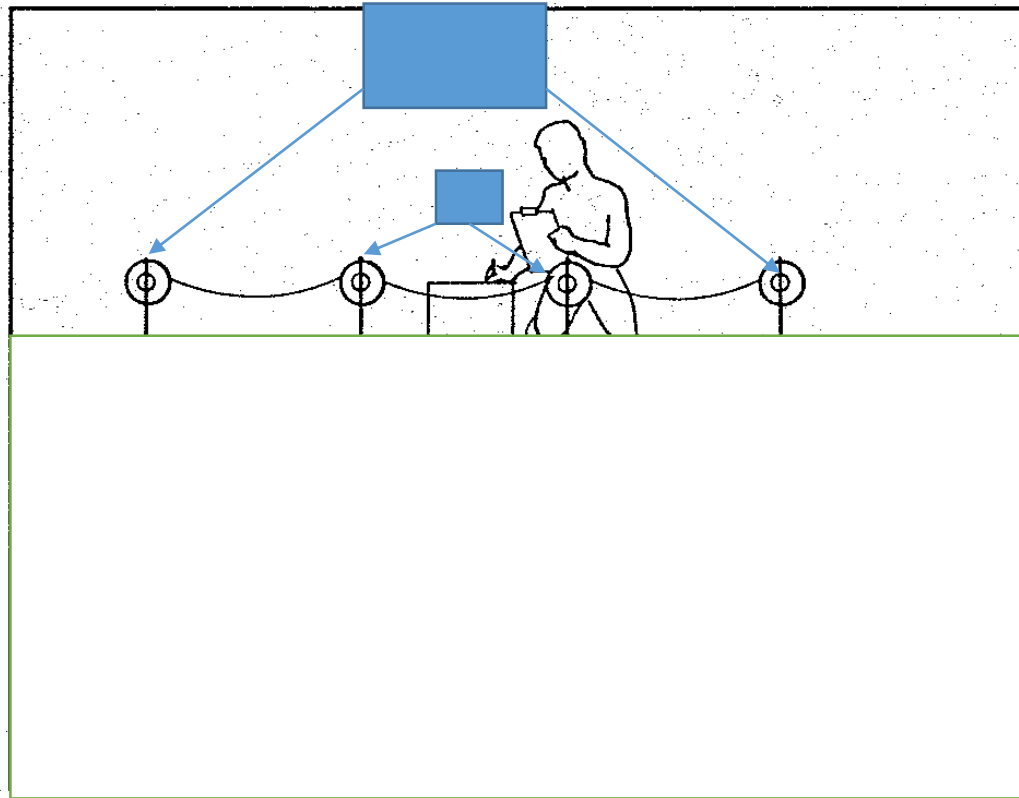


GEOELECTRICAL METHOD



S. N	Detail of Lectures	Lectures
1	Electrical Properties of rocks	2
2	Potentials in homogenous media. Equipotential surface generated by single and two electrodes. Effects of inhomogenous ground. Analogy between optical and electrical images	3
3	Fundamental relation between potential, apparent resistivity, resistivity transform and layer distribution of a stratified earth (multiplayer).	3
4	Electrode Configuration, Geometrical constant, definition of apparent resistivity.	3
5	Application of linear filter theory analogy. Frequency characteristics of Schlumberger filter. Sampling interval, Shanon's Sampling theorem. Nyquist Rule. Determination of Sampling Interval.	4
6	Determination of Schlumberger filters coefficients. Sinc response of the Schlumberger filter. Filter coefficients, length of filter.	4
7	Recurrence relation, Flathe and Pekris Recurrence relations. Determination of resistivity transform by using Pekris Recurrence Relation.	3
8	Potential due to a point source in an anisotropic medium. Triangle of anisotropy, Paradox of Anisotropy, Principle of equivalence and suppression	3
9	Self-Potential Method: Causes of Self-Potential, Interpretation of SP Data	3
10	Introduction, Sources of IP, Membrane polarization, Electrode polarization, Time and Frequency Domain measurements. Chargeability, Frequency effect and metal factor. Apparent Chargeability over layered earth, Application in Hydrocarbon Exploration	7
11	Electrical resistivity tomography: Principle and Acquisition, Frechet Derivative for homogenous half-space, 1-D view of the sensitivity function- depth of investigation, 2-D view of the sensitivity function lateral and vertical resolution of the different arrays	5
12	Mise-a-la-masse Method	2

Table 1.1 *Resistivities of metals and elements (at zero frequency)*

Metals	Resistivity (ρ) $\times 10^{-8}$ (ohm-m)
Aluminium	2.5
Arsenic	35
Beryllium	5.5
Chromium	15.3
Copper	1.6
Gold	2.0
Graphite (carbon)	36 to 100 (current flow parallel to cleavage)
Graphite (carbon)	2800 to 9,90,000 (current flow across cleavage)
Iron	9.0
Lead	19
Molybdenum	4.3
Nickel	6.3
Platinum	9.8
Silver	1.5
Tin	10.0
Uranium	30.0
Zinc	5.5
Zirconium	42

Table 1.2 Resistivities of minerals (at zero frequency)

Mineral	Formula	Resistivity (ρ) (ohm-m)	
		Range	Average
Sulphides			
Argentinite	Ag ₂ S	1.5 to 2.0×10^{-3}	1.7×10^{-3}
Bornite	Fe ₂ S ₃ .nCu ₂ S	2.5×10^{-5} to 0.5	3×10^{-3}
Chalcocite	Cu ₂ S	3×10^{-5} to 0.6	10^{-4}
Chalcopyrite	Fe ₂ S ₃ .Cu ₂ S	1.2×10^{-5} to 0.3	4×10^{-3}
Cinnabar	HgS		2×10^7
Covelite	CuS	0.30 to 83×10^{-6}	2×10^{-5}
Galena	PbS	6.8×10^{-6} to 3×10^2	2×10^{-3}
Molybdenite	MoS ₂	10^{-3} to 10^6	10
Pentlandite	(Fe,Ni) ₉ S ₈	1 to 11×10^{-6}	
Pyrrhotite	Fe ₇ S ₈	6.5×10^{-6} to 5×10^{-2}	10^{-4}
Pyrite	FeS ₂	2.9×10^{-5} to 1.5	3×10^{-1}
Sphalerite	ZnS	1.5 to 10^7	10^2
Stibnite	Sb ₂ S ₃	10^5 to 10^{12}	5×10^6
Arsenic-sulphur compounds			
Arsenopyrite	FeAsS	2×10^{-5} to 15	10^{-3}
Cobaltite	CoAsS	6.5 to 130×10^{-3}	
Oxides			
Bauxite	Al ₂ O ₃ .nH ₂ O	2×10^2 to 6×10^3	
Braunite	Mn ₂ O ₃	0.16 to 1.2	
Cassiterite	SnO ₂	4×10^{-4} to 10^4	0.2
Chromite	FeCr ₂ O ₄	1 to 10^6	
Cuprite	Cu ₂ O	10^{-3} to 300	30
Haematite	Fe ₂ O ₃	3.5×10^{-3} to 10^7	
Ilmenite	FeTiO ₃	10^{-3} to 50	
Limonite	2Fe ₂ O ₃ .3H ₂ O	10^3 to 10^7	
Magnetite	Fe ₃ O ₄	52×10^{-6} to 5.7×10^3	
Manganite	MnO.OH		

Manganite	MnO.OH		
		10 ⁻² to 0.5	
Psilomilane	KMnO.MnO ₂ .nH ₂ O	0.04 to 6 × 10 ³	
Pyrolusite	MnO ₂	5 × 10 ⁻³ to 30	
Quartz	SiO ₂	4 × 10 ¹⁰ to 2 × 10 ¹⁴	
Rutile	TiO ₂	30 to 10 ³	5 × 10 ²
Uraninite (pitchblende)	UO ₂	1 to 200	
Wolframite	Fe, Mn,WO ₄	10 to 10 ⁵	
Others			
Anhydrite	CaSO ₄	10 ⁷ to 10 ¹⁰	
Coal (anthracite)		10 ⁻⁴ to 2 × 10 ⁵	
Coal (bituminous)		0.6 to 10 ⁵	
Coal (various)		10 to 10 ¹¹	
Coal (lignite)		9 to 200	
Diamond	C	10 to 10 ¹⁴	
Graphite (massive)	C	10 ⁻⁶ to 5 × 10 ⁻³	
Fluorite	CaF ₂	8 × 10 ¹³	
Mica (biotite)		9 × 10 ² to 10 ¹⁴	
Mica (muscovite)		10 ¹¹ to 10 ¹²	
Oil (crude)		10 ⁹ to 10 ¹⁶	
Water (meteoric)		30 to 10 ³	
Water (surface igneous rocks)		0.1 to 3 × 10 ³	
Water (surface sediments)		10 to 100	
Water (soil)		100	100
Water (natural igneous rocks)		0.5 to 150	9
Water (natural sediments)		1 – 100	3
Water (sea)		0.2	0.2
Water (3% salinity)		0.15	0.15
Water (20% salinity)		0.05	0.05

Table 1.3 Resistivities of various ores

Ore	Other minerals	Gangue	Resistivity (ρ) (ohm-m)
Pyrite			
18 %	2% chalcopyrite	80%	300
40%	20%	40%	130
60%	5% (ZnS) + 15%	20%	0.9
75%	10% (ZnS) + 5%	10%	0.14
95%	5%		1.0
95%	—	5%	7.0
Pyrrhotite			
41% to 58%	—	59%–42%	$2.2 \text{ to } 2.3 \times 10^{-4}$
70% to 82%	—	21%–18%	$1.4 \text{ to } 8.5 \times 10^{-5}$
95%	—	5%	1.4×10^{-5}
Others			

(Contd.)

SbS ₂			$4 \times 10^3 \text{ to } 3 \times 10^7$
FeAsS (60%)	FeS (20%)	20% SiO ₂	0.39
FeAsS			$10^{-4} \text{ to } 10^{-2}$
Cu ₂ FeS ₄			3×10^{-3}
Cu ₂ FeS ₄ (40%)		60% SiO ₂	7×10^{-2}
Fe, Mn, Wo ₄	CoAsS		$10^3 \text{ to } 10^7$
PbS (massive galena)			7×10^{-2}
PbS (50 to 80% galena)			$10^{-3} \text{ to } 3$
Iron			
Fe ₂ O ₃ (haematite)			0.1 to 300
Fe ₂ O ₃ (massive haematite)			2.5×10^3
Fe ₂ O ₃ (fine-grained haematite)			2.5×10^3
Fe ₃ O ₄ (magnetite)			5 to 8×10^3
Fe ₃ O ₄ (magnetite 60%)			45
Fe ₂ O ₃ (fine-grained haematite)			2.5×10^3
Zinc			
30%	5% PbS, 15% FeS	50%	0.75
70%	3% Chalcopyrite, 17% PbS, 10% FeS		20
80%	10% PbS, 10% FeS		1.7×10^3
80%	2% Chalcopyrite, 1% PbS, 2% FeS	15%	1.3
90%	5% PbS	5%	130
Copper			
Cu ₂ S (chalcocite)			3×10^{-2}
CuFeS ₂ (chalcopyrite)			$10^{-4} \text{ to } 1$
CuFeS ₂ 80%	10% FeS	10%	0.66
CuFeS ₂ 90%	2% FeS	8% SiO ₂	0.65
Others			
FeCr ₂ O ₄ (chromite)			10^3
FeCr ₂ O ₄ 95%		5% Serpentine	1.2×10^4
MnO ₂ (pyrolusite) colloidal ore			1.6
MoS ₂ (molybdenite)			$2 \times 10^2 \text{ to } 4 \times 10^3$
Graphite (massive)			$10^{-4} \text{ to } 5 \times 10^{-3}$
Graphitic shale			$10^{-3} \text{ to } 10$
Graphitic slate			0.13

Table 1.4 Resistivities of igneous, metamorphic, sedimentary rocks, and sediments

Rock type	Resistivity range (ohm-m)
Igneous rocks	
Andesite	1.7×10^2 to 4.5×10^4
Basalt	10 to 1.3×10^7
Dacite	2×10^4
Diorite	10^4 to 10^5
Gabbro	10^3 to 10^6
Granite	3×10^2 to 10^6
Lavas	10^2 to 5×10^4

