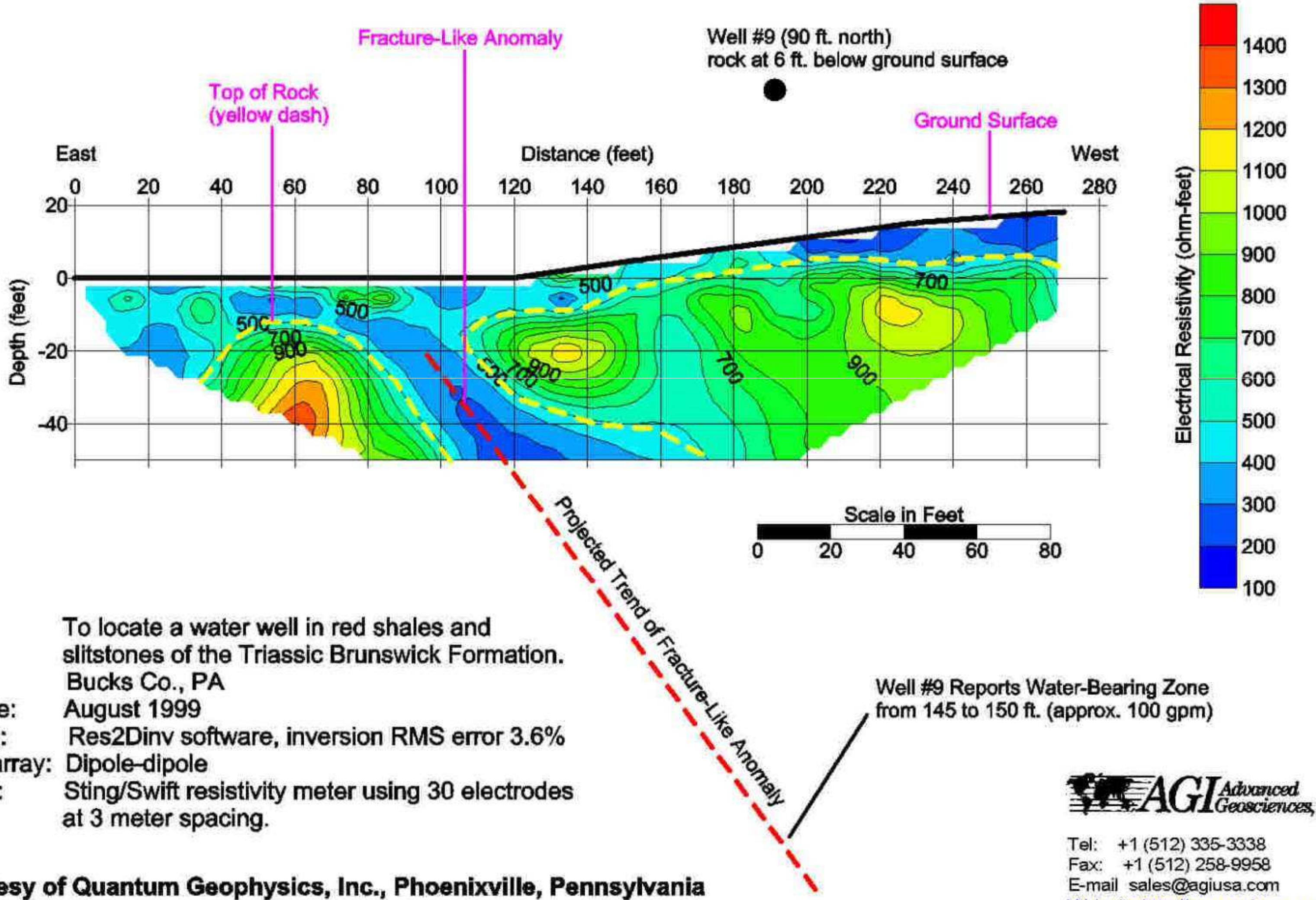
- Benefits:
  - –Automatic, it helps to remove *user bias. However sometimes the user's bias is needed to produce a decent model*
  - –Automatically removes differences associated with different electrode collection schemes.



Interpretation Issues - Resolution

- General 2D and 3D surveys
  - Basically, spatial resolution falls off as you get further away from the surface. Need larger bodies/higher contrasts at greater depths to be detectable
  - <u>Near surface very well resolved</u> – min. horizontal resolution equal to minimum electrode separation
  - <u>Depth resolution is array dependent</u>
  - REMEMBER – Over-interpretation is very easy given the non-uniqueness of physics as well as the inverse problem. Thus need to be careful.