Olivine norite	10^3 to 6×10^4
Peridotite	3×10^3 to 6.5×10^3
Metamorphic rocks	
Gneiss	6.8×10^4 to 3×10^6
Graphitic schists	10 to 100
Marble	10^2 to 10^{12}
Quartzite	10 to 10^8
Schists	20 to 10^4
Skarn	2.5×10^2 to 2.5×10^6
Slates	6×10^2 to 4×10^7
Tuffs	2×10^3 to 10^5

Sedimentary rocks and sediments	
Argillites	10 to 8×10^2
Dolomite	3.5×10^2 to 5×10^3
Limestone	50 to 10^7
Marls	3 to 70
Sandstones	1 to 6.4×10^8
Shale (consolidated)	20 to 2×10^3
Sediments	
Alluvium and sands	10 to 800
Clays	1 to 120
Clay (unconsolidated and wet)	20
Conglomerates	2×10^3 to 10^4
Moraine	8 – 4000
Oil sands	4 to 800

Table 1.5 *Effect of water content in rock resistivity*

Rock	Percentage (%) of water (H ₂ O)	Resistivity (ohm-m)
Basalt	0.95	4×10^4
Basalt	0.49 to 0.26	9×10^5 to 3×10^7
Basalt	0	1.3×10^8
Diorite	0.02 to 0	5.8×10^5 to 6×10^6
Dolomite	2 to 0.96	5.3×10^3 to 8×10^3

Granite	0.31	4.4×10^3
Granite	0.19 to 0.06	1.8×10^6 to 1.3×10^8
Granite	0	10^{10}
Limestone (organic)	11	0.6×10^3
Olivine-pyroxene	0.028 to 0.014	2×10^4 to 4×10^5
Olivine-pyroxene	0	5.6×10^7
Peridotite	1.1 to 0.03	3×10^3 to 2×10^4
Peridotite	0.016 to 0	10^6 to 1.8×10^7
Pyrophyllite	0.76 to 0.72	6×10^6 to 5×10^7
Pyrophyllite	0.7 to 0	2×10^8 to 10^{11}
Sandstone (arkosic)	1.26 to 1.0	10^3 to 1.4×10^3
Sandstone (coarse-grained)	0.39 to 0.18	9.6×10^5 to 10^8
Sandstone (medium-grained)	1.0 to 0.67	4.2×10^3 to 3.2×10^6
Sandstone (medium-grained)	0.1	1.4×10^8
Siltstone	0.54 to 0.44	1.5×10^4 to 8.4×10^6
Siltstone	0.38	5.6×10^8

Formation Factor

Archie (1942) provided the most acceptable equation for the conductivity of water-bearing formations as

$$\sigma = a\sigma_w W^m$$

where σ is the conductivity of rock formation, σ_w is the conductivity of the electrolyte present in the pore spaces, W is the volume fraction of water present in the rock assuming the entire pore spaces are completely filled with water, and a and m (cementation factor) are parameters depending on the nature of rock formations. When the pore spaces are partially filled with water then the equation changes to

$$\sigma = a\sigma_w S^\alpha \phi^m$$

where, S is the fraction of pore space filled with water, α is the saturation exponent and ϕ is the porosity. The saturation exponent in general lies between 1.5 and 3.0. It is usually assumed to 2.0 where there is no evidence to the contrary.

Relationship between the formation factor (F), defined as *ratio of rock matrix resistivity (ρ_m) to the resistivity of water saturating it (ρ_w)*, with fractional water content for all the three types of rock formations.

Formation factor is the backbone of electrical logging in the oil industry. This has been subsequently extended to groundwater exploration. Formation factor may be expressed as the ratio of rock-matrix resistivity with that of the resistivity of the electrolyte filling the pore spaces, i.e.,

$$F = \frac{\rho_m}{\rho_w}$$

Considering all points together, Archie (1942) provided the following empirical relation, known as *Archie's law*, between formation factors of rock samples with their porosities:

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

Electrical Properties of Rocks and Minerals

What Are Minerals?

Minerals are naturally occurring, inorganic substances with a definite chemical composition and crystalline structure. They are the building blocks of rocks. Each mineral has a specific chemical formula, often comprising elements such as silicon, oxygen, carbon, and iron. These elements combine in specific ways to form the distinct structures and properties of each mineral.

For example, quartz is a common mineral made up of silicon and oxygen (SiO_2). It forms crystals and is known for its hardness and glassy luster. Feldspar, another common mineral, also contains silicon and oxygen but combines with other elements like aluminum, potassium, or calcium, leading to different types of feldspar with varying colors and properties.

What Are Rocks?

Rocks are aggregates of one or more minerals or mineraloids (minerals lacking a crystalline structure). They form through various geological processes, including cooling of molten material, compression, and cementation of sediments, or alteration by heat and pressure.

There are three main types of rocks:

Igneous Rocks: Formed from the cooling and solidification of molten rock (magma or lava). Granite, for example, is an igneous rock composed mainly of quartz, feldspar, and mica. Its speckled appearance results from the interlocking crystals of these minerals.

Sedimentary Rocks: Formed from the accumulation and compaction of sediments, which can include fragments of other rocks, minerals, and organic material. Sandstone is a sedimentary rock primarily composed of quartz grains that have been cemented together over time. The mineral content in sandstone largely depends on the source of the sediment.

Metamorphic Rocks: Formed when existing rocks are subjected to intense heat and pressure, causing them to change physically and chemically. Marble is a metamorphic rock that originates from limestone (which is mainly composed of the mineral calcite) but becomes denser and more crystalline due to the metamorphic process.

Key Differences Between Rocks and Minerals

Composition: Minerals have a fixed chemical composition and structure, while rocks are mixtures of various minerals. For instance, basalt, an igneous rock, typically contains minerals like pyroxene, olivine, and plagioclase.

Formation: Minerals form through specific processes such as crystallization, while rocks are formed through a variety of processes, including cooling, sedimentation, and metamorphism.

Appearance and Properties: Minerals exhibit unique physical properties like color, luster, hardness, and cleavage, which help in their identification. Rocks, on the other hand, often have a composite appearance reflecting the minerals within them. For example, the banded appearance of gneiss, a metamorphic rock, results from the alignment of minerals like quartz, feldspar, and mica under pressure.

While rocks and minerals are closely related, understanding the distinction between them is crucial in geology. Minerals are the pure substances with specific compositions that combine to form rocks, which are the more complex, heterogeneous materials making up Earth's crust. By studying both, geologists can unravel the history and processes that have shaped our planet over billions of years.

CLASSIFICATION OF ELECTRICAL METHODS

Electrical prospecting involves the detection of surface effects produced by electric current flow in the ground. There is a much greater variety of techniques available than in the other prospecting methods, where one makes use of a single field of force or anomalous property - gravitation, magnetism, elasticity, radioactivity. Using electrical methods, one may measure potentials, currents, and electromagnetic fields that occur naturally - or are introduced artificially - in the earth.

Furthermore, the measurements can be made in a variety of ways to determine a variety of results. Basically, however, it is the enormous variation in electrical conductivity found in different rocks and minerals that makes these techniques possible.

Electrical methods include self-potential (SP), telluric currents and magnetotellurics (MT), resistivity, including mise-a-la-masse, electromagnetic (EM), including AFMAG, and induced polarization (IP).

They are often classified by the type of energy source involved, that is, natural or artificial. On this basis the first three and AFMAG above are grouped under natural sources and the remainder as artificial. Such a classification can be made for prospecting methods in general. Hence gravity, magnetics, and radioactivity are included in the natural source methods, whereas seismic requires artificial energy.

ELECTRICAL PROPERTIES OF ROCKS AND MINERALS

Several electrical properties of rocks and minerals are significant in electrical prospecting. They are natural electrical potentials, electrical conductivity/resistivity), and the dielectric constant.

Magnetic permeability is also an indirect factor. Of these, electrical conductivity is by far the most important, whereas the others are of minor significance.

Certain natural or spontaneous potentials occurring in the subsurface are caused by electrochemical or mechanical activity. The controlling factor in all cases is underground water. These potentials are associated with weathering of sulfide mineral bodies, variation in rock properties (mineral content) at geological contacts, bioelectric activity of organic material, corrosion, thermal and pressure gradients in underground fluids, and other phenomena of similar nature.

There are four principal mechanisms producing these potentials; the first is mechanical, the latter three chemical.

(i) Electrokinetic potential:

This is also known as streaming potential, this is observed when a solution of electrical resistivity ρ and viscosity η is forced through a capillary or porous medium. The resultant potential difference between the ends of the passage is

$$E_k = - \frac{\zeta \Delta P k \rho}{4 \pi \eta}$$

where τ is the adsorption (zeta) potential, ΔP is the pressure difference, and k is the solution dielectric constant.

(ii) Liquid-junction (diffusion) potential:

This is due to the difference in mobilities of various ions in solutions of different concentrations. The value is given by

$$E_d = - \frac{R\theta(I_a - I_c)}{Fn(I_a + I_c)} \ln\left(\frac{C_1}{C_2}\right)$$

where R is the gas constant, F is the Faraday constant, θ is the absolute temperature, n is the valence, I_a and I_c are the mobilities of anions and cations, and C_1 and C_2 are the solution concentrations.

(iii) **Shale (Nernst) potential**

When two identical metal electrodes are immersed in a homogeneous solution, there is no potential difference between them. If, however, the concentrations at the two electrodes are different, there is a potential difference given by

$$E_s = - \frac{R\theta}{Fn} \ln \left(\frac{C_1}{C_2} \right)$$

For $n = 1$, $\theta = 298$ K, this becomes (E_s in millivolts)

$$E_s = -59.1 \log(C_1/C_2)$$

The combined diffusion and Nernst potentials are known as the *electrochemical*, or *static, self-potential*. For NaCl at $T^\circ\text{C}$, the electrochemical self-potential (in millivolts) is

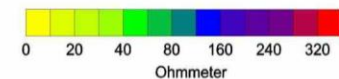
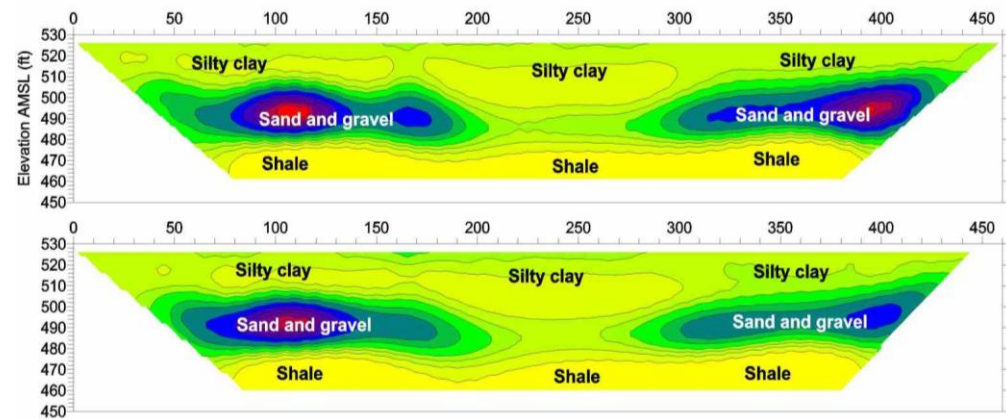
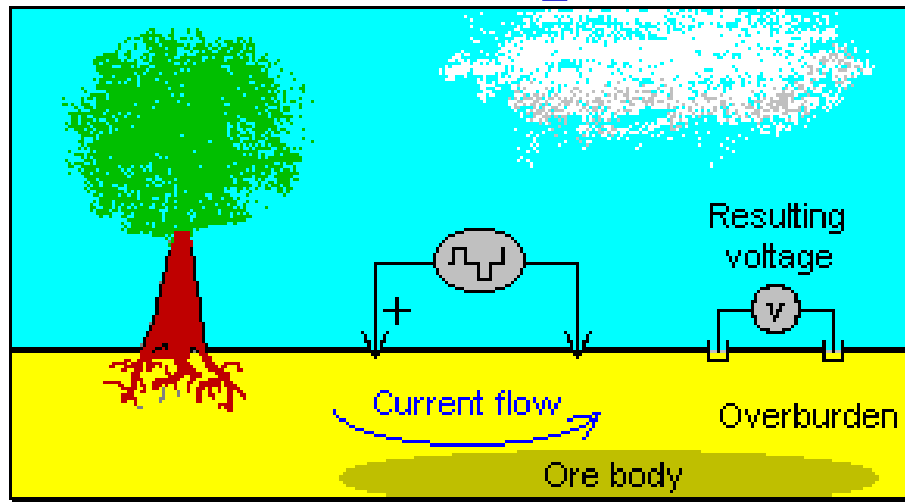
$$E_c = -70.7 \frac{(T + 273)}{273} \log \left(\frac{C_1}{C_2} \right)$$

(iv) **Mineralization potential:**

When two dissimilar metal electrodes are immersed in a homogeneous solution, a potential difference exists between the electrodes. This *electrolytic contact potential*, along with the static self-potential, considered in (i), (ii), and (iii) is undoubtedly among the basic causes of the large potentials associated with certain mineral zones and known as *mineralization potentials*.