Locating Water Bearing Fracture Zones in Bedrock



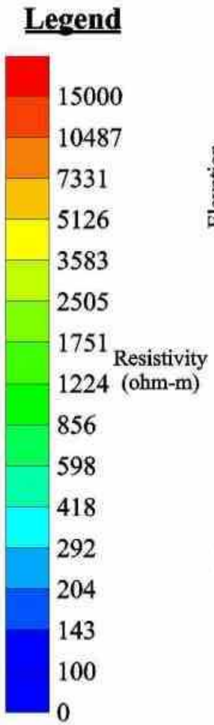
Well #9 Reports Water-Bearing Zone from 145 to 150 ft. (approx. 100 gpm)

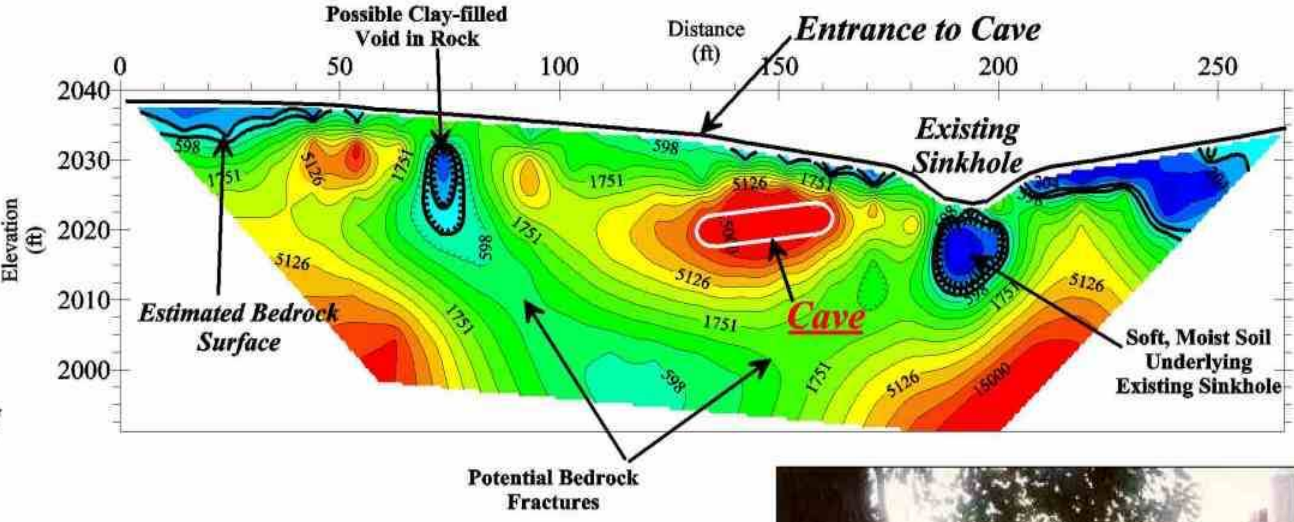
Objective:	To locate a water well in red shales and slitstones of the Triassic Brunswick Formation.
Location:	Bucks Co., PA
Survey date:	August 1999
Processing:	Res2Dinv software, inversion RMS error 3.6%
Electrode array:	Dipole-dipole
Equipment:	Sting/Swift resistivity meter using 30 electrodes at 3 meter spacing.

Courtesy of Quantum Geophysics, Inc., Phoenixville, Pennsylvania

AGI Advanced Geosciences, Inc.

Tel: +1 (512) 335-3338
Fax: +1 (512) 258-9958
E-mail sales@agiusa.com
Web site http://www.agiusa.com



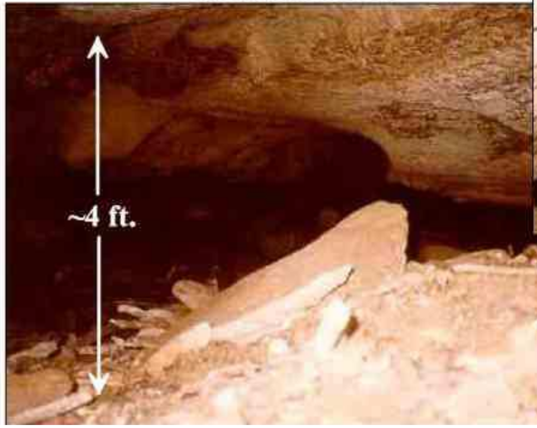


Scale

Horizontal: 1" = 40'
Vertical: 1" = 25'