These potentials, which are especially pronounced in zones containing sulfides, graphite, and magnetite, are much larger than those described in the preceding sections; values of several hundred millivolts are common and potentials greater than 1 V have been observed in zones of graphite and alunite

Earth Properties and Basic Theory

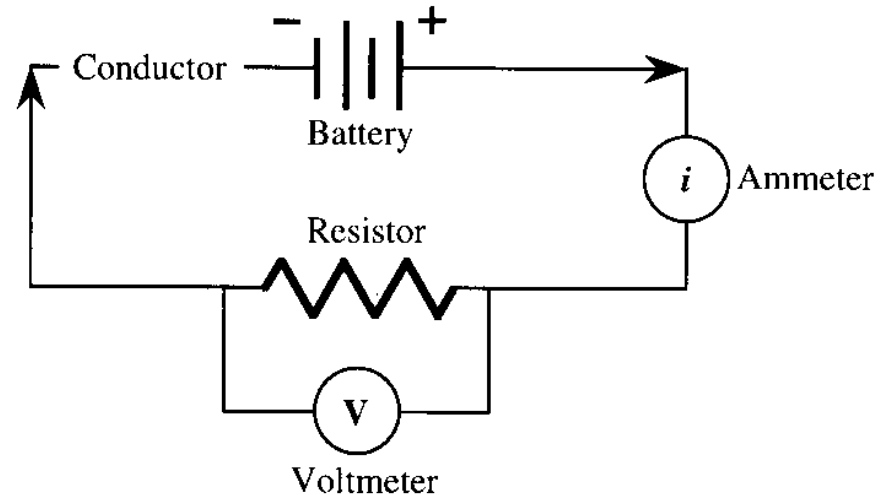


Electricity Basics

Voltage V - Electrical potential energy per unit charge [volts]

Current i - amount of charge per unit time [amperes]

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



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

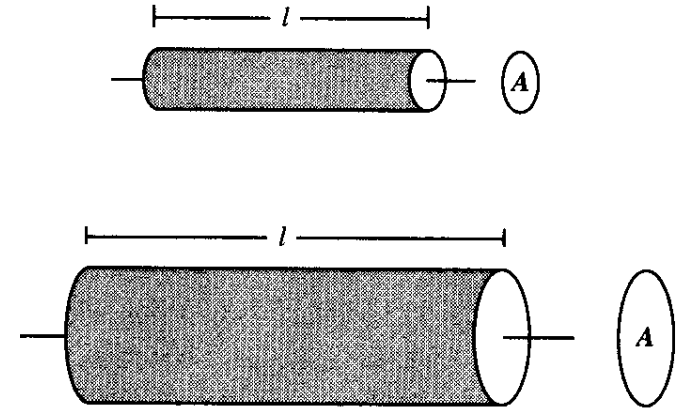
However, no units of length in this form of Ohm's law.

Resistivity

Resistance includes length and area

We want resistivity ρ [ohm m] because:

- It is a material property
- No geometry included



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

\uparrow length \rightarrow \uparrow resistance
 \uparrow area \rightarrow \downarrow 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


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

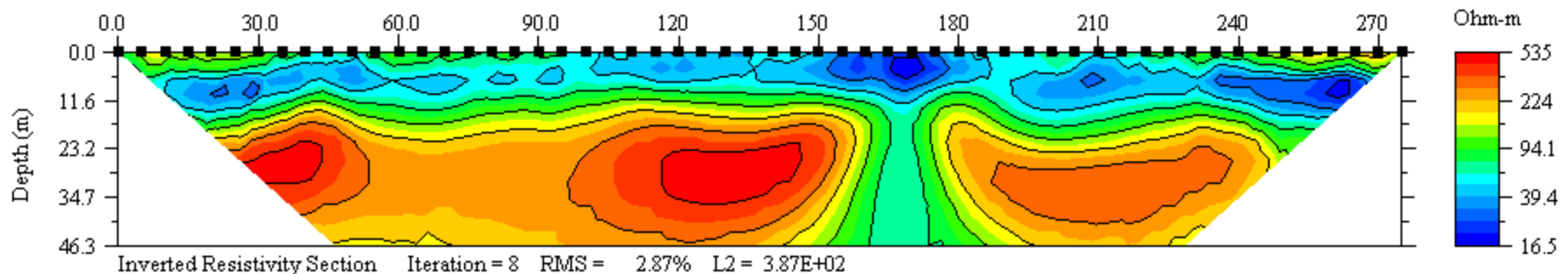
When looking at a solid, Ohm's law can be written as:

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

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

Resistivity of Geologic Materials

- The resistivity of the subsurface depends upon:
 - The presence of certain metals
 - Especially metallic ores
 - The temperature of the subsurface
 - Geothermal energy!
 - The presence of archeological features
 - Graves, fire pits, post holes, etc...
 - Amount of groundwater present 
 - Amount of dissolved salts
 - Presence of contaminants
 - % Porosity and Permeability



A resistivity profile

Archie's Law

- Porous, water-bearing rocks / sediments may be ionic conductors. Their “formation resistivity” is defined by *Archie's Law*:

$$\rho_t = a\rho_w\phi^{-m}s_w^{-n}$$

$\phi \equiv$ porosity

$s_w \equiv$ water saturation

$a \approx 0.5 - 2.5$

$n \approx 2$ if $s_w \geq 0.3$

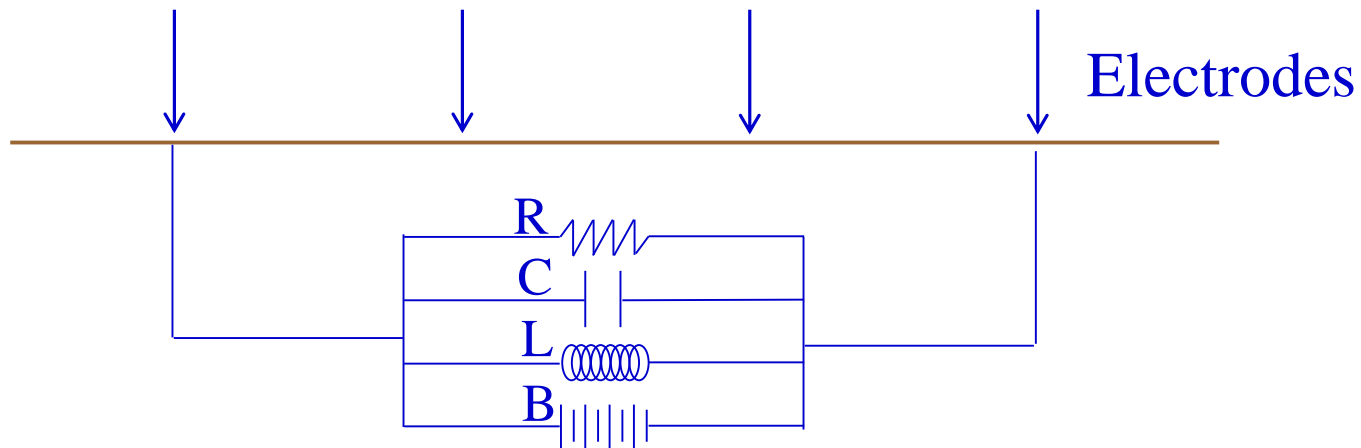
$m \equiv$ cementation ≈ 1.3 (Tertiary) – 2.0 (Palaeozoic)

– Archie's law is an empirical model

- Note the exponents...what does this imply about the range of resistivity of geologic materials?