Looking into Cave from Entrance

Approximate 25 ft Wide Room Inside Cave

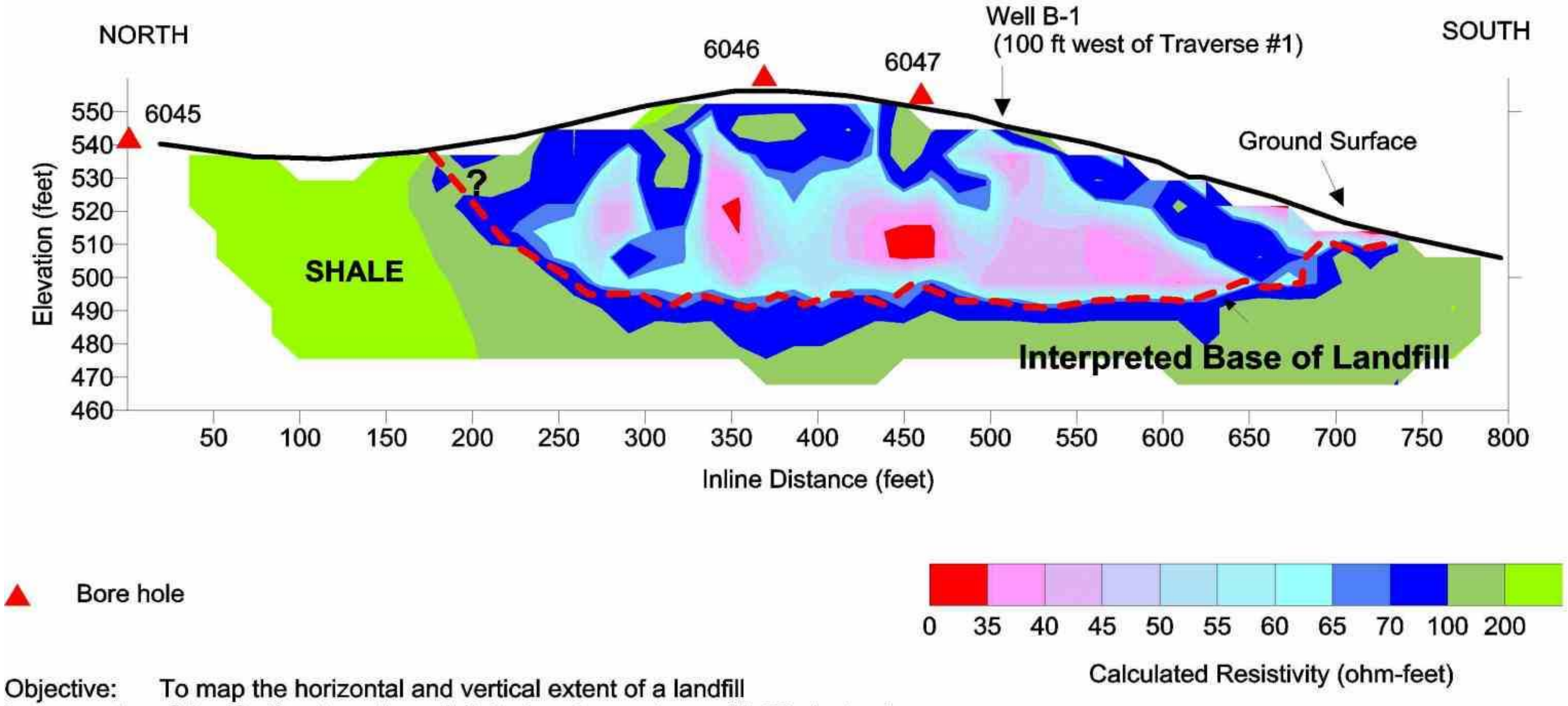


The above two-dimensional resistivity profile was conducted over top of the cave shown. Data was recorded using the Sting/Swift automatic system with 28 electrodes at 2 m spacing in a dipole-dipole array. Soil coverage was thin, rock was within 6 inches of the ground surface above the cave. Adjacent to the cave entrance was an existing sinkhole. Both the cave and fractures beneath the sinkhole can be seen in the profile.