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

General Rules of Thumb For Resistivity

Highest R

Igneous Rocks

Why? Only a minor component of pore water

Metamorphic Rocks

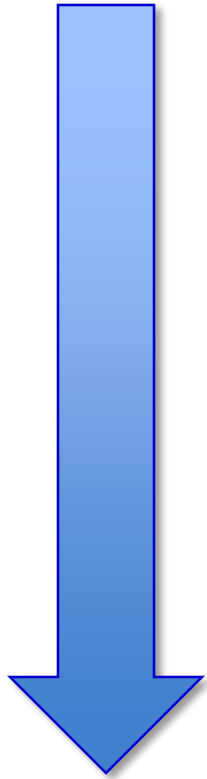
Why? Hydrous minerals and fabrics

Sedimentary Rocks

Why? Abundant pore space and fluids

Clay: super low resistivity

Lowest R

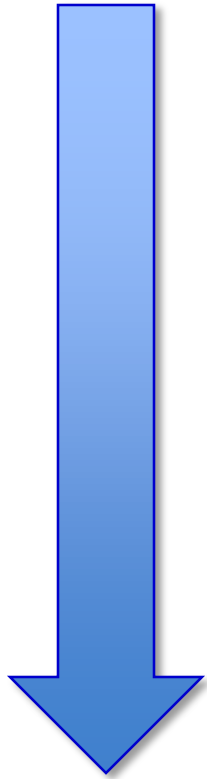


General Rules of Thumb For Resistivity

Highest R

Older Rocks

Why? More time to fill in fractures and pore space



Lowest R

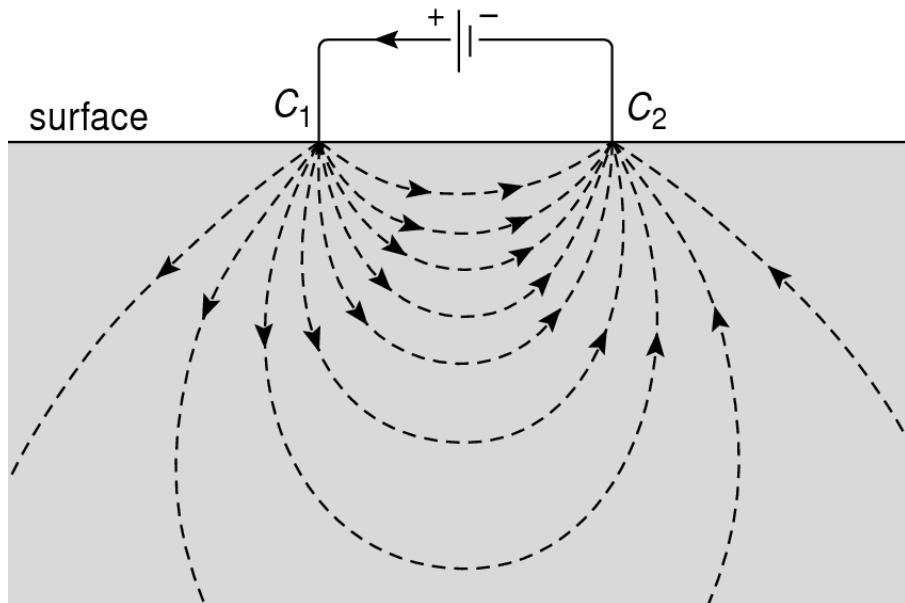
Younger Rocks

Why? Abundant fractures and/or pore space

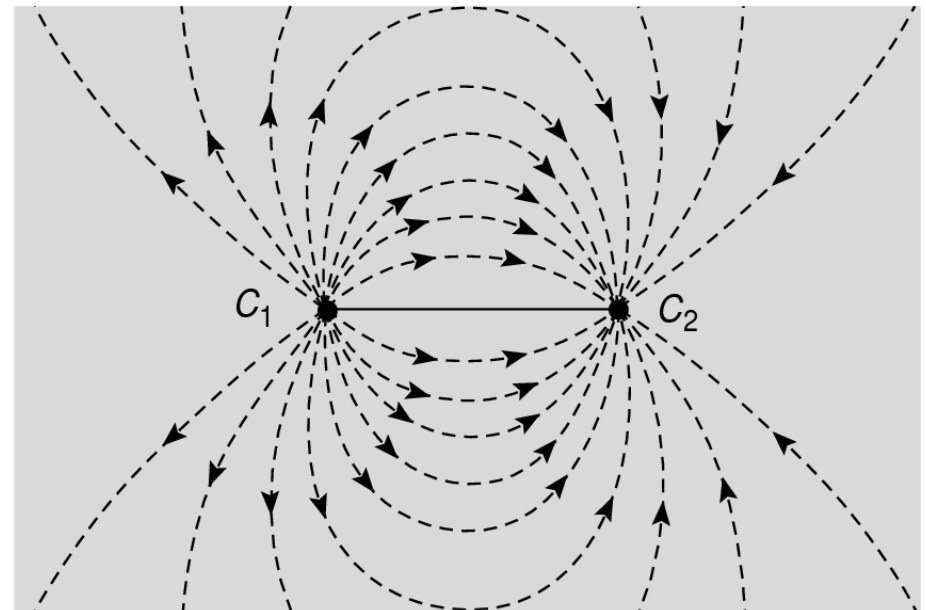
Subsurface Current Paths

- About 70% of the current applied by two electrodes at the surface stays within a depth equal to the separation of the electrodes
- Typically your electrode spacing is 2x your target depth
 - But this depends on array type (we'll cover this later)

(a) section



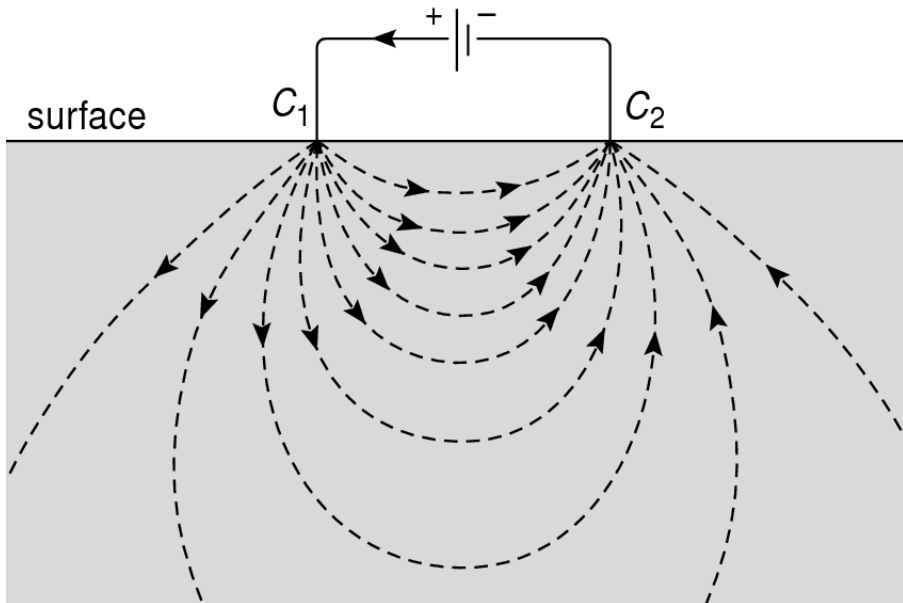
(b) plan



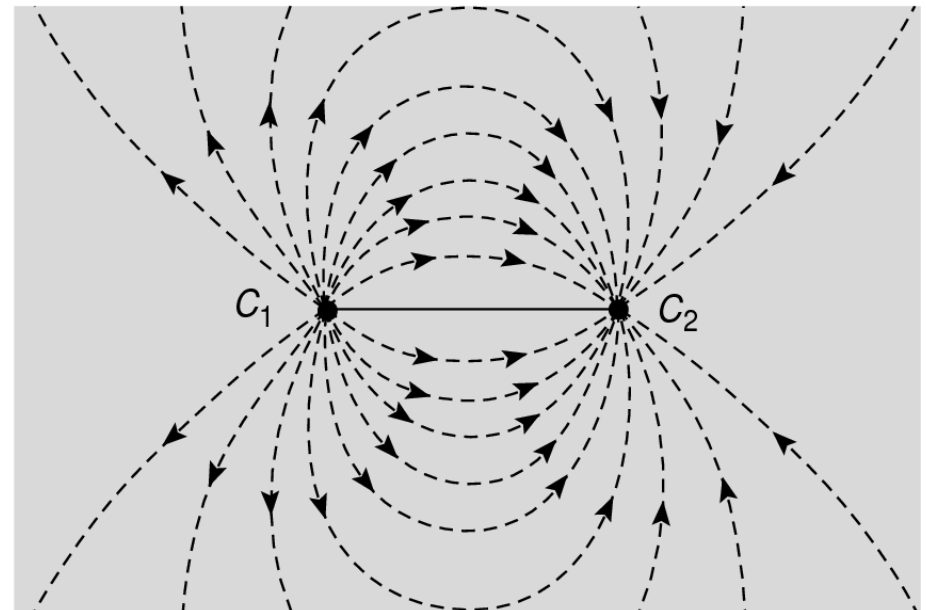
Subsurface Current Paths

- Why does electricity spread out and follow a curved path in the subsurface?
 - A thin layer has a large resistance $R = \rho \frac{l}{a}$
 - Electricity follows the path or area of least resistance

(a) section

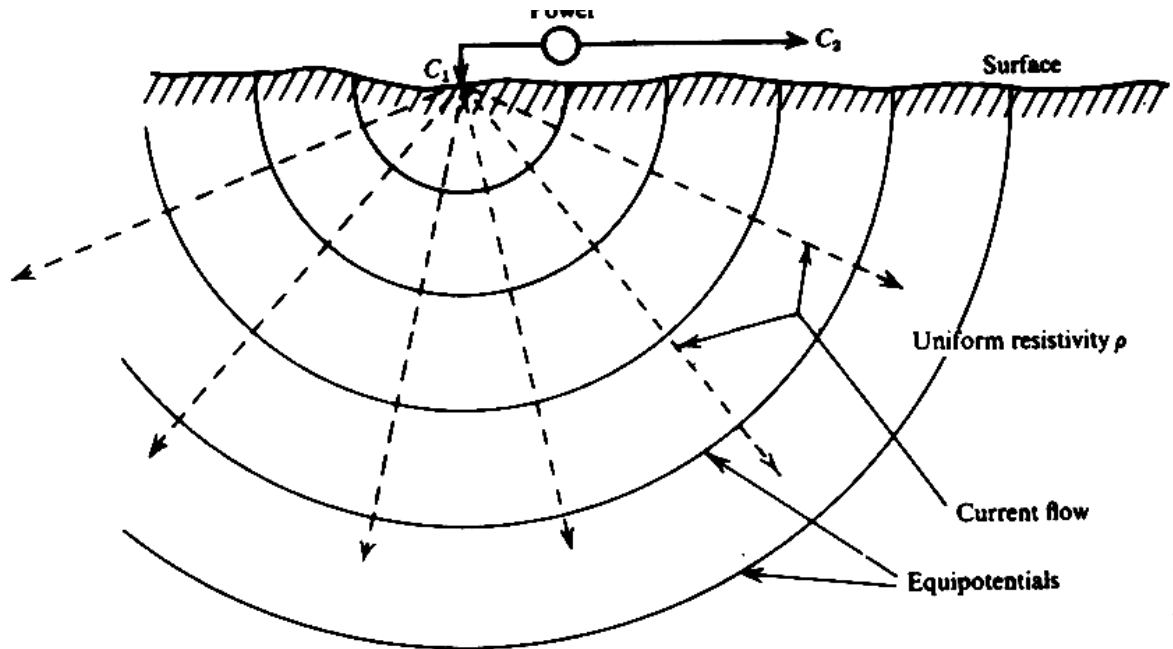


(b) plan



Current Source on Surface

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

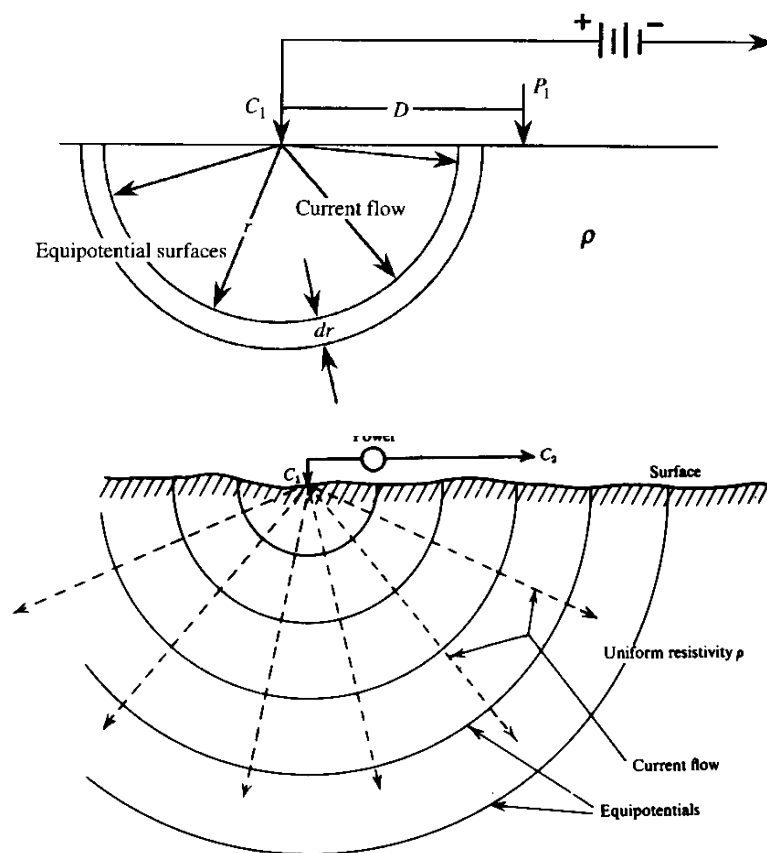


Boundary conditions:

- 1) As $r \Rightarrow \infty$, $V \Rightarrow 0$.
- 2) V is continuous across any boundary
- 3) Tangential \mathbf{E} continuous across any boundary
- 4) Normal \mathbf{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:



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

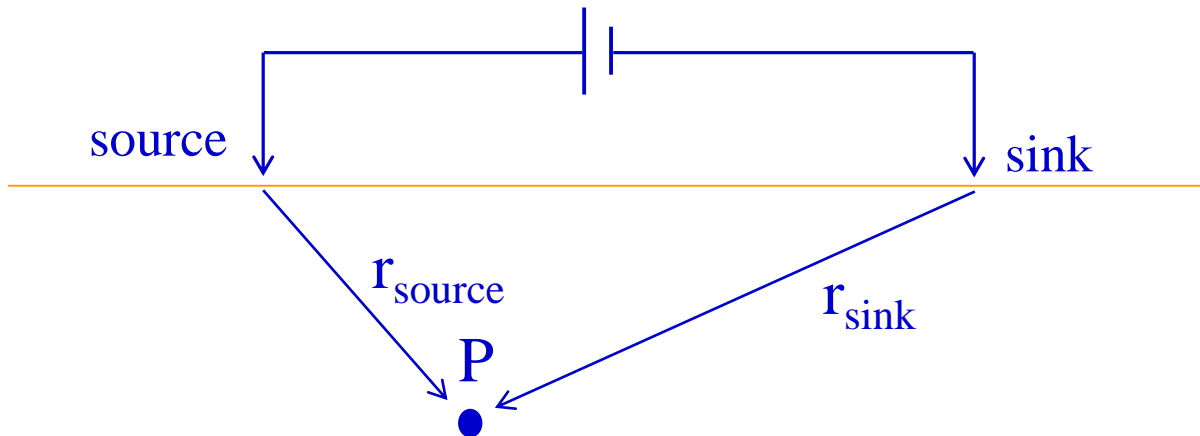
Voltage decreases as the inverse of the distance from the current source.