Courtesy of
Schnabel Engineering
Web site http://www.schnabel-eng.com

AGI Advanced Geosciences, Inc.
Tel: +1 (512) 335-3338
Fax: +1 (512) 258-9958
E-mail sales@agiusa.com
Web site http://www.agiusa.com

Mapping the Limits of a Municipal Landfill



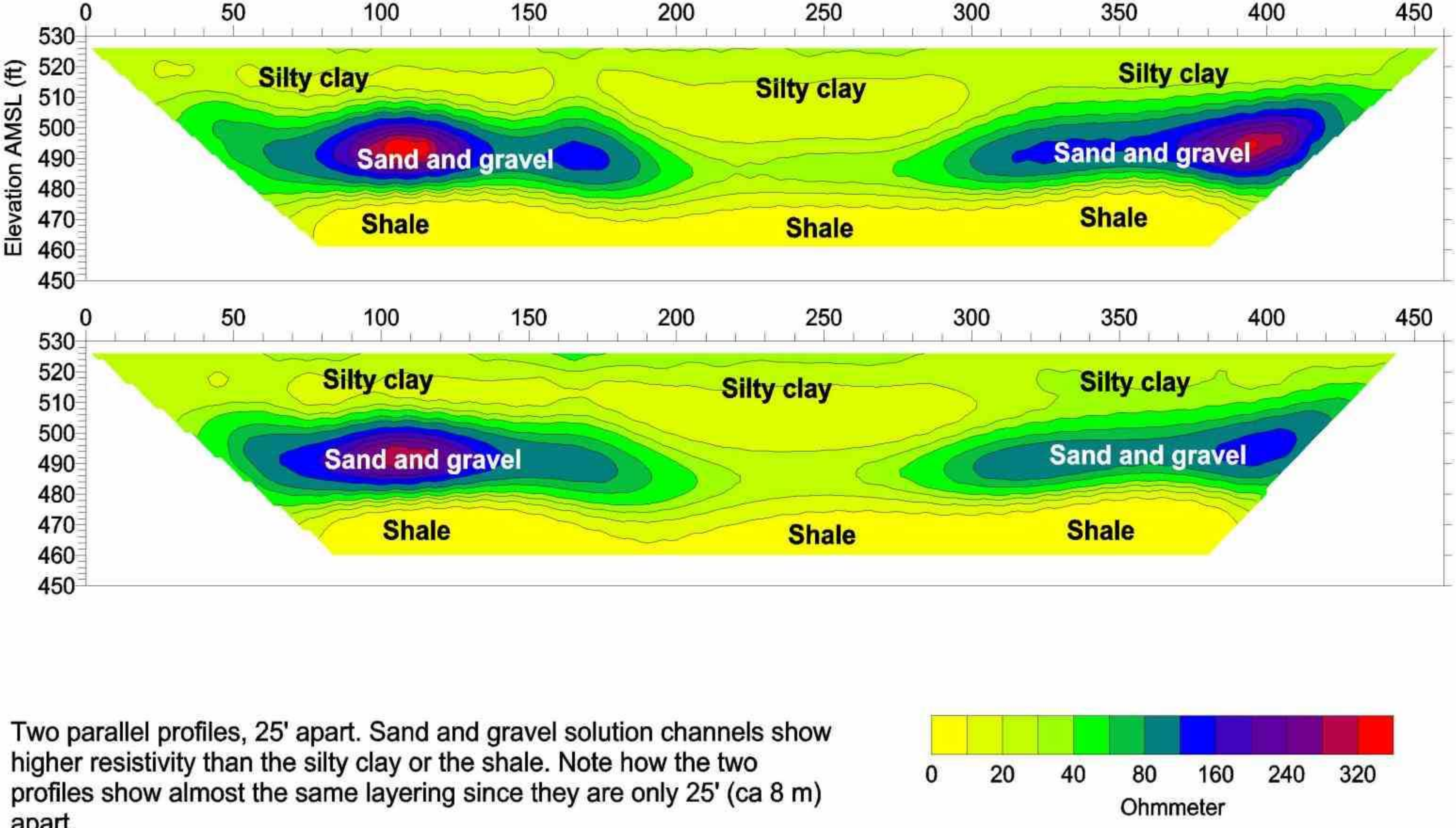
Objective: To map the horizontal and vertical extent of a landfill
Instrument: Sting/Swift automatic resistivity imaging system, with 56 electrodes at 6 meter spacing
Method: Dipole-dipole electrode array
Processing: Inversion and topographic correction using the Res2Dinv software
Units: Feet and ohmfeet

Courtesy of
SAIC
An Employee-Owned Company
GEOPHYSICAL SERVICES
Middletown, Pennsylvania

AGI Advanced Geosciences, Inc.