Shape of constant voltages are hemispheres for a single point source

$$\begin{aligned} V_D &= \int_D^\infty dV = \frac{i\rho}{2\pi} \int_D^\infty \frac{dr}{r^2} = \frac{i\rho}{2\pi} (-1) \frac{1}{r} \Big|_D^\infty \\ &= \frac{i\rho}{2\pi} (-1) \left(\frac{1}{\infty} - \frac{1}{D} \right) = \frac{i\rho}{2\pi D} \end{aligned}$$

Two Current Electrodes: Source and Sink

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



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

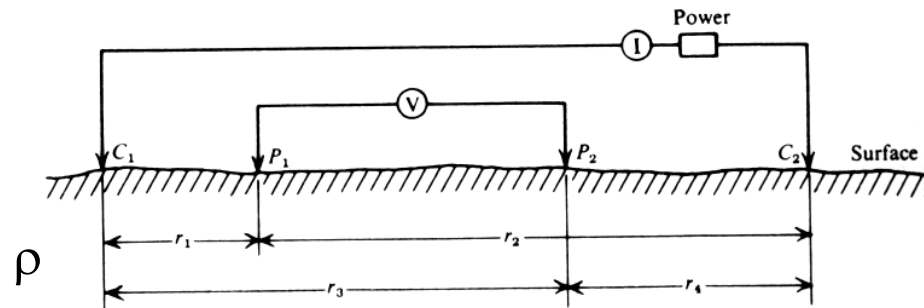
$$V_{\text{sink}} = \frac{i\rho}{2\pi r_{\text{sink}}}$$

Total Voltage at P:
(superposition)

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

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

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

Can be rewritten

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

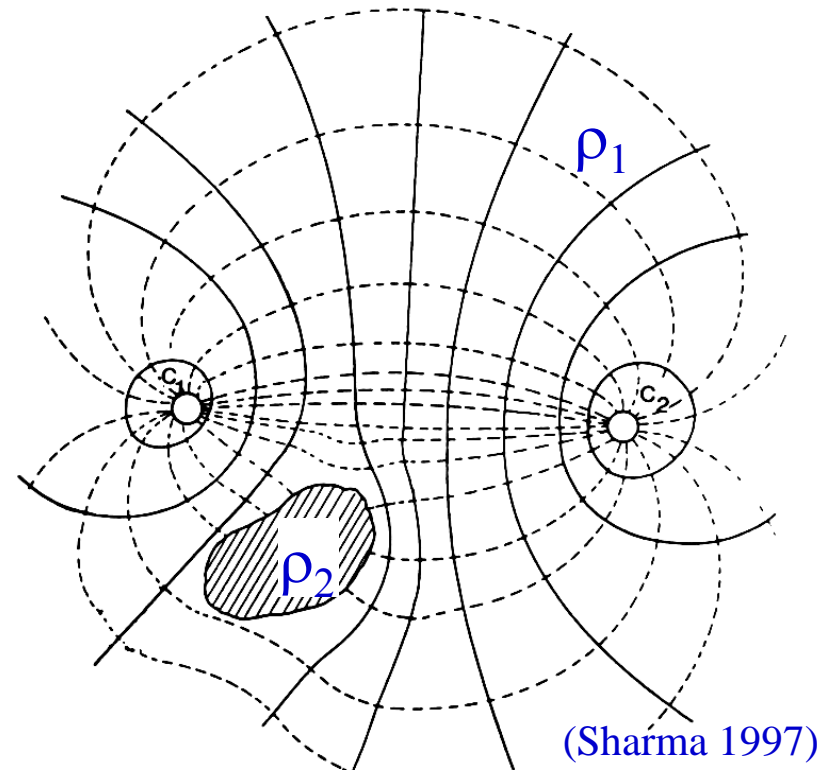
where $2\pi G$ is the *Geometrical Factor* of the array.

Apparent Resistivity

Previous expression can be rearranged in terms of resistivity:

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

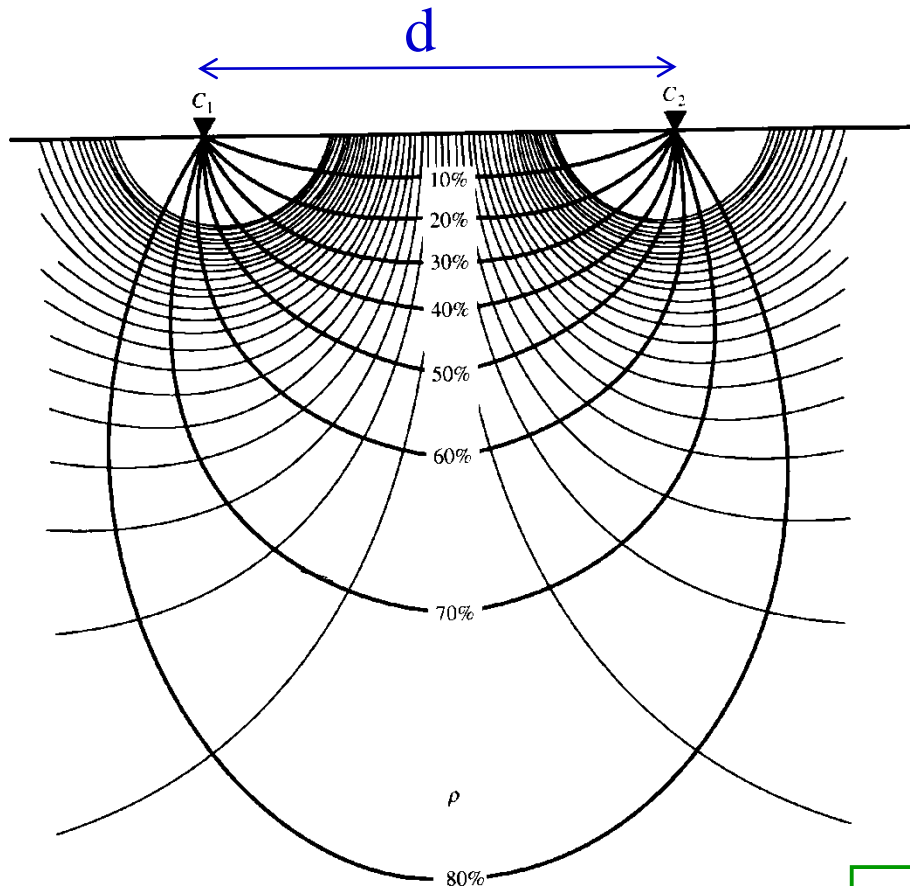
This can be done even when medium is inhomogeneous. The result is then referred to as *Apparent Resistivity* ρ_a .



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

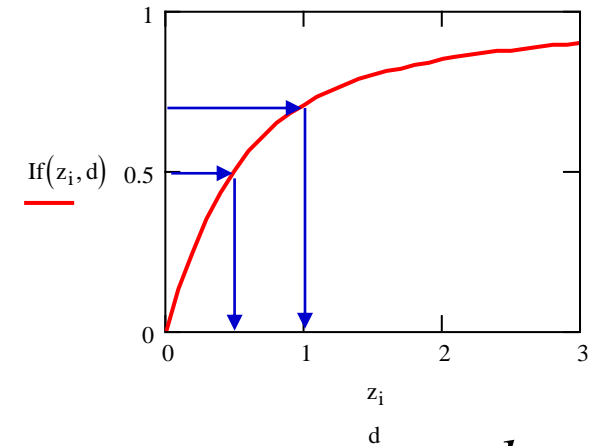
Current Distribution

Homogeneous medium



fraction total current

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



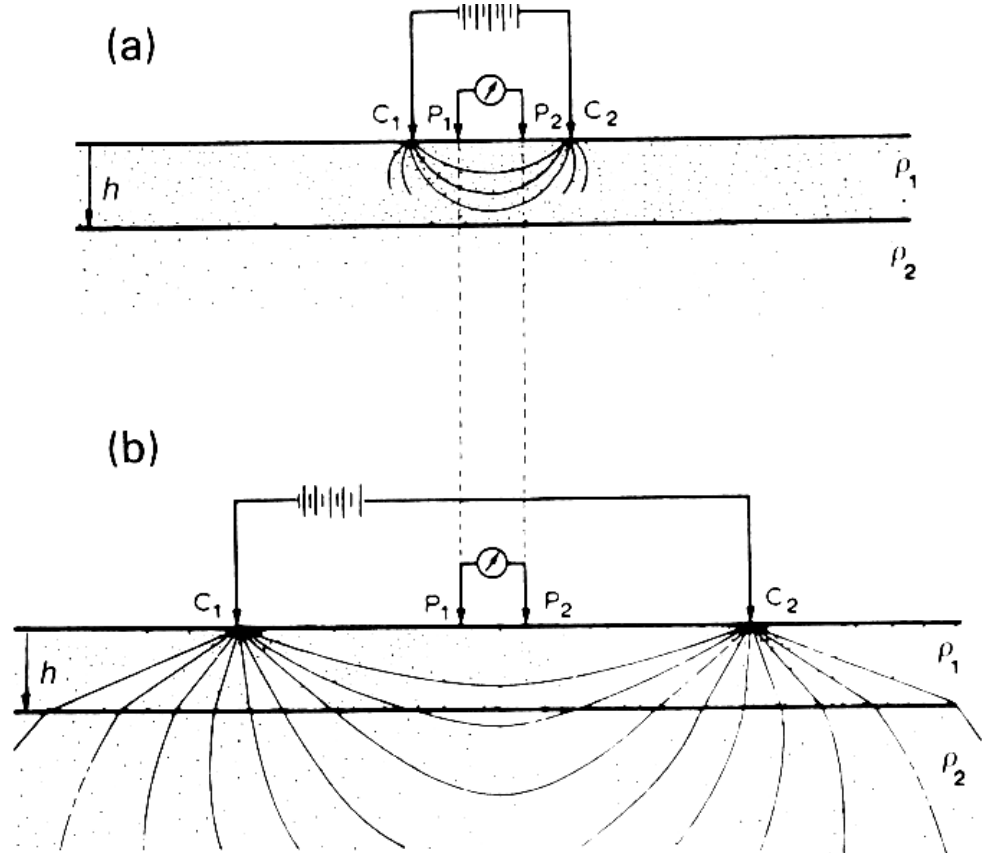
$$i_f = 0.5 \text{ at } z = \frac{d}{2}$$

$$i_f = 0.7 \text{ at } z = d$$

Wider spacing \rightarrow Deeper currents

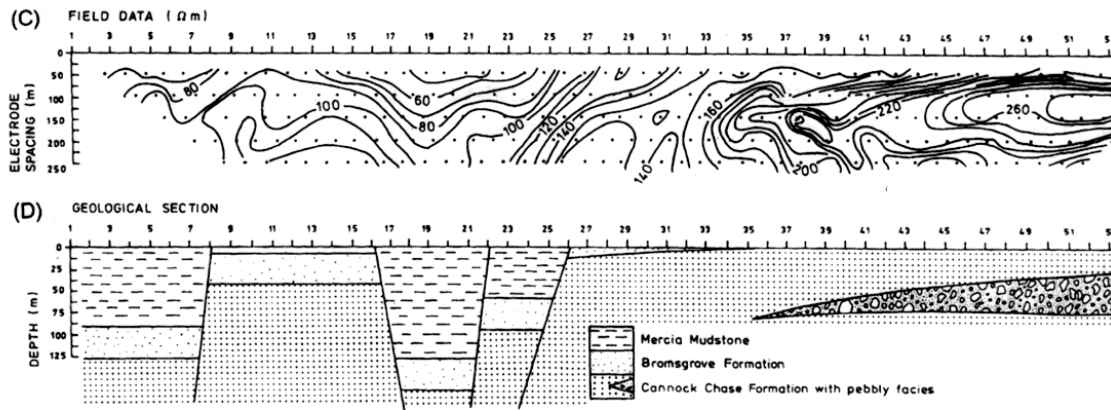
Vertical Electric Sounding

- 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.



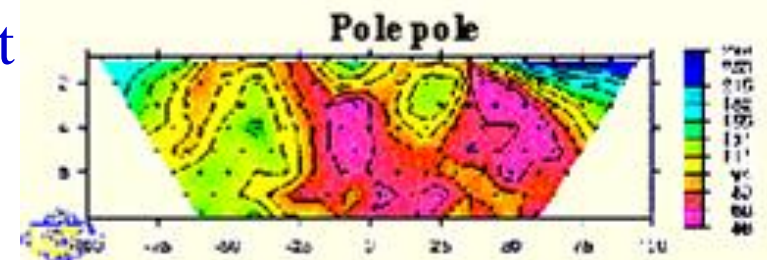
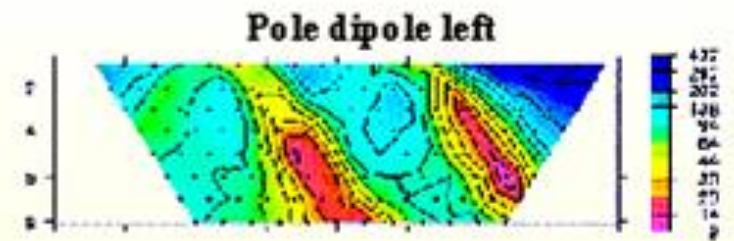
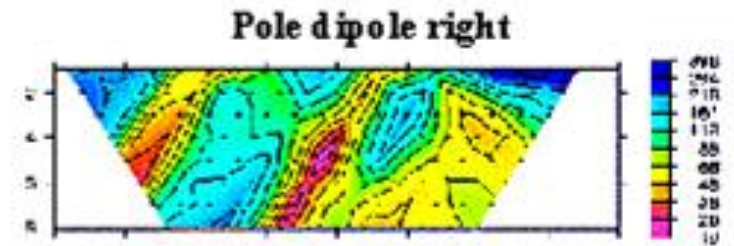
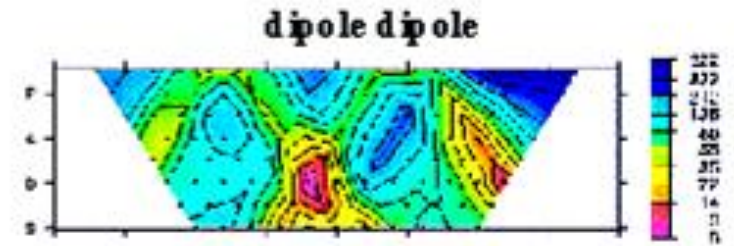
(Sharma 1997)

Pseudo-Sections



(Reynolds 1997)

- Can sometimes be used to qualitatively assess geology
- Warning: Can also prove to be very difficult to interpret directly, with different arrays yielding very different results.



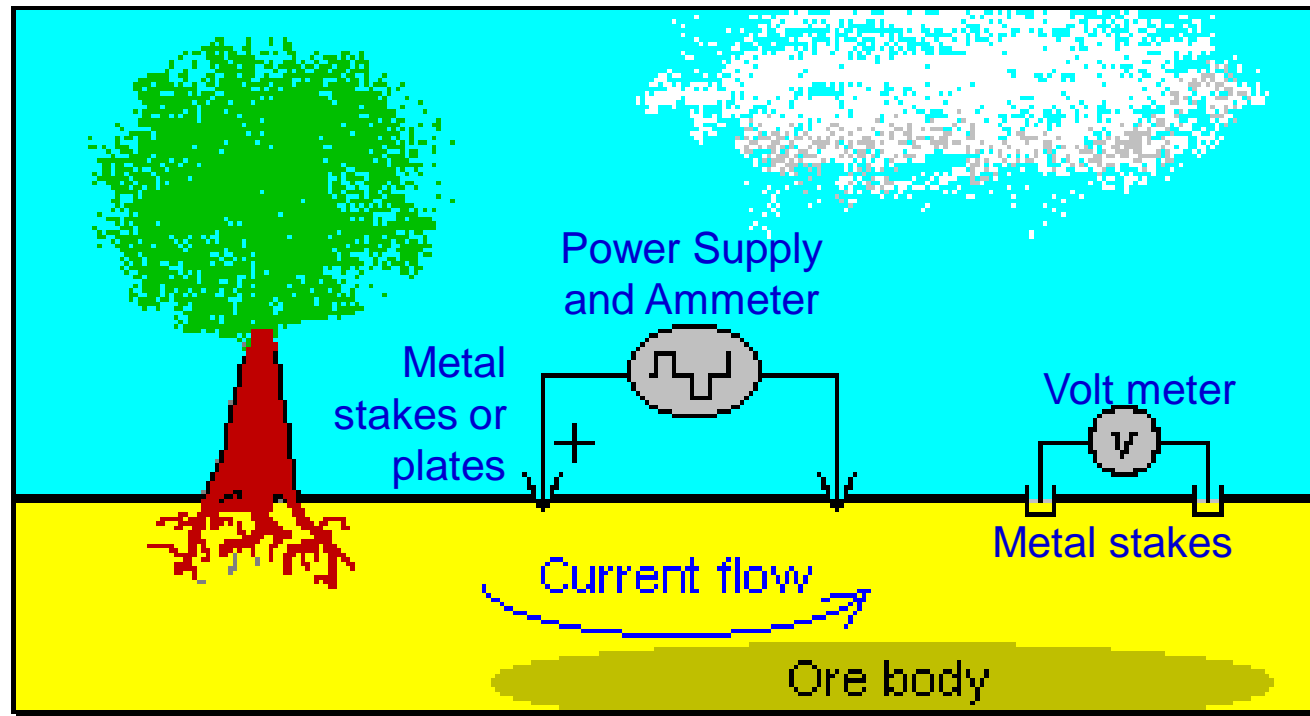
Measurement Systems

Transmitter

- Power Supply
 - DC
 - AC (more common)
- Ammeter
- Metal electrodes

Receiver

- Voltmeter
- Metal Electrodes



Generalized Profile Interpretation

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

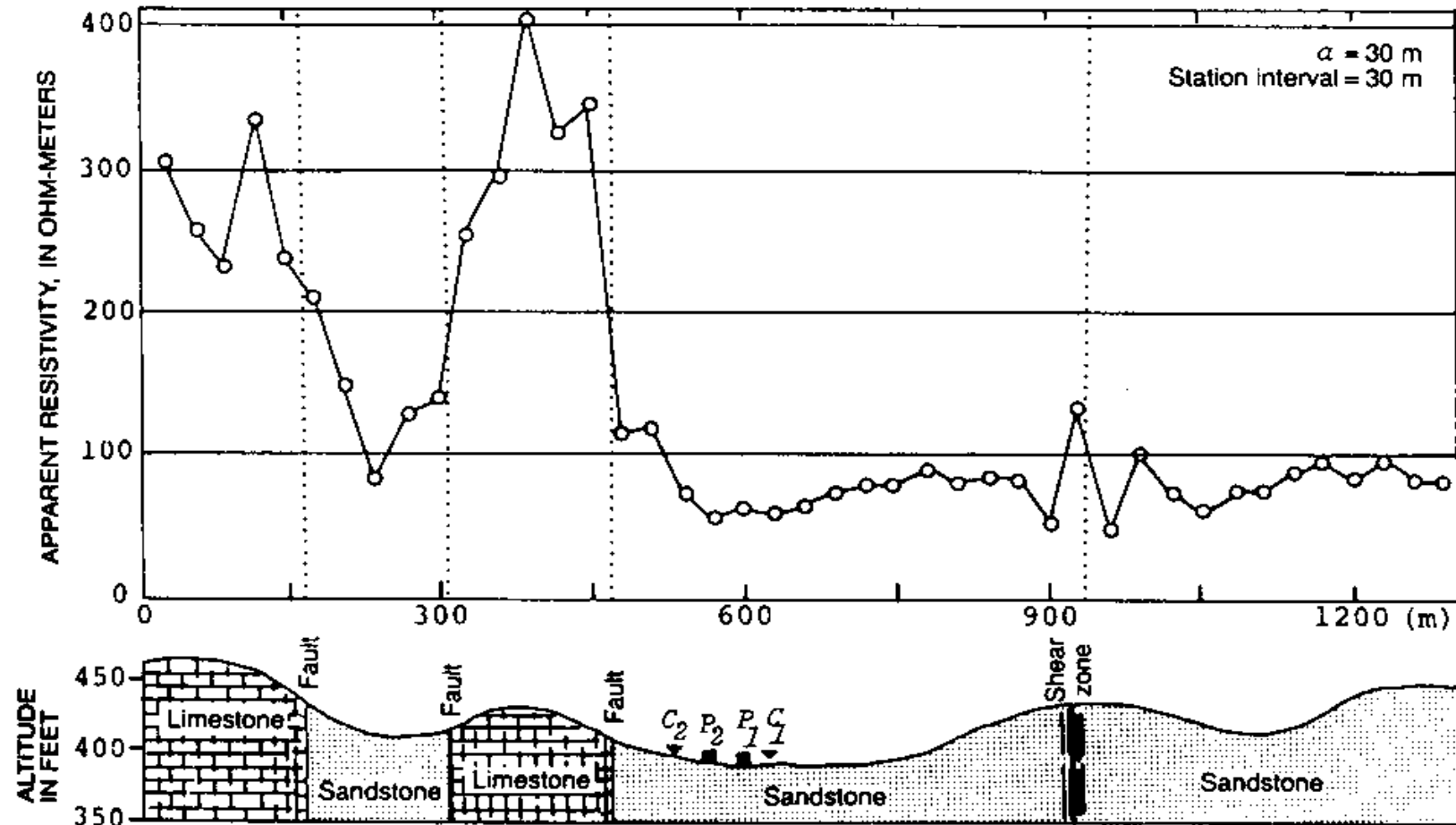
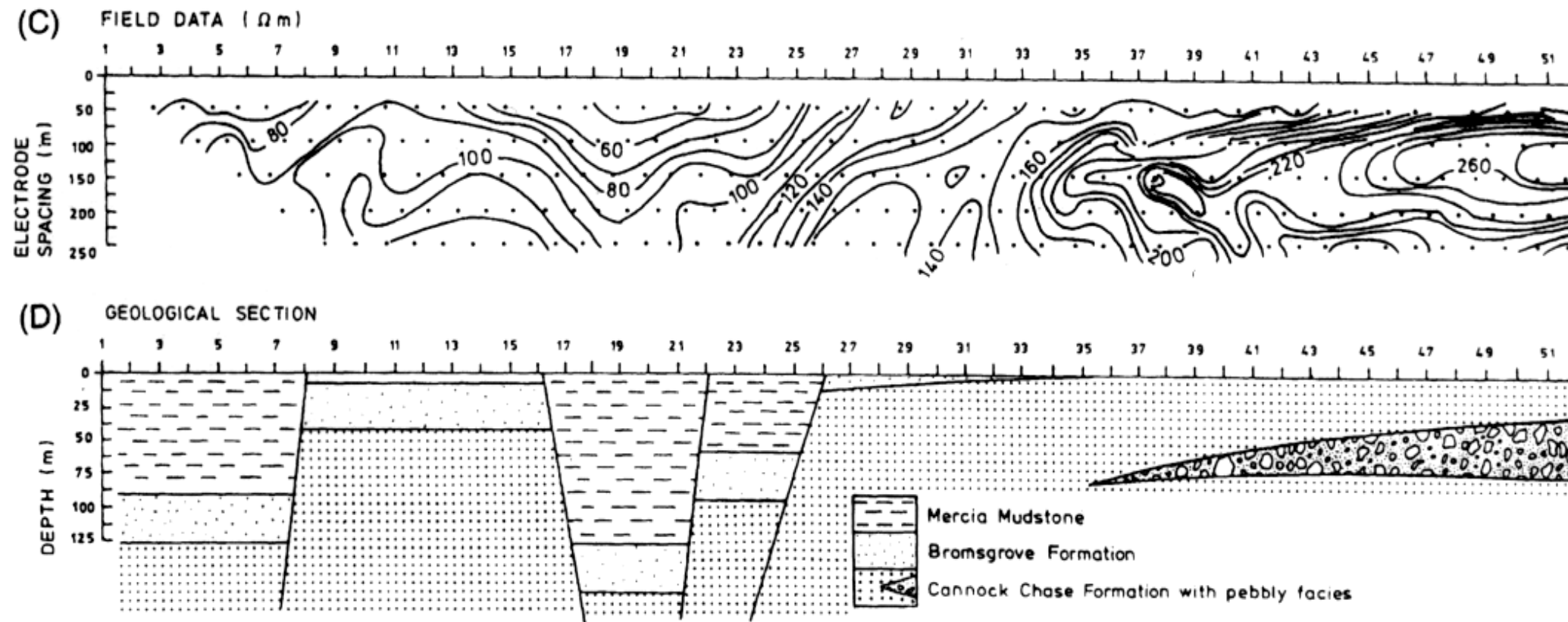


Fig. 6.19 Horizontal resistivity profile across a shear zone and limestone fault block in Illinois; Wenner configuration. (After Hubbert, 1932.)