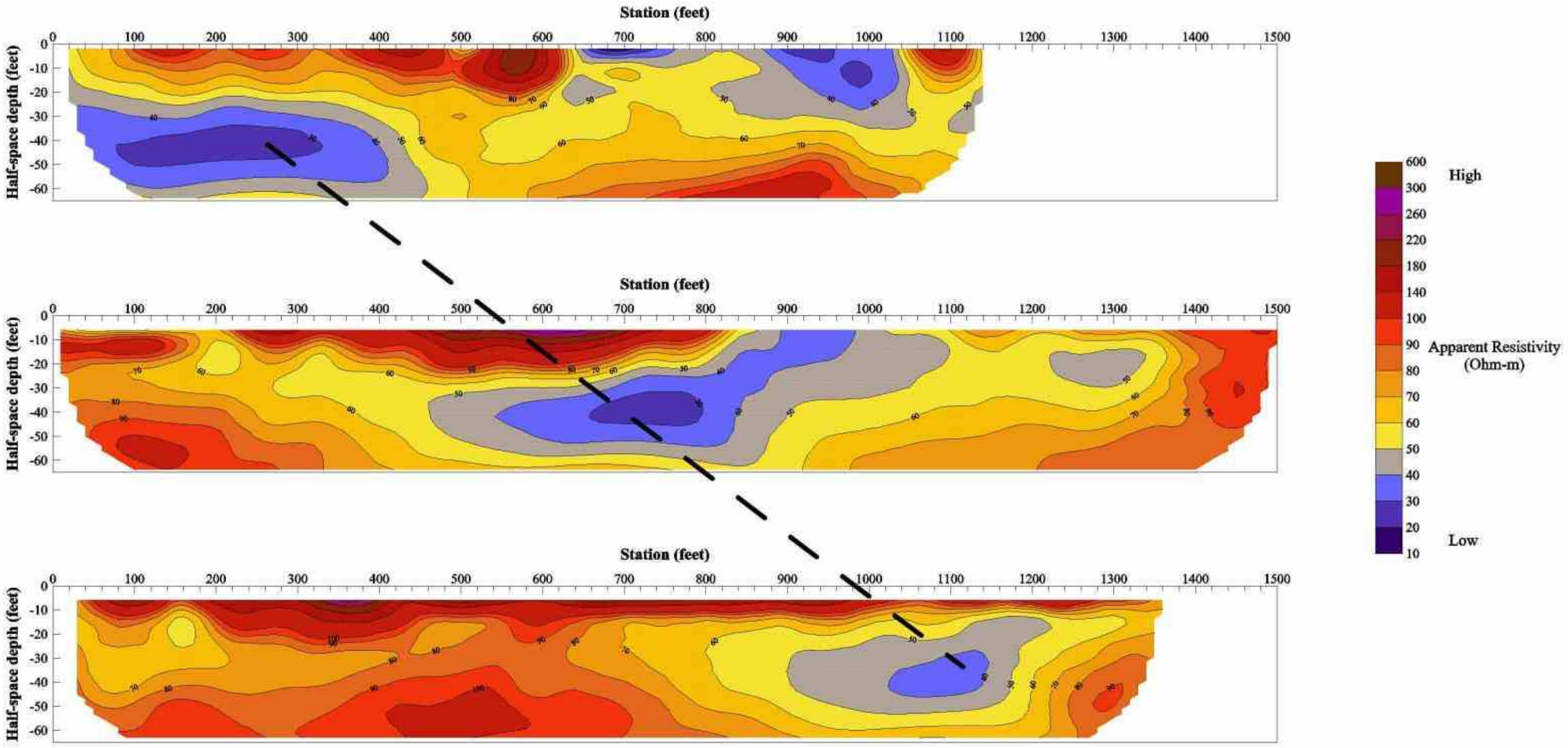
Tel: +1 (512) 335-3338
Fax: +1 (512) 258-9958
E-mail sales@agiusa.com
Web site http://www.agiusa.com

Mapping of Stratigraphy
Sand and Gravel Lenses in Clay Environment



Two parallel profiles, 25' apart. Sand and gravel solution channels show higher resistivity than the silty clay or the shale. Note how the two profiles show almost the same layering since they are only 25' (ca 8 m) apart.