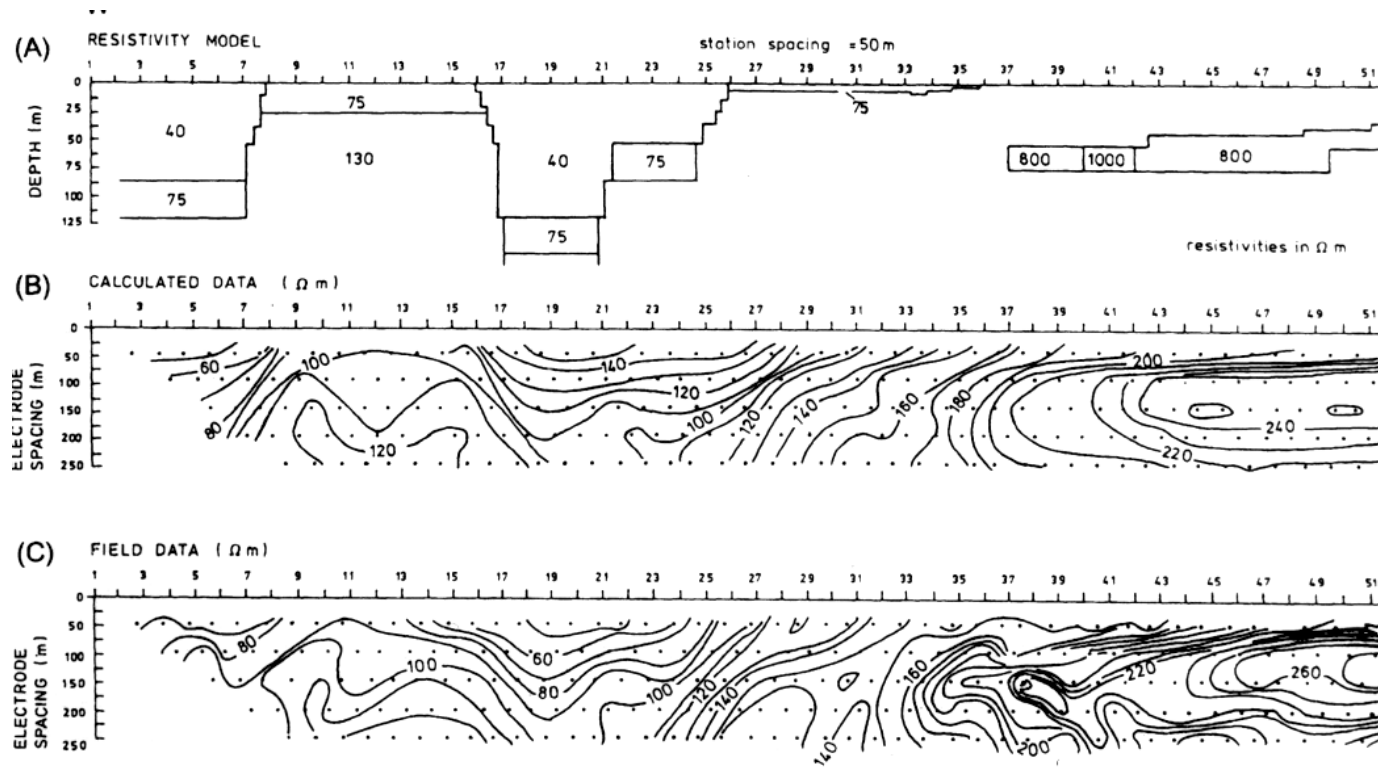
Qualitative 2D Profile Interpretation

- 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

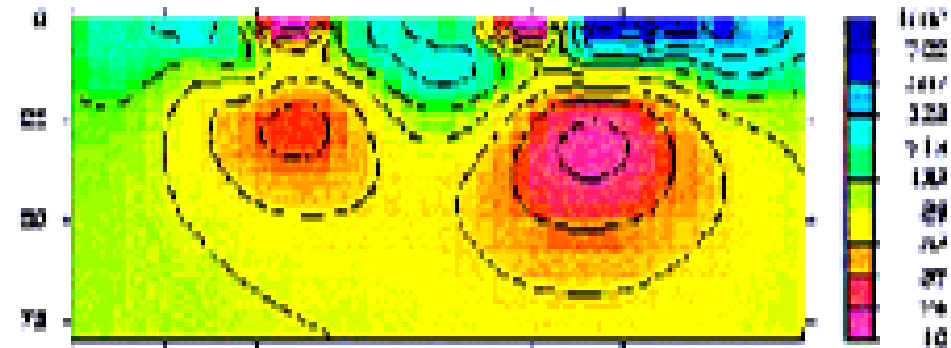
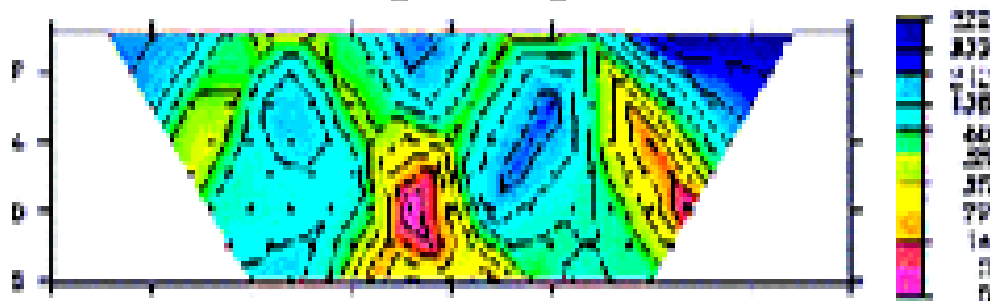
- Using mathematical expressions that describe the physics to calculate the data that would result from a given combination of geoelectric model and electrode configuration.
- Generally a *linear* process.
- Forward modeling produces *unique* results.



Computerized Interpretation: Inverse Modeling

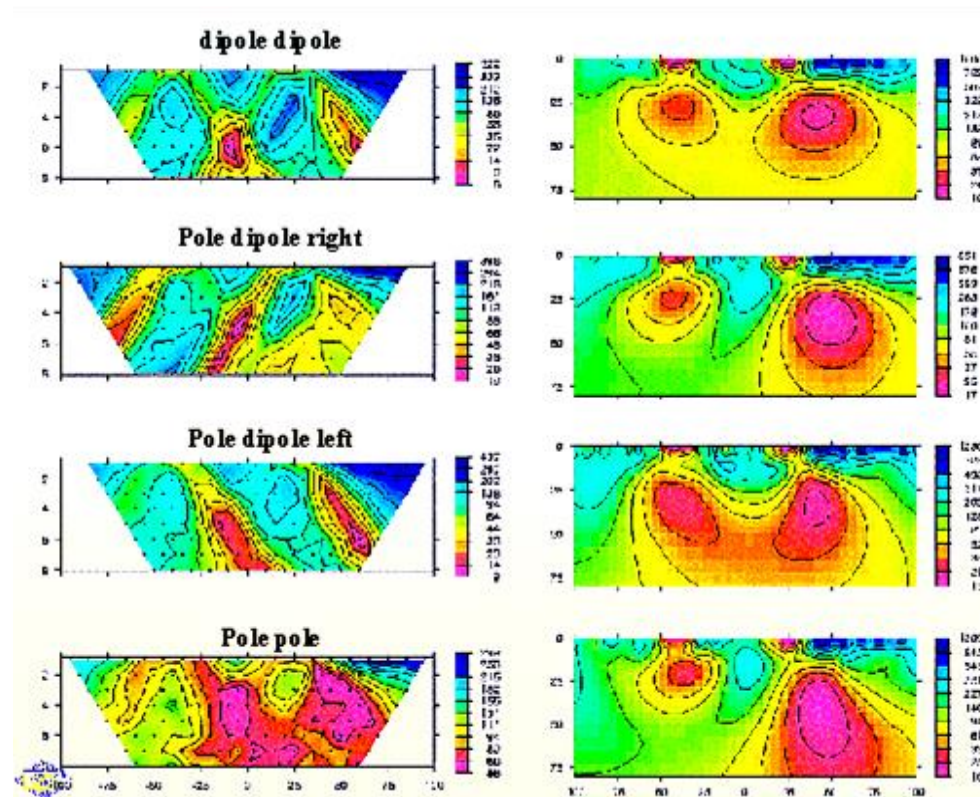
- Going the opposite direction. We measure data and know the array configuration, and through *inversion* wish to determine a geoelectric model that would produce data similar to those measured.
- Problems:
 - Generally problem is non-linear.
 - Problem is non-unique. Thus must add constraints of some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

dipole dipole



Inverse Modeling

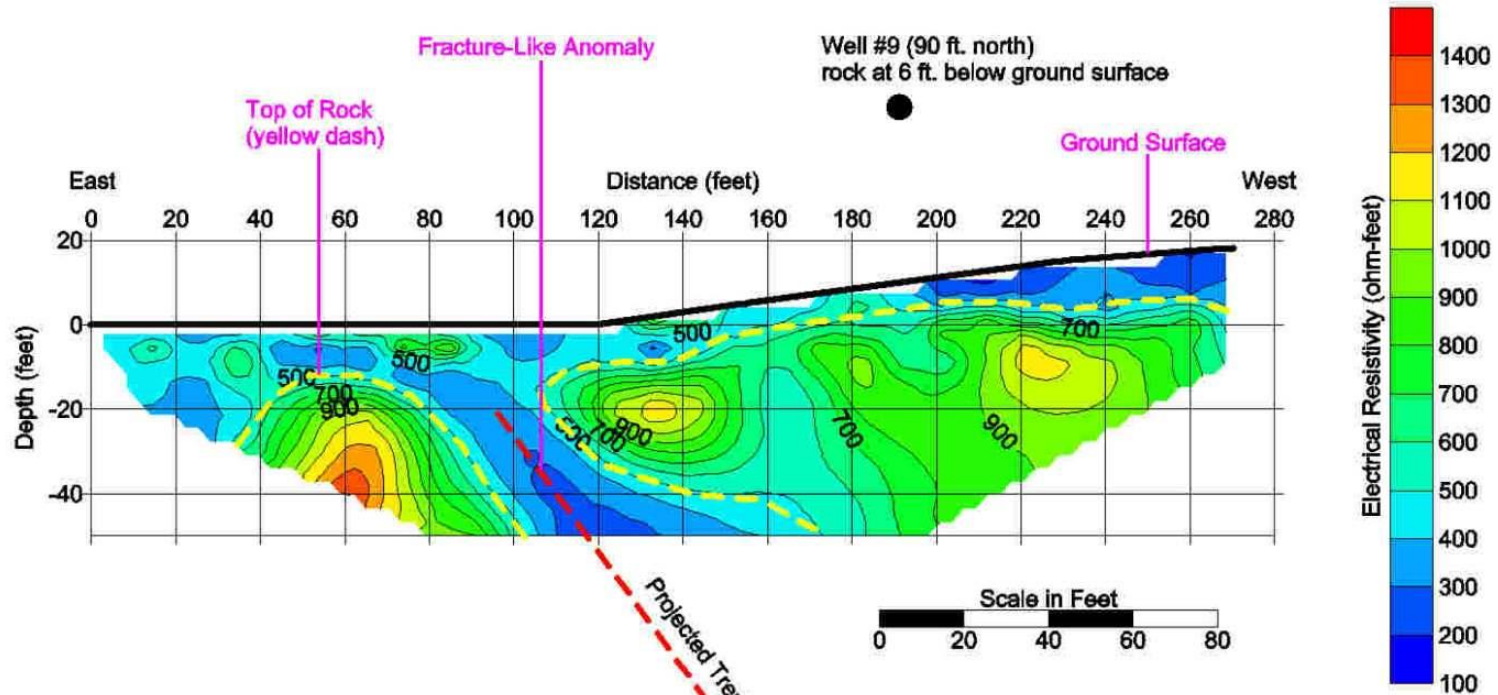
- Benefits:
 - Automatic, it helps to remove *user bias*. *However sometimes the user's bias is needed to produce a decent model*
 - Automatically removes differences associated with different electrode collection schemes.