Plume Mapping Using High Resolution Resistivity



Objective: The objective was to map the extent of a pollution plume
Survey date: 1996
Instrument: Sting R1 using manual cables
Method: Pole-pole array
Spacing: 5 - 200 feet
Units: Feet and Ohmmeter

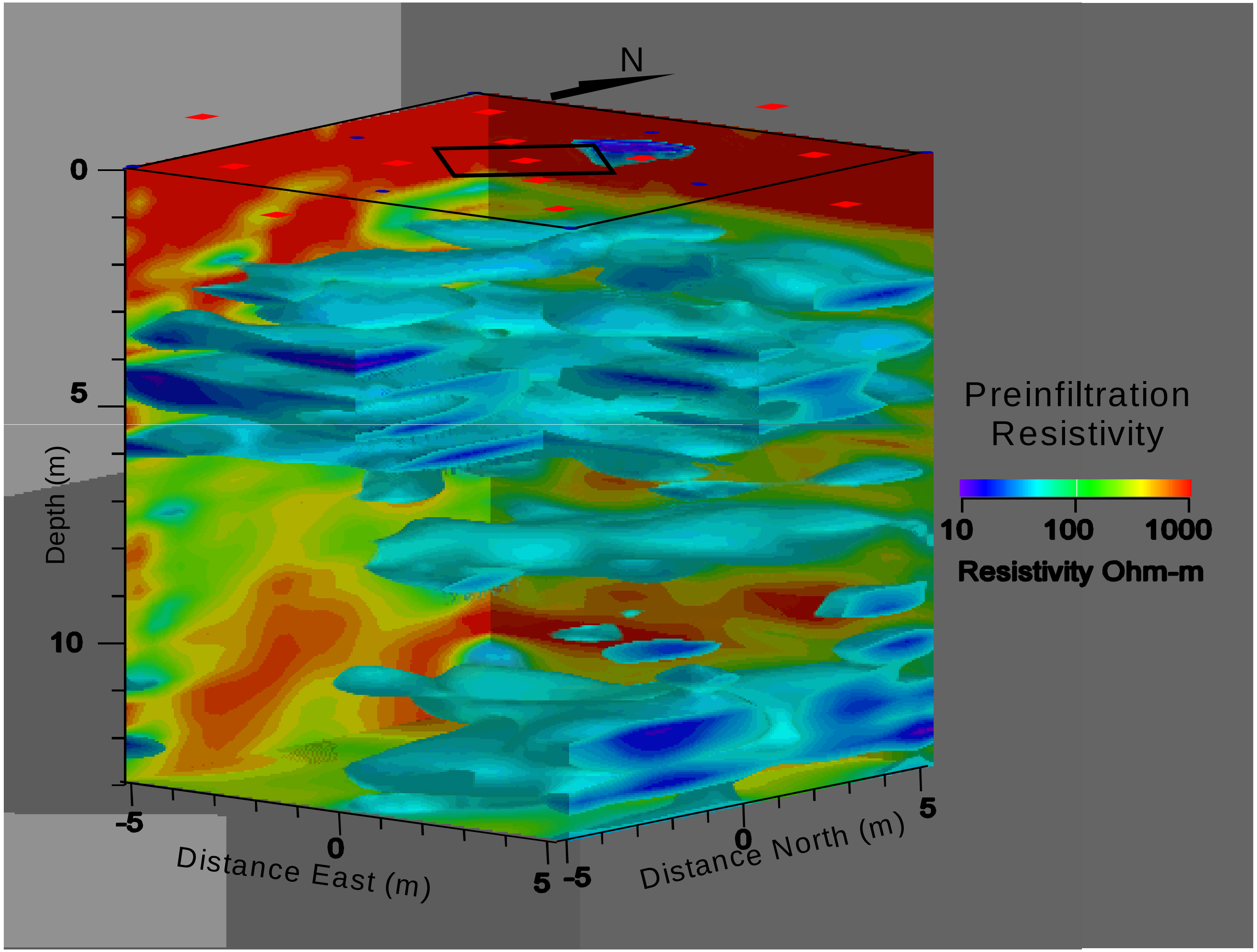
Vertical Exaggeration: 3:1
0 50 100 150 200 250 (feet)

Courtesy of
hydroGEOPHYSICS, Inc.
Tucson, Arizona

AGI Advanced Geosciences, Inc.

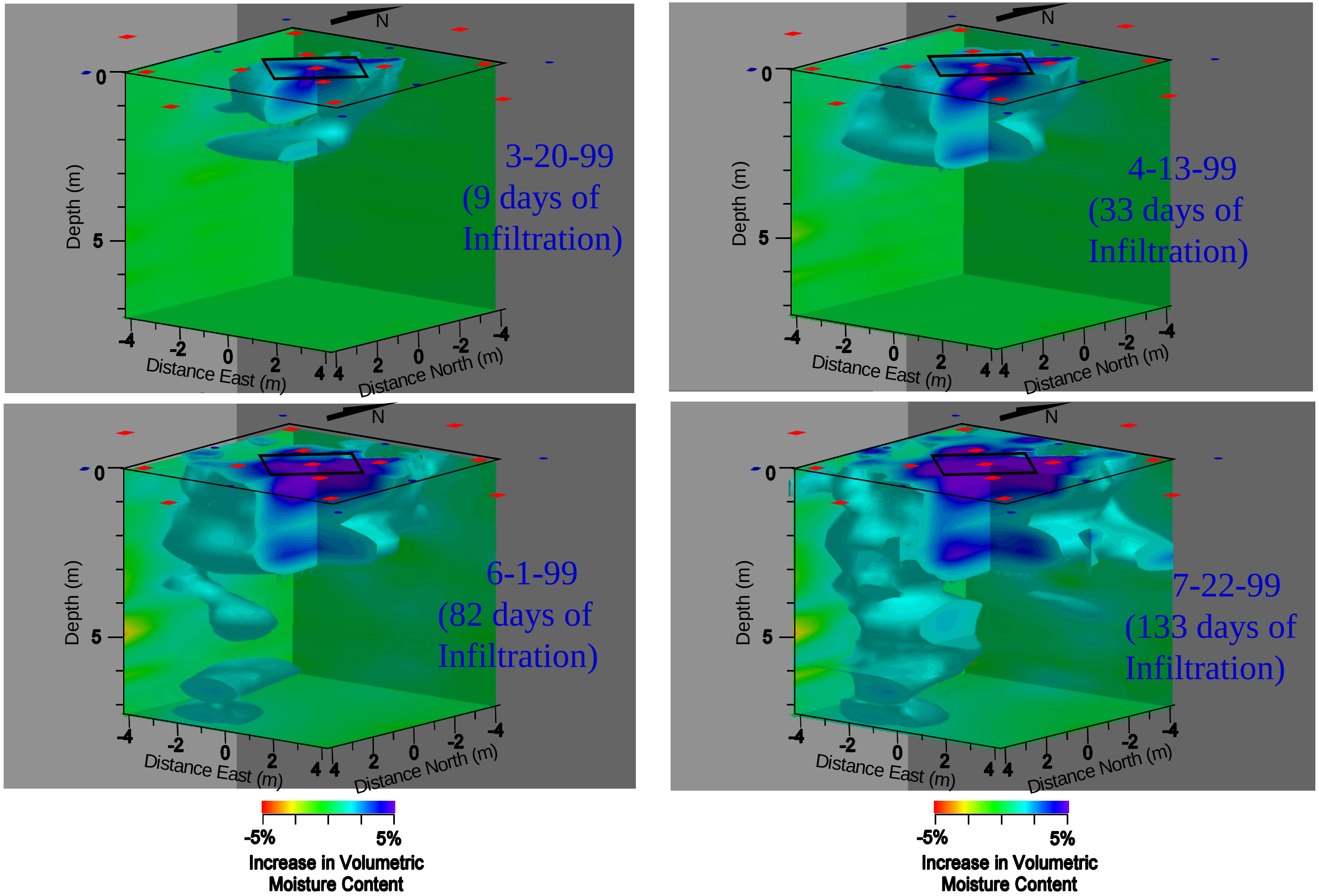
Tel: +1 (512) 335-3338
Fax: +1 (512) 258-9958
E-mail sales@agiusa.com
Web site http://www.agiusa.com

Hydrologic/Contaminant Studies



Source: Alumbaugh and co-workers

Hydrologic/Contaminant Studies



3-20-99
(9 days of
Infiltration)

4-13-99
(33 days of
Infiltration)

6-1-99
(82 days of
Infiltration)

7-22-99
(133 days of
Infiltration)

Source: Alumbaugh and co-workers