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
 - Near surface very well resolved – min. horizontal resolution equal to minimum electrode separation
 - Depth resolution is array dependent
 - 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



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.

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

Courtesy of Quantum Geophysics, Inc., Phoenixville, Pennsylvania

AGI Advanced Geosciences, Inc.

Tel: +1 (512) 335-3338

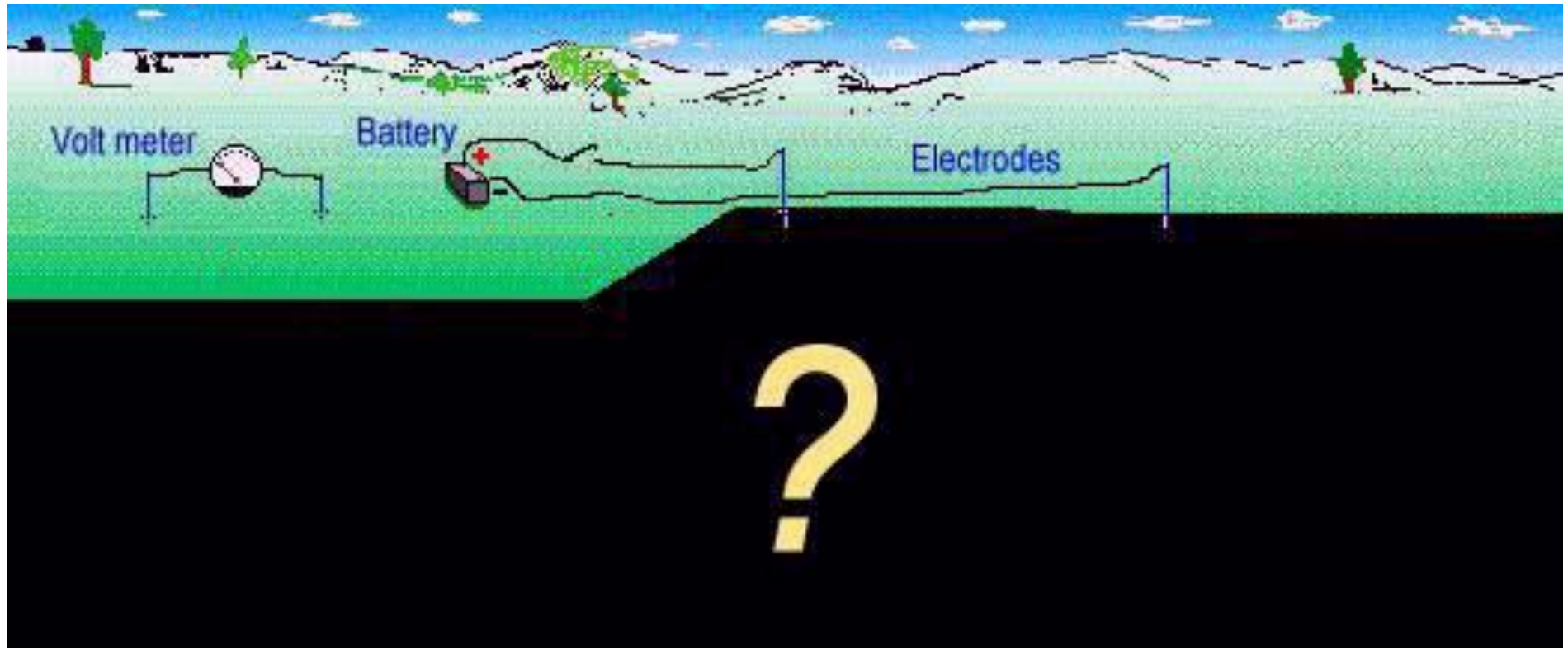
Fax: +1 (512) 258-9958

E-mail: sales@agiusa.com

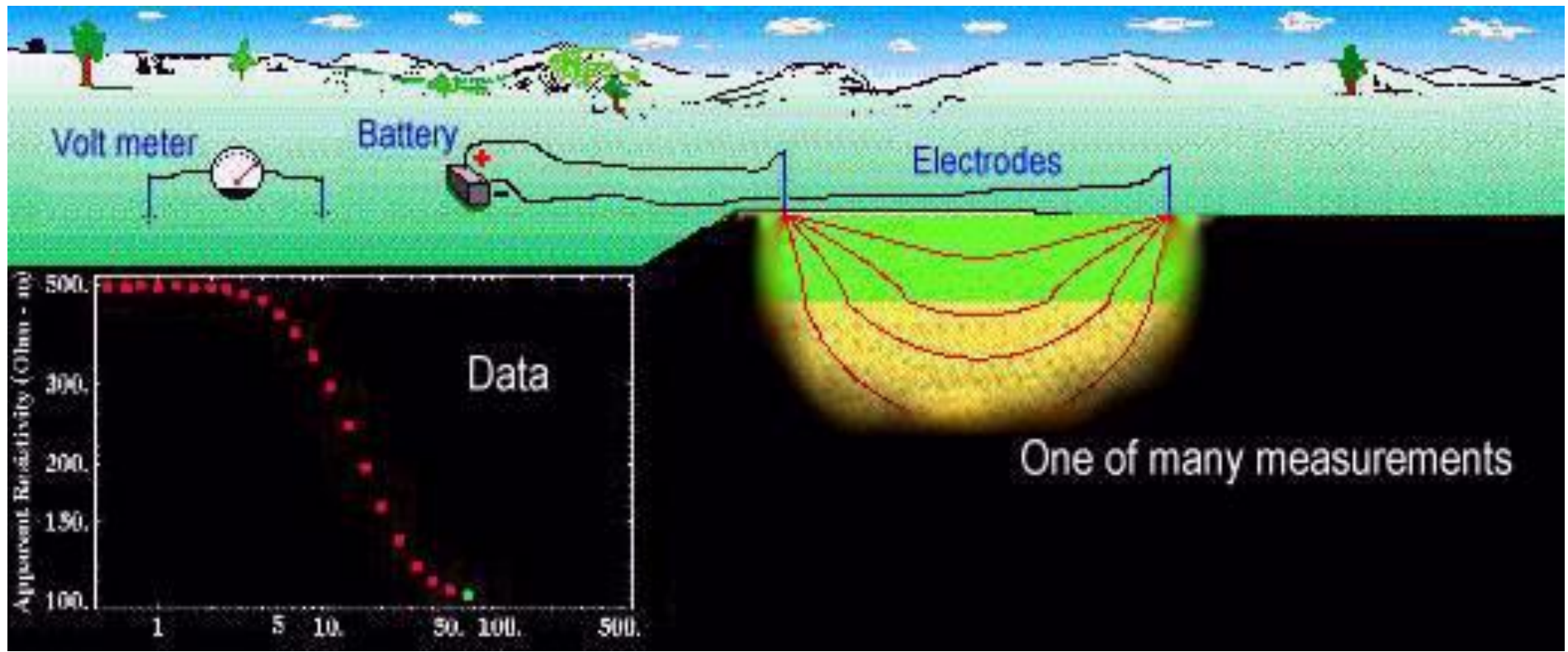
Web site: <http://www.agiusa.com>

An example of how the distribution of a physical property (electrical conductivity in this case) can be measured to provide information about geologic materials.

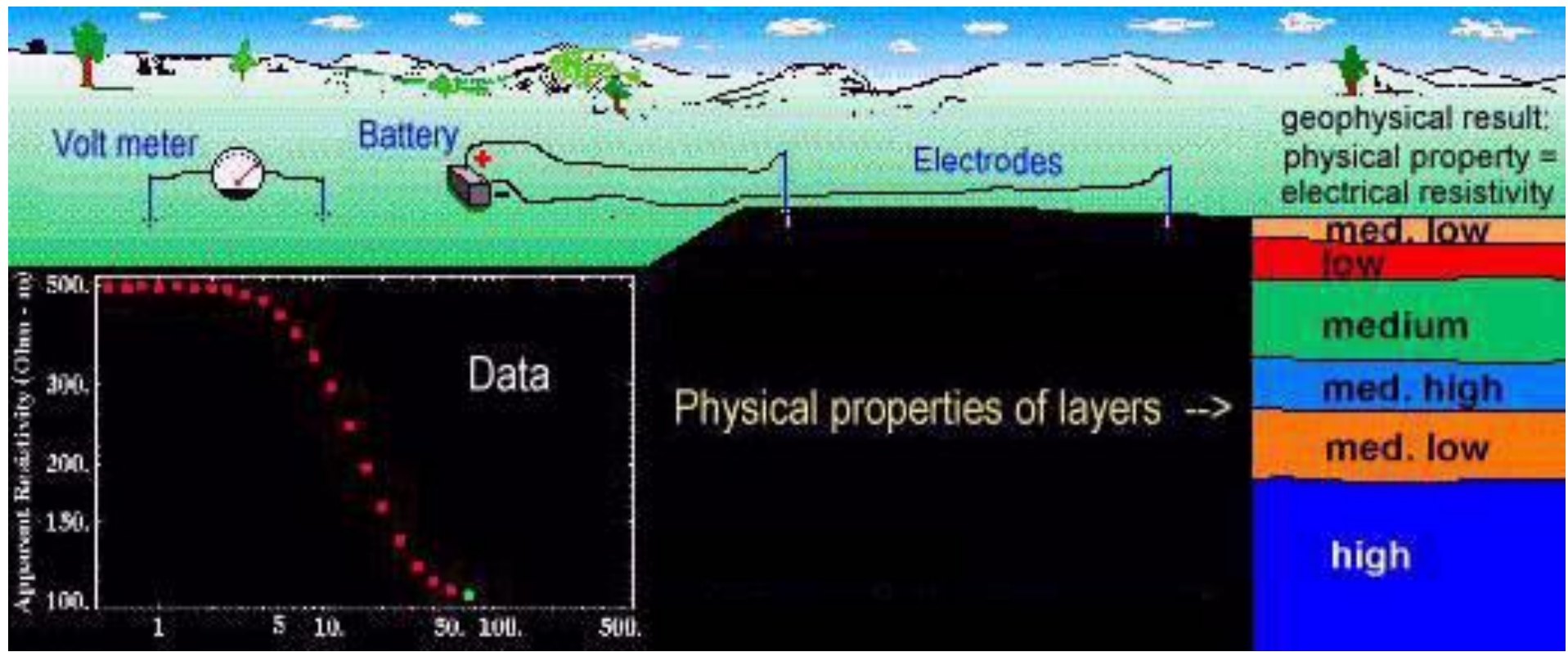
1. The physical properties under this surface are unknown. A geophysical survey - DC resistivity in this case - is used to generate data.



2. Current is injected into the ground, and resulting voltages are measured as electrode geometry varies. In this case, voltages get smaller as electrodes are separated further and further apart.



3. Inversion of this data set produces an estimate of a "layered earth" or 1D model of the relevant physical property - electrical conductivity.



4. Interpretation converts the model into geological information.

